

DTIC FILE COPY

AGARD-AG-301 VOL.2

1

AGARD-AG-301 VOL.2

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

TRIPLE ANGELES 32230 NED 40 SUR SEINE FRANCE

AD-A225 265

AGARDograph No.301

Aircraft Trajectories Computation—Prediction—Control

(La Trajectoire de l'Avion
Calcul—Prédiction—Contrôle)

Volume 2

DISTRIBUTION STATEMENT A

Approved for public release
Distribution Unlimited

DTIC

ELECTE

JUL 17 1990

S

D

D

NORTH ATLANTIC TREATY ORGANIZATION



DISTRIBUTION AND AVAILABILITY
ON BACK COVER

90 07 16 310

NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARDograph No.301

Aircraft Trajectories
Computation—Prediction—Control

(La Trajectoire de l'Avion
Calcul—Prédiction—Contrôle)

VOLUME 2

Air Traffic Handling and Ground-Based Guidance of Aircraft

Edited by

André Benoît
Programme Director



Accession For	
NTIS CRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;
- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture,
- Improving the co-operation among member nations in aerospace research and development;
- Exchange of scientific and technical information;
- Providing assistance to member nations for the purpose of increasing their scientific and technical potential,
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced directly from material supplied by AGARD or the authors.

Published May 1990

Copyright © AGARD 1990
All Rights Reserved

ISBN 92-835-0562-X



*Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ*

Préface

Quels que soient la complexité de la situation aérienne et le potentiel de navigation des aéronefs, le contrôle de la circulation reste assuré par l'homme. Les technologies modernes sont utiles au contrôleur, mais uniquement pour l'accomplissement de tâches d'importance secondaire; nullement au niveau décisionnel. Par contre, le pilotage automatique est chose courante, même au cours des phases critiques du vol. De plus, les techniques modernes permettent de planifier un vol et de réaliser son déroulement d'une manière entièrement automatique.

Aussi, la gestion de la circulation aérienne présente-elle à l'heure actuelle des caractéristiques qui relèvent du paradoxe.

D'une part le commandant de bord, responsable de la sécurité du vol (il y va de la vie de plusieurs centaines de personnes, dont la sienne), est en mesure de suivre une trajectoire programmée dans les quatre dimensions avec une précision élevée grâce à une gestion du vol informatisée couplée au guidage et pilotage automatiques.

D'autre part, la structure de l'espace aérien — adaptée aux possibilités humaines — oblige à découper le vol en une série de phases. Les tâches de contrôle sont réparties entre plusieurs organismes, chaque phase se déroulant pratiquement indépendamment des phases antérieures et ultérieures. A titre d'exemple, le contrôle d'un vol Bruxelles-Londres — d'une durée de 45 minutes environ, peut comporter jusqu'à cinq phases — sans computer sectorisation, contrôle d'aérodrome, contrôle d'approche et contrôle au sol.

Cette situation changera sous l'impulsion de facteurs économiques, opérationnels et technologiques agissant dans le même sens. L'adaptation du segment sol au potentiel de pilotage et de navigation des avions aura pour conséquence la rationalisation et l'automatisation des opérations de gestion et de contrôle avec comme corollaire une exploitation efficace, voire maximale, de la capacité disponible.

Le concept de la Zone de Convergence (ZOC) constitue un premier pas dans ce sens. Il a pour objet l'intégration en temps réel du contrôle de la navigation aérienne dans une zone étendue comprenant une région terminale importante et éventuellement plusieurs aéroports secondaires. EUROCONTROL, l'Organisation européenne pour la sécurité de la navigation aérienne, en collaboration avec des organismes nationaux de contrôle de la navigation aérienne, des instituts de recherche et plusieurs compagnies aériennes des Etats membres, est en Europe à l'origine de ces développements. Par la suite plusieurs pays ont réalisé des versions plus spécifiques en vue d'une utilisation opérationnelle immédiate.

L'approche française, connue sous l'acronyme MAESTRO, marque le franchissement d'une étape importante dans l'évolution du processus d'automatisation du contrôle. Aidés d'un ordinateur jugeant de la manoeuvrabilité d'un aéronef, une équipe de deux contrôleurs en route et d'un contrôleur d'approche chevronnés procèdent, en étroite collaboration, pendant la phase en route, à une "prérégulation" du trafic entrant. Ils veillent à étaler les arrivées aux points d'entrée dans les zones de contrôle terminales, situés à quelque 50 nm des pistes. Les contrôleurs d'approche savent désormais qu'il est possible de faire atterrir les aéronefs sans recourir de façon systématique aux attentes habituelles; un de leurs collègues ayant contribué à la recherche de la solution. En principe, lorsque le présent volume sera mis sous presse, l'approche MAESTRO devrait avoir été adoptée par le Centre de contrôle Nord de la France pour le trafic à destination d'Orly. C'est avec le plus grand intérêt que l'on suivra l'évolution de cette collaboration devenue essentielle entre le contrôleur et son aide informatique.

Ce deuxième volume du traité sur les trajectoires de vol est consacré pour l'essentiel aux méthodes, procédures, techniques et technologies utiles voire indispensables à l'amélioration future — à court et à moyen terme — de la gestion du trafic aérien. L'assistance informatique à la prise de décisions est essentielle s'il s'agit de prévoir et de maîtriser le déroulement des événements tels que l'attribution des créneaux d'atterrissage et la prévention des conflits — ceux qui, faute de mesures, se produiraient inévitablement. Une attention particulière est accordée à la régulation du trafic et au guidage des vols dans un environnement 4-D avec contraintes sur les temps d'arrivée.

Après une brève description des perspectives européennes, ce volume met l'accent sur l'utilisation en temps réel de la prédiction et du contrôle de trajectoires — aspects fondamentaux et applications, le guidage des aéronefs à partir du sol, la poursuite radar, le rôle potentiel des satellites dans le domaine de la surveillance, l'influence de la qualité des prévisions météorologiques et le réalisme de l'avion dans les techniques de simulation de la gestion et du contrôle du trafic aérien.

André Benoît
Directeur du programme
Membre de la Commission Guidage et Pilotage

Preface

Irrespective of the complexity of the traffic situation or the navigation potential of the aircraft, the control of air traffic is at present carried out by the human controllers. Clearly, assistance from modern technology is available, but for the conduct of ancillary tasks, never at the decision level. In contrast, pilots rely on automatic guidance, especially in the most critical phases of flight. Further, the present trends in aircraft operations make it realistic to envisage the planning of a complete flight, or an appreciable part thereof, with little subsequent intervention from the pilot.

Accordingly, the present handling of air traffic exhibits the following paradoxical characteristics.

On the one hand, the captain responsible for the safe conduct of the flight — several hundred human lives involved, his own included — will be able to plan a 4-D trajectory and execute this plan with a high degree of accuracy, trusting the on-board computerized navigation, guidance and control equipment.

On the other hand, the air traffic handling organization cuts the flight into slices and distributes the control tasks to the controllers of the relevant units, each phase being controlled practically independently of what has happened previously and regardless of what the subsequent unit will do. For example, a straight 45-minute Brussels to London flight may comprise up to 5 different control phases, not to mention sectorization, aerodrome/tower and taxi control.

This situation must and will change, under the influence of several essential factors acting in the same direction, which include the requirements covering an increased use of the available capacity, more consideration for the economy of flight operations and adequate adaptation of air traffic handling practice to the individual aircraft's 2-D, 3-D or 4-D navigation capability.

The Zone of Convergence (ZOC) concept constitutes an initial step in an attempt to meet these requirements. It aims at integrating on-line the handling of air traffic over an extended area including and surrounding a main Terminal Manoeuvring Area (TMA) and possibly secondary airports. In Europe, the concept was initially developed at the European Organisation for the Safety of Air Navigation, EUROCONTROL, in co-operation with air traffic control units, research institutions and several airlines of the Organisation's Member States. Subsequently, specific versions designed for immediate operational use were initiated by several national authorities.

The French approach, known under the acronym MAESTRO, constitutes a remarkable step in the evolution of the Air Traffic Control (ATC) automation process. With the assistance of the computer assessing the aircraft's range of manoeuvrability, a team of 3 duly selected en-route (2) and approach (1) controllers working in close co-operation, "pre-regulate" the inbound traffic while en-route, ensuring a properly scheduled set of deliveries at the entries (geographical fixes, some 50 nm from the runways) into the TMA. As a result, the approach controllers know that the problem of bringing the aircraft down to the runway without the systematic use of "stacking" has a solution. Further, they also know that one of their colleagues was involved in the negotiation of the solution. When this volume is printed, MAESTRO will in principle be in operation in the North Control Centre of France, for the traffic inbound to Orly. It will be most interesting to follow the evolution of this essential co-operation, namely the controller and his computerized assistant.

The second volume of the treatise on Aircraft Trajectories is mainly devoted to methods, procedures, techniques and technologies considered for the benefit of air traffic handling.

The emphasis is placed on some preliminary aspects relating to the computerized decision assistance to be provided to the air traffic controller for the determination and control of future events, such as the allocation of landing time slots, avoidance of conflicts — otherwise certain to happen — or any other critical situation. Special attention is given to the regulation of traffic and the guidance of flights in a time-of-arrival constrained environment.

The main parts of the volume cover successively, general requirements and European prospects, on-line use of aircraft trajectory prediction, including fundamentals, applications, ground-based guidance of aircraft, radar tracking, the potential role of the satellite for surveillance, the impact of the quality of meteorological forecasts and specific consideration of air traffic handling simulations.

André Benoît
Programme Director and Editor
Guidance and Control Panel

Guidance and Control Panel Officers

Chairman: Ir P.Ph. van den Broek
Department of Aerospace Engineering
Delft University of Technology
Kluyverweg, 1
2629 HS Delft
Netherlands

Deputy Chairman: Prof. E.B. Stear
Executive Director
Washington Technology Center
University of Washington
376 Loew Hall — FH-10
1013 NE 40th Street
Seattle, WA 98195
United States

TECHNICAL PROGRAMME

Programme Director and Editor: Dr André Benoit
Faculté des Sciences Appliquées
Université Catholique de Louvain
B-1348 Louvain-la-Neuve
Belgium

European Organisation for the Safety of Air Navigation
EUROCONTROL
Engineering Directorate
72, rue de la Loi
B-1040 Bruxelles
Belgium

PANEL EXECUTIVE

From Europe
CDT Moustafa Mouhamad (FAF)
Executive, GCP
AGARD-NATO
92200 Neuilly-sur-Seine
France
Telephone: 33(1)4738 5780 — Telex: 610 176F

From USA and Canada
Executive, GCP
AGARD-NATO
APO New York 09777

ACKNOWLEDGEMENT/REMERCIEMENTS

The Programme Director and Editor and the Guidance and Control Panel wish to express their appreciation to all authors and co-ordinators who contributed to this AGARDograph and made its publication possible.

Le Directeur du Programme et la Commission Guidage et Pilotage tiennent à remercier tous les auteurs et coordonnateurs qui contribuèrent à la réalisation et la publication de cette AGARDographie.

Activities in Air Traffic Handling

Over the past 20 years, the Guidance and Control Panel of the Advisory Group for Aerospace Research and Development to the North Atlantic Treaty Organization has devoted part of its activities to the fascinating field known historically as Air Traffic Control.

The Panel's contributions listed below cover in particular, the air and ground components considered as parts of a single system, the methods, techniques and technologies applicable to or usable for the management of the flows of aircraft and the control of individual flights, the integration of control phases over extended areas such as in the Zone of Convergence type concepts, the 4-D guidance of aircraft in critical conditions, the ever-increasing level of automation and its impact on the essential role of the human acting on-line in the control loop.

AIR TRAFFIC CONTROL SYSTEMS

Guidance and Control Symposium, Edinburgh, Scotland,

26—29 June 1972.

AGARD-CP-105, April 1973.

A SURVEY OF MODERN AIR TRAFFIC CONTROL

AGARDograph AG-209, Vols. I and II

July 1975.

PLANS AND DEVELOPMENTS FOR AIR TRAFFIC SYSTEMS

Guidance and Control Panel Symposium, Cambridge, Mass., United States

20—23 May 1975.

AGARD-CP-188, February 1976.

AIR TRAFFIC MANAGEMENT: Civil/Military Systems and Technologies

Guidance and Control Symposium, Copenhagen, Denmark,

9—12 October 1979.

AGARD-CP-273, February 1980.

AIR TRAFFIC CONTROL IN FACE OF USERS' DEMAND AND ECONOMY CONSTRAINTS

Guidance and Control Symposium, Lisbon, Portugal,

15 October 1982.

AGARD-CP-340, February 1983.

EFFICIENT CONDUCT OF INDIVIDUAL FLIGHTS AND AIR TRAFFIC

or Optimum Utilisation of Modern Technology

(Guidance, control, navigation, surveillance and processing facilities)

for the Overall Benefit of Civil and Military Airspace Users

Guidance and Control Symposium, Brussels, Belgium,

10—13 June 1986.

AGARD-CP-410, December 1986.

AIRCRAFT TRAJECTORIES: Computation—Prediction—Control

AGARDograph AG-301, Vols. 1, 2 and 3:

Volume 1 FUNDAMENTALS

FLIGHT IN CRITICAL ATMOSPHERIC CONDITIONS

IMPACT OF NEW ON-BOARD TECHNOLOGIES ON AIRCRAFT OPERATION

Volume 2 AIR TRAFFIC HANDLING AND GROUND-BASED GUIDANCE OF AIRCRAFT

Volume 3 ABSTRACTS — BIBLIOGRAPHY — CONTRIBUTORS

ON-LINE HANDLING OF AIR TRAFFIC

Guidance & Control Aspects

AGARDograph AG-321, in preparation

Condensed Contents

Detailed Contents of all three volumes follow

VOLUME 1

PREFACE

PART I FUNDAMENTALS

PART II FLIGHT IN CRITICAL ATMOSPHERIC CONDITIONS

PART III IMPACT OF NEW ON-BOARD TECHNOLOGIES ON AIRCRAFT OPERATION

VOLUME 2

PART IV AIR TRAFFIC HANDLING

PART V GUIDANCE OF AIRCRAFT IN A TIME-BASED CONSTRAINED ENVIRONMENT

PART VI SURVEILLANCE

PART VII METEOROLOGICAL FORECASTS

PART VIII AIRCRAFT OPERATION IN AIR TRAFFIC HANDLING SIMULATION

VOLUME 3

PART IX BOOK OF ABSTRACTS

PART X BIBLIOGRAPHY (with Index)

PART XI LIST OF CONTRIBUTORS (with Index)

Contents

VOLUME 1

	Page
PREFACE (F)	iii
PREFACE (E)	iv
GUIDANCE AND CONTROL PANEL OFFICERS AND PROGRAMME DIRECTOR	v
GCP ACTIVITIES IN AIR TRAFFIC HANDLING	vi
CONDENSED CONTENTS	vii

Reference

PART I — FUNDAMENTALS

A — GENERAL OUTLINE OF THE PROBLEM

INTRODUCTION A L'ETUDE DES TRAJECTORIES D'AVION: Schéma Général des Problèmes Posés par Frédéric Haus	1F
---	----

INTRODUCTION TO THE STUDY OF AIRCRAFT TRAJECTORIES: General Outline of the Problem by Frédéric Haus	1E
---	----

B — COMPUTATION OF OPTIMAL TRAJECTORIES

OPTIMAL TRAJECTORIES OF AIRCRAFT AND SPACECRAFT by Antonio Miele	2
---	---

C — NON-LINEAR MODELS OF AIRCRAFT

COMPARISON OF A MATHEMATICAL ONE-POINT MODEL AND A MULTI-POINT MODEL OF AIRCRAFT MOTION IN MOVING AIR by R.Brockhaus	3
--	---

DETERMINATION DES LOIS DE GUIDAGE QUASI-OPTIMALES EN TEMPS REEL POUR DES TRAJECTOIRES D'AVIONS DE COMBAT (Computation of Sub-Optimal Real-Time Guidance Laws for Combat Aircraft Trajectories) par H.T.Huynh	4
---	---

PART II — FLIGHT IN CRITICAL ATMOSPHERIC CONDITIONS

A — GENESIS OF WIND AND INFLUENCE ON AIRPLANE TRAJECTORIES

CRITICAL ASPECTS OF TRAJECTORY PREDICTION: Flight in Non-Uniform Wind by Bernard Etkin and David Alexandre Etkin	5
---	---

EFFECT OF WIND AND WIND VARIATION ON AIRCRAFT FLIGHT — PATHS K.U.Hahn, T.Heintsch, B.Kaufmann, G.Schänzer and M.Swolinsky	6
--	---

B — FLIGHT CONTROL IN WINDSHEAR

AIRCRAFT FLIGHT IN WINDSHEAR by D.McLean	7
---	---

HOW TO FLY WINDSHEAR b. Paul Camus	8
---------------------------------------	---

C — FLIGHT SIMULATION**WIND MODELS FOR FLIGHT SIMULATION**

by K.U.Hahn, T.Heintsch, B.Kaufmann, G.Schänzer and M.Swolinsky

9

**PART III — IMPACT OF NEW ON-BOARD TECHNOLOGIES ON
AIRCRAFT OPERATION****A — FLIGHT MANAGEMENT IN AIR TRANSPORT****AIRCRAFT TRAJECTORY — PREDICTION AND CONTROL IN THE AIR TRANSPORT
FLIGHT MANAGEMENT COMPUTER SYSTEM**

by Peter J.Howells

10

B — CREW/AUTOMATION INTERFACE**IMPACT OF NEW TECHNOLOGY ON OPERATIONAL INTERFACE: From Design Aims
to Flight Evaluation and Measurement**

by J.J.Speyer, C.Monteil, R.D.Blomberg and J.P.Fouillot

11

VOLUME 2**PART IV — AIR TRAFFIC HANDLING****A — REQUIREMENT: INTEGRATION OF CONTROL PHASES****OPTIMUM ON-LINE HANDLING OF AIR TRAFFIC OVER WESTERN EUROPE**

by André Benoît and Sip Swierstra

12E

REGULATION TEMPS REEL OPTIMALE DU TRAFIC AERIEN EN EUROPE OCCIDENTALE

par André Benoît et Sip Swierstra

12F

B — PROSPECT: A FUTURE EUROPEAN AIR TRAFFIC SYSTEM CONCEPT**THE EUROCONTROL FUTURE ATS SYSTEM CONCEPT AND THE PROGRAMME OF
STUDIES, TESTS AND TRIALS**

by V.Vachiéry

13E

**LE CONCEPT DU FUTUR SYSTEME ATS EUROCONTROL ET LE PROGRAMME
D'ETUDES, ESSAIS ET EXPERIMENTATIONS**

par V.Vachiéry

13F

C — ON-LINE PREDICTION OF AIRCRAFT TRAJECTORIES**(i) General Discussion****PREDICTION OF AIRCRAFT TRAJECTORIES**

by Stanley Ratcliffe

14

(ii) Fundamentals**AIRCRAFT DYNAMICS FOR AIR TRAFFIC CONTROL**

by P.Y.Willems

15

(iii) Applications**THE APPLICATION OF TRAJECTORY PREDICTION ALGORITHMS FOR PLANNING
PURPOSES IN THE NETHERLANDS ATC-SYSTEM**

by J.N.P.Beers, T.B.Dalm, J.M. ten Have and H.Visscher

16

GENERATION OF AIRCRAFT TRAJECTORIES FOR ON-LINE OPERATION

by André Benoît and Sip Swierstra

17

D — AIR TRAFFIC MANAGEMENT**(i) Optimisation: Models and Techniques**

- OPTIMIZATION MODELS AND TECHNIQUES TO IMPROVE AIR TRAFFIC MANAGEMENT** 18
by Lucio Bianco

(ii) Man/Computer Interface

- THE HIGH-RESOLUTION GRAPHIC DISPLAY** 19
A possible man/machine interface for a computer assisted ATC management system
by Carlos Garcia Avello

**PART V — GUIDANCE OF AIRCRAFT IN A TIME-BASED
CONSTRAINED ENVIRONMENT**

A — CONTEXT — OBJECTIVES — PLANS

- 4-D CONTROL OF CURRENT AIR-CARRIERS IN THE PRESENT ENVIRONMENT:** 20E
Objectives — Status — Plans
by André Benoît

- REGULATION 4-D DANS L'INFRASTRUCTURE ACTUELLE: Point de la Situation** 20F
et Objectifs à Atteindre
par André Benoît

- NAVIGATION 4-D EN CIRCULATION AERIENNE** 21
par Nicole Imbert et Marc Pèlerin

B — GENERAL DISCUSSION

- ON THE AUTOMATION OF FUTURE ATC CENTRES IN THE LIGHT OF THE** 22
CONCEPT OF THE "ZONE OF CONVERGENCE"
by Victor Attwooll

C — GUIDANCE AND CONTROL: PRINCIPLES AND CONCEPTS

- THE CONTROL OF INBOUND FLIGHTS: Basic Principles** 23E
by André Benoît and Sip Swierstra

- LE GUIDAGE DES VOLS JUSQU'AU SEUIL DE PISTE: Principes Généraux** 23F
par André Benoît et Sip Swierstra

- GUIDANCE CONCEPTS FOR TIME-BASED FLIGHT OPERATIONS** 24
by Dan D.Vicroy

- 4-D DESCENT TRAJECTORY GENERATION TECHNIQUES UNDER REALISTIC** 25
OPERATING CONDITIONS
by David H.Williams and Charles E.Knox

D — CONDUCT OF AIR TRAFFIC CONTROL IN A ZONE OF CONVERGENCE

- EXPERT SYSTEMS FOR THE GENERATION OF TERMINAL AREA ARRIVAL PATHS** 26
FOR CIVIL TRANSPORT
by Robert W.Simpson

- A DESCRIPTION AND EVALUATION OF "TIMER": A Time-Based Terminal Flow-Control** 27
Concept
by Léonard Credeur and William R.Capron

- USE OF 4D RNAV IN TIME-BASED EN ROUTE ARRIVAL METERING** 28
by R.L.Erwin and K.H.Izumi

- AIR TRAFFIC MANAGEMENT AND AIRCRAFT GUIDANCE IN A ZONE OF** 29
CONVERGENCE
by André Benoît and Sip Swierstra

E — GROUND-BASED 4-D GUIDANCE OF AIRCRAFT IN MOVING ATMOSPHERE

- GROUND-BASED 4-D GUIDANCE OF FLIGHTS IN STRONG WIND** 30E
by André Benoît and Sip Swierstra

- GUIDAGE QUADRIDIMENSIONNEL A PARTIR DU SOL DE VOLS OPERANT PAR VENT FORT** 30F
par André Benoît et Sip Swierstra

- A PILOTED SIMULATOR EVALUATION OF GROUND-BASED 4D DESCENT ADVISOR ALGORITHM** 31
by Thomas J.Davis, Steven M.Green and Heinz Erzberger

F — THE COMPUTER/CONTROLLER/PILOT DIALOGS

- THE AIR TRAFFIC CONTROLLER FACING AUTOMATION: Conflict or Co-Operation** 32E
by André Benoît, Sip Swierstra and René de Wispelaere

- LE CONTROLEUR DE LA CIRCULATION AERIEENNE ET L'AUTOMATISATION: Conflit d'Intérêts ou Convergence?** 32F
par André Benoît, Sip Swierstra et René de Wispelaere

PART VI — SURVEILLANCE**A — RADAR TRACKING**

- AIRCRAFT TRAJECTORY RECONSTITUTION ON THE BASIS OF MULTI-RADAR PLOT INFORMATION** 33
by Pieter van der Kraan

- BAYESIAN MULTI-SENSOR TRACKING FOR ADVANCED AIR TRAFFIC CONTROL SYSTEMS** 34
by H.A.P.Blom, R.A.Hogendoorn and F.J.van Schaik

- THE USE OF DOWNLINKED MEASUREMENTS TO TRACK CIVIL AIRCRAFT** 35
by Chris C.Lefas

B — SATELLITE TECHNIQUES

- L'APPORT DES TECHNIQUES SATELLITAIRES A LA SURVEILLANCE DE LA NAVIGATION AERIEENNE** 36
(Contribution of the Satellite Techniques to the Surveillance of Air Traffic)
par Olivier Carel

PART VII — METEOROLOGICAL FORECASTS**A — IMPACT OF FORECASTS QUALITY ON TRAJECTORY PREDICTION**

- DEVELOPMENTS TO ENHANCE METEOROLOGICAL FORECASTING FOR AIR TRAFFIC SERVICES** 37
by M.E.Cox and D.A.Forrester

PART VIII — AIRCRAFT OPERATION IN AIR TRAFFIC HANDLING SIMULATION**A — REALISTIC OPERATION AND MOTION OF AIRCRAFT**

- INTEGRATION OF AIRCRAFT CAPABILITY IN AIR TRAFFIC HANDLING SIMULATIONS** 38
by André Benoît, S.Swierstra and Yves Delnatte

B — FLIGHT OPERATIONS WITHIN A TERMINAL AREA

- SIMULATION OF AUTOMATED APPROACH PROCEDURES CONSIDERING DYNAMIC FLIGHT OPERATIONS** 39
by Manfred Ficke and Adreas Hörmann

VOLUME 3

PART IX — BOOK OF ABSTRACTS

A

PART X — BIBLIOGRAPHY

B

A — GLOSSARY

B — REFERENCES

C — INDEX

PART XI — LIST OF CONTRIBUTORS

C

A — CONTRIBUTORS AND AFFILIATIONS

B — INDEX

PART IV

Air Traffic Handling

OPTIMUM ON-LINE HANDLING OF AIR TRAFFIC OVER WESTERN EUROPE (*)

by

André Benoit and Sjp Swierstra

European Organisation for the Safety of Air Navigation
EUROCONTROL
Engineering Directorate
72, rue de la Loi, B - 1040 Brussels (Belgium)

SUMMARY

For today's airlines Western Europe is not very large and the flights they make within it do not last very long. Consequently it should be possible within such an area as Western Europe (defined for simplicity as the non-oceanic area covered by the EUROCONTROL route charges system) to arrange ATC clearances and instructions so that any flight will, from departure clearance to touch-down (including therefore departure and arrival routes, standard or otherwise), be conducted in accordance with airline policy and without the changes to route and profile due to short-term planning which are so disruptive to air traffic.

The present paper recommends an approach for the on-line handling of air traffic over such an area, covering in particular the integration of control phases from departure to destination. This leads to (a) a central on-line optimal definition of departure/arrival sequences and essential characteristics of all flights and (b) a series of regional units to implement the relevant proposals/directives. This should provide the optimum integration of adjacent Zones of Convergence in which the time and altitude at which aircraft enter and leave each Zone are precisely controlled and are affected by the traffic conditions in their corresponding space/time sphere of influence.

As a prerequisite to the above, a system is hereby proposed for the purpose of accurately predicting and controlling the 4-D trajectory of an aircraft over any part of a flight, and in particular that part which extends from entry into until exit from the airspace of a given control centre.

1. INTRODUCTION

Much consideration has been given by ATC authorities to the future of air traffic systems in Europe and a number of publications have been devoted to the subject. The most recent one is to be published by the Royal Institute of Navigation next March (1). Their common characteristics usually include:

- (a) a catalogue of the deficiencies of the present systems;
- (b) another catalogue of the technologies involved including voice communications, data transmission, navigation, surveillance, data processing, human access to computer knowledge and the generation of decisions, together with the possible impact, immediate or delayed, of such decisions on air traffic;
- (c) additional considerations which cover other aspects such as the significance of the term "beneficial"; these may reflect the specific interests or the policy of particular institutions or simply the philosophy of their authors.
- (d) finally, a more or less comprehensive list of actions to be undertaken through research and development and at European government levels to define and progressively implement a new version of air traffic handling which is "beneficial" to the future European aviation community.

In contrast, the present paper will set out a more modest point of view, in fact a practical approach supported by studies and tests conducted as part of the "Studies, Tests and Trials" work programme undertaken within the Engineering Directorate of the EUROCONTROL Agency. This approach aims at providing the ATC community with adequate tools to handle air traffic efficiently in the face of a large number of sometimes contradictory demands, and in spite of the numerous constraints which may (and probably will) evolve with the political situation in Europe.

(*) This paper has been presented at the International Seminar "ATC 2000" on the subject of Research and Development leading to advanced ATC concepts and systems, EUROCONTROL Institute, Luxembourg, February 23-24-25, 1988.

(1) "The future air navigation in European regions" by R. Rawlings, The 1988 International Conference, The Royal Institute of Navigation, London, U.K., 22-24 March 1988.

In other words, the approach and techniques proposed for the handling of air traffic are compatible on the one hand with the criteria whereby appropriate weightings are allocated to the conservation of natural resources (fuel, land, airspace), operating economy, airspace capacity, flight crew workload and passenger convenience and, on the other hand, with the developments anticipated in various related technologies, in airborne equipment in particular, in data processing in general, and in data transmission capabilities.

After the above introduction, the remainder of the paper deals in turn with the following points :

- (a) Applicability in terms of time-scale and boundaries;
- (b) The link with the Zone of Convergence concept of which a summary is given for this purpose;
- (c) Fundamentals of the proposed on-line handling of air traffic;
- (d) Relationship with the Operational advent of advanced technologies including a section devoted to the accurate 4-D control of flights;
- (e) Dedicated real-time simulation facilities;

while the conclusions will include recommendations regarding developments and related tasks.

2. TIME-SPACE EXTENT AND BOUNDARIES

2.1. Air traffic handling

The approach proposed essentially applies to the on-line components of air traffic handling, namely both the on-line component of traffic management and the control of each individual flight. Accordingly, on the air traffic handling timescale, the initiation of action is concomitant with the entry of an aircraft into the airspace controlled. When this occurs, the first action belongs in the field of traffic management, while implementation of the subsequent control directives follows later as appropriate (2).

The on-line handling of air traffic as considered here is independent of any previous management action (of which the latest upstream contribution is the traffic regulation or limitation exercised at the appropriate level of air traffic flow management), although the results may and presumably will be affected by it. In other words, the on-line handling of air traffic as considered here (with the exception of the conflict-free character of the transfer of flights between similar adjacent units) deals with the traffic as it enters randomly into the geographical area covered - which would, ideally, be the whole of Western Europe; it determines an optimum trajectory for each aircraft involved, in terms of the overall situation, and subsequently ensures that each aircraft flies accordingly, within acceptable limits, in spite of all disturbances affecting the situation.

2.2. Geographical area and timescales

Ideally, a European air traffic handling system should cover the whole of Europe, or at least that part of it currently referred to as Western Europe. Obviously there are still some differences in membership between the European Community and the European Organisation for the Safety of Air Navigation; for the sake of this presentation, however, it is not necessary to go into this particular question, since the main principles will be conveyed in a manner independent of the ultimate number of participants, although it is worth noting that the efficiency and benefits for the aviation community as a whole increase with the extent of the area concerned.

Brussels, considered as a focal point of Europe, is within one hour's flight of a number of major airports : from a half to one hour from Amsterdam, Paris, London and Frankfurt; from one to one and half hours from Zurich, Milan, Dublin and Vienna. For such flights and more especially for shorter ones, any extension of the time or distance flown, either through holding or vectoring, has an appreciable negative impact on flight economy. Further, the annual growth rate of air transport remains rather high and it is to be expected that the density and complexity of air traffic will continue to increase appreciably over the next ten years. This in turn will increase the level of runway utilisation of existing airports, with the consequence that any disturbance, including even a slight increase in traffic density, will lead to a considerable and disproportionate increase in delays.

Accordingly, in view of the geographical scale of Europe, the on-line handling of air traffic should (a) cover areas within one to two hours flight from a selected fairly central point, and (b) consider each flight as a complete entity, not as a succession of phases. This means that management timescales are of the same order, and clearly implies a need for tools to implement the subsequent control directives while ensuring overall stability yet operating along predictions of the same order of magnitude.

(2) "On-line management and control of air traffic"
by André Benoît,
NATO ASI Series, Vol. F38,
Springer Verlag, Berlin, Heidelberg 1987.

3. THE ZONE OF CONVERGENCE : A PRACTICAL INTERMEDIATE STEP

At this stage, it is appropriate to summarise the essential characteristics of the Zone of Convergence approach, considered as a practical intermediate step in the integration of the control phases for all flights approaching a main terminal. This will make it possible to point out the guidelines of the overall project, the continuity aspects, elements of comparison and differences. Additional information on the ZOC concept and assessment are available elsewhere [(3), (4)].

3.1. Configuration and scenarios

The Zone of Convergence concept aims at optimising the overall traffic by assigning each individual aircraft a 4-D trajectory which meets as far as possible the request expressed by the operators, within the set of constraints resulting from the traffic situation, the capacity available and the limitation of the range of control variables.

Geographically, the ZOC surrounds and includes a major terminal area (and possibly secondary aerodromes also), and extends as far as is convenient depending on the local conditions, but usually up to 150 or 200 NM. The benefits which should be achieved have been assessed in terms of fuel and operating economy, and to a certain extent safety, for two typical areas, namely the South-East of England and Belgium, including London and Brussels terminal areas respectively, which are representative of high and medium-traffic-density terminal areas in Western Europe.

3.2. Control variables

Except for those flights originating inside the area itself, the control variables mainly consist of (a) at the management level, the combined sequencing/scheduling of arrivals on the runway, namely the determination of the sequence of arrival times and (b) at the traffic control level, the cruise/descent speed profile for each individual flight, and possibly the ground track, particularly in the final phases of flight in the case of non-direct approach.

3.3. Essential components

The Zone of Convergence concept includes two distinct although closely-related components. The "sequencer" determines and/or confirms the set of trajectories compatible with present constraints; subsequently, when appropriate, the "flight controller" generates the control directives automatically in a way which makes it possible to so guide the aircraft that its arrival in the landing stream may be precisely timed.

3.4. Benefits

Although the first sequencer developed was designed chiefly to minimise the overall flight cost (i.e. the fuel consumed and flight duration combined), appreciable improvements have been made in terms of "expeditiousness", capacity (maximum use of available landing capacity) and safety; nevertheless, although appreciable, these improvements apply only to those parts of the flights conducted in the ZOC.

4. ON-LINE HANDLING OF AIR TRAFFIC OVER EUROPE

4.1. Basic objectives

It is our purpose to propose a system suitable for the On-Line Handling of Air Traffic (OLHAT) over a European area which includes several main terminals, for example an OLHAT area "centred" on Brussels and including Amsterdam, Frankfurt, Paris and London, and extending to the north, south, east and west as appropriate.

In such an OLHAT area, any flight - the entire flight or a part of a flight as appropriate - should be conducted as a single entity and control phases duly integrated over the entire part of the flight taking place inside the area. At this stage, it is sufficient to indicate that those flights originating outside the area differ essentially from those originating inside the area due to the fact that their initial conditions at entry are "imposed" and as a consequence "frozen" (as is also the case of flights entering a ZOC area).

-
- (3) "Optimum use of cruise/descent control for the scheduling of inbound traffic"
by André Benoît and Sip Swierstra.
International Conference sponsored by Flight International on "Fuel Economy in the Airlines",
The Royal Aeronautical Society,
London, U.K., April 1980.
Also EUROCONTROL Report 802013, February 1980.
 - (4) "Air Traffic Control in a Zone of Convergence : Assessment within the Belgian airspace"
by André Benoît and Sip Swierstra.
Paper presented at the 14th Congress of The International Council of the Aeronautical Sciences
(ICAS),
Toulouse, France, September 10-14, 1984.
Also EUROCONTROL Report 842009, April 1984.

The criterion used to derive an optimised set of trajectories with sufficient flexibility to meet a variety of requirements will normally take into account not only economic aspects (including flight duration and fuel consumed) but also deviations from departure and arrival times, these being duly weighted and integrated over the area covered.

4.2. Illustrative scenario

When an aircraft enters the OLHAT area - either as a departure originating inside the area or as a flight coming from outside - an optimum trajectory is determined for the entire part of the flight to be conducted within the area. This determining of trajectory is made in accordance with the criterion selected (an "optimiser" is acting at the on-line traffic management level), in conformity with the range of control available and is limited by the series of applicable constraints. At the same time (this is also the case with the ZOC approach), the trajectories of other aircraft already in the area - but for which the range of control possibilities is still available - may also be modified so as to minimise the global criterion and provide the operators, on the whole, with the best possible service. Subsequently, each aircraft will be guided accurately by the ground-based control unit operating in close cooperation with the aircraft crew, so as to maintain precise timing for critical events, landing included.

Accordingly, given the geography and timescales involved, it becomes possible to plan flights in Europe, including the departure and arrival sequences, in such a way that any flight would, from its departure clearance until landing at its destination, be conducted in accordance with airline policy, without any of the changes to route and profile due to short-term planning that are disruptive to air traffic.

In an OLHAT area, the main variables available for the on-line management and subsequent control include the take-off and landing time sequences and the transit times in the area, these two sets of variables being subject to quite different sets of constraints.

4.3. Relationship with related disciplines and technologies

An academic approach to the subject has been made (5) and, from a scientific viewpoint, methods are available for conducting the optimisation in a way compatible with real-time operation. It should be noted that the control of air traffic as set out in this paper applies from the start of take-off until touch-down. The ground movements prior to the start of take-off or subsequent to touch-down are not covered. The extension of the work to such phases of flights involves an appreciably different approach and is not envisaged in the present programme.

The stability of the solutions obtained from the optimisation process is highly dependent on the subsequent control of the critical events of the set of flights involved since the situation (traffic, meteorological conditions, human factors, knowledge of aircraft state vector and operational capability, etc.) is continuously evolving.

This point has been given particular attention and will be outlined in Section 5. below.

In terms of surveillance, navigation and communications, the proposed OLHAT system is compatible with the airlines' present methods of flight operation but will of course benefit from particular improvements. As in the case of the ZOC concept, it relies on the availability of DME stations; the advent of Mode S with its data-link capability will be sufficient to allow the transition to be made from R/T voice communication to automated data transmission.

The experience gained during the ZOC control exercises makes us believe that the interfaces implying human involvement, both in the cockpit and on the ground, will probably be much easier to handle than previously anticipated. For the pilots, this already appears to be the case; as far as the new controller is concerned, he will probably converse with the OLHAT system knowledge "as he would with a friendly adviser, in simple terms and in full confidence" (2). Accordingly, the operational handling of air traffic which takes place should raise no difficulty as regards the human aspects.

Clearly, the major difficulties are of a different order; these are expected to occur at the organisational level in a number of areas including the defining, collecting, transfer and on-line processing of information, the standardising of protocols for the automatic exchange (ground/ground and ground/air) of information to be used on-line, the structure of the jurisdiction over the reorganised airspace, etc.

5. GROUND-BASED GUIDANCE OF FLIGHTS (TIME-OF-CRITICAL-EVENTS CONSTRAINED)

5.1. Flight predictor / Controller module

In order to ensure the stability of any system designed to regulate a flow of air traffic efficiently without a series of buffers such as are provided by stacking and path-stretching, yet allowing each aircraft to fly in near-optimum conditions, it is necessary to have a reliable prediction module complemented by a trajectory controller to deal with all the perturbations that can affect the normal conduct

(5) "Gestion automatisée du trafic aérien sur un ensemble d'aéroports",
by Khan Mohammadi, Sohrab.
Thèse n° 81/1983, Ecole Nationale Supérieure de l'Aéronautique et de l'Espace,
Toulouse, France, October 1983.

of a flight. These comprise uncertainties in meteorological forecasts, alterations to initial plans, aircraft operation options, uncertainty regarding aircraft characteristics (performance and mass included), human fallibility in the cockpit and on the ground, and other particular events and incidents.

5.2. Prediction and control accuracy

In order to ensure maximum use of the available capacity, in particular as regards runways, it is necessary to keep separations at their minimum operational values and possibly reduce them by reducing the uncertainty component of the safety margins.

Particular attention has been given to these aspects over the last ten years and it is felt that the trajectory of an aircraft can now be controlled so as to maintain the time-of-arrival within 5 to 10 seconds of a prediction made up to two hours ahead.

5.3. Sources of information

The information required is readily available from aircraft manufacturers and completed whenever necessary by the airlines' specific operating procedures. The basic information thus obtained is then converted to provide the data suitable for on-line operation.

5.4. Ground/air dialogue

The interfaces between the trajectory prediction unit and the control unit have two essential features, namely automatic data exchange and dialogues involving human participation. These latter have been given special attention (6). At this stage, the control directives appear entirely compatible with aircraft operation and the experiments conducted to date with air traffic controllers are certainly encouraging.

6. INTEGRATION OF AIRCRAFT IN SIMULATIONS

6.1. Integration of the aircraft/crew/equipment

The representation of the aircraft in present ATC simulation facilities is generally extremely simple and is unsuitable for assessing the various aspects of the approach proposed. In this system, aircraft trajectory prediction and control are highly accurate and the response of the pilot (including auto-pilot/FMS) is an inherent part of it.

Accordingly, a series of facilities have been developed so as to integrate the aircraft, crew and equipment in the OLHAT simulations.

6.2. Flight Simulator

In order to test and assess validly the ground/air procedures used and in particular to pass the guidance directives from the ground to the aircraft, controllers and flight crews have to be present in the overall navigation, guidance and control process.

The amount of organisation that this requires is obviously appreciable and it is accordingly desirable to limit the relevant simulation sessions to a minimum, if only for economy reasons.

This has led to the development of a programmable flight simulator usable on the so-called "Personal Computer". The operator controls the flight director and the resulting trajectories reproduce the combination of "flight crew/actual aircraft" with a high degree of accuracy in all phases of flight (7).

6.3. Creation of a low-cost multi-aircraft environment

A series of such PC-simulators can be used to simulate a number of aircraft of different types flying in any desired conditions. They can be operated in three basic modes :

1. Manually as would be done by a pilot.
2. In a semi-automatic mode where the operators enter information as received from the ground-based trajectory controller.

(6) "The Air Traffic Controller facing automation : Conflict or cooperation"
by André Benoît, Sip Swierstra and René De Wispelaere.
The Royal Institute of Navigation,
29-30 September - 1 October 1987, London, U.K.
Also EUROCONTROL Report 872008, April 1987.

(7) "A Simulation facility for assessing the next generation of 4-D air traffic control procedures"
by André Benoît and Sip Swierstra.
Proceedings of the 15th International Congress of the Aeronautical Sciences, London, U.K.,
September 1986.
Also EUROCONTROL Report 862017, June 1986.

3. In an automatic mode where the control directives are transmitted via a ground-air automated data exchange and directly input into the cockpit control facilities (this mode is used for a variety of exercises with a limited number of operators).

6.4. Integration of full-scale airline flight simulators in ATC simulations

Once procedures have been established and tested in the above environment, they should be tried out in realistic types of situation. To this end, cooperation programmes have been established with several airlines and training centres in Europe. It is then possible to simulate an air traffic area in which a number of aircraft are flown with the realism indicated in the preceding paragraph, while two of the aircraft are actually full-scale flight simulators operated by qualified airline crews with the directives being transmitted over the R/T by professional air traffic controllers (see the exercises conducted using British Airways B-737 and B-757 and SABENA B-737 and DC-10 simulators).

7. CONCLUSIONS

In Western Europe the increase in traffic density and the complexity of air traffic flows from the geographical standpoint are such as to make it necessary to envisage, plan and implement the facilities for handling traffic in terms of safety, capacity, operating economy and flight crew workload. The present paper recommends placing particular emphasis on the on-line handling of air traffic and by integrating the different phases of flights over "extended areas" of which a typical example might be a geographical zone including the Brussels, Amsterdam, London, Frankfurt and Paris terminal areas and extending to the north, south, east and west as appropriate.

The advantage of this would be that any flight cleared to depart from any runway in the area would, until arriving at the boundary of the area - or landing at its destination if this were within the area - be conducted in accordance with airline policy and without the changes to route and profile due to short-term planning which are so disruptive to air traffic.

Some of the tools required for handling traffic in the way recommended above have been designed or are under development at the Engineering Directorate of the EUROCONTROL Agency. This is the case in particular as regards the prediction, guidance and control of trajectories. In this field, the tests conducted to date in conjunction with air traffic controllers and airline crews have proved fully satisfactory from the viewpoints of both accuracy and aircraft operation.

Furthermore, fast-time and preliminary real-time simulations using real traffic flows in the Zones of Convergence of London and Brussels have led to practical sequencing/scheduling strategies.

This experience together with the knowledge accumulated in various European research institutions makes it possible to envisage a joint and successful effort to establish the technical and operational basis of the proposed recommendation.

REGULATION TEMPS REEL OPTIMALE DU TRAFIC AERIEN EN EUROPE OCCIDENTALE (*)

par

André Benoît et Sip Swierstra

Organisation Européenne pour la Sécurité de la Navigation aérienne
 EUROCONTROL
 Direction Technique
 rue de la Loi, 72, B-1040 Bruxelles (Belgique)

SOMMAIRE

Pour les compagnies aériennes, l'Europe occidentale est devenue un espace bien exigü et les vols y sont de courte durée. Pour plus de commodité, nous entendons ici par "Europe occidentale" la région desservie par le système EUROCONTROL de redevances de route ; à une telle échelle, il devrait être possible de délivrer les autorisations et les instructions de contrôle de telle manière que tout vol, depuis son départ jusqu'au point de prise de contact avec la piste d'atterrissage (c'est-à-dire pour la totalité de l'itinéraire, ce qui inclut notamment les routes d'arrivée, normalisées ou non) puisse être exécuté en conformité de la politique générale décidée par sa compagnie et sans subir les déroutements et modifications de profil de vol qu'impose la planification à court terme et qui perturbent tant la fluidité du trafic aérien.

Le présent exposé vise à recommander une méthode pour la régulation des vols en temps réel pour l'ensemble de cette région, en particulier l'intégration des différentes phases de contrôle depuis le départ jusqu'à l'arrivée. A cette fin, il faut que les séquences d'arrivée et les séquences de départ, ainsi que les principales caractéristiques de tous les vols en cause soient définies au mieux, en direct et à partir d'un point central, et que soient mis en place une série d'organismes régionaux chargés de veiller à l'application des propositions ou directives de régulation. Un tel système optimiserait l'intégration de zones de convergence adjacentes pour lesquelles les heures et les altitudes à l'entrée deviendraient - tout comme les instants d'atterrissage dans une zone unique - subordonnées aux conditions de trafic prévalant dans l'ensemble d'une telle région étendue.

Dans un premier temps, le système de calcul, de prédiction et de contrôle de la trajectoire dans les quatre dimensions mis au point pour la zone de convergence est étendu à l'ensemble du vol depuis son entrée - éventuellement un décollage - jusqu'à sa sortie - éventuellement un atterrissage - de la région de contrôle étendue ainsi constituée, l'ensemble de l'espace aérien concerné relevant d'un centre de gestion déterminé.

1. INTRODUCTION

Depuis longtemps, les autorités du contrôle de la circulation aérienne se penchent sur l'avenir des systèmes ATS en Europe et de nombreuses publications y ont été consacrées. L'étude la plus récente à ce sujet sera publiée, en mars prochain, par le Royal Institute of Navigation (1). Ces diverses publications présentent des points communs, que l'on peut généralement résumer comme suit :

- a) liste des faiblesses des systèmes actuels ;
- b) liste des technologies utilisées, depuis les communications en phonie, transmission des données, navigation, surveillance, traitement des données, accès aux données informatisées et prises de décisions jusqu'à l'incidence immédiate ou différée de telles décisions sur le trafic aérien ;
- c) réflexions sur d'autres aspects, tels que la signification du terme "bénéfique" ; ces réflexions traduisent parfois les intérêts spécifiques ou la politique générale d'institutions particulières, ou tout simplement les thèses de leurs auteurs ;

(*) Cette communication fut présentée au Séminaire International "ATC 2000" ; Institut EUROCONTROL de la Navigation Aérienne ; Luxembourg, 23-24-25 février 1988. Aussi, Rapport EUROCONTROL, 882004(F), février 1988.

(1) "The future air navigation in European regions", R. Rawlings, The 1988 International Conference, The Royal Institute of Navigation, London, U.K., 22-24 mars 1988.

- d) enfin, liste plus ou moins exhaustive des actions à engager, sur le plan de la recherche et du développement ainsi qu'à l'échelon des gouvernements des pays d'Europe afin de définir et de mettre progressivement en oeuvre une régulation nouvelle de la circulation aérienne qui soit "bénéfique" à la future communauté aéronautique européenne.

A l'opposé, le présent document, dont l'objet est de répondre à une ambition beaucoup plus modeste, se propose d'évoquer le problème sous un angle pratique en s'appuyant sur des études et des expérimentations réalisées dans le cadre du Programme d'Etudes, d'Essais et d'Expérimentations de la Direction Technique de l'Agence EUROCONTROL. Il s'agit de donner à la communauté des services ATC les outils appropriés pour acheminer le trafic aérien avec efficacité dans un contexte où la demande est forte, ses exigences quelquefois contradictoires, et les contraintes nombreuses, contraintes qui suivront probablement le cours de l'évolution politique en Europe.

En d'autres termes, la méthodologie et les techniques proposées pour la prise en charge du trafic sont compatibles, d'une part, avec une juste pondération de critères tels que la conservation des ressources naturelles (les combustibles, les terres, l'espace aérien), l'économie d'exploitation, la capacité de l'espace aérien, la charge de travail du personnel navigant et le confort des passagers pour qui attentes et par suite retards, peuvent être gênants, coûteux, voire critiques et d'autre part, avec les progrès technologiques escomptés en particulier dans le domaine des équipements embarqués, du traitement de l'information d'une manière générale, et de la transmission des données.

Le présent exposé traite ensuite des points suivants :

- (a) possibilités de mettre en oeuvre, dans certaines limites de temps et d'espace, les méthodes et techniques proposées ici ;
- (b) rapports entre ces dernières et le concept ZOC (Zone de Convergence), dont l'essentiel est rappelé ci-après ;
- (c) principes élémentaires de la méthode de régulation de la circulation aérienne en temps réel ;
- (d) relation avec l'avènement de technologies de pointe, notamment le contrôle quadridimensionnel précis des vols ;
- (e) moyens propres de simulation en temps réel ;

et propose, en conclusion, les grandes lignes des développements et tâches futures dans ce domaine.

2. APPLICATION DANS L'ESPACE ET DANS LE TEMPS : ETENDUE ET LIMITES

2.1. Régulation du trafic aérien

La démarche proposée s'applique principalement aux composantes "on line" du processus de régulation, à savoir la composante en ligne de la gestion du trafic aérien et le guidage et contrôle de chaque vol. Partant, sur le plan chronologique, l'intervention est déclenchée dès lors que l'aéronef pénètre dans l'espace contrôlé. Dès cet instant, l'action relève de la gestion du trafic, la mise en application des directives du contrôle se produisant ultérieurement, au moment voulu.

Or, la régulation des vols en temps réel, telle qu'elle est conçue ici, est absolument distincte de toute mesure de gestion en amont (dont la dernière manifestation aura été la régulation voire la limitation décidées au niveau GCTA compétent), encore que sur le plan pratique, elle en soit malgré tout tributaire. Ceci signifie qu'à l'exception des transferts entre organismes analogues adjacents, la régulation temps réel s'appliquerait sans risques de conflits à n'importe quel vol pénétrant dans la région géographique considérée, c'est-à-dire - idéalement - l'ensemble de l'Europe occidentale. L'approche proposée permettrait de déterminer la trajectoire optimale de chaque aéronef compte tenu de la situation générale et garantirait le respect de cette trajectoire, dans des limites acceptables, indépendamment de tout élément susceptible de perturber la situation (2).

2.2. Limites géographiques et exploitation dans le temps

Dans l'idéal, un système européen d'acheminement des vols devrait englober toute l'Europe ou, à tout le moins, ce qu'il est convenu d'appeler l'Europe occidentale. Personne n'ignore que la Communauté européenne et l'Organisation européenne pour la Sécurité de la Navigation aérienne ne groupent pas ou pas encore exactement les mêmes pays mais, pour les besoins de la démonstration, il n'est sans doute pas nécessaire de s'y attarder ; l'énoncé des principes essentiels étant en fin de compte indépendant du nombre des participants, encore qu'il soit utile de relever que l'efficacité et les avantages que ce système offre à la communauté aéronautique dans son ensemble sont directement proportionnels à l'étendue de la région considérée.

(2) "On-line management and control of air traffic",
André Benoît,
NATO ASI Series, Vol. F38, Springer Verlag, Berlin, Heidelberg 1987.

Bruxelles, que l'on peut prendre comme plaque tournante de l'Europe, n'est situé qu'à une heure de vol de plusieurs grands aéroports (trente à soixante minutes suffisent pour rallier Amsterdam, Paris, Londres et Francfort), et à 1h-1h $\frac{1}{2}$ de Zurich, Milan, Dublin et Vienne. Pour les vols entre ces points, et davantage encore sur des distances plus courtes, tout allongement de la durée de vol ou de la distance parcourue, en raison soit des circuits d'attente, soit de mesures de guidage, influe d'une manière nettement défavorable sur l'économie du vol. En outre, le taux de croissance annuel du transport aérien se maintenant à un niveau plutôt élevé, il y a tout lieu de s'attendre à une augmentation sensible de la densité et de la complexité du trafic aérien dans les dix années à venir. Il en résultera une utilisation plus intensive des pistes d'aéroport, de sorte que toute perturbation, fût-ce une très légère augmentation du volume de trafic, se traduira par un accroissement important, et disproportionné, des retards.

En conséquence, vu les dimensions géographiques de l'Europe, la régulation en temps réel du trafic aérien devrait d'une part, s'appliquer à une région dont le rayon représenterait une à deux heures de vol à partir du point central et, d'autre part, considérer chaque vol du début à la fin comme une seule entité et non plus comme une succession de phases distinctes. Ceci signifie que les marges temporelles disponibles pour la gestion sont elles-mêmes très limitées et qu'il faudra des outils appropriés pour appliquer les directives du contrôle et préserver la stabilité globale tout en assurant l'exploitation des vols sur la base de prévisions à échéances comparables à celles des durées de vol.

3. LA ZONE DE CONVERGENCE : ETAPE INTERMEDIAIRE

Il n'est sans doute pas inutile de résumer, à ce stade, les caractéristiques essentielles du concept de la "Zone de Convergence", ZOC, jugée constituer, sur le plan pratique, une étape intermédiaire dans le sens de l'intégration des diverses phases de contrôle de la totalité des vols se dirigeant vers une grande région terminale. Ainsi pourrons-nous mettre en évidence les lignes directrices des deux concepts, les aspects de continuité entre les deux, leurs points communs et leurs différences. Le lecteur trouvera un complément d'information sur la ZOC dans d'autres publications [(cf. références (3) et (4))].

3.1. Configuration et scénarios

Le concept ZOC vise à optimiser les flux de trafic par l'attribution, à chaque aéronef, d'une trajectoire définie dans les quatre dimensions et répondant, dans la mesure du possible, à la demande de l'exploitant mais tenant compte de la situation de trafic, de la capacité disponible, ainsi que des limites des variables de contrôle.

Géographiquement, la ZOC englobe une grande région terminale (le cas échéant, elle peut aussi inclure des aérodromes secondaires) et offre les dimensions les plus vastes possibles, avec un rayon généralement compris entre 150nm et 200nm. Les avantages qu'un tel concept devrait offrir ont été évalués en termes d'économies de carburant et d'exploitation, et, dans une certaine mesure, de sécurité ; les évaluations ont été faites pour deux régions caractéristiques, à savoir le sud-est de l'Angleterre et la Belgique, c'est-à-dire pour les régions terminales de Londres et de Bruxelles, représentatives de régions terminales présentant, pour l'ouest de l'Europe, une densité de trafic respectivement forte et moyenne.

3.2. Variables du contrôle

Sauf pour les vols au départ d'un point situé à l'intérieur de la ZOC, les variables de contrôle sont, principalement, de deux ordres :

- a) sur le plan de la gestion des vols, régulation/ordonnancement des arrivées sur la piste (détermination de la séquence des heures d'arrivée) ;
- b) sur le plan du contrôle de la circulation aérienne, profil de vitesse de montée/descente pour chaque vol et, le cas échéant, trajectoire au sol, en particulier pour les phases finales de vol en approche non directe.

(3) "Optimum use of cruise/descent control for the scheduling of inbound traffic",
André Benoît et Sip Swierstra.
International Conference sponsored by Flight International on "Fuel Economy in the Airlines",
The Royal Aeronautical Society, London, G.B., avril 1980.
Aussi Rapport EUROCONTROL 802013, février 1980.

(4) "Air Traffic Control in a Zone of Convergence : Assessment within Belgian airspace",
André Benoît et Sip Swierstra.
14th Congress of the International Council of the Aeronautical Sciences (ICAS),
Toulouse, France, September 10-14, 1984.
Aussi, Rapport EUROCONTROL 842009, avril 1984.

3.3. Principaux éléments constitutifs

Le concept de la Zone de convergence repose sur deux composantes distinctes quoique très étroitement liées. Le "séquenceur" détermine et/ou confirme l'ensemble des trajectoires compatibles avec les contraintes en vigueur ; au moment opportun, le "contrôleur de vol" génère ensuite automatiquement les directives de contrôle permettant de guider l'aéronef de telle façon que l'instant d'atterrissage puisse être prévu et maintenu avec une précision rigoureuse.

3.4. Avantages

Bien que le premier séquenceur mis au point visait essentiellement à rendre minimum le coût global de l'ensemble des vols (c'est-à-dire conjointement la consommation de carburant et la durée de vol), des améliorations non négligeables ont été réalisées en ce qui concerne la fluidité du trafic, la capacité (exploitation maximale de la capacité disponible de prise en charge à l'atterrissage) et la sécurité. Pour être profonds, ces changements n'ont toutefois qu'une portée limitée puisqu'ils n'affectent que les parties des vols effectuées dans une ZOC.

4. REGULATION TEMPS REEL DU TRAFIC AERIEN EN EUROPE

4.1. Objectifs fondamentaux

L'objectif que nous poursuivons est de proposer, pour l'Europe, un système de régulation en temps réel de la circulation aérienne, dénommé système OLHAT (On-Line Handling of Air Traffic) dans une région englobant plusieurs grandes zones terminales ; cette région pourrait être centrée, par exemple, sur Bruxelles et inclure Amsterdam, Francfort, Paris et Londres avec, le cas échéant, un prolongement vers le nord, le sud, l'est et l'ouest.

Dans une région OLHAT ainsi définie, tout vol serait exécuté, en totalité ou en partie, comme s'il ne formait qu'une seule entité dont les différentes phases de contrôle seraient judicieusement intégrées pour toute la partie du vol exécutée dans cette région. A ce stade, il suffira d'indiquer que les vols au départ d'un point situé en dehors de la région diffèrent considérablement de ceux qui sont originaires d'un point situé dans la région puisque les conditions initiales correspondantes, c'est-à-dire celles qui prévalent au point d'entrée de la région, sont en quelque sorte imposées et donc "figées" (comme pour les vols pénétrant dans une ZOC).

Le critère appliqué pour calculer un ensemble optimisé de trajectoires suffisamment souples pour permettre de répondre à une gamme diversifiée d'exigences tiendra généralement compte d'aspects économiques, notamment la durée du vol et la consommation de carburant, mais aussi de tout écart par rapport aux heures de départ et d'arrivée, celles-ci étant dûment pondérées et intégrées sur l'ensemble de la région couverte.

4.2. Type de scénario

Lorsqu'un aéronef pénètre dans la région OLHAT - qu'il ait décollé à l'intérieur ou à l'extérieur de la région - sa trajectoire optimale est déterminée, pour la totalité du vol dans cette région, sur la base du critère choisi (un "optimiseur" intervient au niveau de la gestion directe du trafic aérien) en fonction de la gamme des mesures de contrôle disponibles et des limites inhérentes aux contraintes en vigueur. En même temps, tout comme dans le concept ZOC, la trajectoire des autres aéronefs présents dans le système (et pour lesquels toute la gamme des possibilités de contrôle est encore disponible) peut être modifiée pour assouplir au maximum le critère global et offrir aux exploitants le meilleur service possible. Ensuite, chaque aéronef est soumis à un guidage précis par l'organisme de contrôle au sol, qui coopère étroitement avec l'équipage afin que les heures prévues pour les phases critiques, y compris l'atterrissage, soient rigoureusement respectées.

Vu les dimensions de la région en cause et la durée de la présence des aéronefs dans cette région, il devient donc possible de planifier les vols en Europe, départs et arrivées inclus, de telle manière que tout, depuis le moment de l'obtention de l'autorisation de décollage jusqu'à l'atterrissage à l'aéroport de destination, puisse être effectué en conformité de la politique générale de la compagnie dont il relève, sans subir les déroutements et modifications de profil de vol qu'impose la planification à court terme et qui perturbent tant l'écoulement du trafic aérien.

Dans une région OLHAT, les principales variables disponibles pour la gestion du trafic en direct, étroitement associées aux durées de vol dans la région, sont les séquences des instants de décollage et d'atterrissage, ces deux ensembles de variables étant bien entendu soumis à des contraintes très différentes.

4.3. Points communs avec d'autres disciplines ou technologies

La notion de base a déjà fait l'objet d'études théoriques (5) et, du point de vue scientifique, il existe des méthodes d'optimisation compatibles avec les exigences de l'exploitation en temps réel.

Il y a lieu de noter que le contrôle de la circulation aérienne évoqué dans le présent document s'entend comme s'appliquant du début des manoeuvres de décollage (lâcher des freins) jusqu'au toucher des roues, à l'exclusion donc des mouvements au sol avant le positionnement de l'aéronef en vue du décollage et après la prise de contact avec la piste à l'atterrissage. Si l'on voulait élargir le champ des travaux pour y inclure ces deux phases de roulement au sol, il y aurait lieu d'envisager le problème sous un tout autre angle, ce que notre programme actuel ne prévoit pas.

La stabilité des solutions auxquelles aboutit le processus d'optimisation est largement subordonnée à la maîtrise des moments critiques de chacun des vols présents dans le système puisque la situation globale (trafic, conditions météorologiques, facteurs humains, position et vitesse, moyens opérationnels, etc.) est en évolution constante. Au Chapitre 5, nous avons accordé à ce problème une attention plus particulière.

Sur le plan de la surveillance, de la navigation et des communications, le système OLHAT proposé est compatible avec les méthodes d'exploitation de vol actuelles mais il ne manquera pas, bien entendu, de bénéficier des perfectionnements à venir. Comme le concept ZOC, il a besoin pour fonctionner de stations DME; la mise en service du Mode S et de ses liaisons numériques automatisées assurera la transition entre les communications radiotéléphoniques actuelles et les transmissions automatisées de données futures.

L'expérience acquise au cours des essais du concept ZOC donne à penser que la question des interfaces exigeant une intervention humaine, tant dans le poste de pilotage qu'au sol, sera probablement beaucoup plus aisée à régler que prévu. Cette hypothèse semble du reste déjà se vérifier pour les pilotes; quant au niveau contrôleur, celui-ci tiendra sans doute avec le système expert OLHAT une conversation semblable à celle qu'il aurait avec un conseiller amical, en termes simples et en pleine confiance. Il s'ensuit qu'en ce qui concerne les aspects humains, l'acheminement opérationnel des vols ne devrait poser aucun problème difficile.

Manifestement, les principales difficultés sont d'un tout autre ordre et l'on peut s'attendre qu'elles apparaîtront au niveau de l'organisation, notamment pour la définition, la saisie, le transfert et le traitement en direct de l'information et comprendront, en particulier, la normalisation des protocoles à utiliser dans les échanges informatisés (sol/sol et sol/air) des informations à exploiter en direct, la structure juridictionnelle de l'espace aérien dans sa nouvelle organisation, etc.

5. GUIDAGE DE L'AVION A PARTIR DU SOL AVEC CONTRAINTES SUR EVENEMENTS CRITIQUES

5.1. Module de prédiction et de contrôle des vols

Si l'on veut assurer la stabilité de tout nouveau système conçu en vue de la régulation efficace d'un courant de trafic aérien et libéré des divers "tampons" que sont, par exemple, l'étagement du trafic ou l'allongement de la trajectoire, tout en permettant à chaque aéronef d'exécuter son vol dans des conditions quasi-optimales, il est indispensable de disposer d'un module de prévision fiable, doublé d'un "contrôleur" automatique de trajectoire chargé d'atténuer les effets des perturbations susceptibles d'influer sur la conduite normale du vol, qu'il s'agisse de prévisions météorologiques incertaines, de modifications aux plans de vol initiaux, des différentes options d'exploitation des aéronefs, d'incertitudes quant à leurs caractéristiques (y compris la masse et les performances), de l'éventualité d'une erreur humaine (tant du côté de l'équipage que des contrôleurs) ou encore d'autres événements ou incidents particuliers.

5.2. Précision de la prévision et du contrôle

Afin d'exploiter au mieux la capacité disponible, en particulier celle des pistes, il faut que les normes d'espacement soient maintenues au niveau minimum acceptable, voire réduites par une action sur la composante aléatoire des marges de sécurité.

Une attention toute particulière a été accordée à ces aspects au cours des dix dernières années et maintenant notre sentiment général est que la trajectoire d'un aéronef peut être définie et contrôlée de manière telle que l'instant d'arrivée, estimé avec un préavis pouvant aller jusqu'à deux heures, soit respecté à 5-10 secondes près.

(5) "Gestion automatisée du trafic aérien sur un ensemble d'aéroports",
Khan Mohammadi, Sohrab, Thèse n° 81/1983,
Ecole Nationale Supérieure de l'Aéronautique et de l'Espace,
Toulouse, France octobre 1983.

5.3. Sources d'information

Les informations nécessaires sont aisément disponibles auprès des constructeurs ; le cas échéant, elles sont complétées à l'aide des procédures d'exploitation propres aux compagnies. L'ensemble des renseignements ainsi obtenus est alors converti en données exploitables en direct.

5.4. Dialogue sol/air

Les interfaces entre l'élément chargé de la prévision des trajectoires et l'élément de contrôle se caractérisent essentiellement par des échanges de données automatisées et la conduite de dialogues avec la participation de l'homme; ce dernier point a du reste fait l'objet d'une étude particulière - cf. référence (6). Au stade actuel, les directives de contrôle apparaissent compatibles avec l'exploitation des aéronefs, et les expérimentations réalisées avec le concours de contrôleurs de la circulation aérienne sont certainement encourageantes.

6. INTEGRATION D'AERONEFS AUX EXERCICES DE SIMULATION

6.1. Intégration aéronef/équipage/équipement

Dans les centres de simulation ATC actuels, la représentation d'aéronefs généralement d'une simplicité extrême, se prête très mal à l'évaluation des différents aspects de la méthode proposée. Dans notre système, la prévision et le contrôle des trajectoires sont d'une très grande précision, et la réaction du pilote, de même que celles du pilote automatique et du FMS, en sont parties intégrantes.

C'est pourquoi l'on a mis au point toute une série de moyens et d'installations permettant d'intégrer aéronef, équipage et avionique aux simulations OLHAT.

6.2. Simulateur de vol

Afin de mener à bien l'évaluation des procédures sol/air utilisées et, en particulier, de transmettre les directives de guidage du sol à l'aéronef, contrôleurs et équipages doivent être présents d'un bout à l'autre du processus de navigation, de guidage et de contrôle.

Le volume de travail que l'organisation d'une telle simulation implique est, de toute évidence, considérable de sorte qu'il est souhaitable, ne fût-ce que pour des raisons d'économie, de réduire les sessions de simulation au minimum.

Cet impératif a débouché sur la mise au point d'un simulateur de vol programmable et utilisable sur un ordinateur individuel (type PC ou AT). L'opérateur commande le directeur de vol et les trajectoires qui en résultent reproduisent la combinaison "équipage/aéronef" avec une précision élevée pour toutes les phases de vol (?).

6.3. Création d'un environnement multi-aéronefs de faible coût

On peut utiliser une série de simulateurs sur PC pour représenter plusieurs aéronefs de types différents et opérant dans n'importe quelles conditions de vol. Les trois modes de base sont les suivants :

1. exploitation manuelle, identique à celle que pratiquerait un pilote ;
2. exploitation semi-automatisée, dans laquelle les opérateurs mettent les informations en machine comme ils le feraient s'ils les recevaient du contrôleur (au sol) de trajectoire ;
3. exploitation automatisée, dans laquelle les directives de contrôle sont transmises par liaison automatisée sol/air et directement relayées aux équipements de bord (ce mode d'exploitation est utilisé pour toute une gamme d'exercices réalisés avec un nombre limité d'opérateurs).

(6) "The Air Traffic Controller facing automation : Conflict or co-operation",
André Benoît, Sip Swierstra et René De Wispelaere.
The Royal Institute of Navigation.
29-30 september - 1 october 1987, Londres, G.B.
Aussi Rapport EUROCONTROL 872008, avril 1987.

(7) "A simulation facility for assessing the next generation of 4-D Air Traffic Control procedures"
André Benoît et Sip Swierstra.
15th Congress of the International Council of the Aeronautical Sciences,
Londres, G.B., septembre 1986.
Aussi Rapport EUROCONTROL 862017, juin 1986.

6.4. Intégration de simulateurs de vol de compagnies aériennes à des simulations ATC

Une fois les procédures établies et testées dans l'environnement décrit ci-dessus, elles doivent être mises à l'épreuve dans des situations réalistes. A cette fin, des programmes ont été mis au point en coopération avec plusieurs compagnies aériennes et établissements de formation d'Europe. Ces programmes permettent de simuler une région où un certain nombre de vols sont exécutés entièrement en concordance avec la réalité, tandis que deux des aéronefs du système sont en fait des simulateurs de vol, en vraie grandeur, desservis par des équipages dûment qualifiés de compagnies aériennes ; quant à la transmission des directives, elle est assurée par des contrôleurs aériens professionnels sur les fréquences radio-téléphoniques (cf. exercices réalisés avec quatre simulateurs : un B-737 et un B-757 de la British Airways, et un B-737 et un DC-10 de la SABENA).

7. CONCLUSIONS

L'augmentation de la densité et de la complexité du trafic aérien en Europe occidentale sont telles que, compte tenu des dimensions géographiques de cette région, il est devenu indispensable de planifier et de mettre en oeuvre les moyens voulus pour acheminer le trafic dans les meilleures conditions de sécurité, de capacité, d'économie d'exploitation et de charge de travail des équipages. Nous recommandons qu'une importance toute particulière soit accordée à la régulation du trafic aérien en temps réel et que les différentes phases de vol soient intégrées sur des zones plus vastes, dont un exemple type pourrait être une région englobant les zones terminales de Bruxelles, Amsterdam, Londres, Francfort et Paris et s'étendant, pour autant que de besoin, vers le nord, le sud, l'est et l'ouest.

L'avantage de cette démarche est que tout vol autorisé à décoller d'une piste quelconque de cette région serait exécuté, jusqu'à sa sortie de la région - ou jusqu'à son atterrissage si l'aéroport de destination y est situé - en conformité de la politique générale des compagnies sans subir les changements de route ou de profil qu'impose le contrôle de planification à court terme et qui nuisent tant au bon écoulement du trafic aérien.

Certains des moyens nécessaires à la régulation du trafic telle qu'elle est recommandée ci-dessus existent déjà ou sont en cours d'élaboration à la Direction technique de l'Agence EUROCONTROL, notamment pour ce qui est de la prévision, du guidage et du contrôle des trajectoires. A cet égard, les essais réalisés à ce jour en coopération avec des contrôleurs de la circulation aérienne et des équipages de vol ont donné des résultats entièrement satisfaisants en ce qui concerne tant les exigences de la précision que l'exploitation des aéronefs. En outre, les simulations temps accéléré et les premières simulations temps réel, réalisées à l'aide de données concernant des courants de trafic réels dans les zones de convergence de Londres et de Bruxelles, ont permis de mettre au point des stratégies pratiques pour l'ordonnement du trafic.

L'expérience acquise et les connaissances cumulées de divers établissements européens de recherche nous autorisent à envisager un travail concerté qui ne manquera pas de déboucher sur la mise en place des préalables techniques et opérationnels indispensables à la mise en oeuvre de la recommandation proposée.

THE EUROCONTROL FUTURE ATS SYSTEM CONCEPT

and

THE PROGRAMME OF STUDIES, TESTS AND TRIALS

V. Vachiéry
Engineering Directorate
European Organisation for the Safety of Air Navigation
EUROCONTROL
72, rue de la Loi. B-1040. Bruxelles

1. INTRODUCTION

It is clear that the era of the simultaneous but uncoordinated development of ground-based ATC systems on one hand and of airborne navigation, guidance and communications systems on the other is definitely over. Two factors, namely the considerable growth in air traffic and aircraft operators' desire for maximum economy of operation, nowadays make it essential that such systems, in the air and on the ground, should harmoniously complement each other and it is the task of those responsible for Air Traffic Management (ATM) to ensure that appropriate solutions are employed to achieve this.

Planners are agreed that to increase both the airspace capacity for traffic and the efficiency with which traffic is handled while maintaining the essential requirements of safety involves two essential components :

- (i) Close collaboration between aircraft in flight and the ATC services. This can be achieved by the use of a data link between the on-board computers of the FMS (Flight Management System) and ATC computers on the ground and is a pre-requisite for the accurate prediction of aircraft flight paths, not only in space but also in time, i.e. in four dimensions.
- (ii) A greater degree of automation, not only to assist in routine operations but also in the decision-making processes both in the air and on the ground.

These aspects of the situation are clearly taken into account in the "Future ATS System Concept Description" (EUROCONTROL Document No. 87.1007 of May 1987). This concept is the fruit of work by experts from the Member States and the EUROCONTROL Agency, together with representatives from the user organisations IATA, IACA and IAOPA and the European industry organisation AECMA, and was approved by the EUROCONTROL Permanent Commission of Ministers in July 1987.

The refining of the concept and its subsequent implementation around the year 2000 necessitates the carrying out by the EUROCONTROL Organisation of a substantial programme of research, studies, tests and trials, using the resources of the Member States and the EUROCONTROL Agency. Certain parts of the programme are in fact already being actively undertaken.

The present paper sets out, firstly, the essential characteristics of the concept, the principles which should guide its implementation, the ATC functions and its main components, namely the surveillance, communications and navigation systems, and the various aspects connected with automated assistance.

This is followed by an account of the studies, tests and trials programme connected with the development of the concept, including a reference to the resources to be deployed both in the Member States and within the EUROCONTROL Agency.

2. DESCRIPTION OF CONCEPT

2.1. General

The future ATS system concept necessarily results from an evolving and continuous process, which does not however prevent it from including some revolutionary changes compared with the current system. The main components of the future concept are expected to be available towards the end of the 1990s. The concept itself is intended to cover a period extending up to the years 2010/2015.

Several lines of action were considered, from continuing with the present system up to a completely "open sky" concept, including "maximum capacity" and "maximum segregation" concepts and a concept in which the whole of the traffic would be planned by computer.

The "semi-open sky" concept was the one adopted. With this concept airspace utilisation should become more efficient as the philosophy of close coordination and flexibility applied today in the Upper Airspace is progressively extended down to a lower level. Moreover, even though it will be necessary to continue to utilise a basic network of published routes, the organisation of airspace and navigation will be based on area navigation (RNAV). In addition, this concept will be a move in the direction of the elimination of reserved air spaces whether permanent or semi-permanent.

As set out the concept adopted concerns the following components of the air traffic system :

- Air Traffic Control
- Air Traffic Flow Management
- Airspace Management
- Airspace and Route Structure
- Navigational Facilities.

The Working Group which was responsible for the description of the future ATS System Concept desired that it should be acceptable outside the EUROCONTROL area and would be a tool that could be used for ATS planning for the whole of the ICAO EUR Region.

2.2. Main principles

The following is a list of the main principles by which the development and operation of the future ATS system should be guided :

1. Conformity with ICAO Standards and Recommended Practices.
2. Continuity of safe operations.
3. Provision of adequate redundancy in Navigation, Surveillance and Communications systems.
4. Duplication of facilities to be kept to a minimum consistent with operational efficiency and safety.
5. A balance of the human responsibility (pilot and controller) and automated assistance.
6. The ATS system to serve the whole of the airspace and the totality of the traffic.
7. Airspace organisation to be based on an area control concept rather than a fixed route network concept.
8. Maximum utilisation of the capabilities of advanced airborne equipment.
9. Utilisation of Minimum Performance Specifications.
10. Cost-effectiveness analysis and operational/technical judgement for policy decisions.
11. Air traffic management functions to be essentially ground-based.
12. Capacity for coping with demands.
13. A balance to be achieved between air traffic demand and ATC capacity.
14. Avoidance of airspace segregation.
15. Except when vectored by a radar unit, the responsibility for aircraft navigation should rest with the pilot.
16. No systematic priority to be accorded to any particular class of traffic.
17. Functional harmonisation of services.
18. Compatibility in data exchanges.

2.3. ATC functions

The functions to be performed by air traffic control have been listed and are as follows :

Function ATC 1 : Avoidance of in-flight collisions.

Within this function there are 3 levels of conflict prevention :

- Medium-term (from 5 to 20 minutes) : this is handled by ATC issuing clearances;
- Short-term (of the order of 2 minutes) in which a ground-based facility acts as a safety net;
- Automatic warning of the pilot by anti-collision systems, the warning time being of the order of 30 seconds. The provision of such systems is optional. The system can be based on airborne components alone or on a combination of airborne and ground-based devices.

Function ATC 2 : Avoidance of collisions on the ground.

Function ATC 3 : Advice for the avoidance of collisions with the ground.

Function ATC 4 : Ensuring optimum efficiency for the operation of each aircraft in flight.

Function ATC 5 : Provision of up-to-date information to flight crews, e.g. weather conditions and the status of ground facilities.

Function ATC 6 : Ad hoc assistance to individual flights on request.

Function ATC 7 : Real-time acquisition and real-time relay of weather information from aircraft in flight. (This is especially important for accurate prediction of the flight path.)

Function ATC 8 : Identification of flights for defence purposes.

Function ATC 9 : Activities related to ATFM.

Function ATC 10 : Exchange of information for airspace management purposes.

Function ATC 11 : ATC support in SAR action (pour mémoire).

Function ATC 12 : Provision of information for route charges purposes (pour mémoire!!!!).

2.4. Data input into the system

The level of performance of the ATC functions is dependent upon the quality of the data input into the ATC system. These data are obtained from the use in combination of the surveillance, communications and navigation systems. In each of these fields basic improvements have to be provided.

2.4.1. Surveillance system

The search for an increase in the potential density of traffic through the reduction of separation minima implies improvements in the surveillance system with regard to :

- accuracy in position information ;
- the timely detection of gross errors in navigation;
- reliability in the identification of aircraft.

Within the period of the concept, surveillance will continue to be provided through the use of ground-based radars.

Secondary surveillance radar will have improved performance through the use of monopulse techniques.

SSR Mode S will, in areas of high traffic density, provide suitable improvements such as :

- an improvement in the reliability of SSR information (viz. position, identification, altitude);
- an improvement in the monitoring and prediction of the movement of aircraft in the vertical plane;
- the automatic acquisition by the ground systems of flight identifications through the use of the data link;
- the automatic acquisition, also by means of the data link, of certain airborne navigational data which will make it possible to improve the ground tracking of aircraft and flight path prediction;
- the renewal rate of information on each aircraft will be selectively adjusted in accordance with instantaneous ATC needs.

The setting up of Mode S radar stations is an example of the type of implementation which should be carefully coordinated at the ICAO regional level. This aspect is of special importance in the EUROCONTROL study programme.

Dependent surveillance, i.e. the provision by the airborne system of position information to the ground system, will find a potential application with the Mode S radar system and its air-ground data link or with the use of satellite. An initial development based on the use of Mode S could facilitate the subsequent introduction of satellite techniques in this field. Suitable investigation into the problems of reliability and integrity of these systems will of course be necessary. However, dependant surveillance, which is already under discussion on a worldwide basis (the ICAO FANS Committee), is considered to be the best option where independent surveillance is not available, as in the case with low-level or oceanic operations.

A satellite-based independent cooperative surveillance system whereby position can be determined on board the aircraft, on the ground or by the space segment of the system, has potential advantages compared with ground-based radars. However, as this is a system whose operational coverage could extend well beyond the airspace of the European region, it would seem premature at the present stage to include this type of surveillance system in the concept.

Primary radar should no longer be required for those types of airspace where traffic conditions and SSR detection reliability are such as to ensure that a safe radar service is provided. However, the need for primary radar will continue to exist for those airspaces in which it is necessary to render the operation of non-SSR-equipped aircraft compatible with the services provided to SSR-equipped aircraft (namely around major terminal areas), and also to satisfy a continued need with regard to military requirements.

2.4.2. Communications system

The linking of the airborne and ground-based computers by an automatic data link will be a most important development in air-ground communications, and could be as important as the introduction of radar was in the past.

A data link is necessary in order that the ground-based system can acquire the airborne data which is needed for improvement to sector capacity and to obtain the full advantage of the automated assistance envisaged in the future concept. In addition, a data link should help to provide airborne access to ground data bases such as those of the AIS and MET services.

Speech communications will remain the most practical method of dialogue between pilots and controllers. The volume of speech communications will, however, depend on the degree of utilisation of the automatic air-ground data link. Nevertheless, full VHF coverage will continue to be of prime importance. However, where large sea areas, for example, are concerned, there is the possibility of replacing it by satellite voice links.

Ground-ground communications will experience a considerable increase in the automatic exchange of data for which the CIDIN and the public data transmission networks will be the facilities employed. This will allow the rational utilisation of a distributed data base system which will be provided for the use of ATC.

2.4.3. Navigation system

The future concept is based on the use of Area Navigation (RNAV) which is an airborne-interpreted method of navigation allowing routings free from the siting constraints of ground-based facilities. This complies with the recommendation of the Seventh EUR Regional Air Navigation Meeting and the Air Navigation Plan which recognises two classes of RNAV equipment, basic RNAV and precision RNAV; this classification is in line with the Required Navigation Performance Capability (RNP) concept.

Area Navigation will have the advantage that within the period covered by the concept the vast majority of aircraft will be equipped with FMS; 60 to 70 % of airline aircraft will be so equipped in 1995 and subsequently this proportion should increase appreciably.

The use of satellites will depend upon the standards of performance that can be ensured in high traffic-density airspace.

2.5. Automation

Automated assistance will play an ever-increasing part in the air traffic control process.

The growth in traffic demand will require that the capacity of the airspace be significantly increased and that ATC be provided with the facilities for taking action in a flexible manner and without constraints for the user. It is only through the extensive use of automated assistance that this can be achieved, and full use will need to be made of computers in providing the capability for the following :

- Storing and processing large quantities of data,
- Assessing small variations hardly detectable by human operators,
- Rapidly simulating predictable future situations.

The man-machine relationship, by which the real benefits of computer assistance are largely conditioned, needs to be improved by new capabilities in display techniques and computer dialogue which are being developed in various fields. These will have to be adapted to the particular needs of ATS.

System reliability and integrity are subjects of major concern arising from the increased use of automation in a field in which safety is of overriding importance.

Compatibility between the processing systems of adjacent areas will be essential.

The transition from one level of automation to another and the implementation of automated facilities in adjacent centres are matters which will need to be carefully studied.

The EUROCONTROL concept sees three applications of automatic assistance :

- Flight path prediction,
- Improvements in organising the expected traffic situation,
- Automatic assistance in monitoring.

The contribution of increased automation to control capacity is illustrated in the following diagram.

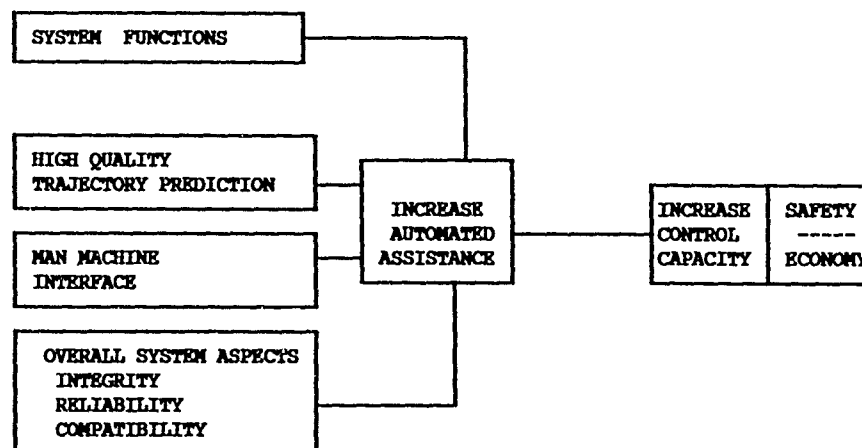


Fig.1

2.5.1. Flight path prediction

The achievement of significant improvements in the organisation of the traffic situation and the application of automated assistance for monitoring activities require the ability to make high-quality prediction of aircraft flight paths.

The EUROCONTROL concept distinguishes between two types of flight path prediction :

- (i) That required for the short-term prevention of collisions, which consequently has a short reaction time, a low false-alarm rate and a high-detection probability;
- (ii) That required in support of systems for the planning and sequencing of traffic which cover, for example, the pre-structuring of traffic in a given control sector and the achieving of optimum arrival sequencing.

Each type of flight path prediction thus has its own requirements as regards the nature and the source of the data employed, the frequency of updating and the level of performance.

It has to be emphasised that the provision of an automatic air-ground data link is the necessary condition which will allow the limitations in the use of flight path prediction techniques to be overcome since it will allow communication between the PMS/FMS systems and the ground-based computer systems.

2.5.2. Organisation of the expected traffic situation

This concerns the harmonisation of strategic and tactical measures. In fact, control efficiency depends upon, firstly, the ability to forecast traffic situations and to influence these situations by planning measures and, secondly, the possibility of deciding on tactical measures which are consistent with the planned situation.

During the period of application of the concept, artificial intelligence will have made marked progress and it is likely that computers will then be able to be used to reproduce organised, planned, traffic situations and to rationalise them as necessary by adaptation to specific sets of circumstances.

In addition, the combination of high-quality flight path prediction, of selective display facilities and warning features will allow the problems involved to be categorised and assigned different degrees of priority and make it possible to assist controllers in organising the expected traffic situation and in monitoring the safe progress of each flight from take-off to landing.

2.5.3. Automatic assistance in monitoring

The Concept emphasises the following aspects of automated assistance in this field :

- The identification of non-conflict situations,
- The ensuring of safety,
- Improvements in the management of arriving flights.

2.5.3.1. Identification of non-conflict situations

It is considered that the ability to identify real non-conflict situations with certainty should improve control capacity in a significant degree. It would in fact allow the controller to concentrate his attention on the flights which actually pose a problem and would reduce the number of interventions on the part of ATC, with the result that unnecessary disturbances which detract from the optimum conduct of the flight are eliminated.

2.5.3.2. Ensuring safety

This is a matter which is dealt with at three levels; in decreasing order of the time involved these are :

- Prevention of in-flight collisions by the controller, with the assistance of automatic warning aids, particularly in areas of high traffic density.
- The use of a short-term conflict alert (STCA) facility, based on a maximum of 2 minutes warning time and using only data that is obtained automatically from the surveillance system.
- The use of airborne collision-avoidance systems (ACAS); it is expected that the carriage of such systems will not be mandatory for some time.

2.5.3.3. Improvements in the managing of arrival flights

There will be a need to adopt procedures and to set up facilities which will aim at providing the optimum utilisation of available runways and landing capacity; this will minimise delays while respecting the users' requirements for optimum descent flight paths.

Automated assistance will play an important role here in several ways, namely in the general organisation of traffic, the determining of the landing sequence, the acquisition and processing of flight profile data and the preparation of air traffic control messages.

2.6. Procedures

The procedures employed will be directly dependent on the quality of the surveillance, communications and navigation systems and the capabilities of the ATC system.

2.6.1. Separation minima

It is considered that the following minima will apply :

Vertical separation

1000 feet at all levels.

Horizontal separation

- (i) Lateral separation : 7 to 8 NM between parallel routes continuously monitored by radar and with some form of automatic deviation warning.
- (ii) Longitudinal separation : 10 NM if an automatic conflict alert system is utilised.
- (iii) Radar separation : 5 NM or 3 NM as specified by ICAO.

2.6.2. Airspace sectorisation

The airspace will continue to be divided into sectors. However, automatic conflict-detection techniques should enable the planning of air traffic to be performed over a length of flight path involving several (executive) control sectors. The ability of aircraft to maintain cleared conflict-free tracks will reduce the number of occasions on which ATC intervention will be necessary.

2.6.3. Route network

The RNAV capability of aircraft will make it possible to rely on a basic route network and offer increasing freedom in the application of "off-route" flight paths and the introduction of closely-spaced parallel tracks.

2.7. Summary of the concept and its principal features

The traffic densities that are forecast for the beginning of the coming century are such as to give rise to the recommendation of an evolution towards a "semi-open sky" concept which will make it possible to deal with the problems of capacity. The concept is based on the use of area navigation and area control and is designed to increase flexibility and efficiency in the utilisation of airspace; in particular, permanently or quasi-permanently reserved airspaces will virtually disappear.

Other essential features are the use of SSR Mode S and the setting up of an air-ground data link. The development of automatic ground-ground data links will also be involved.

Control capacity will be increased through an increase in automated assistance.

The concept requires the use of flight path prediction of high quality. In this connection, automatic links between on-board PMS/FMS and ATC computers on the ground will play an essential role.

3. THE EUROCONTROL ORGANISATION'S PROGRAMME OF STUDIES, TESTS AND TRIALS AND OF RESEARCH AND DEVELOPMENT

3.1. The EUROCONTROL Convention

The Protocol amending the EUROCONTROL International Convention stipulates that the Organisation, consisting of the Permanent Commission (at the ministerial level) and the Agency (the executive organ) shall, amongst others, undertake the following tasks :

- o to promote and conduct studies, tests and trials relating to air navigation ; to collect and distribute the results of studies, tests and trials carried out by the Contracting Parties in the field of air navigation ;
- o to coordinate the Contracting Parties' research and development programmes relating to new techniques in the field of air navigation.

3.2. Facilities and resources

3.2.1. The EUROCONTROL Agency

The EUROCONTROL Agency has study departments at its headquarters in Brussels and substantial hardware and software facilities at the EUROCONTROL Experimental Centre at Brétigny-sur-Orge in the Paris area. These facilities include air traffic control simulators, a computer complex, software tools and test benches for different purposes. A large part of EUROCONTROL's expertise and resources are devoted to its programme of studies, tests and trials.

3.2.2. The Member States

Experts from Member States assist in the preparation and carrying out of the studies, tests and trials programme. However, some of the Member States have not only their own ATC research and development establishments but also aeronautical research and development establishments. This is particularly advantageous in the context of the future concept given the need to combine expertise from both of these fields.

3.2.3. Project PHARE (Programme for Harmonised ATM Research in the EUROCONTROL Organisation)

In the EUROCONTROL concept, major importance is attached to the combining in the future of certain research and development activities in the aeronautical field with research and development activities in the ATC field (the latter will require a detailed knowledge of aircraft performance and avionics).

In this connection, the EUROCONTROL Agency has recently launched an initiative which it is proposing will take shape under the name of the project PHARE. The purpose of this project is to find the means of harmonising the ATM research and development work performed by aeronautical research and experimental establishments with the work performed by ATC research establishments.

The establishments concerned are the following :

- (a) Aeronautical establishments
 - CEV, Brétigny, and CERT, Toulouse, both in France
 - DFVLR, Brunswick, the Federal Republic of Germany
 - NLR, Amsterdam, The Netherlands
 - RAE, Bedford, United Kingdom.
- (b) ATC establishments
 - ATCEU, Hurn, and RSRE-AD4, Malvern, both in the United Kingdom
 - BFS, Frankfurt, the Federal Republic of Germany
 - CENA, Athis-Mons, and STNA, Paris, both in France
 - DFVLR and NLR, listed under (a), which also have ATC research departments
 - EUROCONTROL Experimental Centre (EEC), Brétigny, France.

The PHARE initiative, in which establishments in non-Member States would be able to participate, should have the following features and capabilities :

- o Be multi-disciplinary
- o Facilitate access to flight test aircraft, flight simulators and real-time ATC simulators
- o Make it possible to analyse the tests and trials carried out and provide essential feedback to system designers
- o Stimulate research through the exchange of staff, ideas and results
- o Assist in the harmonising of action along the lines of the EUROCONTROL ATM concept.

PHARE is an ambitious programme but it is one that is essential for the evaluation and implementation of the systems which will have to cope with the problems to be faced in the year 2000.

3.3. The Studies, Tests and Trials Programme connected with the Concept

The key items in this programme are the following :

- The improvement of the surveillance and air-ground communications systems (Mode S Radar and automatic data link)

- The increase in automation involving in particular an improvement in 4D flight path prediction and close coupling between the pilot and the controller.
- The improvement in evaluation methods (using "demonstrators" providing a realistic representation of the airspace concerned) and in training facilities.

An important part of the programme is devoted to the analysis of the conditions to be met in order that the ground-based systems may in the future have the necessary facilities for the acquisition and the utilisation of the relevant on-board flight parameters.

The following diagram is an indication of the inter-relationship of the main components to be considered in the programme.

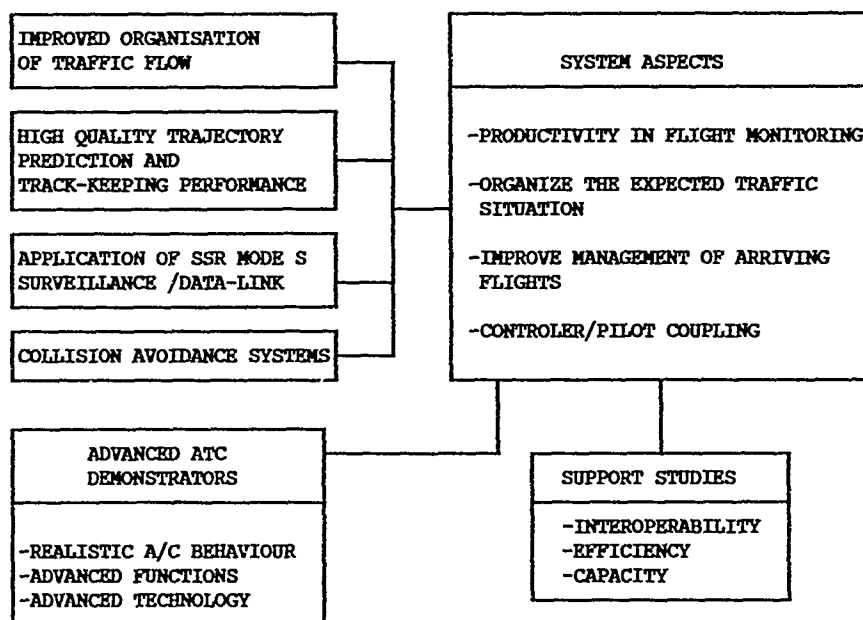


Fig.2

3.3.1. Mode S radar and automatic data link

The Agency has always been closely interested in developments in secondary radar along the lines of ADSEL/DABS and when the need arose at the beginning of the 1980s to envisage the adoption by ICAO of standards for the Mode S radar system, a trial and evaluation programme was put in hand.

At the present stage, this programme includes :

- the validation and proposal of standards to be sent to ICAO
- studies intended to identify the problems inherent in the transition from the current type of SSR towards Mode S
- studies connected with the operation of the system and the utilisation by ATC of the automatic data link.

3.3.1.1. The facilities employed

(i) Ground-based facilities

France and the United Kingdom are currently setting up three Mode S radar stations between them: the station in France is located in the Paris area, while the two in the United Kingdom are located respectively at Malvern and Gatwick (the latter being mobile).

(ii) Airborne equipment

The Member States are jointly financing by means of the Agency's budget the development and acquisition of thirty Mode S transponders of performance level 4 as specified in the Annex 10 to the ICAO Convention. These transponders should have been delivered by 1988 and will make it possible to test the technical operation and the surveillance part of the data link. However, the transponders have to be supplemented by an item of equipment which will allow the evaluation of the ATC applications of the data link. A study has therefore been made of a unit which will bring together the appropriate on-board data and process it for transmission to the ground and also distribute the data transmitted to the aircraft from the ground : this item of equipment is called a Data Link Processing Unit (DLPU).

A contract has recently been concluded for the development of 12 Data Link Processing Units. These will be installed on airline aircraft for the majority of the trials, but flight test aircraft will also be used.

(iii) Other equipment

The evaluation programme is based on the use of ground interrogators, on-board Mode S transponders and DLPUs for the data link evaluation. However, the programme also requires various analysis and evaluation tools such as arithmetical simulation models and a system known as the Data Link and Transponder Analyser System (DATAS) which it is envisaged will be produced jointly with the FAA.

3.3.1.2. Programme timetable

Having been preceded by the installation as from 1983 of the ground stations and on-board equipment, the evaluation programme should enter its active phase in 1988 as regards the surveillance function and the multi-site aspects, and continue in 1989 and beyond in connection with the ATC applications of the data link. The programme also includes studies into airborne collision-avoidance systems (ACAS) which have already been, or will be, the subject of experiments conducted in France and the United Kingdom.

3.3.2. Satellite communications ; the PRODAT project

Together with the United Kingdom and Spain, the EUROCONTROL Agency is a member of the group engaged in the ATC experimental programme known as PRODAT which is sponsored by the European Space Agency. This programme should serve as a basis for additional studies in the field of automatic dependent surveillance (ADS).

3.3.3. Increased automation

3.3.3.1. General

The increased use of automated systems in the decision-making process (an increase which is essential in order to cope with the growth in traffic demand) entails research and development at several levels, the following in particular :

- The man-machine dialogue
- An improvement in flight path prediction necessitating, firstly, the evaluation of, and improvement in, the quality of the input data, in particular the components of the aircraft state vector and weather data, and, secondly, the development of the algorithms concerned
- The system functions as described in 2.5. above
- System reliability and integrity (these are always-present concerns).

3.3.3.2. The man/machine dialogue

In the context of the introduction of "strip-less" ATC systems, the Agency has begun to evaluate the problems connected with the man/machine dialogue in a highly-automated environment. This matter has recently been the subject of real-time trials and simulations concerned in particular with the use of a colour code for the different items of information presented to the controller. This programme is continuing and may be extended to other aspects of the man/machine dialogue such as the introduction of speech recognition, and may go so far as to develop minimum operational performances for the dialogue and display system intended for use by the controller.

3.3.3.3. Flight path prediction

During the decades ahead, the aircraft to be handled will be equipped with avionics of different degrees of capability, from 4D-FMS to 2D-RNAV. In addition, air/ground data exchange equipment will progressively be installed.

ATC will therefore find itself in a situation in which, to put it in simple terms, there will be two categories of aircraft to handle :

- (a) One category will be able automatically to determine, transmit to ATC, and follow (and, if necessary, recalculate) optimum flight profiles ; this will enable ATC to "negotiate" an acceptable flight profile rather than predict the flight path to be followed ;
- (b) Another category which although able to comply with the separation standards in force, will not be able to follow a flight profile with any greater degree of accuracy than that of the predicted flight path which is calculated by ATC from the data that is available to it.

It can therefore be envisaged that the data defining the predicted flight paths used by ATC will be obtained from two different sources, one on board the aircraft and the other by ATC on the ground. In both cases the data link will be essential for the transmission of the flight path as determined by the on-board FMS or of the data comprising the aircraft state vector.

The studies to be put in hand or pursued further can be summarised as follows :

- The detailed evaluation of the accuracy with which the presumed flight path of the aircraft in space and time is monitored.

- The development and validation of the algorithms for the calculation of the flight path ; it may be noted that the quality of the input data and the complexity of the algorithms vary according to the length of the period of time with which the prediction is concerned.
- Research into the methods whereby accurate weather data can be obtained by ATC centres on the ground and on board aircraft in flight.

3.3.3.4. System functions

As referred to above, the EUROCONTROL concept covers two other major fields in connection with the prediction of flight paths. These are :

- Improvements in organising the expected traffic situation
- Automated assistance in monitoring activities, which covers the identification of non-conflict situations, the ensuring of safety and improvements in the management of arriving flights.

Preliminary studies have already begun on some of these aspects. In the case of others, the studies and trials are a continuation of these activities which are already in progress, for example, flight path prediction, improvements in the short-term conflict alert system, assistance in conflict detection and resolution as a part of the CAPE planning function and ACAS studies.

In yet other cases such as improvements in the management of arriving flights, the research work, trials and operational evaluations have already been carried out for several years either within the EUROCONTROL Agency (e.g. Zones of Convergence) or in the Member States (e.g. COMPASS, HAP, MAESTRO, TCSDG-UK).

3.3.4. Evaluation and training methods and facilities; ATM demonstrators

3.3.4.1. General

Up to the present time, the research, trials and operational evaluation carried out prior to the introduction of new functions have placed relatively little importance on a global systems approach which would take due account of the factors involved in the ground-based ATC system as well as the factors involved in the air traffic situation.

The result is that in the experiments and trials carried out the aeronautical side of the overall situation is represented either in an over-simplified way (aircraft performance, simulation of flight path, and so on) or in a too restricted manner (e.g. exercises of an experimental type in which the aircraft behave in a realistic manner but whose traffic sample is small as regards both the number and types of aircraft). The same is true as regards ATC training and re-training facilities.

This could be acceptable if the ATC system were capable of adapting itself to the advances in aircraft design without there being any significant dialogue between aircraft designers and ATC planners.

In this connection, however, it is clear that foreseeable developments will require a change of attitude : both the future growth of traffic and the potential capabilities of the avionics installed in today's aircraft demand that an overall approach should be adopted.

3.3.4.2. ATM demonstrators

In view of the foregoing the facilities used for ATM evaluation and training have to evolve towards a closer and more realistic integration of the airborne and ground-based components of the air traffic control system. Such an evolution, whose importance can easily be appreciated, is not at all easy to put into effect. This has already been found when, for example, there has been a need to have documentation containing actual performance data of aircraft, to know the algorithms of Flight Management Systems or to get to grips with the problems of the interface between integrated flight data systems and an air-ground and ground-air automatic data link.

It is evident that in the medium term the desired changes are very much conditioned by what exists at the present time whether in actual use or in an advanced stage of experimental development, for example, Mode S.

It is extremely important that the initial stages of implementation of the Concept should take into account the longer-term aims so that the transition to higher levels of performance can take place smoothly.

The need for a realistic representation of the airborne side of the equation when evaluating future ATM system functions has already been taken into account in a number of trials in which the essential component was the use of airline flight simulators (for different types of aircraft) which were actually "piloted" by airline flight crews (ZOC/Cintia is an example).

Similarly, where real-time simulation systems are concerned, the necessary arrangements have been made to replace the simulated navigation of aircraft of the "blip driver" kind by sub-systems which provide realistic behaviour of the different types of aircraft in service.

In the various stages of research and trials, it will be increasingly important to have the interactive participation of advanced flight simulators, of flight test aircraft and, in the ultimate stages, of actual airline aircraft.

Moreover, while accepting that the future concept will have to come about as the result of a continuous and evolving process of implementation of new functions, it may be considered that the production of demonstrators which incorporate the most advanced forms of technology and a number of revolutionary concepts such as artificial intelligence, automatic speech recognition, automatic conflict resolution and other automatic systems, will be such as to bring about fruitful reflection on what is involved. This is the path that the Agency proposes to follow in the development of the tools required for the research programme that is linked with the concept for the year 2000 and beyond - and in which the first (and modest) step consists in carrying out a real-time simulation that has been given the name of ARC 2000.

3.3.4.3. Training methods and facilities

The methods and facilities for the training and re-training of personnel will of necessity have to be adapted to the changes in the ATM system and take its new aspects into account. In this connection also, a number of studies and developments have begun to indicate new courses of action that can be followed in the years ahead.

4. CONCLUSIONS

Two of the main characteristics of the ATM concept are the use of an air-ground and ground-air data link to ensure close cooperation between aircraft in flight and the ATC services on the ground, and the introduction of automation into decision-making processes.

The medium-term solutions include, firstly, an improved aircraft navigation system leading to RNAV and, secondly, an improved surveillance system through the use of Mode S which will introduce the long-awaited automatic data link.

There is not much time remaining to take appropriate action in response to the need for an increase in the capacity of the air traffic management system.

The substantial programme of research and trials involved in the progressive implementation of the ATM concept necessitates due reflection and concerted action between all the parties concerned together with the provision of the resources required, whether tools or expertise, in both quality and quantity.

Active community cooperation - in the wide sense of the term - is more than ever essential.

LE CONCEPT DU FUTUR SYSTEME ATS EUROCONTROL

et

LE PROGRAMME D'ETUDES, ESSAIS ET EXPERIMENTATIONS

V. Vachiéry

Direction Technique
Organisation Européenne pour la Sécurité de la Navigation Aérienne
EUROCONTROL
72, rue de la Loi. B-1040. Bruxelles

1. INTRODUCTION.

L'ère des développements parallèles et non concertés des systèmes au sol et de l'avionique de guidage, de navigation et de communications est révolue. La recherche de conditions d'exploitation économiques optimales d'une part, et la nécessité de faire face à un trafic croissant d'autre part, imposent aux responsables de la Gestion du Trafic Aérien (Air Traffic Management-ATM) des solutions qui marient harmonieusement les technologies disponibles au sol et à bord.

Les concepteurs s'accordent à penser que l'accroissement de la capacité et de l'efficacité de la gestion du trafic tout en respectant les impératifs de sécurité, impliquent deux éléments essentiels:

- Une concertation étroite entre le domaine "AIR" et le domaine "SOL", rendue possible par une liaison de données entre les calculateurs des systèmes de guidage embarqués (FMS) et les calculateurs au sol. Cette liaison est la condition nécessaire à une prévision précise de la trajectoire de l'avion dans l'espace et dans le temps (trajectoires 4-D).
- Une intensification du recours à l'automatisation, non seulement à l'appui des opérations de routine mais également dans le processus de décision aussi bien à bord qu'au sol.

Ces aspects sont bien pris en compte dans la "Description du Concept du Futur Système ATS" d'EUROCONTROL (Doc 87.1007 de Mai 1987). Ce concept, auquel ont travaillé les experts des états membres et de l'Agence ainsi que des représentants d'organisations d'utilisateurs (IATA, IACA, IAOPA) et de l'industrie européenne (AECMA) a été approuvé sur le plan des principes par la Commission des Ministres d'EUROCONTROL en Juillet 1987.

L'affinement du concept et sa matérialisation, à l'horizon 2000, impliquent le déploiement, au niveau de l'Organisation d'un vaste programme de recherche, études, essais et expérimentations qui fera appel aux ressources des états membres et de l'Agence. Certaines parties du programme connaissent déjà une activité intense.

Dans ce qui suit, on passera d'abord en revue les caractéristiques essentielles du concept, les principes qui doivent en guider la mise en oeuvre, les fonctions ATC et les composantes principales, à savoir, les systèmes de surveillance, de communications et de navigation, et les aspects liés à l'assistance automatisée.

On présentera ensuite le programme d'études essais et expérimentations qui s'attache au développement du concept, en faisant référence aux ressources à déployer, tant dans les états membres qu'au sein de l'Agence.

2. DESCRIPTION DU CONCEPT.

2.1. Généralités.

Le concept futur doit résulter d'un processus évolutif et continu, ce qui n'exclut pas qu'il comporte des changements révolutionnaires par rapport au système actuel. Ses constituants principaux sont censés apparaître à la fin des années 1990. Il vise une période s'étendant jusqu'à 2010/2015.

Plusieurs approches ont été considérées allant du statu quo à un concept à "ciel ouvert" en passant par des concepts à "capacité maximum", à "ségrégation maximum" ou à un concept de trafic totalement planifié par ordinateur.

C'est un concept à "ciel semi ouvert" qui a été retenu :

Il tend à une utilisation plus efficace de l'espace aérien par l'application progressive aux niveaux inférieurs de la notion de coordination étroite et de souplesse d'emploi de l'espace telle qu'elle prévaut actuellement dans l'espace supérieur.

Il est basé sur la navigation de surface (RNAV) et sur un contrôle de surface (il restera nécessaire d'avoir recours à un réseau succinct de routes publiées).

Il s'oriente vers la suppression de la notion d'espaces réservés permanent ou semi-permanent.

Le concept tel qu'il est décrit concerne les domaines suivants:

- Contrôle de la circulation aérienne;
- Gestion des courants de trafic;
- Gestion de l'utilisation de l'espace aérien;
- Espace aérien et réseau de routes;
- Installations de navigation;

Les experts qui ont oeuvré à la description du concept ont eu pour souci de le rendre acceptable en dehors de la zone EUROCONTROL et d'en faire un outil utilisable pour la planification ATS pour l'ensemble de la région EUR de l'OACI.

2.2. Les Principes.

Les principes devant guider la réalisation et l'exploitation du futur système ATS sont résumés ci-dessous:

1. Conformité aux normes et pratiques recommandées de l'OACI.
2. Continuité et sécurité des opérations.
3. Redondance appropriée pour les équipements de Navigation, de Surveillance et de Communications.
4. Minimisation de la duplication des moyens.
5. Equilibre des responsabilités humaines (pilote et contrôleur) en milieu automatisé.
6. Le système dessert l'ensemble de l'espace et la totalité du trafic.
7. Organisation de l'espace aérien basée sur un concept de contrôle de surface par opposition à un concept à réseau de routes fixes.
8. Exploitation maximale des possibilités des équipements de bord modernes.
9. Utilisation de la notion de spécifications de performances minimales.
10. Orientations basées sur l'analyse coût/efficacité et l'appréciation opérationnelle-technique.
11. Fonctions de gestion du trafic assurées essentiellement par les services au sol.
12. Aptitude à faire face aux demandes.
13. Equilibre entre la gestion des courants de trafic (ATFM) et les services de contrôle (ATC).
14. Eviter la ségrégation de l'espace.
15. Le pilote est responsable de la navigation (sauf guidage Radar).
16. Pas de règles de priorité systématiques.
17. Harmonisation fonctionnelle des services.
18. Compatibilité des échanges de données.

2.3. Les fonctions ATC.

les fonctions ATC ont été répertoriées comme suit:

Fonction ATC 1 : Eviter les collisions en vol.

Cette fonction s'exerce à trois niveaux:

- à moyen terme (de cinq à vingt minutes) -Service ATC-
- à court terme (de l'ordre de deux minutes) Dispositif type "Filet de sauvegarde".
- Immédiat (de l'ordre de trente secondes). Optionnel. Système soit totalement embarqué ou mixte air-sol.

Fonction ATC 2 : Eviter les collisions au sol.

Fonction ATC 3 : Eviter les collisions avec le sol.

Fonction ATC 4 : Assurer l'efficacité optimale pour la conduite du vol de chaque aéronef.

Fonction ATC 5 : Mise à jour de l'information de vol nécessaire aux équipages (conditions météo, état des installations au sol, etc...).

Fonction ATC 6 : Assistance ad-hoc sur demande.

Fonction ATC 7 : Acquisition et retransmission en temps réel, par le sol d'information météo disponible à bord. (ceci est particulièrement indispensable pour une bonne prévision de trajectoire).

Fonction ATC 8 : Identification des vols pour les besoins de la défense.

Fonction ATC 9 : Activités liées à la gestion des courants de trafic.

Fonction ATC 10 : Echanges d'information pour la gestion de l'utilisation de l'espace aérien.

Fonction ATC 11 : Assistance ATC aux opérations SAR (pour mémoire).

Fonction ATC 12 : Fourniture d'informations pour le calcul des redevances (pour mémoire!!!!).

2.4. Les données d'entrée au système.

Le niveau de performance des fonctions de contrôle est conditionné par la qualité des données d'entrée au système ATC. Ces données résultent de la combinaison de l'exploitation des systèmes de Surveillance, de Communications et de navigation.

Dans chacun de ces domaines des améliorations fondamentales sont à prévoir.

2.4.1. Le système de surveillance.

La recherche d'un accroissement de la densité potentielle du trafic par une réduction des espacements implique pour le système de surveillance des améliorations dans :

- la précision du relevé de position;
- la détection en temps voulu des erreurs grossières de navigation;
- la fiabilité dans l'identification des aéronefs;

Pour la période considérée, la surveillance continuera d'être assurée par des radars au sol.

Le radar secondaire de surveillance sera l'objet d'améliorations par les techniques "monopulse".

Le SSR Mode S permettra, dans les zones à forte densité de trafic :

- l'amélioration de la fiabilité des informations SSR (position, identification, altitude);
- l'amélioration de la surveillance et de la prévision des déplacements dans le plan vertical;
- l'acquisition automatique par le sol, grâce à la liaison de données, des indicatifs d'appel;
- Par cette même liaison de données, l'acquisition automatique des paramètres du vecteur d'état de l'avion et d'autres données disponibles à bord, avec pour conséquence la possibilité d'améliorer la qualité de la poursuite et de la prédiction de trajectoire;
- l'adaptation sélective à chaque aéronef de la cadence de renouvellement des informations en fonction des besoins du moment de l'ATC;

La mise en place de station Mode S est le type même d'action qui demande à être soigneusement coordonnée au niveau régional OACI. Cet aspect revêt une importance toute particulière dans le programme d'études d'EUROCONTROL.

La "surveillance dépendante", (possibilité de fournir au sol des informations de position mesurées à bord) trouvera un potentiel d'application avec le mode S, sa liaison de données air-sol, ou l'utilisation de satellites spatiaux. Il est considéré que l'emploi, dans un premier temps de la technologie Mode S sera de nature à faciliter l'introduction ultérieure de la technologie "satellites". Bien entendu, des investigations sont nécessaires aux plans de la fiabilité et de l'intégrité des systèmes.

La surveillance dépendante, étudiée à l'échelon mondial par le comité FANS de l'OACI, peut être vue comme le meilleur choix dans le cas où la surveillance indépendante ne peut raisonnablement être mise en oeuvre, par exemple vols océaniques ou à basse altitude.

Un système coopératif indépendant à base de satellites, qui permettrait une mesure de position de l'avion à bord, au sol, ou par le segment spatial, présente théoriquement des avantages par rapport à un système radar au sol. Toutefois, il s'agirait ici d'un développement qui dépasse la seule Europe. Il a semblé prématuré, à ce stade, de retenir ce type de système.

Le radar primaire ne devrait plus être utilisé dans les espaces où les conditions de trafic et la détection du radar secondaire de surveillance (SSR) sont telles qu'un service sûr peut être garanti. Toutefois son emploi demeurera nécessaire, soit en combinaison avec le SSR pour faire face à des situations de trafic mixte (avions dotés ou non de SSR, par exemple autour de zones terminales importantes) soit pour satisfaire à des impératifs militaires.

2.4.2. Le Système de Communications.

Les Communications Air-Sol, connaîtront une avancée importante, de par l'introduction d'une liaison de données automatisée entre le bord et le sol. On estime que ce fait aura des implications aussi considérable que l'introduction, en son temps, du radar.

Une telle liaison est essentielle pour l'acquisition de données à bord, pour tirer le plein bénéfice d'une assistance automatisée qui permette d'accroître la capacité d'absorption du trafic. Elle offre par ailleurs la possibilité, dans l'avenir, de permettre depuis le bord, l'interrogation de bases de données au sol telles que Météo, AIS etc..

Les Communications verbales demeureront indispensables comme le moyen le plus pratique de dialoguer entre pilotes et contrôleurs. Leur volume dépendra, bien entendu, de l'intensité de l'emploi de la

liaison automatique de données Air-Sol. Il reste qu'une couverture VHF complète restera nécessaire, à laquelle se substituera pour les régions maritimes par exemple, la possibilité d'utiliser des liaisons phonie par satellites.

Les Communications Sol-Sol connaîtront un développement considérable des échanges automatiques dont le CIDIN et les réseaux publics de transmission de données constitueront le support. Ceci permettra l'utilisation rationnelle du système informatique à bases de données distribuées que comporte l'ATC.

2.4.3. Le système de navigation.

Le futur système se fonde sur l'emploi de la navigation de surface (RNAV) qui permet de s'affranchir de l'implantation des installations au sol. Il est en conformité avec la recommandation de la Septième EUR RAN et le plan de navigation aérienne qui distingue RNAV de base et RNAV de précision. Il fait appel au concept de niveau de performance requis (RNP).

Il bénéficiera du fait que, dans la période considérée la grande majorité des avions seront dotés de FMS (60 à 70% des appareils des flottes commerciales en 1995), proportion qui devrait ensuite augmenter sensiblement.

L'infrastructure du système de navigation dépend strictement de décisions à intervenir au plan de l'OACI.

L'utilisation de satellites sera fonction des niveaux de performance garanti dans les espaces à forte densité de trafic.

2.5. L'automatisation.

L'assistance automatisée prendra une part de plus en plus prépondérante dans le processus de contrôle. L'accroissement de la demande de trafic nécessitera que la capacité de l'espace aérien soit significativement augmentée et que le contrôle se donne les moyens d'intervenir avec souplesse et de façon non contraignante pour l'utilisateur. Ceci n'est possible que par un recours accru à l'assistance automatisée et en se dotant de possibilités:

- de stockage et de traitement de grandes quantités d'information
- de détection de petites variations difficilement discernables par l'opérateur humain
- de simulation rapide de situations futures prévisibles.

La relation homme-machine, qui conditionne largement les bénéfices réels de l'assistance automatisée, devrait pouvoir être améliorée par le fait du développement des techniques de visualisation et de dialogue auquel on assiste dans divers domaines. Il faudra les adapter aux besoins spécifiques ATM.

La fiabilité et l'intégrité du système constituent des sujets de préoccupation majeurs suscités par un recours accru à l'informatique dans un domaine où la sécurité doit prévaloir.

La compatibilité entre systèmes de traitement sera primordiale.

La transition d'un niveau d'automatisation vers un niveau supérieur et la prise en compte des actions menées dans les centres voisins devra faire l'objet d'une attention toute particulière.

Le Concept EUROCONTROL distingue trois domaines principaux :

- La prédiction des trajectoires.
- L'amélioration dans l'organisation de la situation de trafic envisagée,
- L'assistance automatique à la surveillance,

La contribution du recours accru à l'automatisation à l'augmentation de la capacité du contrôle est illustrée dans le diagramme suivant:

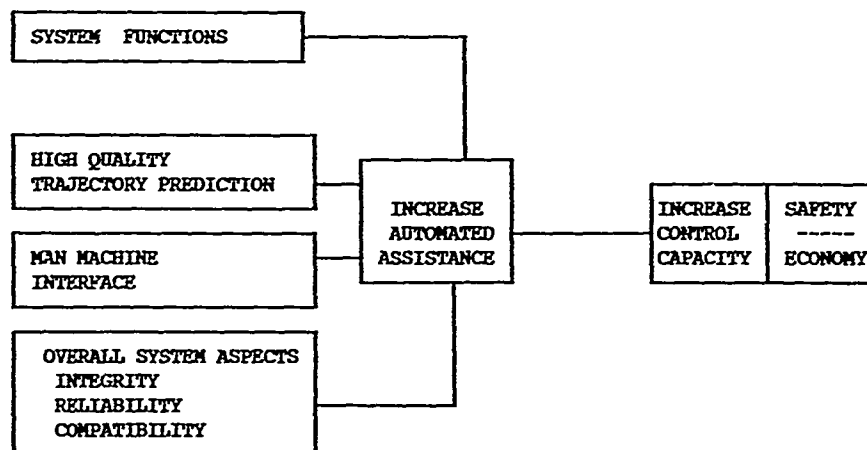


Fig.1

2.6. Procédures

Les procédures employées seront bien entendu fonction directe de la qualité des systèmes de surveillance, communications et navigation ainsi que de la performance du système de contrôle au sol.

2.6.1. Minima de séparation

Il est considéré que les minima suivants seront appliqués :

Séparation verticale

- 1000 pieds à tous les niveaux.

Séparation horizontale

- latérale : 7 à 8 miles nautiques entre routes parallèles ,sous surveillance radar et avec détection automatique d'écart.
- longitudinale : 10 miles nautiques, à condition d'utiliser un dispositif d'alerte automatique aux conflits.
- radar : 5 NM ou 3NM tel que prescrit par l'OACI.

2.6.2. Sectorisation

L'espace aérien continuera à être découpé en secteurs. Toutefois les techniques de prédiction de conflits devraient permettre à la planification de s'exercer sur des tronçons intéressant plusieurs secteurs exécutifs. L'aptitude des avions à suivre des routes autorisées exemptes de conflits aura pour conséquence une réduction des interventions de l'ATC.

2.6.3. Réseau de routes

La possibilité de navigation de surface permettra de se reposer sur un réseau de routes de base et donnera plus de latitude aux trajectoires "hors route" et à l'introduction de routes parallèles rapprochées.

2.7. Résumé du concept et idées forces

Les densités de trafic prévisibles à l'horizon 2000 amènent à préconiser une évolution vers un concept à "ciel semi-ouvert" qui soit de nature à faire face aux problèmes de capacité .

Il est basé sur la navigation de surface et sur un contrôle de surface.

Il tend à augmenter la souplesse et l'efficacité de l'exploitation de l'espace aérien; en particulier, la notion d'espace réservé permanent ou quasi permanent devrait disparaître.

Il est fondé sur l'utilisation du SSR Mode S et sur l'exploitation d'une liaison de données entre le sol et le bord.

Il implique le développement des liaisons automatiques sol-sol.

L'accroissement de capacité de contrôle est obtenue par une augmentation de l'assistance automatisée.

Il nécessite une prédiction de trajectoire de haute qualité. Une liaison automatique entre PMS/FMS et calculateurs au sol joue ici un rôle primordial.

La fonction de gestion des courants de trafic s'appuie sur une Banque Centrale de Données alimentant les unités ATFM.

3. ETUDES ESSAIS EXPERIMENTATIONS et RECHERCHE et DEVELOPEMENT DE L'ORGANISATION EUROCONTROL

3.1. La Convention EUROCONTROL

le Protocole amendant la Convention internationale EUROCONTROL stipule qu'entre autres tâches, l'Organisation, constituée de la Commission permanente (au niveau des Ministres) et de l'Agence (organe exécutif) est chargée de :

- promouvoir et exécuter des études,des essais et expérimentations touchant la navigation aérienne; rassembler et diffuser le résultat des études, essais et expérimentations effectuées par les Parties contractantes dans le domaine de la navigation aérienne;
- coordonner les programmes de recherche et développement des Parties contractantes relatifs aux nouvelles techniques dans le domaine de la navigation aérienne;

3.2. Moyens et Ressources

3.2.1. Agence EUROCONTROL

L'Agence dispose, au siège à Bruxelles, de départements d'études, et du **Centre** Expérimental EUROCONTROL situé à Brétigny-sur -Orge (France), dans la région parisienne.

Le Centre Expérimental est doté d'importantes ressources en matériel et logiciel (simulateurs de contrôle de la circulation aérienne, centre de calcul, outils logiciels, bancs d'essais etc...). Il consacre une part importante de son savoir-faire et de ses ressources au programme d'Etudes, Essais et Expérimentations (E.E.E).

2.5.1. Prédiction de trajectoires.

L'obtention d'améliorations significatives dans l'organisation de la situation de trafic et l'assistance automatique à la surveillance passe par la nécessité de disposer d'un système de prédiction de trajectoire de haute qualité.

Le concept a distingué deux types de prédiction :

- L'un, utilisé dans des fonctions de prévention d'abordage à court terme et permettant par conséquent un temps de réponse rapide, une faible probabilité de fausse alarme et forte probabilité de détection.

- l'autre, destiné à supporter les fonctions de planification et d'ordonancement du trafic telles que la préstructuration du trafic d'un secteur de contrôle et l'optimisation de la séquence d'arrivées.

Chaque type de prédiction a donc ses exigences propres en matière de nature, d'origine des données, de fréquence de mise à jour et de performance.

Il convient de souligner que l'existence d'une liaison automatique air-sol est la condition nécessaire à la suppression des limitations d'emploi des techniques de prévision de trajectoire en ce qu'elle ouvrira la voie à la communication entre les systèmes PMS/FMS et les systèmes d'ordinateurs au sol.

2.5.2. Organisation de la situation de trafic envisagée

Ceci est du domaine de l'harmonisation des fonctions stratégiques et tactiques. En effet, l'efficacité du contrôle dépend, d'une part, de l'aptitude à prévoir les situations de trafic, à agir sur ces situations par des mesures de planification et, d'autre part, de la possibilité de décider de mesures tactiques qui cadrent avec la situation prévue.

A l'horizon considéré, on estime que les techniques relatives à l'intelligence artificielle auront évolué de sorte à pouvoir reconstituer des situations de trafic organisées et les rationaliser en fonctions de circonstances spécifiques.

De plus la combinaison d'un système de prévision de trajectoire de haute qualité, de moyens sélectifs de visualisation et de dispositifs avertisseurs, devrait permettre de sérier les problèmes par ordre de priorité et assister le contrôleur dans l'organisation du trafic et dans le suivi du bon déroulement du vol du décollage à l'atterrissage.

2.5.3. Assistance automatique à la surveillance

Le concept met l'accent sur les aspects suivants:

- L'identification des situations non conflictuelles.
- La garantie de sécurité.
- L'amélioration de la gestion des vols à l'arrivée.

2.5.3.1. Identification des situations non conflictuelles.

On considère que la détection avec certitude des situations de non conflit réelles devrait améliorer de façon significative la capacité du contrôle. Ceci permettrait en effet de concentrer l'attention sur le trafic qui pose problème et de réduire les interventions de l'ATC avec pour conséquence la suppression de perturbations inutiles à la conduite optimale du vol.

2.5.3.2. Garantie de sécurité

Elle intervient à trois niveaux, par ordre de temps décroissant:

- Prévention des collisions par le contrôleur, avec assistance automatisée, particulièrement dans les zones à haute densité de trafic.
- Dispositif d'alerte aux conflits à court terme (à terme de 2 minutes maximum) basé au sol et utilisant exclusivement l'information dérivée automatiquement du système de surveillance.
- Emploi de systèmes anti-collision embarqués (ACAS); ce dernier élément pourrait rester optionnel pour quelque temps.

2.5.3.3. Amélioration de la gestion des vols à l'arrivée

Il conviendra de mettre en place des procédures et des moyens qui permettent d'exploiter de manière optimale la capacité d'atterrissage disponible et par là de minimiser les retards, tout en respectant des profils de vol conformes aux desiderata des usagers.

Ici encore l'assistance automatisée devrait jouer un rôle important que ce soit au niveau de l'organisation générale du trafic, de l'ordonancement des séquences d'atterrissage, de l'acquisition et du traitement des données de profil de vol ainsi que de l'élaboration des messages de contrôle.

2.6. Procédures

Les procédures employées seront bien entendu fonction directe de la qualité des systèmes de surveillance, communications et navigation ainsi que de la performance du système de contrôle au sol.

2.6.1. Minima de séparation

Il est considéré que les minima suivants seront appliqués :

Séparation verticale

- 1000 pieds à tous les niveaux.

Séparation horizontale

- latérale : 7 à 8 miles nautiques entre routes parallèles ,sous surveillance radar et avec détection automatique d'écart.
- longitudinale : 10 miles nautiques, à condition d'utiliser un dispositif d'alerte automatique aux conflits.
- radar : 5 NM ou 3NM tel que prescrit par l'OACI.

2.6.2. Sectorisation

L'espace aérien continuera à être découpé en secteurs. Toutefois les techniques de prédiction de conflits devraient permettre à la planification de s'exercer sur des tronçons intéressant plusieurs secteurs exécutifs. L'aptitude des avions à suivre des routes autorisées exemptes de conflits aura pour conséquence une réduction des interventions de l'ATC.

2.6.3. Réseau de routes

La possibilité de navigation de surface permettra de se reposer sur un réseau de routes de base et donnera plus de latitude aux trajectoires "hors route" et à l'introduction de routes parallèles rapprochées.

2.7. Résumé du concept et idées forces

Les densités de trafic prévisibles à l'horizon 2000 amènent à préconiser une évolution vers un concept à "ciel semi-ouvert" qui soit de nature à faire face aux problèmes de capacité .

Il est basé sur la navigation de surface et sur un contrôle de surface.

Il tend à augmenter la souplesse et l'efficacité de l'exploitation de l'espace aérien; en particulier, la notion d'espace réservé permanent ou quasi permanent devrait disparaître.

Il est fondé sur l'utilisation du SSR Mode S et sur l'exploitation d'une liaison de données entre le sol et le bord.

Il implique le développement des liaisons automatiques sol-sol.

L'accroissement de capacité de contrôle est obtenue par une augmentation de l'assistance automatisée

Il nécessite une prédiction de trajectoire de haute qualité. Une liaison automatique entre PMS/FMS et calculateurs au sol joue ici un rôle primordial.

La fonction de gestion des courants de trafic s'appuie sur une Banque Centrale de Données alimentant les unités ATFM.

3. ETUDES ESSAIS EXPERIMENTATIONS et RECHERCHE et DEVELOPEMENT DE L'ORGANISATION EUROCONTROL

3.1. La Convention EUROCONTROL

le Protocole amendant la Convention internationale EUROCONTROL stipule qu'entre autres tâches, l'Organisation, constituée de la Commission permanente (au niveau des Ministres) et de l'Agence (organe exécutif) est chargée de :

- promouvoir et exécuter des études,des essais et expérimentations touchant la navigation aérienne; rassembler et diffuser le résultat des études, essais et expérimentations effectuées par les Parties contractantes dans le domaine de la navigation aérienne;
- coordonner les programmes de recherche et développement des Parties contractantes relatifs aux nouvelles techniques dans le domaine de la navigation aérienne;

3.2. Moyens et Ressources

3.2.1. Agence EUROCONTROL

L'Agence dispose, au siège à Bruxelles, de départements d'études, et du **Centre** Expérimental EUROCONTROL situé à Brétigny-sur -Orge (France), dans la région parisienne.

Le Centre Expérimental est doté d'importantes ressources en matériel et logiciel (simulateurs de contrôle de la circulation aérienne, centre de calcul, outils logiciels, bancs d'essais etc...). Il consacre une part importante de son savoir-faire et de ses ressources au programme d'Etudes, Essais et Expérimentations (E.E.E).

3.2.2. Etats membres

Les Etats membres dont les experts collaborent à l'élaboration et à l'exécution du programme E.E.E disposent, pour certains, non seulement d'établissements de recherche et développement à vocation circulation aérienne, mais également d'établissements de recherche et développement à vocation essentiellement aéronautique.

Ceci est particulièrement intéressant dans le contexte du futur Concept compte tenu de la nécessité de combiner les deux domaines d'expertise.

3.2.3. L'initiative PHARE (Programme for Harmonised Atm Research in the EUROCONTROL organisation)

Les éléments essentiels du concept confèrent une importance primordiale, pour le futur, à la combinaison de certaines activités de recherche et développement du domaine aéronautique et des activités de recherche et développement du domaine ATC (nécessité d'une connaissance fine du domaine de performances de l'avion et de l'avionique).

L'Agence EUROCONTROL a pris récemment à ce sujet une initiative qu'elle se propose de concrétiser par le projet PHARE. Il s'agit de trouver les moyens d'harmoniser les actions de recherche et développement des établissements de recherche et expérimentations à vocation essentiellement aéronautiques, ressortant du domaine ATM, avec celles des établissements homologues à vocation essentiellement ATC.

Les établissements concernés sont:

- pour ce qui concerne le domaine aéronautique :

Le CEV - BRETIGNY et le CERT - TOULOUSE (FRANCE).
 Le NLR - AMSTERDAM (PAYS BAS).
 Le DFVLR - BRUNSWICK (RFA).
 Le RAE - BEDFORD (ROYAUME UNI).

- pour ce qui concerne l'ATC :

Le CENA - ATHIS-mons et le STNA - PARIS (FRANCE).
 Le BFS-Est FRANCFORT (RFA).
 L'ATCEU - HURN et RSRE-AD4 - MALVERN (ROYAUME UNI).
 Le Centre Expérimental EUROCONTROL- BRETIGNY.
 Le DFVLR et le NLR ont également des activités ATC.

L'initiative PHARE, à laquelle d'autres établissements, en dehors des états membres, pourraient participer, devrait :

- être multidisciplinaire ;
- faciliter l'accès aux avions laboratoire, aux simulateurs de vol et aux simulateurs ATC temps réel ;
- permettre l'analyse des expérimentation et le retour d'information indispensable aux concepteurs ;
- stimuler la recherche par l'échange de personnel, des idées et des résultats ;
- aider à la convergence vers le concept ATM des états membres d'EUROCONTROL ;

Il s'agit d'un programme ambitieux mais essentiel pour l'évaluation et la mise en oeuvre des moyens destinés à faire face aux problèmes qui se posent à l'horizon 2000.

3.3. Programme d'Etudes, Essais, et Experimentations lié au Concept

Les points clefs du programme sont:

- L'amélioration du système de surveillance et des communications Air-Sol (Système MODE S et liaison automatique de données).
- L'augmentation de l'automatisation qui passe en particulier par une amélioration de la prévision de trajectoires en 4D et par un couplage étroit entre le pilote et le contrôleur.
- L'amélioration des méthodes d'évaluation (Démonstrateurs faisant appel à une représentation réaliste de la partie "air") et des moyens de formation.

Une large place est faite à l'analyse des conditions à réunir pour que les systèmes au sol puissent disposer dans l'avenir des moyens permettant d'acquérir et d'exploiter les paramètres du vecteur d'état de l'avion.

Le diagramme qui suit donne une indication de l'inter-relation des principales composantes du programme.

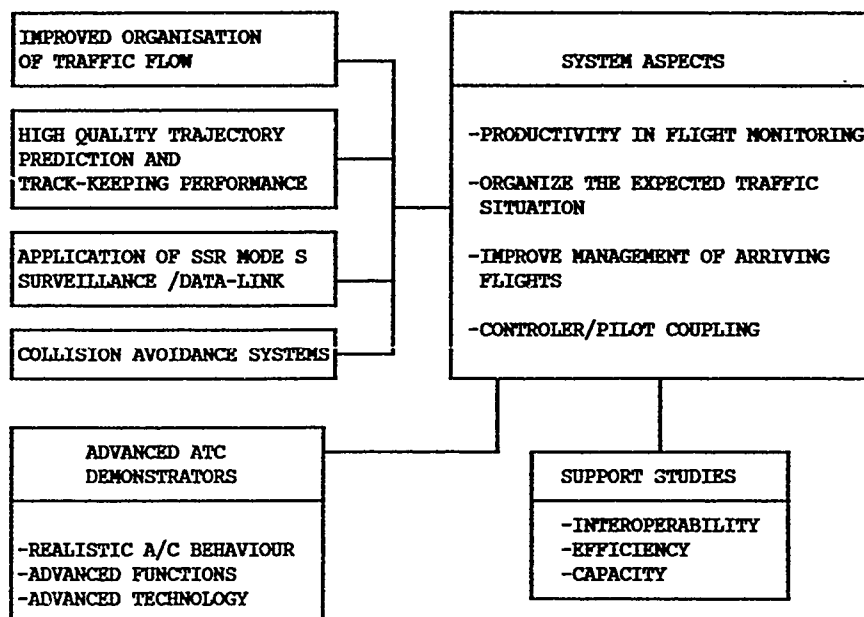


Fig.2

3.3.1. Système Mode S et liaison automatique de données

L'Agence s'est toujours intéressée de près aux développements du Radar Secondaire dans la direction ADSEL/DABS et, au début des années 1980, lorsque la nécessité d'envisager de faire adopter par l'OACI des standards pour le système Mode S s'est manifestée, un programme d'évaluation et d'essais a été mis sur pied.

Au stade actuel, ce programme comprend:

- Une partie orientée vers la validation et la proposition de standards à destination de l'OACI;
- Des études destinées à identifier les problèmes inhérents à la transition du SSR vers le Mode S;
- Des études dans le cadre de l'exploitation du système et de l'utilisation opérationnelle de sa liaison automatique de données;

3.3.1.1. Les moyens mis en oeuvre

-Équipements au sol :

La France et le Royaume Uni mettent actuellement en place trois stations Mode S situées dans la région parisienne pour la France et à Malvern et Gatwick (en conteneur mobile) pour le Royaume Uni.

-Équipements embarqués :

Les Etats membres financent en commun par le budget de l'Agence le développement et l'acquisition de 30 répondeurs Mode S dont les performances sont au niveau 4 de l'annexe 10 de l'OACI.

La livraison de ces transpondeurs devrait être terminée en 1988.

Ceux-ci permettront d'expérimenter la partie surveillance et la fonction technique de la liaison de données. Il est nécessaire de compléter ces transpondeurs par un dispositif permettant d'évaluer les applications opérationnelles du data-link.

On a donc procédé à l'étude d'une unité permettant l'assemblage et le traitement des données disponibles à bord pour transmission au sol et la distribution de l'information transmise en retour du sol vers l'avion. Il s'agit d'un processeur de liaisons de données (Data Link Processing Unit).

Un contrat récent vient d'être conclu pour le développement de 12 processeurs de liaison de données. Il est prévu que ces équipements de bord soit embarqués sur des avions commerciaux pour la plupart des essais. Des avions laboratoires seront également utilisés.

Autres moyens:

Le programme d'évaluation est basé sur l'utilisation des interrogateurs au sol, des répondeurs Mode S embarqués et des DLPUs pour l'évaluation "Data-Link". Il nécessite des outils d'analyse et d'évaluation divers tels que modèles de simulations arithmétiques et un analyseur du système data-link/transpondeur connu sous le nom de DATAS (Data Link and Transponder Analyser System dont la réalisation est envisagée conjointement avec la FAA.

3.3.1.2. Déroulement du programme

Le programme d'évaluation, précédé par le lancement en 1983 de la mise en place des stations sol et des équipements de bord devrait rentrer dans sa phase active en 1988 pour ce qui est de la fonction surveillance et des aspects multisites, et se poursuivre en 1989 et au-delà pour ce qui est des applications opérationnelles de la fonction data-link. Il comporte par ailleurs des études dans le domaine des systèmes anti-collision embarqués (ACAS) qui ont déjà fait ou feront l'objet d'expérimentations conduites par la France et le Royaume-Uni.

3.3.2. Communications par satellites. Expérimentation PRODAT.

L'Agence EUROCONTROL, avec l'Espagne et le Royaume Uni fait partie du groupe des expérimentateurs ATC du programme PRODAT patronné par l'Agence Spatiale Européenne. L'expérimentation devrait servir de base au lancement d'études supplémentaires dans le domaine de la surveillance dépendante automatique.

3.3.3. Automatisation accrue.

3.3.3.1. Généralités

L'augmentation du recours à l'assistance automatisée dans le processus de prise de décision, indispensable pour faire face à l'accroissement de la demande de trafic, implique des recherches et développements à plusieurs niveaux notamment :

- Dialogue homme-machine;
- Amélioration de la prédiction de trajectoire impliquant:
 - l'évaluation et l'amélioration de la qualité des données d'entrée en particulier des composantes du vecteur d'état de l'avion et des données Météo;
 - la mise au point des algorithmes;
- Fonctions "système" telles que décrites plus haut en 2.5;
- Et toujours sous-jacentes les préoccupations relatives à la fiabilité et l'intégrité du système;

3.3.3.2. Dialogue homme-machine

L'Agence a commencé à évaluer, dans le contexte de l'introduction de systèmes "sans strips", les problèmes liés au dialogue homme-machine dans un environnement fortement automatisé. Ceci a fait l'objet récemment d'expérimentations et de simulations en temps réel en particulier liées à l'utilisation du codage par la couleur des informations présentées au contrôleur. Ce programme se poursuit et pourrait s'étendre à d'autres aspects tels que l'introduction de la reconnaissance du langage parlé. Par extension, il se peut qu'il se concrétise vers le développement de performances opérationnelles minimum relatives au sous système de présentation et de dialogue à l'usage du contrôleur.

3.3.3.3. Prédiction de trajectoire

Il faudra faire face, dans les décades à venir à une population mixte pour ce qui est du niveau d'équipement des avions. Ceci ira du FMS-4d au RNAV-2d. Progressivement, la possibilité d'échanges de données air-sol sol-air va s'installer.

On va donc se trouver dans une situation où schématiquement:

- une catégorie d'appareils disposera de possibilités à bord d'automatiquement prévoir, faire connaître au sol, suivre et éventuellement recalculer des profils de vol optimaux, ce qui devrait permettre au sol plutôt que de faire une prédiction de trajectoire, de négocier le profil de vol acceptable;
- une autre catégorie d'appareils, qui, tout en navigant dans des conditions conformes aux normes de séparation en vigueur, ne sera pas à même d'assurer le suivi d'un profil de vol avec une précision meilleure que celle de la prédiction de trajectoire élaborée au sol à partir des données disponibles;

On peut donc envisager que la description des trajectoires prédites utilisée par l'ATC résultent de deux traitements différents, l'un effectué à bord et l'autre effectué au sol.

Dans les deux cas le data-link est indispensable pour la transmission soit de la description de trajectoire élaborée par le FMS, soit pour la transmission de données du vecteur d'état de l'avion.

Les études à mener ou à poursuivre concernent en résumé:

- L'évaluation fine de la précision de suivi de la trajectoire supposée de l'avion dans l'espace et dans le temps;
- Le développement et la validation des algorithmes de calcul de trajectoire; à noter que la qualité des données d'entrée et la complexité des algorithmes diffère selon l'échéance de la prédiction;
- La recherche des moyens d'acquisition au sol et à bord de données météorologiques précises;

3.3.3.4. Fonctions "système"

On l'a vu plus haut, le Concept EUROCONTROL distingue avec la prévision des trajectoires deux autres domaines principaux :

- L'amélioration dans l'organisation de la situation de trafic envisagée,
- L'assistance automatique à la surveillance qui couvre,
 - L'identification des situations non conflictuelles.
 - La garantie de sécurité.
 - L'amélioration de la gestion des vols à l'arrivée.

Des études préliminaires ont été commencées sur certains de ces aspects.

Pour d'autres les études et expérimentations sont un prolongement d'activités déjà en cours (prévision des trajectoires, perfectionnement du système d'alerte aux conflits à court terme, assistance à la détection et à la résolution des conflits dans la fonction de planification-CAPE-, études ACAS etc..).

Enfin, dans d'autres cas tels que l'amélioration de la gestion des vols à l'arrivée, des travaux de recherche, expérimentations, et évaluations opérationnelles sont poursuivis depuis plusieurs années soit au sein de l'Agence (Zones de Convergence), soit dans les Etats Membres (COMPASS, HAP, MAESTRO, TCSDG-UK).

Méthodes et moyens d'évaluation et de formation. Démonstrateurs ATM.

3.3.3.5. Généralités.

Jusqu'à présent, la recherche, l'expérimentation et l'évaluation opérationnelle préalables à la mise en service de fonctions nouvelles font une part relativement faible à une approche système globale qui tienne dûment compte aussi bien des aspects sol que des aspects air.

Il en résulte que le domaine "air" est représenté, dans les expérimentations, de façon, soit par trop schématique (performances, simulation de trajectoire etc...) soit par trop limitée (exercices d'expérimentation avec un comportement réaliste de l'avion mais un trafic réduit quant au nombre et aux types d'appareil).

Il en va de même pour ce qui est des moyens de formation et de perfectionnement ATC.

Ceci pouvait être acceptable dans la mesure où le système ATC était capable de s'adapter à l'évolution de l'avion même en l'absence de concertation entre les concepteurs du monde aéronautique et des services de contrôle.

Il est clair que l'évolution prévisible implique un changement d'attitude à cet égard et qu'à la fois l'accroissement du trafic à venir et les performances potentielles de l'avionique des avions modernes imposent une approche globale.

3.3.3.6. Démonstrateurs ATM.

En conséquence de ce qui précède, et en particulier, les moyens d'évaluation et de formation de l'ATM devraient évoluer dans le sens d'une intégration plus étroite et plus réaliste des aspects air et sol. Cette évolution, dont l'importance se conçoit aisément n'est pas forcément facile à mettre en oeuvre. On a pu déjà le constater quand il s'est agi par exemple de disposer de catalogues des performances réelles des avions, d'accéder aux algorithmes des FMS ou de d'aborder les problèmes d'interface entre les systèmes intégrés des données de bord et une liaison automatique de données air-sol sol-air.

Il est évident qu'à moyen terme l'évolution est fortement conditionnée par ce qui existe actuellement soit en exploitation soit dans un état avancé d'expérimentation (ex: Mode S).

Il est extrêmement important que les premières étapes de mise en oeuvre du concept prennent en compte les objectifs à plus long terme afin de ménager des transitions sans heurts à des niveaux de performance plus élevés.

La nécessité d'une représentation réaliste de la partie "air" dans les moyens d'évaluation des fonctions du système ATM futur est déjà prise en compte dans certaines expérimentations dont la composante essentielle est constituée par l'utilisation des simulateurs de vol de types d'avions divers pilotés par les équipages des compagnies aériennes (cf. Zoc/Cintia).

De même, pour ce qui est des systèmes de simulation en temps réel, des dispositions sont prises pour remplacer la navigation des avions du style "blip driver" par des sous-systèmes permettant d'introduire un comportement réaliste des divers types d'appareils en exploitation.

Enfin, il sera de plus en plus indispensable de pouvoir disposer, aux divers stades de la recherche et de l'expérimentation, de la participation interactive de simulateurs de vol avancés, d'avions laboratoires et dans les phases ultimes de la participation d'avions de ligne.

Par ailleurs, tout en acceptant que le concept futur doive résulter d'un processus évolutif et continu au niveau de la mise en oeuvre de fonctions nouvelles, il est permis de penser que la réalisation de démonstrateurs intégrant les technologies les plus avancées et quelques notions "révolutionnaires"

(intelligence artificielle, reconnaissance automatique du discours, résolution automatique des conflits, système tout automatique ...) serait de nature à provoquer une réflexion féconde.
C'est la voie que se propose de suivre l'Agence dans le développement des outils nécessaires au programme de recherche lié au concept des années 2000 et au delà, la première et modeste étape consistant en l'exécution d'une simulation en temps réel baptisée **ARC 2000**.

3.3.3.7. Methodes et moyens de formation.

Les méthodes et moyens de formation et de perfectionnement du personnel devront nécessairement être adaptées à l'évolution du système ATM et prendre en compte ses aspects nouveaux.
Ici encore, des études et des développements ont commencé à générer des axes d'actions à poursuivre dans les années à venir.

4. CONCLUSIONS

Deux des caractéristiques marquantes du concept ATM sont l'étroite coopération des éléments air et sol via une liaison de données, ainsi que l'intervention de l'automatisation dans les processus de décision.

Les solutions à moyen terme passent par :

- un système de navigation amélioré conduisant à la navigation de surface ;
- un système de surveillance amélioré par le Mode S qui apporte la liaison automatique de données tant attendue ;

Il reste peu de temps pour réagir à la demande d'accroissement de la capacité du système de gestion du trafic aérien.

Le vaste programme de recherche et d'expérimentations qu'implique la mise en oeuvre progressive du concept nécessite une réflexion et des actions concertées entre toutes les parties prenantes et la mise en place des ressources nécessaires qu'il s'agisse des outils ou de l'expertise, en qualité et en quantité.

Plus que jamais, une coopération active communautaire - au sens large du terme - est impérative.

PREDICTION OF AIRCRAFT TRAJECTORIES

by

Stanley Ratcliffe BSc, FRIN, FRAeS

2, Mason Close, Malvern, WR14 2NF, U.K.

Summary

Air traffic management, in designing route structures, drawing up rules for flight in various types of airspace, and in framing the instructions for air traffic controllers, are concerned with predicting the behaviour, often on "worst-case" assumptions, of each class of traffic with which they may have to deal. The present paper will concentrate on the problems of on-line trajectory prediction to a time-horizon perhaps a little longer than the estimated time of the flight or as short as a few tens of seconds, the object being to predict and avoid collision with terrain or with another aircraft, and to ensure that any in-flight delays due to traffic congestion along the route are absorbed as economically as possible. Military aircraft are concerned with the avoidance of anti-aircraft missiles and in intercepting airborne targets. This latter problem may, very loosely, be regarded as collision avoidance in reverse, and will be briefly discussed in what follows, as will the problem of terrain-following by high performance low-flying military aircraft. The conclusion will draw attention to areas where further R&D would seem desirable.

1. Prediction Techniques and Parameters.

1.1 General

Prediction is used as part of some process of planning the future. The predicted situation at some future time, the "time-horizon", is compared with some criterion, and attempts are made to modify the scenario until the predicted outcome is satisfactory. In ATC, for example, the main objective is a situation in which the predicted relative position of each pair of aircraft shows them as having a safe separation. If a pair of aircraft fail to meet the criteria, the aircraft are said to be "in conflict", and the "conflict resolution" process involves modifying the trajectory of at least one of the aircraft in order to eliminate the conflict between the two aircraft originally involved, as well as between these aircraft and any other airspace users.

Planners are free, within limits, to choose the time-horizon to which they work. At a time-horizon of one microsecond, the change in the future position of any point on a subsonic aircraft can be predicted with an error not greater than 0.25 mm., but the time available to modify the situation is quite inadequate. At a time-horizon of a few days, any conflict could easily be avoided, if only it could be predicted. The problem is illustrated in Fig.1.

Fig. 1 (a) shows, as a function of the time-horizon, the confidence with which the relative position of two aircraft can be predicted. Fig. 1 (b) shows, to the same time-scale, the possibility of evading any predicted conflict by a change in one or both trajectories. In Fig. 1 (c), the above curves are superimposed, and the only scope for effective remedial action is within the shaded area. There is a deliberate omission of any quantitative values on the time-scale and, for that matter, of any attempt to give quantitative definition of "certainty" in Fig. 1a or "possibility" in Fig. 1b. From a later argument it will emerge that T_{min} is about 20 secs. and T_{max} may be as long as the duration of the flight of both aircraft.

Note that the curves of Fig. 1 (a) and 1 (b) have, roughly, mirror-image symmetry. This is because a manoeuvre by the aircraft in response to an equipment failure or to some other unplanned event is subject to constraints similar to those on an aircraft manoeuvring to avoid collision. Fig. 1 (c) implies that, whatever time-horizon is adopted, there is no infallible solution to the collision avoidance problem.

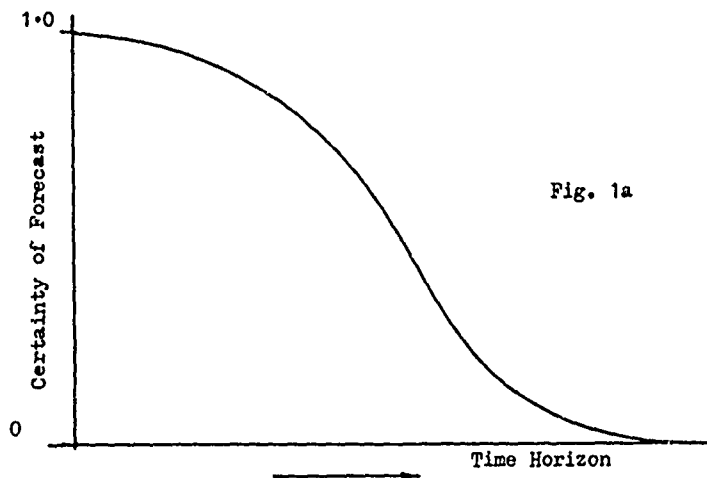
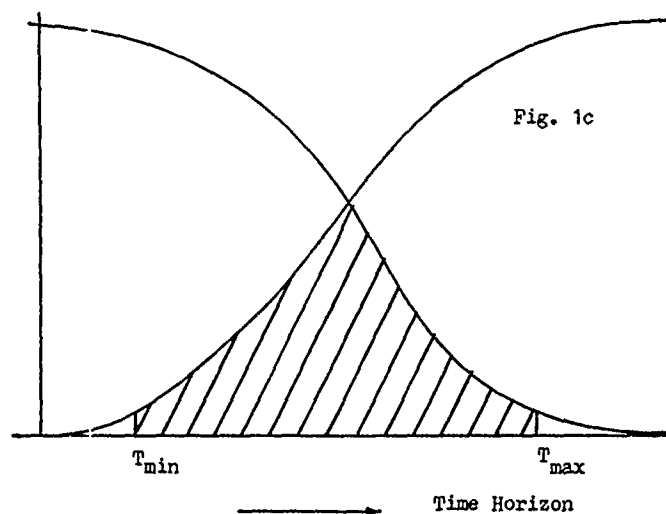
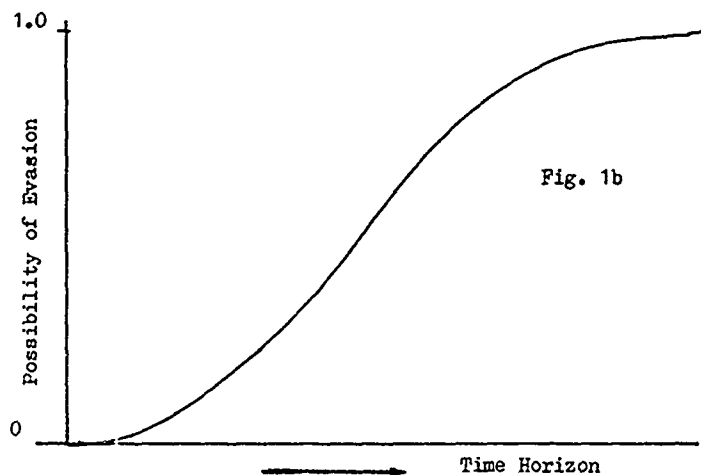


Fig. 1a



1.2 One-Line Trajectory Prediction

1.2.1 The Use of Prediction

In pursuit of various objectives, prediction processes can be used in many different ways. It may be necessary to predict the time of arrival at some waypoint of interest, to direct the traffic towards some target, to confirm that an aircraft is not deviating seriously from an agreed profile or timetable, to check that an aircraft is going to stay clear of some prohibited area, or to predict the relative position of two aircraft at some future time, for purposes of rendezvous or avoiding a dangerously close approach.

Predictions can be based on the observed or reported absolute or relative position of the aircraft, or on the known intended profile. Predictions for a short lead-time are commonly based on the current position and the short-term history of this data. Longer-period decisions are usually based on a more detailed knowledge of the aircraft intention.

1.2.2. Multiple Time Horizons.

Most ATC systems, which can tolerate only an extremely low probability of failure, achieve reliability not by reliance on any one mechanism, but by a hierarchy of sub-systems, working at different time-horizons, each aimed to detect and compensate for any earlier failure (Ratcliffe & Gent, 1974).

For example, ATC plans perhaps 15 mins. ahead when dealing with airways traffic, but a radar controller may intervene with perhaps only 60 secs. to go if some error seems to threaten safety of traffic, whilst the pilot may see a threat perhaps 25 secs. before closest approach, and initiate some escape manoeuvre. If these various protection mechanisms are truly independent of each other, the task of achieving the necessary low overall risk of collision is made much simpler.

A roughly similar situation arises, perhaps, when a military aircraft attempts an interception. A ground control organisation directs a fighter to a position where the target is visible to the pilot or to a short-range radar, the pilot manoeuvres the aircraft to a position where he can launch a short-range air-air missile, and the missile, in turn, uses a relatively simple guidance mechanism to home onto the target.

Sections 1.3 and 1.4 below will respectively deal with ground-based and airborne prediction.

1.3 Ground-Based Prediction

1.3.1 Flight Plans.

A controller in an ATC centre, in addition to his background knowledge of aircraft performance and of the routes flown, normally has three sources of information about an aircraft under his jurisdiction. These are the flight plan, reports from the aircraft, and data from radar sensors.

For aircraft proposing to fly in airspace under control by civil ATC, the flight plan is a document which, in addition to giving certain background information, defines the flight profile proposed for a given trip. It includes the route to be followed, the desired cruising level, the air speed/Mach No. which the aircraft is to maintain during the three regimes of climb, cruise, and descent, together with the planned time of departure. Airlines commonly file flight plans which are to be stored in computers in ATC centres and used repeatedly during the following season. These plans, or appropriate extracts from them, are held in each ATC centre on the planned route. When the plans are first drawn up, fast time simulation exercises are sometimes held to check that the total traffic demand on sensitive regions is not likely to exceed the predicted capacity. Nearer departure time, often on the day of departure, additional measures may be needed to limit traffic peaks. These processes are based on estimates of total demand rather than on detailed forecasts of individual aircraft movements. Such "flow control" process can barely be said to be "on-line", and will not be considered here. It should be noted that most flight plans are drawn up before there is any means of predicting wind, hence the use of airspeed to define the trajectory. For the same reason, the height gained in climb between two waypoints is not defined. In descent, in a "Zone of Convergence", to be discussed elsewhere in this ACARDOGRAPH, it is possible for an airline pilot and his flight management computer to achieve a specified height and time at a given waypoint. At efficient cruising levels, however, a jet aircraft has only a limited range of possible airspeeds, much less than the range of winds that may be experienced (Bloodworth, 1986). This situation sets a major limitation on the accuracy with which it is possible to make long-term predictions of aircraft time of arrival.

1.3.2. Departure Time Uncertainty

For short and medium haul flights, an even greater uncertainty arises from the difficulty in predicting an aircraft's actual time of departure. For an airline, the aircraft and their ground servicing facilities represent a massive capital investment which must be exploited as effectively as possible. The previous paragraph gave one of the reasons why the arrival times of incoming flights cannot be accurately predicted, and, in consequence, congestion arises on the airport ramps, in demands for minor maintenance, and in the aircraft turn-round process in general. These, in turn, lead to delays in subsequent departures. A study at Heathrow (Drew et al., 1982) showed that 10% of departing flights were late by 30 mins. or more.

When the flight commences, the flight-plan data on aircraft is revised as necessary by the ATC unit currently having the aircraft under its jurisdiction. The actual time of departure replaces the original estimate, there may be restrictions on the climb, necessary to avoid conflicts with other aircraft, and the cleared cruising level may differ from that originally requested. ATC may make further changes during the flight, in response to pilot requests or for traffic reasons. About ten minutes before the aircraft is due to be handed over to an adjacent centre, a message is passed, by telephone, telex, or computer-computer data link, alerting the next sector to the impending arrival and giving the flight level planned for the handover at the boundary.

Flight-plan based ATC is only fully applicable to aircraft with advanced navigation systems and adequate skilled crew flying a defined route. Although pilots of light aircraft are required to file flight plans, mainly to assist search and rescue in the event of a crash, ATC cannot rely too heavily on the aircraft's declared intention as an accurate predictor of the trajectory to be followed. For example, an aircraft whose pilot does not hold an instrument rating is required to fly under Visual Flight Rules, keeping his aircraft clear of clouds. Any resulting changes to height or heading cannot be anticipated by the ATC system, which has no knowledge of clouds. Flights by military aircraft in controlled airspace can be treated in the same way as those by Civil airliners. Training flights by high-performance military aircraft remain, as far as possible, outside controlled airspace which they cross, if necessary, under close radar surveillance. Such flights are commonly under military control. The aircraft may have only a one-man crew who is practising some military activity which may use the terrain to reduce the risk of detection by enemy radar. Flights may be less predictable, and surveillance from the ground is more difficult. Under some circumstances, the best ATC can do is to assign the aircraft some dedicated region of airspace and to protect it, as far as possible, from intrusion by other aircraft.

1.3.3 ATC Use of Aircraft Position Reports

Before the introduction of radar, ATC could update the flight-plan data only with the aid of position reports from the aircraft. In controlled airspace, such reports were made at intervals of 30 miles or so, giving the height and time at a "reporting point", together with forward estimates for the next, named, reporting point. In regions such as the North Atlantic, where radar cover is not available, voice reports from the pilot remain the only source of on-line data for ATC. One obvious weakness of aircraft position reports is that any navigational error can cause the aircraft to stray from the agreed profile whilst continuing to report conformity to it. Another difficulty is that voice reports from aircraft can only be used by any automated component of the ATC system after the manual input of voice-derived data by the human controller, who may regard the computer assistance as inadequate compensation for the added task of feeding data into a keyboard and then checking for errors.

Regions where aircraft are outside radar line-of-sight are frequently also regions where air-ground communications are sometimes unreliable. The N. Atlantic, for example, has to rely on HF communication. At unfavourable times, the signal strength available at the ground receiver may be poor, and the HF bandwidth available for long-range communication may, at best, be barely adequate to handle the traffic offering. The ICAO FANS Committee, at the time of writing, is discussing the case for the adoption of satellite-based communication systems for air-ground-air working. Some of the possible implications of such a step will be discussed in sections 1.3.4 and 1.3.5 below.

Given a precise flight plan, high-grade navigation equipment and a skilled crew, unpredictable deviations from the agreed flight plan will still sometimes arise. Unexpected and possibly violent manoeuvres may result from equipment failures or from the perception by the crew that they are faced with some hazard more serious than that of mid-air collision with traffic known to ATC. It should be noted that Annex 2 to the ICAO Convention, para. 2.4, lays down that "the pilot-in-command of an aircraft shall have the final authority as to the disposition of the aircraft whilst he is in command". The longer the time-horizon, the more likely is an unexpected event within the period which ATC is considering. To allow for these eventualities, ATC normally aims to provide greater separation when the time-horizon is large, over the ocean for example. Over the years, limitations of airspace capacity have led to a reduction in separation standards, and hence to a reduction in the time-horizon to which part, at least, of the ATC task is carried out. This approach demands a rapid supply of data on the relative positions of proximate aircraft, and this has been made possible by the use of ground radar surveillance systems.

1.3.4 Turn Detection

A significant limitation on radar data for the prediction of future trajectories is that, at best, it can only yield data on the aircraft regarded as a point in space. If the aircraft goes into a banked turn, for example, the centre of gravity of the aircraft experiences a displacement that increases as time squared. This may take a significant time to exceed the uncertainties in the position of the aircraft as reported by the radar. To an observer in the aircraft itself, the onset of bank and the changing heading will be obvious after only a second or two. For an aircraft cruising at 500 knots in a 10 degree banked turn, the relationship between the heading change by the aircraft, the corresponding lateral displacement, and the time elapsed since the start of the turn, is shown in Table 1.

Change in Heading (degrees)	Displacement (N. Miles)	Time (secs.)
10	0.31	26
20	1.24	52
30	2.76	78

Table 1.

Lateral Displacement of a 500 knot aircraft as a function of Heading Change

Such an aircraft would typically have changed heading by about 20 degrees before a controller viewing a present-day radar could confidently conclude that the aircraft was turning away from its original track. Given a knowledge of heading, the incipient turn could be detected after a change of only 2 or 3 degrees, taking only about 10% of the time needed using radar data. For a more detailed discussion of the use of bank or heading data, see the results of some studies for Eurocontrol (Lefas and Thomas, 1981). The behaviour in the short term of an aircraft commanded to turn, climb or descend is also discussed in section 2.1 below.

The time taken to detect a deviation from the planned track is important in two respects. Obviously, any delay in detecting a deviation will result in a bigger displacement of the aircraft from the planned position. Further, if it is desired to take action to restore the aircraft to its original track, the aircraft will continue to move away from the plan until such time as the original heading has been restored. If this restoring manoeuvre is carried out with the opposite direction of bank but with the same bank angle, the maximum displacement of the aircraft from the planned trajectory will be twice that at which the aberration was detected, even neglecting time delays in decision-taking, message passing, and the initiation of the restoring manoeuvre. These latter effects will also become more serious with delays in detection, since the cross track velocity will increase linearly with time until some action is initiated.

Various draft proposals are under discussion by the FANS study groups for the data link which is intended to provide a satellite-based cooperative surveillance system. These include provision, at the discretion of the ground station, for the inclusion in the air-ground message of various items of air-derived data.

The suggested items on the data list may have been more strongly influenced by the availability of this data on the digital data bus of present generation airliners than by any study of the ATC requirements or the communications trade-offs.

1.3.5 Ground-Based Inter-Aircraft Comparisons

No automatic data link can supply the ground system with a knowledge of the behaviour of the aircraft and the air mass surrounding it, that is comparable with that available to the pilot. Given suitable data from a number of aircraft in a given vicinity, the ground system may, however, be capable of deducing information from the population as a whole which is superior to that available to the individual aircraft. Consider, for example, aircraft height-keeping. Vertical separation is defined by ATC on the basis of barometric pressure. Pressure data is converted in the aircraft altimeter system into "Height" on the basis of an assumed surface atmospheric pressure and a model of the variation of pressure with altitude. The atmospheric model gives the pressure that is assumed to exist at a given height, given stagnant air, i.e. in the absence of any effects due to the aircraft. This "static pressure", is needed for the measurement of both height and airspeed/Mach number. The aircraft samples the pressure at a "static vent" ideally located at a point on the fuselage where air is stagnant. In practice the observed pressure will always be to some extent influenced by speed and the aircraft's angle of attack. Prototype aircraft are carefully calibrated and the aircraft altimeter system corrects the results on the basis of this calibration.

No checks are made to compare the pressure errors of aircraft in airline service with those of the prototypes. Effects such as minor imperfections in the aircraft skin, wrinkles due to stretching of the skin, or irregularities due to minor repairs, can introduce systematic errors. Aircraft often have more than one static vent, but these are linked within the altimeter system, and no cross-checks are possible. Any error may therefore persist for a long time, and will apply to altimeter displays in the cockpit, the height data in the flight management computer, and in the data telemetered to ATC. With the advent of satellite-based navigation systems, there is finally available a means of introducing some highly desirable redundancy into height measurement. Measurement of the distance from the aircraft to Earth's centre is an essential step in the accurate determination of position, even when only plan position is required. Only under very special circumstances is it possible, at the present day, to establish accurately the relationship between geocentric and barometric height. Even surface pressure is not generally available, and pressure at any point some distance above Earth's surface will also vary with the temperature, and entropy in general, of the air column beneath it. It is difficult to see how ATC can base separation on the geocentric height of some aircraft and the pressure height of others, so that, unless and until satellite-derived data is available on all aircraft, barometric height is likely to remain the basis of vertical separation by ATC.

If, however, each equipped aircraft reported every few minutes the difference between the geocentric and barometric heights observed on the aircraft, ATC could compare reports from different aircraft in the same vicinity. The surveillance system would then have a powerful tool for the detection of even small systematic errors in individual altimeters, as well, presumably, as for improving the accuracy of airspeed measurements. Given a knowledge, from telemetered data, of the relationship between heading and track for a number of aircraft travelling in various directions at approximately the same height, there is a possibility of computing local wind to greater accuracy than would otherwise be possible.

1.4 Airborne Prediction

1.4.1 North Atlantic Traffic

At the present time, aircraft crossing the N. Atlantic, as well as certain other lightly populated regions, suffer from the erratic nature of air-ground communications and the absence of any independent surveillance system. Pilots and ATC alike must therefore place considerable reliance on air-derived data. Aircraft operating on the N. Atlantic organised track system mainly rely on inertia-navigation systems with built-in Kalman filtering. This generally enables aircraft to keep accurate tracks. Cross-track errors, which build up roughly linearly with time, have been observed to have a two-sided exponential distribution with a standard deviation of 3 or 4 nautical miles on exit from the track system (Brooker, 1983). No doubt, the same aircraft fly in other sparsely-populated regions with comparable accuracy, although data is sparse. Where ground-based nav aids are available, the Kalman filter can use the more accurate data to update the inertial system, with a subsequent reduction in error.

As quoted above, the standard deviation of cross-track errors is only 3-4 miles, but it has been considered necessary, in order to achieve an adequately low collision risk, to separate tracks by at least 60 NM. (Brooker, 1984). The error distribution, as observed on aircraft leaving the N. Atlantic tracks, includes a fraction of the order of one in "a few thousand" having cross-track errors of 30 NM. or more. These errors are believed to be mainly due to mistakes in data entry to the aircraft's navigation equipment, either because of errors in documents on the flight-deck, failures in communication between pilot and ATC, or keyboard errors by the pilot. The method used for conflict prediction is determined by the nature of the data available concerning "own" aircraft and any potential threat. The alarm criteria are conditioned by the mechanism used to establish the location, the intentions (if known) of any aircraft of interest, the accuracy of the sensor data, and the frequency with which it is updated.

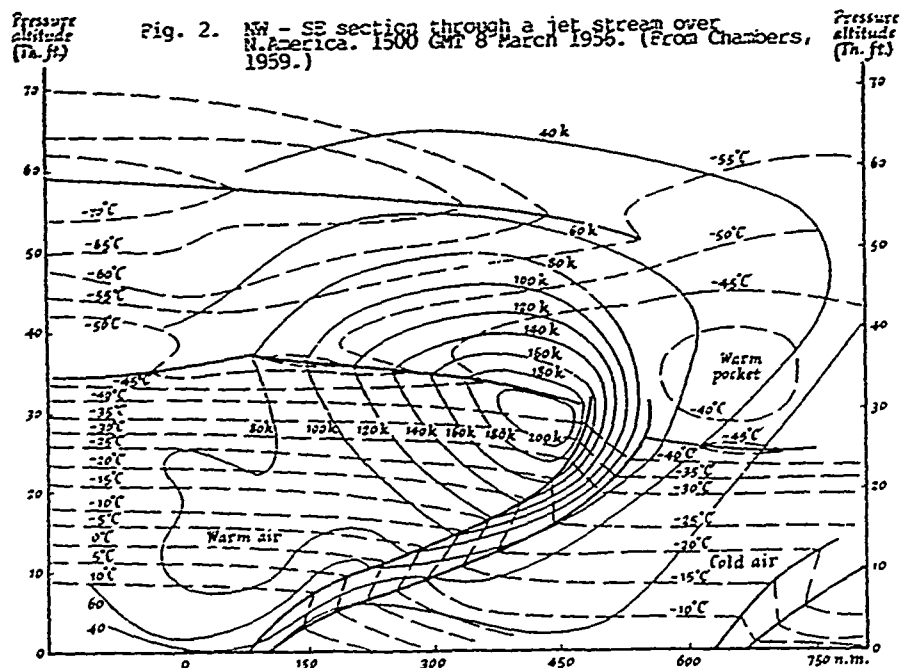
1.4.2 Jet Streams

The pilots of jet aircraft at cruising level suffer from a difficulty mentioned in Sec. 1.3 It is not possible, given the range of winds experienced at high levels, to regulate the flight so as to cruise at a pre-planned ground speed.

Since all civil jets at a given flight-level will cruise at approximately the same Mach Number, it might be supposed that wind would have no more than a very small effect on the relative ground-speed of two proximate aircraft. Unfortunately, this assumption does not always hold. Over the N. Atlantic, for example, Easterly tracks are commonly planned to allow aircraft to benefit from the "jet streams" which frequently are capable of giving a 100 knot boost to the aircraft ground speed.

Fig. 2. (Chambers, 1959) shows a vertical gradient, above the core of the jet stream at about 32,000 ft. of about 2 knots per 100 feet, and, in another region to one side of the core, of a horizontal gradient of 2.2 knots per nautical mile. At the present day, a mean difference in the relative height of two proximate aircraft may, due mainly to altimeter static calibration errors, easily be 500 ft., and cross-track errors may differ by four miles or so. If the track is nearly parallel to the jet stream, the resulting difference in ground-speed may persist for some time. It can be argued that an inadvertent overtaking manoeuvre is not very hazardous if the two aircraft are, in fact, separated by the vertical or lateral spacing suggested above, but ATC would not accept either of these as an adequate guarantee of safety. After consideration of all the risks involved, and assuming that ATC would usually detect and deal with any overtaking hazard, the N. Atlantic separation planning group decided that a 10 minute (i.e. about 80 NM.) separation could safely be adopted in conjunction with the existing 60 NM. lateral and 2000ft. vertical separation rules. The need for this considerable longitudinal spacing, it should be noted, follows from the combination of the difficulty of forecasting ground speed with the limited reliability of the communication between air and ATC. Although all predictions are based on air-derived data, the mechanism for testing the along-track separation of existing aircraft is located on the ground.

Although jet streams are of greatest practical importance, perhaps, over oceans where traffic actively seeks to fly in the vicinity of the jet core, the effects are sometimes relevant elsewhere. One jet stream reported over the USA (Anthes et al., 1987) would present an aircraft on an E-W track first with a 100 knot wind roughly from the South, followed about 600 miles later by a 100 knot wind from the North. The same work reports the existence of weaker jet streams (about 40 knot average) to be found at heights of 3000-6000 ft.



1.4.3. Visual Detection of Threats.

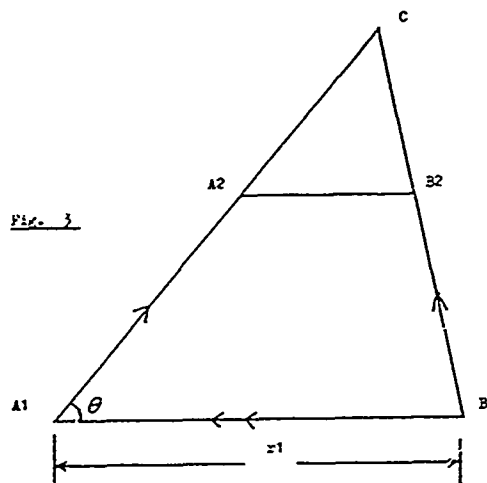
In any airspace outside radar coverage, the ATC system tends to request from aircraft their prediction of time at the next way-point along the route. In fact, ATC normally carries out this calculation within its own facilities, but the air-derived prediction offers a measure of redundancy which may serve to detect navigational blunders either in the air or on the ground. The pilot of an aircraft needs forecasts, of time at destination for example, for other purposes than assisting ATC e.g. for estimating his fuel margin at destination. In general, the accuracy required for these purposes is less than that required by ATC and will not be discussed further here.

For any phase of flight, the pilot's ability to see and avoid a proximate aircraft offers a last defence against collision, no matter whether this risk arises as the result of a blunder by pilot or ATC or simply because of the absence of any other protective mechanism. The pilot's brain and eyeball are universally carried in manned aircraft, and their capabilities and limitations deserve discussion. Air-to-air collision avoidance devices have frequently been suggested as a means of augmenting the pilot's unaided abilities, by substituting radar for human vision, for example. The predication problems associated with these devices will be discussed in section 2.6. Some of the problems, arising from the geometry of relative motion between aircraft, impose limitations on the use for prediction purposes of human vision and radar alike.

1.4.4. Collision Between Two Aircraft in Unaccelerated Flight

See Fig. 3. and consider aircraft A and B, whose dimensions are here assumed to be negligible, in straight-line flight at constant airspeed and due to collide at C. Suppose that wind is substantially constant throughout. At time t say, A_1 and B_1 are the positions of the two aircraft at time t_1 . Theta is the bearing of B from the track of A. At a later time t_2 , the positions are A_2 and B_2 . Since the speeds are constant,

$$OA_1/OA_2 = OB_1/OB_2 = t_1/t_2$$



It follows that the lines A_1B_1 and A_2B_2 are parallel and hence that theta is constant. The velocity of B relative to A is also constant. If r is the distance from A to B, it follows that constant theta implies a constant relative velocity, so that the acceleration along r is zero, and conversely. Under the assumed conditions of straight-line flight at constant speed, with range decreasing, either a constant bearing to the threat or a uniform relative velocity is a sufficient condition for collision. Conversely, if the assumed straight-line flight and constant speed conditions still hold, the collision cannot take place if theta is changing. An example (Ratcliffe, 1985) illustrates the ease with which a manoeuvre by one aircraft can bring about a collision, even though bearing and relative velocity are both changing at a significant rate until a few seconds before the event. Fig. 4 shows the situation in plan view, and Fig. 5 gives range and bearing of one aircraft relative to the other as a function of time to go. Both aircraft are flying at 300 knots, one in a straight line and the other turning to starboard with 20 degrees of bank. 40 seconds before impact, the turning aircraft passes ahead of its straight-line companion, possibly with a vertical spacing of several hundred feet. Between 40 secs. and 20 secs. before impact, range is actually increasing, and it is only at 20 secs. that the "closing range and constant bearing" condition is approximately satisfied.

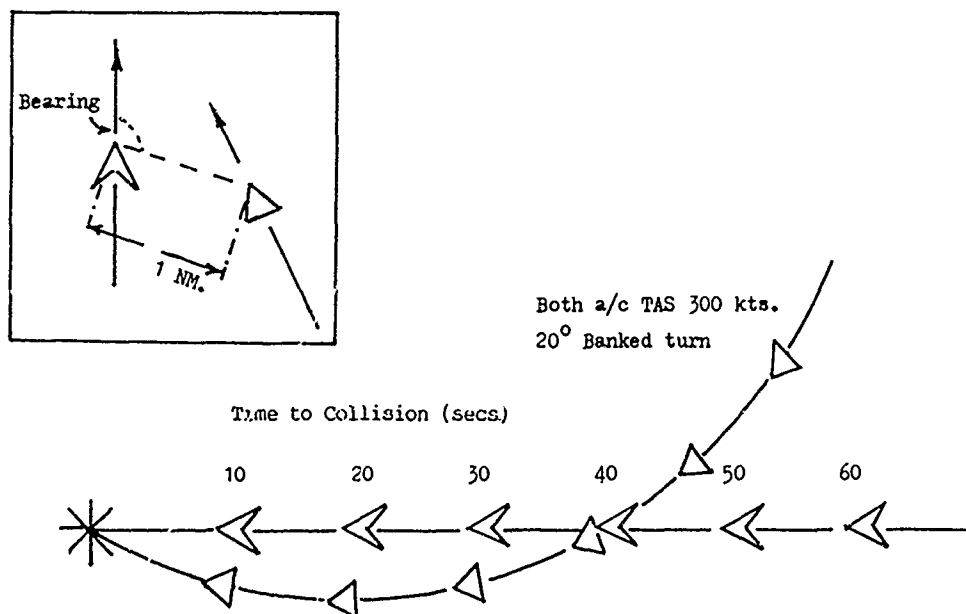


Fig. 4

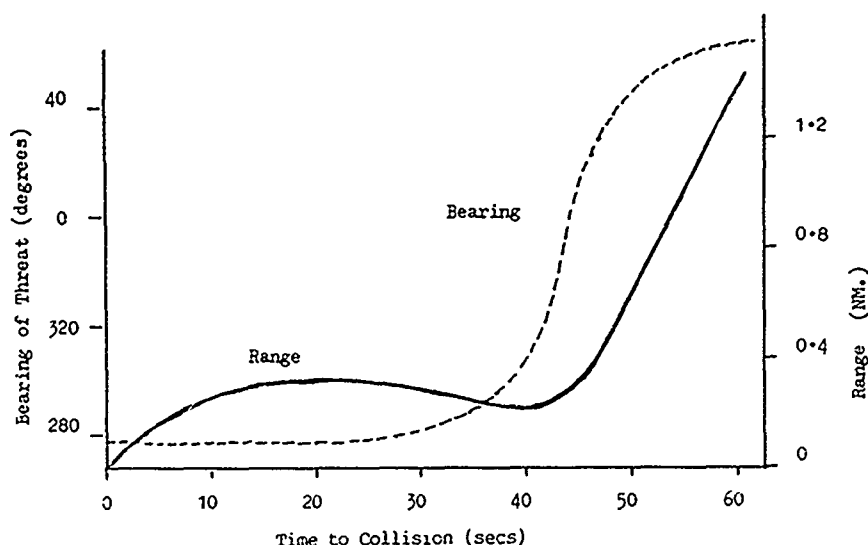


Fig. 5

Consider the relationship between rotation of the sight-line, changing relative velocity, and miss-distance, for aircraft in near-collision encounters (Morrel, 1950). On the straight-line, constant-speed assumption, the threat, as observed by own aircraft, will move along a straight line defined by the threat position and relative velocity. A plane (not necessarily horizontal) can be chosen to include this line and the position of own aircraft. In this plane, let r be the range to the threat from own aircraft, and let θ be the current bearing of the threat relative to some fixed axis. Since the threat moves along a line in the chosen plane, the distance to closest approach can be measured in the same plane. Let this distance be m .

Morrel derives the equations

$$\ddot{r} = m^2/vt^3 \dots\dots\dots(1)$$

$$\text{and } -\dot{\theta} = m/vt^2 \dots\dots\dots(2)$$

where V is the relative velocity of the two aircraft and t is the time to closest approach. Substitution of plausible values for m, v and t into eqns. 1 and 2 reveals how pitifully small are the quantities to be measured. If $V=600$ ft./sec. (355 knots), $t=30$ secs. and the miss distance m is 1000 ft., eqn. 1 shows that $\ddot{r} = 0.062$ ft/sec² i.e. gravity/520.

For the same values, eqn. 2 gives

$$-\dot{\theta} = 0.11 \text{ degrees/sec.}$$

This is approximately the rate of rotation of the hour hand of a watch. Even if we ignore instrumental limitations on the measurement of θ or \ddot{r} , the stability of the airframe itself is too low to justify the "straight line" assumption from which we started. Note that if the 1000 ft. miss distance, discussed above, represented a separation in the vertical plane, the two aircraft, if below 29000 ft., would be deemed safely separated according to ICAO ATC standards.

1.4.5 "See and Avoid"

Since not all flights are conducted under ATC surveillance, and since blunders are possible even under ATC, there is a case for some self-contained airborne device which can warn the pilot of collision risk. Human vision is the one mechanism universally available on an aircraft, and forms the pilots' last, and sometimes only, line of defence. Many pilots are trained to use the "constant bearing" criterion, despite the limitation cited in the previous paragraph.

"See and Avoid" has a number of limitations, not all of which can be discussed at length in the present AGARDOGRAPH. Even when the meteorological conditions are favourable, the pilot may be incapable of seeing the threat, because of physical limitations set by the cockpit windows or by the occupant of an adjacent seat. A surprisingly large proportion of all random threats are to be found outside the region within 30 degrees of own heading. (Ratcliffe and Ford 1982). The pilot may also fail to detect a threat when in flight in clear sky because of the tendency for his eyes to focus on some portion of the airframe, leaving him effectively in a short-sighted condition. Alternatively, when flying at night over densely-populated areas, the ability to see navigation or anti-collision lights of a threatening aircraft may be degraded by the large number of lights, white or coloured, flashing or not, to be seen on the Earth's surface. More relevant to the present paper are the problems of deciding whether, having observed a potential threat, some evasive action is called for. To avoid collision, it is not enough to arrive at the most probable forecast of the future relative trajectory of the threat. There is a need to predict some boundary within which "own" aircraft can be constrained and which the "threat" is sufficiently unlikely to cross within the "time horizon" of the warning process. If such a boundary cannot at present be found, then at least one of the aircraft must modify its trajectory to bring about the desired result. It has been shown, in the context of visual detection of collision risk, that there is a danger, unless the two aircraft can be forced into adopting some complementary strategies, that their independent attempts at avoiding collision may result in the disaster they were trying to avoid.

If the escape manoeuvre is based on visual observation, there are cues such as bank angle, from which it is possible for one pilot to guess the intentions of the other, although once both aircraft attempt to turn away, the relative motion may be too complex to allow rapid and accurate conclusions to be drawn. See, for example, figs. 4 and 5, given earlier.

The numerical example in the previous section of the paper showed the need to detect very low rates of change of bearing. Human eyes are almost always in motion relative to the head (Vernon, 1962). There is a rapid involuntary tremor, a gradual slow drift, and a rapid flick which serves to restore the eyeball to some approximation to its original position. This movement serves to preserve the sensitivity of the retina, but must in some way be compensated for in the brains' data-processing. The ability of the eye to detect slow movement, under the circumstances, is surprisingly high. It is reported that, given 18 seconds or more to observe a target, detection of movement rates of about 9 minutes of visual angle per second was normally achieved (Graham and Orr 1970). There were, however, a significant number of occurrences of, "auto-kinetic" errors, where the observer reported movement of a stationary target. Note that, with the performance just quoted, an observer would be unable to solve the problem posed in the previous section, detection of a 1000 ft. miss distance, 30 secs. before closest approach, with a relative velocity of 400 KT. Note also that Graham and Orr's observers were sitting on a stable platform, and the eye's performance is not likely to be improved by the minor accelerations to which they will be subjected in flight. Using the same assumptions and symbols as in eqns. 1 and 2. suppose that there is a possible error of $\pm u$ in the estimates of θ .

$$\text{From eqn. 2,} \\ m = -\dot{\theta}vt^2$$

Putting the modulus of $\dot{\theta}$ equal to the limit of our uncertainty, u , we find a threshold value of m , M say, below which the situation is indeterminate. M is given by eqn.3.

$$M = uvt^2 \dots \dots \dots (3)$$

For reasonable values of miss distance, the displacement that an aircraft can achieve in time " t ", by lateral manoeuvre under an acceleration A , is nearly $0.5 at^2$. If this displacement is to be greater than the uncertainty M , then A must be greater than $2uv$. Note that, once the displacement due to the escape manoeuvre is large compared with the aircraft dimensions, earlier evasive action does not ease the problem. A more detailed discussion of the problems of visual detection is to be found in the literature (Graham and Orr, 1970).

Earlier reference was made to the problems of a pair of aircraft attempting to adopt complementary manoeuvres. In reality, the problem is less serious than may at first appear, since the experimental evidence suggests that the probability that each aircraft will see the other is low, and the probability that each will succeed in choosing a course of action in the time available is lower still.

1.5 Relative Influence of main Parameters

1.5.1. Prediction Errors.

Predictions are never totally reliable. Control processes based on prediction may vary widely in their sensitivity to these errors. Where the object of prediction is to assist in achieving economy in flight, say, the penalty of failure is much lower than where the object of the control process is to achieve safety:- a probability of collision no higher than, say, one in 10^7 flights. Of course, even a system designed with emphasis on more efficient air transport operations must simultaneously provide an adequate level of safety, and must contain, or be supported by, elements having this objective.

In general, the different confidence levels required in prediction translate into an emphasis on different parts of the prediction error distribution curve. Ignoring, for the moment, the safety problem, a system which achieves a significant saving for, say, 95% of the aircraft can still be very desirable even if there is a loss of efficiency for a random 5% of flights. The emphasis, therefore is likely to be on prediction errors out to one or two sigma (standard deviation) level. Such errors are likely to be the result of minor perturbations in the achieved flight trajectory of the aircraft, combined with minor errors in the instruments on whose data the prediction is based. In this central region of the probability distribution, the error distribution can be predicted, with moderate confidence, at least, either by direct analysis or by "Monte Carlo" models (Benoit, Sweirstra and De Wispelaere, 1986), and the accuracy finally checked by observations on a reasonable number of actual flights.

1.5.2 Aircraft Flight Controls

The problems of predicting aircraft behaviour in this central region of the aircraft probability distribution is complicated by the fact that aircraft are normally guided by the flight control system, which must itself deal with atmospheric turbulence and "noisy" data from the flight instruments. This data is smoothed at various points in a number of cross-coupled multi-loop control systems.

Practical designs for such systems involve some empirical compromises between rigorous theory and the desire to avoid excessive complications in computation. There are also some awkward choices to be made in deciding, in the design process, the relative weight to be attached to imperfections in the control of the various parameters. For example, what is the relative importance of deviations from the specified track and from the specified speed? Perhaps most difficult of all are the compromises between passenger comfort, the avoidance of considerable throttle activity, and precision in following the agreed trajectory. The details of flight control designs are commonly treated as manufacturer's secrets. The system may well offer the pilot a choice between "hard" and "soft" control modes, and he always has the freedom to revert to manual control of the flight.

ATC normally has no knowledge of which of these modes is in use at a given time, so that the ATC model of aircraft performance is necessarily rather "fuzzy". It is possible that future developments in the use of air-ground data links may make possible an improvement in this situation, but pilots are likely to feel that their authority over the handling of the aircraft would be undermined by extensive "bugging" of the flight deck.

Other aspects of prediction of aircraft trajectories will be discussed in Section IV of this AGARDOGRAPH.

1.5.3. Safety

1.5.3.1 The need for an adequate level of safety in flight is a major issue in any type of operation. The very high standard demanded for flights by civil air transport is probably the most difficult of all. A target-level of safety for one region, North Atlantic, selected for purposes of a study in the late 1970's, was 2.5 fatal accidents per 10 million en-route flying hours. The "share" of this risk allocated to mid-air collisions was 0.6 accidents per 10 million hours. The first accident is yet to happen. The design of a system to achieve this safety level is handicapped by the extreme difficulty of collecting enough data on the probability of occurrence of any of the highly unlikely combinations of circumstances such as would almost certainly be necessary for catastrophe. Section 1.2.2. pointed out the policy of using not one monolithic system but a multiplicity of sub-systems each aiming to prevent hazardous situations between aircraft in controlled airspace, but planning to different time-horizons and, when possible, using different data. One advantage of this approach is that, provided the protective mechanisms are independent of each other, it is now possible to allow individual sub-systems, a much higher rate of failure than can be tolerated overall. This, in turn, simplifies the problem of collecting the necessary data on sub-system reliability. Over the North Atlantic, there is presently no technique open to ATC except ground-based control based on pilot reports giving air-derived data. This area is therefore one where the ATC system is, in principle, quite simple, but where theoretical analysis, rather than direct observation, has to make a major contribution to the system design. From the early days of theoretical study (Marks, 1963; Reich, 1966) up to the present day (Brooker, 1984), the North Atlantic has therefore been the main topic of studies in mid-air collision risk.

1.5.3.2 This work begins by allocating a target level of safety for mid-air collision in the area under study. This is then decomposed into a number of component risks, each of which is given a "share" of the target level. Over the North Atlantic, these components are failure of vertical, longitudinal and lateral separation. Failing any better argument, the partition has been arbitrarily set at equal levels for the three components. In areas under radar control, it is usual to decompose risks into failure of either vertical or horizontal separation.

From these target levels, theory is used, in conjunction with whatever data is available and in combination with the judgement of experts in the field, to define "separation standards" which define the target levels below which the spacing should not be allowed to fall. Effectively, ICAO separation standards define the level of trust the controllers should place in the data on which they base decisions. There is, of course, nothing to prevent a prudent controller or local control instructions from providing a bigger spacing should it be judged necessary.

For "see and avoid" operations, the difficulty of accurately assessing the severity of a hazard is such that no useful purpose would be served by defining a minimum spacing. Study of collision avoidance at sea (Goodwin, 1975), normally based on radar data, suggests the concept of a "domain" round own vessel, intrusion into which by another vessel will disconcert the ship-handler. For the TCAS airborne collision-avoidance system, to be discussed in section 2.4 below, the ICAO draft specification, unusually, gives a detailed description of the logic to be included in the equipment but does not define the quantitative objective to be achieved.

1.5.3.3. Section 1.3.5 pointed out that there is, at present, no alternative to the aircraft's aneroid barometer as a means of measuring aircraft height. The ICAO vertical separation standards (1000 ft. below FL290, 2000 ft. above FL290, 4000 ft. between supersonic aircraft and any other) therefore apply to all airspace whether within radar coverage or otherwise. In the horizontal plane, radar makes possible a considerable reduction in the separation minima, 5 NM being usual and 3 NM being permitted for traffic sufficiently near a terminal-area radar. It should be noted that the separation standard is the minimum spacing between two aircraft that should be permitted at closest approach, not the separation at which escape manoeuvres should be initiated. This latter topic will be discussed in sections 3 and 4 below.

The transmitted waveform is so designed that appreciable redundancy exists in the returns from each target as the antenna beam sweeps across it. This redundancy is used in a "signal processor", usually implemented in special-purpose hardware, which is intended, as far as possible, to detect the presence of aircraft targets whilst rejecting ground clutter, weather and other unwanted returns, accidental or otherwise.

Target bearing is derived in the "data extractor" by some logic which searches for the "radar centre of gravity" of the echo from the aircraft. One serious weakness of this scheme is the radar's inability to resolve two targets that are at nearly the same range and separated in azimuth by less than the radar beam-width. If this situation is of short duration, the "radar-tracking" logic, discussed briefly in section 2.2 below, can give positions based on extrapolation from past history. If the radar looks down an airway which contains numerous aircraft following the same track, in plan at least, these situations may not only be relatively common but also persistent.

The data extractor supplies a list of coordinates at which radar targets were found during the most recent sweep by the radar. Primary radar cannot attach an identity to any of these targets. The next stage, "radar data processing", builds aircraft tracks from the plots supplied. Data processing systems are often required to merge plot data from more than one radar to form an overall traffic picture.

Even "crowded" airspace contains large volumes of air and small volumes of metal. If pilots and ATC were both to fail to take any effective steps to avoid collision, such events would still be infrequent, although the loss of life would be intolerable. ICAO, in setting the separation standards, takes account of the fact that failure to enforce the separation standard does not necessarily lead to catastrophe, and such failures, in regions of low traffic density, are less important than when traffic density is higher. We can, perhaps, use the theory of traffic behaviour in uncontrolled flight (Ratcliffe and Ford, 1982) as a rough measure of the probable consequences of failure by controllers and ATC to detect and remedy an impending collision. Broadly, the conclusions are that the rate of collision, given a population "p" randomly distributed in position and heading, in a given volume of airspace is proportional to $p(p-1)$, to the volume occupied by each aircraft divided by the volume of sky, and to the average modulus of relative velocity between pairs of aircraft. In many regions of airspace, aircraft are advised to fly at specified heights e.g. "semicircular" cruising levels or to follow specified routes. The above study considered the effect of each of these measures and concluded that, in all cases investigated, the result was an increase in collision risk. In the study, the aircraft shape was assumed, for ease of computation, to be a right circular cylinder, i.e. to have a circular shape in plan and a rectangular section in the vertical. This is a convenient if very rough approximation to the shape of an aircraft, but an accurate description of the radar separation standard. By substituting the separation standard for the dimensions of the aircraft, the study results can be applied to an assessment of the risks of an ATC "conflict". Although, as will be seen later, constraints on traffic movement often lead to an appreciable simplification of the problems of detecting and resolving conflicts, the study shows that these simplifications are at the expense of an increase in the number of such problems that require to be solved.

1.6 Surveillance Systems.

1.6.6 A surveillance system is a means by which Defence or ATC can sense the position and perhaps the intention of aircraft in which it is interested. Using the terminology of the ICAO FANS Committee, surveillance system can be classed as "cooperative" (secondary radar, SSR) or "non-cooperative" (primary radars). A cooperative radar requires the carriage by each aircraft of a "transponder" which transmits a reply to interrogation by the ground station. Such systems cannot detect any aircraft which does not carry an operating, serviceable, transponder. Non-cooperative surveillance systems, which are essentially mechanisms for detecting discontinuities in the atmosphere, detect all aircraft (assuming adequate sensitivity) but also detect birds, rain and projections from the earth's surface ("ground clutter"). This AGARDOGRAPH is not intended as a radar engineering text book, but problems will be discussed in outline where they have a strong influence on the effectiveness of trajectory determination and prediction.

1.6.2 Primary Radar

1.6.2.1. For defence purposes, primary radar is the principal tool for locating enemy aircraft. Even for ATC, the advantages of a system that does not require the electronic cooperation of every airspace user has many advantages, although, as will be shown later, primary radar now tends to be used by ATC only in a back-up role, and there are ATC authorities who are now seriously questioning whether the expense of primary radar can be justified by their needs.

Although more exotic ground radars are possible, at a price, existing ATC surveillance radars almost invariably use an antenna giving a fan beam in the vertical plane but a narrow beam in plan. The antenna rotates mechanically, usually at a speed of 5-10 rpm. In more elaborate defence radars, this "fan" is derived by adding the outputs of a number of channels each corresponding to a different beam of limited vertical extent. Height-finding is now possible by comparison of the signals in the various beams. This system has the added advantage of giving some protection against rain echoes, ground clutter and enemy countermeasures. An alternative technique is to supplement the fan-beam surveillance system with computer-driven "height-finding" radars each having a narrow beam scanning in the vertical plane. These are steered in azimuth by the surveillance system to make successive height measurements on individual targets of interest.

1.6.2.2 Radar is, at best, capable only of measuring the geometric height of the aircraft relative to the radar. Conversion to barometric pressure, the quantity actually measured by aneroid "altimeters", and on which ATC rules are based, requires more data than is usually available about the air column between the aircraft and ground. Variability in atmospheric refraction sets further limits to the possible accuracy of height measurements by ground radar. At ranges greater than about 20 NM., aircraft height cannot be measured to an accuracy comparable with an aircraft's pressure altimeter system. Ground radar is therefore almost confined to measuring aircraft bearing and slant range from the radar. Traditionally, the radar transmission consisted of a succession of narrow pulses, sufficiently spaced in time to ensure that echoes from the most distant targets would be received before the next transmission, thus avoiding range ambiguities. With advances in data-processing technology, more sophisticated transmissions are now used, the waveform being tailored to the environment and the operating mode in use. The radar receiver, or receivers, convert the radar signals to a lower, more convenient, frequency. The receiver forms a matched-filter designed to maximise signal/noise ratio at the output. The transmitted waveform is so designed that appreciable redundancy exists in the returns from each target as the antenna beam sweeps across it. This redundancy is used in a "signal processor", usually implemented in special-purpose hardware, which is intended, as far as possible, to detect the presence of aircraft targets whilst rejecting ground clutter, weather and other unwanted return, accidental or otherwise.

Target bearing is derived in the "data extractor" by some logic which searches for the "radar centre of gravity" of the echo from the aircraft. One serious weakness of this scheme is the radar's inability to resolve two targets that are at nearly the same range and separated in azimuth by less than the radar beam-width. It is this situation of short duration, the "radar-tracking" logic, discussed briefly in section 2.2 below, can give positions based on extrapolation from past history. If the radar looks down an airway which contains numerous aircraft following the same track, in plan at least, these situations may not only be relatively common but also persistent. The data extractor supplies a list of coordinates at which radar targets were found during the most recent sweep by the radar. Primary radar cannot attach an identity to any of these targets. The next stage "radar data processing", builds aircraft tracks from the plots supplied. Data processing systems are often required to merge plot data from more than one radar to form an overall traffic picture.

1.6.2.3 The methods by which tracks are initiated or terminated are of no immediate interest. Given a list of tracks and a list of plots, the task of the data processor is to associate plots with tracks and to update the latter. The first stage in this process is to use the history of each track to predict the position of the related plot at the next radar sweep. Section 2.2 will discuss this task in some little detail. The accuracy with which this prediction can be made will have a major influence on the ease with which plots and tracks can subsequently be associated. If plots from unwanted targets, such as ground clutter, are present, it may be necessary to maintain tracks on these returns, if only to enable plots to be eliminated before attempting to deal with the aircraft of interest. Even if all plots due to clutter can thus be eliminated, the number of plots remaining is not generally equal to the number of candidate tracks. For example:- radar returns can fade between successive scans, leading to missing plots, two aircraft in close proximity may confuse the radar into reporting a single target, and buildings in the vicinity of the radar may reflect enough power to cause the radar to see both the aircraft and its reflected image.

One simple-minded approach to the association task is to take each plot in turn and attach it to a plausible track to which no assignment has yet been made. Any error in association will have a cumulative effect, so that at the end of the process there will remain a list of unassigned plots and another list of "free" tracks to which none of the unassigned plots can possibly belong. In theory there are better methods. For example, suppose that there is an algorithm which gives the likelihood of any given plot belonging to each of the tracks. It is now possible, using linear programming techniques, to find the assignment of plots to tracks that maximises the sum of the likelihoods i.e. the overall probability of correct assignment. In practice, the volume of computation may be prohibitive, especially in the presence of heavy clutter or countermeasures. A variety of methods have been studied in theory and/or implemented in practice (Farina and Studer, 1985).

1.6.3 Secondary Surveillance Radar (SSR)

1.6.3.1. SSR was invented in response to a need for a device that would enable a military surveillance radar to distinguish between friend and foe. It was also recognised that, to use RT to vector aircraft on the basis of ground radar data, there must be a clear connection between the track on the radar screen and the aircraft's radio call sign. During World War II, the Allied powers developed a common IFF system which ICAO later adopted as the basis of SSR. This system has evolved considerably since its first introduction, and this evolution continues today. It has, so far, always proved possible to retain compatibility between successive generations of equipment in the air and on the ground, so that a modern interrogator can still work with an elderly airborne transponder, and vice versa. SSR differs from primary radar not only in the need for an airborne transponder in each aircraft, but also in the use of different frequencies 1030 MHz for ground-air and 1090 MHz for air-ground messages. Separation of the interrogation and reply frequencies means that weather and ground clutter no longer cause problems. There are, however problems peculiar to SSR, some of which will be discussed, briefly, below.

1.6.3.2. To the user, a major difference between cooperative and non-cooperative surveillance systems, is that cooperative systems can give a reply containing more information than the single-bit message reflected from the skin of the aircraft. The earliest feature of secondary radar was a code giving aircraft identity. In existing SSR, 4096 codes are available, and schemes exist for allocating these in such a way that each civil aircraft within the coverage of a given radar has a unique identity code. This is not only directly useful to the controllers, but also to the radar data processing mechanism. A later addition to the SSR transponders was the ability, not only to give the identity code in response to a "Mode A" interrogation, consisting of a pair of pulses spaced by 8 microseconds, but also, in response to "Mode C" interrogation (21 microsecond spacing), to use the same 4096 codes in another role, to signal the present altitude of the aircraft. Mode C thus offers a SSR surveillance system having three-dimensional information on every suitably equipped aircraft. Carriage is not universal, mainly because of the cost of Mode C to owners of light aircraft. The cost is due, not so much to the added complexity of the transponder, but to the need for a digitiser to be fitted to the altimeter system. Incidentally, a knowledge of aircraft height makes possible a more accurate conversion of slant range data into plan position. Note that, in FANS terminology, SSR Mode C gives "independent" data on slant range and bearing, but "dependent" data on aircraft height.

Because all SSR transponders use the same frequency and message formats, all airborne transponders reply to all interrogators within line of sight, and all interrogators receive replies to all interrogations, however originated. Under normal circumstances, an aircraft will transmit 20-30 replies as the interrogator beam swings past it. Although SSR has advantages over primary radar, it has its own peculiar drawbacks. As with primary radar, it is necessary to process the received signals on the ground, firstly to extract plots and then to use the plots to update tracks. Although, in principle the problems are the same as for primary radar, there are considerable differences of detail.

1.6.3.3 One class of problems arises from imperfections in the polar diagram of the interrogating antenna. Not even in theory can an antenna concentrate all the radiated power in the main beam:- some fraction of the interrogation energy will be radiated in "side-lobes". Further, some of the energy will reach the aircraft after reflection by the Earth's surface or buildings near the radar, and these stray signals may serve to trigger a reply from the transponder, the reply message returning to the interrogator by the same unofficial route. This effect also arises in primary radar, but here the signal returned from the aircraft is proportional to that received from the ground. With SSR, provided the transponder is triggered by the interrogation signal, a full-power reply is returned. For example, if some unofficial transmission path delivers to the aircraft only 10% of the main-beam power, then only 1% of the normal power would return to a primary radar receiver, whereas SSR could receive 10% of the main-beam signal.

Side-lobe problems are dealt with in present-day SSR by radiating, in addition to the interrogation pulse-pair described above, a "side-lobe suppression" (SLS) pulse. This latter is radiated from an antenna having a much broader polar diagram than the main beam. The transponder compares the strength of this pulse with the main pulse-pair, and replies only if the suppression pulse is weaker. The SLS mechanism does not eliminate errors in bearing measurement due to terrain reflections. SSR antennas were originally designed mainly as an add-on attachment to primary radars, and had only a limited vertical aperture. This meant that considerable amounts of the radiated energy reached the Earth's surface. More recent SSR's have antennas with a much larger vertical aperture, thus considerably reducing bearing errors due to terrain problems. The second class of difficulties, largely peculiar to SSR, arises from self interference, where too many aircraft are simultaneously within coverage of too many ground stations. With primary radar, it is usual to stagger the frequencies of adjacent radars. This probability of time overlap between primary radar signals typically about 1 microsecond wide, is, in any case, small. With SSR, a uniform frequency is used world-wide. SSR interrogations and replies (20 microseconds long) are more vulnerable. By staggering the interrogation rates of adjacent SSR's some of the problems can be mitigated, but when two aircraft are on roughly the same bearing and separated by less than 2 NM. in range from the radar, their reply pulse trains will overlap on reception at the interrogator. This "garbling" may cause the plot extractor to deliver "don't know" or nonsense replies. Alternatively, when replies reach the plot extractor unscathed over part of the extent for which the aircraft is within the main beam, the bearing data derived by the "centre of gravity" method may be seriously in error.

In the above discussion, it was explained how a plot extractor could drive bearing information by finding the centre of gravity of a group of replies. Given a more elaborate antenna and receiver system, it is possible to determine bearing from a single reply, or even from a single pulse within the code-train constituting a single reply (Stevens, 1981). This enables a superior design of plot-extractor which gives better performance under garble conditions. Further, this "off-boresight monopulse" technique makes possible a considerable reduction in the interrogation rate that is needed, thus reducing interference between interrogators.

1.6.3.4. By an ingenious exploitation of the side-lobe suppression features of the Mode A/C transponder specification, it has proved possible to introduce a transponder having a further mode of operation (Boves, 1982). The "Mode S" interrogation can be used selectively to interrogate only a specified aircraft, although there is a further mechanism to initiate newly arrived aircraft into the system. Mode S equipped aircraft respond correctly to Mode A or Mode C interrogations from existing ground stations, and Mode S stations can handle aircraft equipped with Mode A or Mode A/C only. Mode S data processing will be discussed in Sec. 2.2.

The Mode S specification is in the latter stages of ICAO Standardisation. The FAA have already proposed to rule that, after 1992, all newly installed transponders in US civil aircraft must meet the Mode S specification. A further feature of Mode S is the provision of additional data-link capability. This is somewhat limited because of system constraints necessary to preserve compatibility with earlier generations of SSR, and the functions for which the link will be used are still under discussion.

1.6.4. Dependent Surveillance

1.6.4.1. Voice Communication

Speech communication between pilot and controller was formerly an important means of passing position data from air to ground, and is still used in some circumstances, e.g. where there is no radar cover. In general, civil and military traffic use different carrier frequencies. For civil aviation, at least, simplex working is used, controllers and pilots transmitting on the same frequency. Offset frequencies allow the use of up to three ground transmitters at different locations, to obtain adequate radio cover at low flight levels over the whole control sector. Diversity reception techniques allow automatic selection between a number of ground stations to give good reception of messages from all aircraft. The system protocol allows all users, pilots, and controller alike, access to the voice link on a first-come first-served basis. Before commencing transmission, pilots are required to listen-out and delay their message if some other user is already using the channel. If the ongoing transmission obviously needs a reply, it is normal to allow time for this as well, although in emergency a pilot or controller may attempt to break-in at this point.

A station that is transmitting is deaf to messages from elsewhere. With offset frequency working, although ATC will receive messages from anywhere in the coverage, aircraft will not always hear each other. It is always possible that two pilots, sharing a common channel and finding it to be silent, may commence transmission more or less simultaneously. In this situation, both messages are liable to be garbled on reception by ATC. An important factor in safety-sensitive ATC-controlled manoeuvres is the time that must be allowed to pass an instruction to a controlled aircraft. With a growing tendency to use highly accurate avionic systems for precise ground-based control of aircraft trajectory, ground-air messages may become more detailed, and voice communication runs an increasing risk of errors in transmission and in the input of revised clearances into computer systems both in the air and on the ground.

Automatic transfer of data between air and ground can include error-checking mechanisms, and offers a faster, more reliable and less laborious means of exchanging routine data. It is generally accepted that such systems are not likely to be capable of handling all possible combinations of circumstances that can arise in an emergency, but most forward planning is based on the assumption that automatic dependent surveillance is likely to play an increasing part in ATC.

1.6.4.2. Automatic Dependent Surveillance

The ICAO Committee on Future Air Navigation Systems (FANS) was set up to plan for an integrated communication, navigation and surveillance (CNS) system for the next 20 years and beyond. Almost instantly, the FANS working groups concluded that satellite-based techniques held the solutions to the problems likely in the future. Essentially, existing radio aids to navigation, other than those needed for instrument landings, would be replaced by NAVSTAR/GPS, GLONASS or possibly other satellite-based navigation systems. Communication, also satellite based, will be on L-band and based on digital transmission. The relevant FANS working group acknowledges the advantages of independent surveillance, but up to the time of writing (September 1987) study activity centres around automatic dependent surveillance (ADS). There is heavy emphasis on over-ocean problems, which seem to offer the first opportunity for a major improvement in the ATC service that can be offered. Many problems require more study before an ADS system can be fully defined. The first phase of the conceptual plan for the evolution of satellite surveillance is based on Mode S SSR, where available, otherwise an ADS will be used, with position data derived from existing navigational data. Cooperative independent surveillance is envisaged in regions where ADS is inadequate, or independence between navigation and surveillance is required. The contest between SSR Mode S and satellite CIS can probably only be resolved when the economics of the two systems are much clearer.

Present thinking on ADS (ICAO FANS, 1987) calls for a "basic" mandatory ADS capability. It is not clear to which aircraft the mandatory requirements will apply. Every ADS report will contain latitude and longitude to a precision of about 25 metres, barometric height to a precision of 2.5 metres, and a "figure of merit" which indicates the quality of the position data on which the report is based. In addition, on request from the ground, the aircraft must supply the time at which the reported position was derived and/or the ADS capability (a list of other ADS facilities which the aircraft can offer) and/or the aircraft identity. Every ADS message contains, in the preamble to the message, a "technical address" which defines the airframe. The "identity", e.g. the airline trip number, normally serves to cross-relate the technical address to the filed flight-plan.

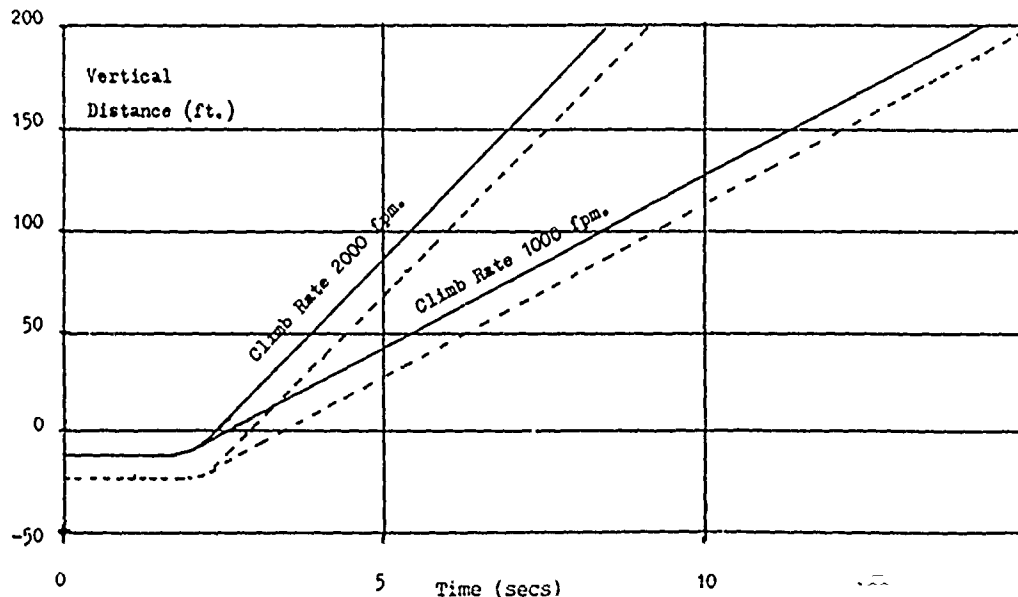
"Extended ADS" facilities, which may be required for flight in certain areas, include latitude and longitude of the next and next-but-one waypoint as stored in the aircraft flight management computer. Required precision is the same as for position reports. The extended facilities also include aircraft track or heading to a precision of 0.1 degree, IAS/Mach No. to a precision of 0.5 knot/0.001 Knot respectively, and vertical rate to a precision of 0.08 metres/sec. The ground system may request any selection from this list, so long as it falls within the reported ADS capability. It is recognised that the resolution figures need to be refined and justified operationally. It has only fairly recently been decided, surprisingly, that whilst waypoint coordinates contribute to the early detection of errors in insertion of data into computers, no useful purpose could be found for the inclusion of the associated altitude.

2. Short-Term Prediction (10 to 150 seconds).

2.1 Aircraft Trajectories.

2.1.1 We are concerned both with the rate at which an aircraft can displace itself from an agreed path, either in response to an ATC instruction or as a result of equipment failure, pilot error, or reaction to some other situation of which ATC may be unaware but which the pilot perceives to be more important than obedience to ATC instructions.

For very short prediction times, we can only expect very small displacements, and the dimensions of the aircraft are relevant. Calculations are usually based on the distance between the centres of gravity of aircraft under discussion. There is no simple rule to determine the spacing between the centres of gravity of two aircraft at the point at which they come into collision. Results of some computer simulations give a more realistic picture of the capability for escape manoeuvres of typical airliners (Gilbert, 1976). This study considered the displacement that could be achieved in a given time, in either the horizontal or the vertical plane, by a typical (in 1976) 100-seat short/medium range transport aircraft and by a typical long-range "jumbo". Each aircraft had a vertical performance that did not differ much between climb and descent, and neither height (studied only above 10,000 ft.) nor airspeed (studied above 250 knots) had much effect on escape capability. Figs. 6, 7 and 8, discussed below, were derived from data in the Gilbert paper.



Consider, first, the pull-up manoeuvre capability illustrated in Fig 6. It is assumed that the elevator input to give 0.5g vertical rate was applied in linearly increasing manner to the final value in 1.0 secs., and maintained until the desired vertical rate was achieved. Thereafter the vertical rate was held constant. The rate is limited by the need to keep airspeed within acceptable limits. Even an infinite vertical acceleration would only slightly change the vertical displacement that could be achieved in 30 secs., say.

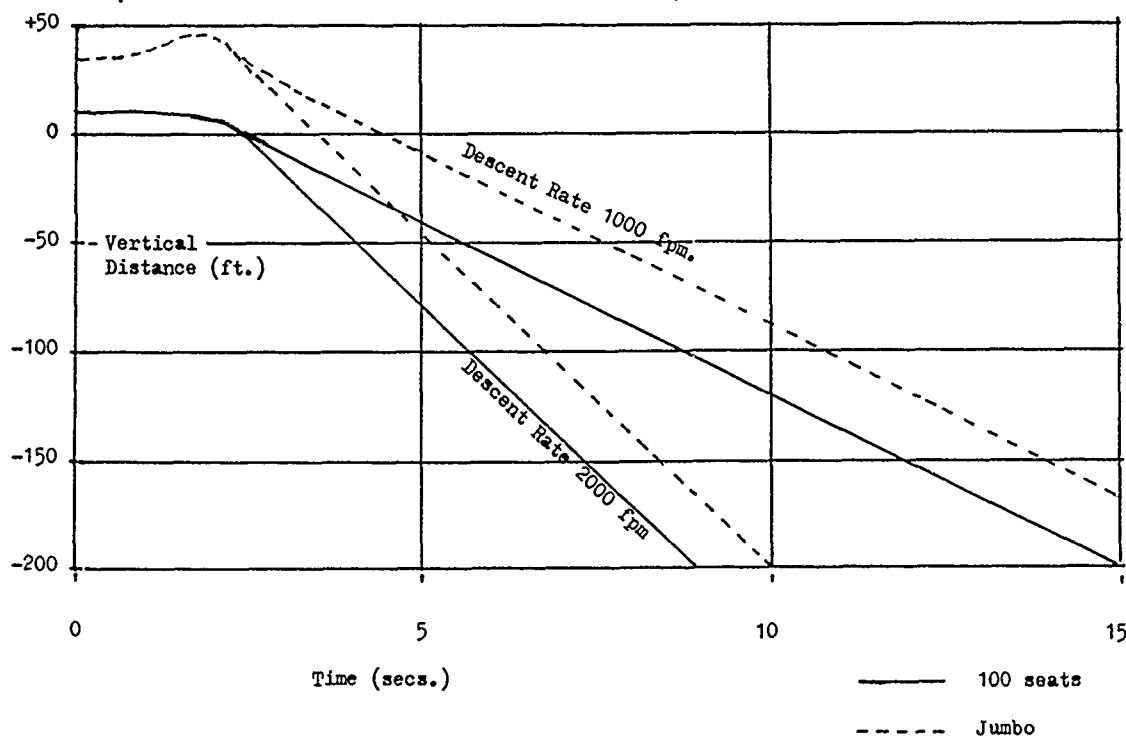
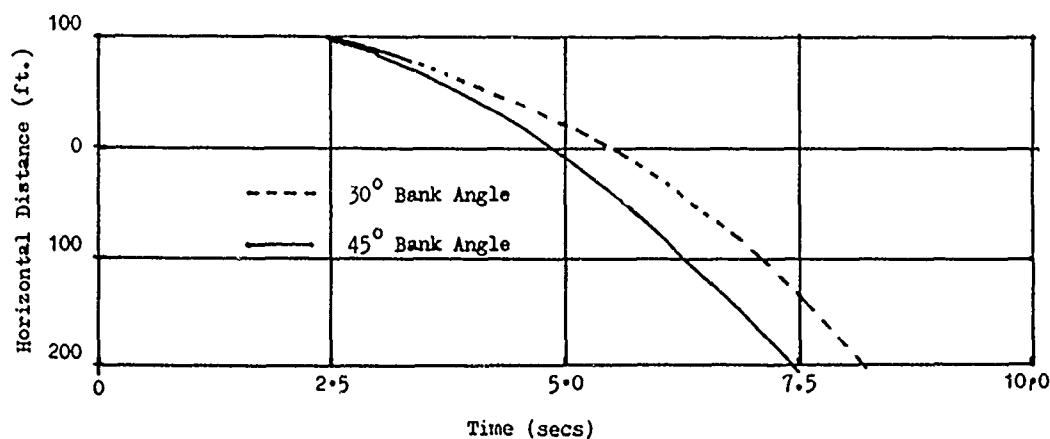


Fig. 7 Trajectory of Fin Tip Following Push-over

Fig 7 shows similar results for a descent manoeuvre under an acceleration applied in the same manner as for fig. 6. Zero height on the vertical scale of figs. 6 and 7 corresponds to the height of the aircraft centre of gravity. For collision avoidance, we are concerned with height of the lowest part of the fuselage, when the aircraft is in climb, and the highest point on the aircraft fin tip when in descent. Note from fig. 7 that the first consequence of putting a jumbo into a dive is to cause the tail fin to rise.

fig 8



Similarly, Fig. 8 shows the behaviour of the wing tip of a jumbo jet when manoeuvred into a turn at bank angles of 30 and 45 degrees. As before, height and airspeed do not strongly influence the behaviour. The curves in Fig. 8 are for half aileron applied at a linear rate over a one-second period, the bank angle being thereafter maintained at the desired value. The horizontal distances are measured from the longitudinal axis through the aircraft centre of gravity. 4 or 5 seconds after the initiation of the manoeuvre, the wing tip is moving away from the original line of flight at a rate proportional to the square of time.

The results in the Gilbert paper are not universally applicable. It is unlikely, for example, that a fully-loaded long-range jumbo could achieve even a 30 degree bank angle soon after take-off. Equally the manoeuvre capability of a high-performance military aircraft may be very different from that shown in figs. 6, 7 and 8. Not only may the aircraft be capable of more rapid turns and higher rates of climb/descent, it may also be capable of a much wider range of airspeed. Performance data on military aircraft may not be available to civil ATC, but at least it will be safe to assume that their manoeuvre capability is, at least equal to that of civil aircraft.

2.1.2 So far, we have discussed the problem of an aircraft manoeuvring to avoid collision, with emphasis on the trajectory of the last point on the airframe to leave the neighbourhood to be avoided. For the classes of aircraft with which figs. 6, 7 and 8 are concerned, we can reasonably use the results to assess the worst-case possibility of a manoeuvre into collision, except that it is now necessary to consider the first point on the airframe to enter the hazard region, rather than the last one to leave it. As 2.1.1 implied, it is not very easy precisely to define the "hazard region". For example, Fig. 8 shows the lateral displacement produced by banked turns. Such a turn can also have an effect in the vertical plane, since, given a 45 degree banked turn and a 100 ft. long wing, the lower wing-tip will drop 70 ft., even for a perfectly banked turn, and a pilot preoccupied with other problems may lose more height from other factors.

2.1.3 As prediction times lengthen, the uncertainties as to an aircraft's future behaviour rapidly become more important than the physical dimensions of the aircraft. The cheese-shaped approximation to the shape of an airframe is, in fact, a precise model of the volume of airspace that ATC radar separation rules lay down as the domain of a single aircraft. For purposes of establishing bounds to the aircraft manoeuvre capability, it may be assumed that an aircraft after a short delay, manoeuvres in the vertical plane at a rate of climb/descent, and that, in the horizontal plane, the effect of a given bank angle is to cause the aircraft to fly an arc of a circle. If "a" is the lateral acceleration due to gravity and θ the bank angle, then, for a perfectly banked turn

$$\tan(\theta) = a/g \text{ --- (5)}$$

For a true airspeed "V", the radius of turn "R" is given by

$$R = V^2/a = V^2/g \tan(\theta) \text{ --- (6)}$$

and the time needed to change heading by ϕ radians is given by

$$t(\phi) = R\phi/V = V\phi/g \tan(\theta) \text{ --- (7)}$$

Figs. 6, 7 and 8 clearly show that a few seconds suffice to produce a dramatic change in an aircraft's trajectory. One cannot safely assume that an aircraft will follow a track which is simply an extrapolation from past history. In a study of the prediction of the rates of climb/descent for A300 commercial airliners, under completely normal conditions, Fron (1984) reported that altitude predictions 30 seconds ahead in time were in error by more than 350 ft. for 20% of time in climb and 25% of time in descent. Data was derived by sampling the output of the aircraft flight data computer at 1 sec. intervals. The results were attributed to the heterogeneity (in temperature and windspeed) of the atmosphere in its vertical dimension. For a time-horizon of 120 secs., with data based on 4 sec. samples, errors exceeded 1000ft. for 40% of the climbing time and 45% of the descent time.

It has been shown that a civil aircraft making a moderate change in heading, 20 degrees, say, may carry out a manoeuvre which differs significantly from the ideal banked turn postulated earlier (Lefas and Thomas, 1981). Probably the most predictable feature of a sub-sonic civil aircraft, once clear of the jet streams discussed in 1.4.2, is the distance it will travel along-track. Changes in airspeed that are likely in 150 secs. or less can have only a small effect on the distance travelled over this time-scale.

2.2 Radar Tracking

2.2.1 Processing Radar Data

2.2.1.1 Section 1.6.2 outlined the process by which the signals from the radar receiver are converted into sets of coordinates representing the position of aircraft observed during the most recent passage of the radar beam. These plots are then assigned to tracks already stored in the computer or, if so desired, used to initiate a new track.

Even after treatment in the signal processor, one second's output of a radar may contain a considerable amount of information. Elaborate processing of the whole of this data is not practicable in real time, and it is normal practice at some stage in the data extraction process to insert some form of "gating" mechanism which passes only data from regions of interest. Once a track is established, the radar tracking logic predicts the position at which the relevant radar echo can be expected at the next radar sweep, and a suitably positioned "window" admits data from the signal processor to the data extractor at the expected time of arrival of the signals. The dimensions of the window are determined by the perceived quality of the stored track data, being large when the track is newly initiated, and small once confidence has been established.

Given that the output of the signal processor still contains many signals in addition to the wanted echoes, a considerable component of the extraction task will be concerned with completing the elimination of clutter. This task will be roughly proportional to the total area of the windows. Additional processing is needed when gates overlap, thus creating problems in deciding to which track a given plot belongs. For this reason, accurate plot predictions make possible a considerable reduction of the overall data-processing task, but, as earlier sections of the paper have pointed out, prediction has its limitations.

2.2.1.2 There are many steps involved in converting radar signals into tracks (Shaw, 1986) and in combining the data from a mixture of primary and secondary radars at a number of different sites into one "air picture" in a control centre. In what follows, discussion will be confined to the problem of filtering noisy plot data to convert it into a smoothed track. It will be assumed that we are deriving data from a conventional ATC radar having a fan beam in the vertical plane which is rotated in azimuth at a uniform rate, the radar delivering slant range and bearing, accompanied, in the case of SSR signals by Mode A, Mode A/C or Mode S data. We will not discuss many other possible forms of primary radar which make available, at a price, more information than the "azimuth and slant range" assumed above. One may, for example have a 3-D capability and/or radial velocity derived from Doppler shift of radar signals. The resulting tracking problems are discussed elsewhere (Farina and Studer, 1985)

2.2.1.3. Tracking filters are usually classified as using "alpha-beta" or "Kalman" tracking algorithms. The alpha-beta tracker is generally simpler and therefore more commonly adopted, but the distinction between these classes arises more from the way in which they are described than from fundamental differences in their method of operation. Stochastic filtering theory assumes that we have data on the evolution of a system (in this instance the "system" being the position of the aircraft) over a period of time. The input to the filtering process is assumed to consist of a "system state vector" whose components are deterministic functions of time together with stochastic processes representing unpredictable variables (noise). The output of the tracking filter is a function of this state after corruption by measurement errors.

Since we have access to the system state only at intervals not less than one radar rotation, at best, we are discussing a discrete-time model, so that the filter operation is defined by difference, rather than by differential, equations. In the Kalman approach to the filter design, rather than a single, high-order, equation defining the operation, it is usual to use a set of first order equations which are more easily handled by vector and matrix methods.

The filtering problem is approached by replacing the physical objects under study, the collection of aircraft, by a mathematical model of the dynamic system whose state can be deduced from a knowledge of the initial condition of the system, the history of the "forcing input," deliberately applied to the various airframes, and of the stochastic disturbances (e.g. those due to the atmosphere) whose statistical properties are known but whose actual values at a given time remain indeterminate. The measurement sensor system, that is, the radar and its data extractor, is similarly represented by a mathematical model which aims to define the relationship between the dynamic system state corresponding to the target aircraft, and the corresponding measurements delivered by the sensor system. The system state vector may well have more dimensions (e.g. velocity, height) than the output of the radar. The measurement data is assumed to be subject to a further set of stochastic errors.

2.2.1.4 Consider an alpha-beta tracker which operates on range and bearing data from a signal processor. Let r_n be the range reported after the n th sweep of the radar, and R_n be the smoothed value of range delivered by the filter. Let \dot{R}_n similarly denote the filter estimate of range rate. Let T be the time interval between radar sweeps, and $P(r, (n+1))$ be the filter's prediction, based on the n th radar sweep, of the value of r at time $(n+1)T$. The tracking algorithm is based on eqns. 7, 8 and 9.

$$R_n = P(r, n) + \alpha(r - P(r, n)) \quad (7)$$

$$\dot{R}_n = \dot{R}_{n-1} + \beta(r - P(r, n))/T \quad (8)$$

$$P_{n+1} = R_n + T \cdot \dot{R}_n \quad (9)$$

The computation becomes slightly more complex if a radar return from the aircraft does not appear in the gate for one or more sweeps. The above equations have delivered a smoothed estimate of the present value of range (eqn.7), of range rate (eqn.8) and an estimate of range at the next radar sweep (eqn.9). Note that $P(r, n)$ in equations 7 and 8 is the value of " r " predicated after the $(n-1)$ th radar sweep. If range is replaced by bearing, the same algorithm can deliver corresponding estimates and forecasts of bearing and bearing rate.

Equations 7 - 9 make no reference to the possibility of any acceleration by the aircraft. In practice, any such accelerations are treated as part of the measurement noise. The behaviour of the tracking algorithm is strongly influenced by the values given to alpha and beta, both of which must have values between zero and unity. Reference to equation 7 will show that, if alpha has the value unity, the smoothed position given for an aircraft will be totally determined by the most recent observation. As alpha falls towards zero, the reported position will be less and less dependent on the recent radar data but more and more based on the earlier history of the track. For a linear filter, such as that illustrated by eqns. 7-9, it is possible to determine values for alpha and beta that are optimal, in the sense that they minimise some defined cost-function (Benedict and Bordner, 1962), whose paper assumed that the object was either to minimise the variance of the position error or of the error in position rate, and came to the happy conclusion that it was possible, in the example studied, that these two objectives could be achieved simultaneously by choosing beta equal to $(\alpha)^2/(2-\alpha)$. The optimal values for alpha and beta depend on the cost-function chosen for minimisation and on the statistical properties of the stochastic disturbances to the dynamic system-state and of errors in the measurement system.

2.2.1.5 The choice of polar coordinates for the alpha-beta tracker has a number of advantages in addition to the elimination of the need for transformation of the coordinates. Measurement errors in bearing should, to a reasonable approximation, be constant over the entire coverage of the radar. Measurements in range will have errors that vary as the square root of the signal/noise ratio, which is a function of the range and echoing area of the target. This latter quantity is a sensitive function of the unknown attitude of the aircraft relative to the radar, so that it is usual to ignore the variation in ranging errors with range.

On these assumptions, errors in both range and bearing are both constant over the entire coverage of the radar and independent of each other. It is for these reasons that the filter could be decoupled into two simpler mechanisms, each using eqns. 7-9, with appropriate values of alpha and beta for each coordinate. The values assigned to alpha and beta can make allowance for the much better accuracy in range than in azimuth measurements.

2.2.1.6. Since the algorithm given in para 2.2.1.4 effectively ignored the possibility of the target aircraft entering a turn, it is hardly surprising that, when the parameters alpha and beta have been optimised for a target in straight-line flight, the tracker does not perform well on a turning target. One common solution is to provide some form of turn-detection logic, so that, if a turn is detected, the logic can use some different values of alpha and beta.

If there is a single tracker mechanism whose parameters are modified when the turn detector issues a report, false alarms in the turn detector can cause a serious loss of track quality, not only until the turn warning is cancelled, but until the tracker has recovered to a steady-state. A better, if more expensive, mechanism is to operate two or more parallel trackers, optimised on the basis of different assumptions about the aircraft trajectory, and to provide further logic to choose between their predictions. (Blom, 1985; Langston, 1987).

Kalman filters can be designed to incorporate a more detailed model of the aircraft dynamics, but the choice of coordinate systems presents a problem. A track-oriented coordinate system gives the possibility of correctly reflecting realistic limits on possible along-track velocity and cross-track and along-track acceleration capabilities. An inertial frame of reference can be used when the aircraft is in straight line flight, with reversion to track oriented coordinates when the logic detects the onset of a turn. In such a system, it is no longer possible to decouple the tracking logic to consider the two dimensions separately.

More elaborate system models will involve an increase in the number of state variables. The first-order equations used in the alpha-beta tracker are replaced with polynomials, and there may be a considerable increase in the cost of computing. Kalman filter design therefore usually involves a compromise between incorporating the full complexity in the dynamic system and measurement models or seeking some simpler approximation which gives a cheaper but adequate performance.

2.2.1.7 When aircraft tracks have been identified and the aircraft intentions are known, from a filed flight plan, for example, it is tempting to use this plan, rather than the track history, as the basis for extrapolation to the next predicted position. A milder version of the same strategy uses flight-plan height to convert data from slant to plan range and modifies the tracker parameters when there is a planned change of heading. The objection can be raised that one of the major functions of radar surveillance is to provide an independent cross-check on an aircraft's compliance with the flight plan. Flight plan aided tracking tends to replace a system that "fails safe" with one that "fails plausible". To a lesser extent, any track smoothing system is open to a similar criticism, since all smoothing mechanisms tend to be incredulous if an aircraft, for some reason, makes an unplanned departure from its previous track. This topic will be further discussed in section 2.2.3.3.

2.2.2 Primary Radar Tracking

2.2.2.1 Because of the problems arising in the presence of rain, ground clutter, or any form of electronic interference, a process based on the automatic initiation of primary radar tracks might rapidly result in system overload. Automatic tracking, if used at all, is normally initiated manually by a controller or assistant, and the initiation process is normally linked to the identification of some target of interest. For friendly aircraft, the identification may be based on a filed flight plan, on pilot-reported position, or on the response of a target to a request to the aircraft for some change of heading. If the radar has some height measuring capability, and some form of height data is available from elsewhere, the identification problem may be eased.

The problem may not be solved permanently by an initial identification. If an aircraft drops out of radar cover and then reappears, it is difficult to be certain that the same aircraft is now being tracked, especially as the earlier failure to detect the aircraft may have resulted from a change in the aircraft aspect, a turn for example. When several aircraft are flying some standard track, possibly relying on vertical spacing to ensure safety, there will be times when two aircraft are at very nearly the same range and bearing. The situation is most common when the route leads towards or away from an airfield radar. The relative speed of such a pair of aircraft may be very low, so that the overlap period is long, and when the aircraft finally separate, identities have been lost or, worse still, confused. Another difficulty, when there is no data on aircraft height, is that only slant range is available from the radar, so that plan position is in some doubt. The problem is most serious when it is necessary to hand-over an aircraft from one radar to another, or where it is necessary to compare the radar coordinates with data from some other source.

2.2.2.2 For civil ATC purposes, primary radar tends to be relegated to a back-up role. Primary radar still has advantages over SSR in addition to its ability to detect an aircraft that has no serviceable transponder. Since primary radar designers have some freedom to choose between a number of radio frequencies, surveillance radars commonly have a narrower beamwidth than can be obtained with an SSR antenna of similar dimensions. Primary radar can also normally resolve two targets whose range difference is more than about 0.2 NM. SSR uses a reply code about 2NM long, and problems begin to arise when two code trains overlap. Monopulse direction-finding, or, better yet, Mode S, should overcome this problem, but at many existing control centres, a hybrid tracking system using SSR, when available, for identification and height, combined with primary radar for more precise range and azimuth should offer advantages. One unfortunate drawback of primary radar, in this role, is the presence, in the vicinity of large cities, of numerous light aircraft below the base of the controlled airspace and without SSR but still contributing a great deal of confusion to the primary radar output and therefore to the tracking problem.

2.2.3 Secondary Radar Tracking

2.2.3.1. Section 1.6.3 gave a brief account of secondary radar and its problems. SSR plot extraction will not be discussed at any length, but one important difference between SSR and primary radar is the absence of weather and ground return clutter and the use of an elaborate reply pattern which must be recognised by the plot extractor before it goes on to examine the details of the reply message. Tests are applied to detect "garbled" replies where there are two or more overlapping messages. Such garbled messages are rejected. Plots are output from the detector when the necessary criteria are satisfied, and the output message includes range, azimuth and the Mode A and Mode C data. Not all transponders give Mode C replies.

2.2.3.2. The Mode A reply may either be one of a set of "discrete" codes so allocated that only one aircraft within the radar coverage, or, at least, within the national boundaries, has a particular code from this set. Each of these codes corresponds to a flight plan held by the ATC authority, and it is possible automatically to initiate a track when a new code from this set is received from an aircraft in the vicinity of the planned track. Sometimes, more than one plot is received from a given aircraft. Section 1.6.3 explained why reflection problems are more troublesome with secondary than with primary radar. Such responses due to mirroring effects can usually be detected and rejected because the reflected path is longer than the direct path. In general, the assignment of plots to tracks is much easier than with primary radar.

Outside controlled airspace, there may be SSR equipped aircraft who are not flying under ATC jurisdiction and it is common practice to issue the same identity code to all such aircraft. If tracks are required on an aircraft giving a non-discrete Mode A reply, it is usually necessary for a controller to identify the aircraft to the tracking system before initiating the track, and the tracking process then more nearly resembles that used with primary radar. Until recently, SSR azimuth data was invariably derived in plot extractors by the centre-of-gravity method. If two aircraft are both within the radar beam at a given time and separated by less than about 2NM, then reply code trains will overlap in time at the receiver, and the garbled signal may be rejected. If the two aircraft are not exactly the same bearing from the radar, the rotating beam may illuminate the first aircraft only, then both of them, and then only the second. On rejection of the garbled data, the mid-point of the range of azimuth over which replies are received may give seriously inaccurate bearings (Wyndham, 1979; Stevens, 1981). There is a limit to the rate at which the transponder can issue reply messages. Similar bearing errors can arise if the transponder is "captured" by a neighbouring radar.

2.2.3.3 Recent SSR radars have used the off-boresight monopulse techniques (Bowes, 1982) to derive azimuth data. This enables azimuth to be derived from even a single pulse in the reply code train, and there is therefore a good chance of extracting some data, at least, from a pair of aircraft whose replies are garbled. Azimuth accuracy, under normal conditions can be ten times better than is possible with the centre-of gravity method. When azimuth data is available from several individual pulses in a reply, it is possible to give a quantitative estimate of the quality of the azimuth data. This enables the tracker to recognise the presence of beam distortion due to multipath problems at the radar site. An additional advantage of monopulse is the ability appreciably to reduce the number of interrogations that need to be transmitted as the beam sweeps past a target, thus reducing the risk of interference between radars. Section 1.6.3 gave a brief account of Mode S SSR. Once an aircraft has been enrolled in the Mode S system, the tracking logic is relatively simple, and elaborate prediction algorithms are not necessary in the data processor. The radar needs to know the relationship between the technical address of the aircraft and its position relative to the radar, in order to schedule the interrogations at times when the aircraft is within the radar beam whilst avoiding collisions with messages from other aircraft, but this barely calls for extrapolation from the previous position. A similar situation is likely to arise with the cooperative dependent surveillance system proposed by the FANS Committee (ICAO FANS 1987).

Both Mode S and the FANS ADS proposal have the ability to transmit to the ground station other data in addition to position. Such a system is able to transmit on the down-link a message giving air-derived heading or bank angle which would significantly assist tracking where better predictions are desirable (Lefas and Thomas, 1981). A similar case might be made for transmission of rate-of-climb data. There seem to be no immediate plans for adopting this suggestion in Mode S. Table I in section 1.3.4 pointed out the value of heading data in the early detection of a turn. Note the distinction between the use for tracking purposes of intention data, as derived from a flight plan, and the present proposal to use air-derived data on the aircraft's actual, current, altitude.

2.3 Terrain Following

2.3.1. Terrain following systems are used by high-performance military aircraft to fly, in all weathers, at a height of only hundreds of feet above the terrain, the object being, as far as possible, to stay below line-of-sight of hostile ground-based installations such as radars. To meet this requirement, it is necessary to map the terrain for some distance along the aircraft's intended path, to compare the terrain profile with the predicted performance of the aircraft, and then to generate manoeuvre commands to the flight control system which would enable the aircraft, as far as possible, to follow the terrain profile at some chosen height. The main emphasis will be on the avoidance of collision with the terrain.

2.3.2 In practice, there will be situations when the manoeuvre capability of the aircraft is inadequate precisely to follow the terrain profile. There must then be some compromise between vertical acceleration and the deviation from the desired profile. Deviations may be defined either in terms of the root-mean-square or peak values of acceleration and deviation. To avoid excessive sink-rates or inadvertent stalling, it is also necessary to set bounds to the vertical rate. Since the risks of hostile action may vary in the course of the mission, as will the aircraft performance (with weight of fuel and payload), the pilot is free to choose his planned clearance altitude on the basis of defence threats and terrain variety. He also needs control of the acceleration constraints.

Safety in the event of equipment failure is a serious problem, especially during training. Failure may be detected either by means built-in to the system hardware or by means of some independent check on clearance altitude (see below). Automatic fly-up commands are issued to the flight controls along with a warning to the pilot.

2.3.3 Military terrain-following systems are not described in great detail in the open literature. The B-1 terrain-following installation (Brinkley et al., 1977) is intended to fly at Mach 0.85 at a low level. The pilot has six options for planned clearance heights between 200 and 1000ft. The primary terrain sensing system is a forward-looking radar with a beam a few degrees wide in azimuth to compensate for drift and, as far as possible, for the consequences of turning flight. There will be times when no returns are received from the forward radar, e.g. in flight over water. A radar altimeter provides local altitude in this situation, as well as data for the mechanism which generates the fly-up command if altitude falls below 80% of the selected clearance height. The flight-control logic is normally based on the data from the forward-looking radar. Over the range $R_{min} \leq R \leq R_{max}$, a flight control vector is generated from the equation.

$$Y_c = k(\theta + B + (H_{clf}/R) - F_s) \dots \dots (10)$$

where k is a constant

θ is the aircraft pitch attitude

B is the greatest elevation angle at which a radar return is received at range R

H_{clf} is the selected clearance altitude

F_s is a "shaped clearance function" dependent on range, velocity, flight path angle and ride-control setting.

The most positive value of Y_c obtained over the range of R becomes the command to the flight-control system.

2.3.4 The flight profile prediction process is implicit in the constant "k", the function F_s , and by the other parameters of eqn. 10. The open literature offers no further details. One weakness of any terrain-following system, unless there exist systems involving a detailed contour map held in the airborne computer, is the system's inability to see over a mountain ridge or round corners in a winding valley. Having adopted flight at low level to avoid detection by ground-based weapon systems, it is inevitable that the airborne radar has only a limited view of the terrain, and a correspondingly limited opportunity to detect, and avoid collision with, other aircraft.

2.4 Airborne Collision Avoidance Devices

2.4.1 It seems desirable to begin by clarifying the terminology. There are three problems that an airborne system may help to solve:-

- (i) The detection of neighbouring aircraft
- (ii) The assessment of collision risk.
- (iii) The choice of an escape manoeuvre

Devices that help with (i) only are "proximity warning" systems, those helping with (i) and (ii) are "collision warning" systems, and devices aimed at all three problems are "collision avoidance" systems.

A collision warning system has obvious advantages if it does not rely on infallible ATC or on the pilots' unrelenting look-out combined with good visibility. For many years, the electronics industry has searched for an airborne device that could fulfill this role. The probability of mid-air collision, other things being equal, is proportional to the square of traffic density. Regions of high density are most common in the USA, where, not surprisingly, mid-air collisions are relatively common also. The majority of serious collisions in terms of lives lost, involve one airliner and a smaller aircraft flying under "Visual Flight Rules", rather than ATC. Since it is difficult to compel the owners of small simple aircraft to fit complex collision-warning devices, there is a strong and obvious case for a warning system based on some mechanism which can be carried by airliners to protect them against light aircraft who need not carry any cooperating equipment. Unfortunately, the technical problems involved in providing such a system have proved too difficult. Certain military aircraft carry airborne primary radar for locating their airborne targets. Details are not readily available, but it is known that the equipments are complex (and therefore expensive to run and maintain) as well as limited in angular coverage. Many of the technical problems can be overcome if the potential threat carries some form of transponder.

2.4.2 The ICAO SSR Improvements and Collision Avoidance Panel (SICASP), set up in 1981, has been studying the topic under the generic title of the "Airborne Collision Avoidance System" (ACAS). Recently, in the light of the 1983 decision by ICAO ANC that ICAO should develop airborne collision avoidance systems based only on SSR Mode S, ACAS appears to have become synonymous with the "Traffic Alert and Collision Avoidance System" (TCAS) which has been the subject of extensive study in the USA. The principle underlying TCAS is the use of the existing SSR transponder. In the USA this is carried even by a significant portion of the airborne "general aviation" population which intermingles with airline traffic.

Since its invention (Litchford, 1976), TCAS has evolved considerably. Many systems described as TCAS, including the original invention, only bear a loose resemblance to the system, or more accurately systems, that now seem likely to be introduced in the USA with ICAO's eventual blessing. TCAS II, the system presently defined in detail, uses air-to-air interrogation of a transponder, at one second intervals, to derive the data needed for its collision-warning logic, to be discussed later in the present paper.

2.4.3 Radio frequency systems have the drawback that the rate of change of bearing of a possible threat cannot be determined to an accuracy even approaching that of a human eye. The limitations resulting from inadequate bearing data were discussed in section 1.4.5 TCAS II does not attempt to use bearing data. The advantage of SSR, however, is that accurate range information is now directly available, and modern SSR-equipped aircraft have transponders capable, in response to Mode C or Mode-S interrogations, of giving height data derived in digital form from the aircraft altimeter. Special features of such data, shared between the two aircraft and derived from a common source, are that the accuracy does not fall off with increasing distance between the two aircraft and that the collision avoidance logic in each aircraft, assuming both to be equipped, will perceive the same problem.

For two aircraft in an impending near-miss situation, one quantity that can be predicted with reasonable precision is the time to closest approach (Morrel, 1956), and this quantity forms the basis of the TCAS warning logic. By automatic tracking of each aircraft within the height and range band of interest it is possible to derive an estimate of range rate, and the ratio of range to range rate, is termed "Tau". If "S" is the relative velocity of the two aircraft, "m" the miss distance, "t" the time to closest approach and "r" the present range, then

$$\text{Tau} = r/\dot{r} = t + \frac{m^2}{S^2} t^2 \text{ --- (11)}$$

provided that both aircraft are in straight-line flight (Ratcliffe, 1982). As the miss distance increases, Tau will increasingly overestimate the time to closest approach. If two aircraft are due to collide but are not both in straight-line flight, Tau may be meaningless. In the situation illustrated in Figs. 4 and 5, for example, range actually increases whilst time to closest approach falls from 40 secs. to 20 secs.

2.4.4 If two aircraft are safely separated on the basis of a Tau-based criterion, there is no need to consult the height data. Similarly, if both aircraft are found to be safely separated in the vertical, no further calculation is needed. If a possible threat fails both these tests, it is necessary to predict height separation at closest approach. In principle, given two aircraft in unaccelerated flight, this is a simple matter. From the history of the height differences, "h" say, between the two aircraft, it is possible to calculate the rate of change of "h", and assuming that "Tau" gives a reasonable approximation to "t", relative height at closest approach can be computed.

There is a difficulty which becomes obvious if we consider the numerical values. Because it is undesirable to have an airborne collision warning device that issues frequent alarms in situations that ATC is allowed to regard as safe, TCAS can only alarm when "t" has fallen to about 20 secs. TCAS II cannot devise horizontal manoeuvres on the basis of range and height data alone, and the vertical displacement that can be achieved by an airliner in 20 secs., say, may well be less than 600 ft. The altimeter data exchanged by SSR messages between the two aircraft is rounded-off to integral multiples of 100 ft., so that height-rate data derived from the difference of the two readings will have an erratic error due to the rounding process. By fitting a smooth curve to the past history of relative height, it is possible to obtain a more precise estimate of height-rate at the expense of a time delay in detecting the onset of any vertical manoeuvre. More recently it has been agreed that, in an aircraft having altitude data generated by a computing device such as the ARINC 706 Air Data System, own height should be supplied to TCAS to a precision of 25 ft. or less. See Andrews (1981) for a more detailed discussion of the tracking logic.

The collision-warning logic is discussed elsewhere (Ford, May 1986). Minor modifications to the logic appear to be continuing. ACAS (basically TCAS II) is the subject of a circular (ICAO 1985) which discusses some of the problems resulting from an inevitable proliferation of SSR interrogations by TCAS aircraft.

2.4.5 TCAS II transmits interleaved Mode C and Mode S interrogations. Replies from aircraft carrying only Mode A SSR will give the aircraft a measure of slant range to the threat, but no information on height. Only part of the TCAS logic can then operate. No manoeuvre advice is possible, since TCAS II, with no information on the bearing of the threat, can only advise escape in the vertical plane. For a threat with Mode A only, TCAS can only offer a proximity warning service.

When TCAS II has height data from a threat carrying Mode C or Mode S facilities, the logic can offer a succession of advisory messages to any aircraft that appears to need them. The first level, proximity warning, is termed the "traffic advisory". If the TCAS system can offer a crude guide to the bearing of the threat, the pilot can be advised of the direction in which the threat might be seen. If the risk becomes more acute, the aircraft will receive a "resolution advisory" message. In its mild form, this message will advise of a limit to the safe rate of climb or descent in the sensitive direction. Finally, the logic may issue more positive advice e.g. "descend at not less than 1500 ft./min."

All TCAS II equipments will be part of, or connected to, a Mode S SSR transponder. If two aircraft in conflict are both carrying TCAS II, there is provision in the logic for an exchange of messages, by way of the Mode S data link, to ensure that evasive action recommended to each aircraft complements that given to its neighbour. The conflict-resolution manoeuvres recommended by TCAS 2, and the performance that results, are outside the scope of this paper (Ford, 1978). Note that almost all the simulation studies of TCAS performance have assumed the aircraft to be originally in straight-line flight.

2.4.6. There are two other versions of TCAS under discussion. TCAS I is a simple system intended to provide a low-cost better-than-nothing facility. After some preliminary study, the FAA announced that they would leave all work on TCAS I to "the market place". TCAS III was envisaged as an enhanced version of TCAS, based on an electronically steerable antenna by means of which it would be possible to determine the bearing of any threat.

This would have the advantage of enabling a threatened aircraft to escape by means of a horizontal manoeuvre, for which many pilots have apparently expressed a preference. It was also argued that the knowledge of threat position, instead of mere range, would eliminate many of the "unnecessary" alarms for which TCAS II is criticised. TCAS III antenna systems bring considerable engineering problems, since it is barely possible to achieve adequate bearing accuracy from an L-band antenna that can be installed in an airliner, and it transpires that perturbations in nominally straight-line flight would be enough to disable the bearing measurements unless bearings are referred to some inertial reference. A study of the unnecessary alerts generated by TCAS II (Spencer and Fee, 1986) reveals that although, after the event, most TCAS II alerts are found to have been unnecessary, at the time the alerts were issued the risk was usually a real one. The "false alarms" arise from the lack of any knowledge of the intentions of a potential threat, and the subsequent need to base the logic on worst-case assumptions. Spencer and Fee concluded that about 50% of TCAS II alerts could be justified on these worst-case assumptions, and that a TCAS III system with the additional horizontal miss-distance logic might increase this to 65-70%. The U.S. Airlines Electronic Engineering Committee (AEEC 1987) reported in February 1987 that the FAA "is still not certain that it should support TCAS III".

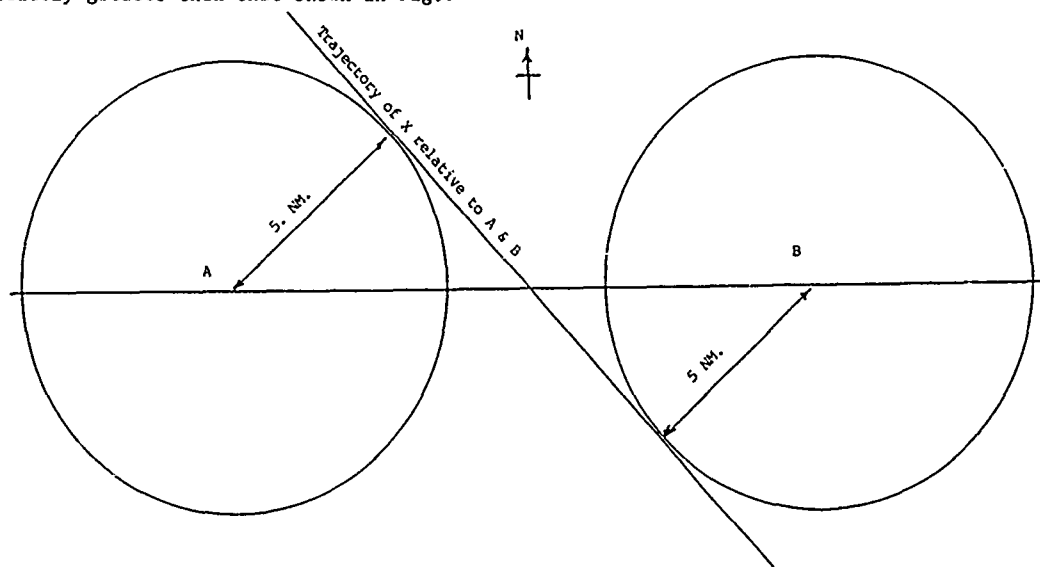
2.5 ATC Short-Term Conflict Alert

2.5.1. Introduction

2.5.1.1. Section 2.4. described one approach to the problem of collision avoidance, based on limited information about the relative position of the threat. It is now intended to discuss the provision of a collision-warning based on data available at the ATC centre. Section 2.2 dealt with the problems of smoothing and extrapolating radar data with a view to deriving the best estimate of aircraft position at the time of the next radar sweep, an estimate needed to steer a tracking gate within the radar processor logic. There is no reason why this same logic should not be used to predict position at a significantly later time, at the expense of deteriorating accuracy, and the algorithms are used in this way if the radar data on a given aircraft is missing for one or more sweeps. For collision warning purposes, the object is not to form the best estimate of the relative position of the two aircraft at some future time, but to give warning if there is a risk that plausible divergences by the two aircraft from their recent trajectories may lead to a hazardous situation. The problem is studied to some future time-horizon which is sufficiently remote to allow time for devising and implementing trajectory changes to ensure the safety of both aircraft.

At the present time, nearly all the tests by ATC for collision risks are carried out by human controllers who are given a set of relatively simple, formal rules which lay down a minimum spacing which ATC is meant to ensure at all times. Controllers may have a choice of separation criteria e.g. aircraft can be separated either in the vertical or horizontal planes. In effect, the separation standard sets an upper limit to the extent to which controllers are allowed to trust the data with which they are working. The controller is always free to exercise discretion and aim at a greater separation than the defined minimum. Similarly, although ICAO lays down and publishes a set of separation standards, there may be more rigorous standards laid down by local authorities to take account of specific problems.

2.5.1.2 The ICAO separation standards are easy to remember but are certainly not ideal. Consider two possible situations, and suppose that the horizontal separation minimum is 5NM. In both cases. In the first example, an aircraft is in level flight along an airway when a second, slower aircraft, travelling in the same direction, is allowed to climb or descend into a position behind it at a spacing of 4 NM. Most controllers and their supervisors would regard this as a perfectly safe situation, despite the technical infringement of the rules. In the second example, a pair of aircraft A and B are travelling from E to W along an airway at the same speed and flight level. A third aircraft, X, also at the same speed, wishes to cross the air route on a N-S path between A and B, and without safe vertical separation from them. Fig. 9 shows the motion of X relative to A and B. The relative velocity of X makes an angle of 45 deg. with the line A-B, and the circles centred at A and B represent the 5 NM. minimum spacing that must be achieved between A and B to justify this manoeuvre is 14.2 NM. The velocity of X relative to A and B may be 700 Knots, or 11 NM/min., and most controllers would regard the proposed manoeuvre as idiotic, even for a spacing between A and B appreciably greater than that shown in Fig.9



2.5.1.3. Given a computer system for predicting collision risks, there is, in principle, no reason why we should not use more elaborate criteria, such as those in TCAS, for assessing the collision threat. If these result in an earlier alarm that is roughly in accordance with controllers intuition, there is no problem. Air traffic management, which presumably acquiesces when a controller exercises his discretion and infringes the separation standards under conditions where there is no real hazard, might, however, find it difficult to accept infringements of the ICAO rules which are formally incorporated in ATC computer software.

2.5.2 "Le Filet de Sauvegard"

2.5.2.1. The "filet de sauvegarde" (safety net) is a collision warning system that has successfully operated for some years in French airspace (Printemps, 1977). Roughly similar systems exist in the USA and in Maastricht (the short-term conflict alert, STCA). An essential feature of the safety net is that it does not interfere with the controller's normal method of working. It should not alarm until the controller could reasonably have been expected to detect a developing conflict and taken remedial action. On the other hand, it should not leave the alarm so late that remedial action is no longer possible. It is only a back-up system, not an alternative means of carrying out ATC.

2.5.2.2. Experimental work suggests that a 2 minute time-horizon is roughly optimal. The system is used only to handle IFR traffic, within radar coverage and under ATC control. Such aircraft are obliged to carry Mode A/C transponders. Radar track data (based on SSR positions for the horizontal plane and on Mode C heights for the vertical) is used, with linear extrapolation, to test for conflict (by ICAO standards) from the current position out to a 2 min. time horizon.

Since aircraft not equipped with Mode C transponders are not necessarily separated in height from other traffic crossing their path, a large number of unnecessary alarms could be generated. This problem was avoided by restricting the system to flights at FL200 or above, i.e. to heights at which the carriage of Mode C SSR is obligatory. Note the difference between the TCAS time-horizon, about 25 secs., and the 2 min. horizon selected here. If the warning is derived from a radar whose update rate is about 6 times less than is possible with TCAS, and if the alarm must go first to a controller who considers the situation before speaking to the pilot, some extension of the horizon is essential. In practice, the choice of the alarm criterion was found to involve a rather sensitive compromise between the level of unnecessary alerts and the risk of failing to warn of genuine dangers. Final choice of the alarm parameters had to be based on real-time radar data rather than on the earlier trials on a less realistic test-bed.

2.5.2.3 The test for conflict is carried out in two stages. The coarse test involves the examination, at 10 second intervals, of the total population of aircraft airborne above FL200, under the jurisdiction of the control centre and being tracked by the radars. Aircraft are sorted, on the basis of their plan position, into one of a set of square boxes, having 32NM. sides. Each aircraft is then tested against other traffic in its own and adjacent boxes. If there is a risk of dangerous encounter, the aircraft pair is passed to a more detailed "fine test" algorithm. This "fine test" issues an alarm if, at any time less than 2 mins. in the future, the horizontal separation between the two aircraft is due to fall below 4.8 NM. whilst at the same time the vertical separation is also predicted to be less than the separation standard. Many of the practical problems with which the algorithms have to deal involve error patterns which arise in Mode A/C SSR data.

2.5.2.4 Results in live operations indicate that only about one in three alarms are judged by the controllers to have been justified. The remaining alarms are usually superfluous, because controllers have already imposed constraints on the aircraft trajectories to avoid precisely the situations which the alarm system is predicting. Since the conflict alert logic has no access to data on the constraints, warnings are issued. A common situation is where there are two aircraft on a route, with one aircraft climbing or descending towards the other. At some earlier time, the controller has instructed the aircraft to stop its climb or descent at next available flight level to that occupied by the second aircraft, with the intention of lifting the constraint once the two aircraft are safely separated in plan. If, on such occasions, the controllers were required to inform the conflict alert system of the restriction they had imposed, the false alarms could be avoided, but the French authorities decided that the false alarms were preferable to an additional keyboard task for the controller.

2.5.3 Automatic Traffic Advisory and Resolution Service. (ATARS)

2.5.3.1. The ATARS system (Lentz et al. 1981), although finally abandoned for reasons which may not have much connection with technical problems, is of interest because it was much more ambitious than devices at present in use. ATARS was a ground-based collision avoidance system intended to operate in parallel with, rather than as part of, the ATC system. It may be thought of as a ground-based equivalent of TCAS which it resembled in respect of some facilities it offered to the pilot. Perhaps the principal function of ATARS (as with TCAS) was to warn of conflicts between aircraft one or both of whom were outside ATC control. It also had a last-ditch back-up role in the event of some failure by ATC to resolve a conflict between a pair of controlled aircraft, but this topic will not be discussed here. ATARS is based on SSR Mode S, not only for surveillance, but also to provide the automatic data link which, amongst other functions, carries the ground-derived messages from ATARS to the pilot. Aircraft choosing to fly outside ATC jurisdiction were not to be required to file flight plans, and, except when offered "advice" from ATARS, such aircraft would be free to fly wherever airspace rules permitted. In any encounter between an ATARS-equipped aircraft and one carrying only Mode A/C SSR, the ATARS aircraft would still receive advice from the ground, but there could be no way of coordinating manoeuvres by the ATARS aircraft with any action taken by the non-ATARS threat.

2.5.3.2. The system had provision for dealing with aircraft of differing levels of sophistication, from low-cost electronics to elaborate graphical displays. Uplink messages to aircraft were to be in "display-independent formats". Warnings were to be issued at a number of different levels:-

- (i) Proximity advisory messages, issued as a guide to enhance visual acquisition at a range which depended on the relative speed of the aircraft involved.
- (ii) Threat advisory messages, warning of a potential collision situation in time to allow pilots to locate the threat visually and to make their own decisions.
- (iii) About 15 secs. after (ii), if the threat persisted, a resolution advisory message would be issued. Negative advisory messages (don't turn left, don't climb) were to be issued in preference to positive advisory messages (dive, turn right), although the latter would be issued if all else failed.

Resolution manoeuvres were said to be "selected from all possible manoeuvres based on consideration of many factors". Since there seemed to be no provision for indication to ATARS of the objective of the flight, or of the type of aircraft to be handled, it would appear that neither the pilot's intentions nor the manoeuvre capability of the aircraft were amongst the factors to be considered when choosing a means of resolving any problem.

2.5.3.3 ATARS was an active project when agreement was reached on the Mode S signal-in-space. Indeed, ATARS largely dictated the data-link capacity that Mode S now offers. A weakness of this link, given the conventional mechanically-scanned SSR antenna, is the 10-12 second interval between successive rotations of an en-route surveillance radar. When radar data was received and processed by ATARS, a message could not be passed to the aircraft until the antenna was again pointing in the correct direction. The rate of rotation of the antenna cannot be much increased if there is to be sufficient time for the exchange of data with all aircraft on a popular bearing from the radar. It was intended that ATARS should use a back-to-back SSR antenna, which has a second beam differing in azimuth by 180 degrees. Used in conjunction with appropriate duplication of parts of the interrogator/receiver system and its tracking logic, this effectively halves the interval between position updates and between opportunities to up-link messages to the aircraft. A more ambitious solution is to provide an electronically steered antenna to replace mechanical scanning or, at least, to superimpose some electronic deflection of the beam on to the motion resulting from the mechanical rotation of the antenna, thus enabling the scanning rate to be modified when more time is needed in a given direction. The need for off-boresight monopulse working, with transmission and reception on different frequencies, cannot simplify the electronic steering problems.

At the stage reached when ATARS was abandoned, it would seem that a serious problem was to ensure that all the processing tasks were completed in the 5-6 sec. interval between SSR updates, since any time overrun would necessarily result in a further 6 second delay.

2.5.3.4 ATARS logic was to be incorporated into the Mode S interrogator stations. Aircraft at high levels could easily find themselves within the radar coverage of more than one station. If each surveillance system was enabled to conduct Mode S interrogations only inside some geographical boundary from which other stations were excluded, there would be problems in the "seam areas" where two aircraft could be in conflict whilst under surveillance from separate ATARS sites, and such conflicts would not be detected. Similarly, a pair of aircraft might cross a boundary whilst still in conflict, and the new ATARS site might not advise the same manoeuvres.

It might be possible to resolve these difficulties by direct ground-ground negotiations. A similar problem arises in a TCAS system, where the logic might advise an aircraft to dive to avoid one problem and then, before this solution has taken effect, advise a climb to avoid a second. This difficulty is overcome in TCAS by means of a Resolution Advisory Register (RAR) forming part of each TCAS equipment. Contents of the RAR are exchanged via the Mode S link, and the TCAS logic gives precedence to any existing constraint in deciding on future recommendations. It was proposed to use the same logic in ATARS conflict resolution. By copying each RAR register to the ground and applying the same precedence rules, it should be possible to arrange that all advice from TCAS and/or ATARS would be self-consistent, even if the decision were not always optimal.

2.5.4 Collision Avoidance by ATC

Having detected the risk of collision, it is necessary for one or other of the aircraft involved to take evasive action. In controlled airspace, both aircraft are, or at least, should be, in the hands of a single controller, who must choose a suitable escape manoeuvre. It is possible, in principle, to involve both aircraft in the process, but the time needed to pass instructions by voice, and to confirm that they are being acted on, may limit the time available for effective manoeuvre by a second aircraft. In this respect the present-day controller is at a disadvantage relative to a system such as TCAS or ATARS, where there is a more rapid data link and logic to ensure that escape manoeuvres by the two aircraft are compatible.

A more serious problem arises when both aircraft are not in touch with the same controller. An evasive manoeuvre commanded by ATC may be incompatible with that selected by the other pilot on the basis of his own perception of the situation, or in response to advice from elsewhere. Situations such as this can easily arise when limitations on the accuracy and/or resolution of the data sensors make it easy to arrive at two different perceptions of the same situation.

In the UK, for example, there is a radar advisory service available to aircraft outside controlled airspace but within about 30 miles of any one of 28 airfield radars, mainly military. The service offers advice from controllers located at the various radars, each controller having his own RT frequency and only limited facilities for coordination with adjacent sites. In this situation, controllers are warned that, unless they have reason to believe that one of the aircraft involved has no means of radio communication, advice on escape manoeuvres should only be given when the controller is in touch with both the aircraft involved. They will, however, advise aircraft of the presence of other traffic in their vicinity.

3. Medium to Long-Term Prediction (2 Mins. or longer).

3.1 General

3.1.1 Section 2 dealt with a number of short-term conflict tests. It is usual, in busy airspace, to provide a radar-based ATC service, and it is now being proposed, in the USA at least, to supplement this with TCAS II. In view of these provisions for collision avoidance, it may not be clear why a significant amount of effort by ATC is concerned with longer-term planning, especially since earlier sections of the present paper have stressed the limitations on accuracy of forward prediction, whose uncertainties certainly increase with the time-horizon.

3.1.2. There are exceptional circumstances in which radar surveillance is not available, either because it is not economically justified or because the aircraft are below line-of-sight of any feasible radar. One such situation arises over oceans, and some of the North Atlantic problems have already been discussed in sections 1.4.1 and 1.4.2. The ATC problems of handling this traffic will be the topic of section 3.2

When radar data is available and can be supplemented by collateral flight plans, it is general practice to back-up the short-term collision avoidance service with some longer-term predictions based on flight plans. There are a number of reasons why this is desirable:-

(i) There is a need for an overall plan for traffic moving in and out of airports and through congested regions of airspace. This aims to enable aircraft to carry out their flights efficiently as well as safely. Clearly this plan must be based on a knowledge of aircraft intentions for some distance ahead of present position.

(ii) As pointed out in section 1.5.3, the use of more than one conflict detection mechanism simplifies the task of achieving a high overall level of safety. For example, a back-up system based on air-derived data offers some measure of protection against radar failure, and an up-to-date flight plan in the hands of ATC means that they are not totally powerless in the event of a communication failure between a given aircraft and the ground, since it is then assumed that the aircraft will attempt to follow the profile laid down in the flight plan and that ATC will keep other aircraft, as far as possible, out of the way.

(iii) The discussion of TCAS in section 2.4, of the "safety net" scheme in section 2.5.2, and of ATARS in section 2.5.3 may have suggested that problems arise when two or more systems having roughly the same time-horizons are simultaneously applied to the same problem. If two collision avoidance systems have very different time-horizons, it is possible to ensure that one of them takes no action until it is clear, beyond doubt, that the longer-term mechanism has failed.

(iv) The flight of an airliner involves a number of air traffic controllers and possibly several control centres. Advance planning of the flight, in as much detail as possible, enables the controllers to prepare in advance for traffic which may later be offered to them by an adjacent control sector.

3.1.3. Section 2.5 concentrated on conflict alert and avoidance mechanisms that could be incorporated in computer software. Any controller who does not have, or does not accept, computer assistance in resolving a conflict on the short time-scales discussed in Section 2, will also be under pressure to do something rapidly, and is therefore likely to concentrate on the short-term hazard rather than on the larger-scale problems of devising a fuel-efficient trajectory or achieving economical use of airspace capacity. When problems are considered on a longer time scale, there is more time to devise a solution, but the issues involved are much more complex, and most conflicts are resolved by human controllers, or by temporary groupings of controllers. This section will therefore lay much more stress on human factors. In addition to the problems of predicting the future, there is another problem as the time-horizon is extended forwards. It is likely that any conflict that can be predicted some time ahead will involve more than one sector in a control centre, more than one ATC centre, or more than one nation. Problems of conflict resolution may now be complicated by problems of telephone communication, language, differing objectives, various human factors and even by political disputes concerning sovereignty over airspace.

3.1.4 Some simple algebra will give a rough indication of the problems facing two controllers who wish to discuss a mutual problem whilst they are separately listening or speaking on RT channels which are independent of each other. Suppose, for simplicity, that all RT exchanges (message + reply) are of unit length, that such messages originate at random times, and that the time for which each channel is occupied is a fraction, L , of the total time available. Suppose, also for simplicity, that any telephone conversation between controllers is also of unit duration. On either of the equally loaded RT channels, the probability that a conversation is in progress at a given instant is L , so that the probability that both controllers will be free to begin to converse at a given instant is $(1-L)^2$.

Since pilots have no way of knowing that a telephone conversation is in progress, any of them may at any time originate an RT message which will interrupt the controllers discussions. On the assumption that such messages originate at random, the probability that one of the RT channels will remain silent for the duration of the telephone discussion can be shown to be $\exp(-L)$, so that the probability that this will happen on at least one of the RT channels is $\exp(-2L)$, and the overall probability that our two controllers will be able, at the first attempt, to commence a conversation that is not subsequently interrupted is given by

$$P = (1-L)^2 \cdot \exp(-2L) \text{ --- (12)}$$

Table II gives P, the probability of achieving such a discussion between controllers, as a function of L, expressed as a percentage of the time for which each RT channel is occupied.

L (%)	0	10	20	30	40	50
P	1	0.66	0.43	0.27	0.16	0.09

Table II. Probability of Uninterrupted Controller/Controller Conversation.

By the time our controller's RT is loaded to 16% of its maximum capacity, they have no more than an even chance of commencing and completing their conversation at any one attempt. In practice, most busy controllers leave their assistants to handle coordination messages to and from other sectors, and there is a tendency to adopt procedures which minimise the need for inter-controller coordination. The penalty is some loss of traffic capacity.

3.2 ATC for the North Atlantic

3.2.1 Sections 1.4.1. and 1.4.2 discussed the problems of predicting aircraft trajectories at cruising levels on the North Atlantic tracks. Most long-term planning by ATC is concerned with traffic moving on fixed routes defined by VOR's and DME's. Such routes are normally declared to be "airways" or "upper air routes". North Atlantic traffic normally follows a system of roughly parallel tracks, the "Organised Track Systems" (OTS). Aircraft must rely on long range nav aids, INS being the most popular. The OTS differs from the airways system:- the location of tracks is flexible, being defined twice daily with a view to enabling economy of aircraft operation. Passenger demands, time-zone differences and airport restrictions on night operations by heavy jets have the combined effect of producing two largely separate flows across the ocean. Westbound flights from Europe commence in the morning and eastbound flights from N. America commence in the evening. The routes used in the two directions are normally different also, since a wind which helps traffic in one direction will hinder it in the other.

One consequence of this pattern is that most, if not all, available flight levels can be used by traffic in one direction, unlike airways, where traffic in adjacent levels are normally occupied by opposing direction traffic. Another property of the OTS is that crossing tracks are rare and relative velocities are therefore low. There must, however, be provision for contingencies, where an aircraft is obliged to divert to some relatively nearby airport, such as Reykjavik, or to return to their hemisphere of origin. When winds are light or roughly N-S, the optimum route is a great circle, and opposite direction flights will have to take different flight levels, as on an airway. Under normal circumstances, however, the traffic pattern is relatively simple, as is, in principle, conflict detection and resolution. In practice, communication difficulties add considerably to the ATC tasks to be described below.

3.2.2 The mechanism by which the tracks are planned and promulgated is of no direct interest to this AGARDOGRAPH. Control of the traffic above FL55, usually, over the N. Atlantic region is shared between the Oceanic Control Areas (OCA's). Most traffic is shared between Gander Oceanic Newfoundland, and Shanwick Oceanic, located at Prestwick, Scotland but with its communications centre near Shannon, Ireland. Centres at Sondrestrom, Greenland and Reykjavik, Iceland, handle more Northerly traffic, and New York Oceanic and Santa Maria, Azores handle traffic to the South. All of these must exchange traffic with numerous other domestic centres on both sides of the ocean. There is a comprehensive communication network linking the oceanic centres, their contiguous domestic ATC centres, and the units providing air/ground communications. Nearly all the ATC centres now have some form of computer system for handling flight plans and clearances, together with any subsequent revisions. Provision exists for direct computer-computer links between Shanwick and Gander, enabling automatic cross-checking of data stored at both sides of the ocean.

3.2.3 Aircraft, before entry into the OAC, are issued with an "ocean clearance" which if all aircraft fly within the limits of their clearances, will provide a safely separated path to the landfall in domestic airspace across the ocean. This long time-horizon is a consequence of the uncertainties of HF communication at bad times. Aircraft normally file flight plans prior to departure, on the basis of the track structure agreed for the period, and should request their oceanic clearance when airborne but as soon as possible before entry to the ocean area, giving an estimate of the time of arrival at the entry boundary. This estimate should be revised as necessary. In general, traffic has to fly for some distance between takeoff and the OCA entry point.

Oceanic controllers at most centres have no radar coverage of their area of jurisdiction. Data is normally displayed on electronic data displays having interactive update mechanisms, with machine-printed flight progress strips as a backup. Shanwick normally has two planning sectors, with provision for a third controller whose main function is as a coordinator. The oceanic clearance is only concerned with flight within the OCA. On receipt of this clearance the pilot is required to request from the appropriate domestic airspace controller a trajectory which will take him from his present position to the specified OCA entry point. He must notify Oceanic if this results in a revision to his estimated time at OCA entry.

One complication arises because domestic ATC normally operates with radar-based separation standards, but must provide Oceanic separations between aircraft arriving at the OCA boundary.

3.2.4. On entry into the OCA, the flight becomes the responsibility of an en-route control sector. At peak periods, Shanwick may have four sectors to handle the traffic. Airspace can be divided between sectors on the basis of either flight levels or according to track. Aircraft are normally required to report their position to the en-route controller on entry, exit or at intervals of 10 degrees of longitude, 30 mins. flight, roughly. The aircraft position report includes the coordinates of the next position at which a subsequent report is due, together with an air-derived estimate of the time at that point. The controller uses this data to check that the aircraft is on the planned track at the correct flight level, and that its plan for the future is consistent, with that held by ATC. If these conditions are not satisfied, ATC will attempt to direct the aircraft back onto the agreed track. The importance of this check is that 50% of major navigational errors over the N. Atlantic are believed to be blunders by the pilots inputting coordinate data into the flight management computer.

Having established that an aircraft is on the planned trajectory, the conflict prediction reduces to testing the present and predicted spacing between the reporting aircraft and those immediately ahead and behind it at the same flight level on the same track. When an aircraft is cleared to change flight level, it must be treated, from the time of the re-clearance until it reports reaching the cleared level as if it occupied old, new and any intermediate levels. When an aircraft reaches the boundary between two OCA's, ATC responsibility is handed over from one centre to the other, but the existing cleared trajectory is still valid unless modified subsequently. Between the two centres, there is an overlap area, 10 degrees of longitude on each side of the boundary, in which both centres need to take an interest in the aircraft because of the possibility of a conflict between two aircraft of which one is being handled by each centre.

3.2.5. A significant fraction of N. Atlantic traffic does not wish to follow the track system to its conclusion. Traffic from Europe to the W. Indies, for example, may well wish to leave for a more southerly track at some stage. These aircraft are normally assigned a track on the appropriate periphery of the track family, so that they can leave the system without serious difficulty. Aircraft leaving the organised track system on what are termed "random" tracks are initially separated by the normal minima, at least, and the same conflict criteria are applied for the rest of the flight. In some contingencies, such as pressurisation failure, an aircraft in the organised track system may be obliged to make an immediate departure from the cleared flight level and/or track. If there is any difficulty in communication with ATC, standard procedure is for the aircraft to turn through 90 degrees, preferably away from the core of the tracks, and to take up a flight level differing by half a vertical separation interval from the levels in normal use. If it is required to continue to follow the original track at a different flight level, the procedure is to adopt a track displaced laterally by 30 NM., i.e. half way between two of the organised tracks. In any case the aircraft should communicate with ATC as soon as possible.

3.2.6. Military air traffic is classified by NATO as belonging to either General Air Traffic (GAT) or Operational Air Traffic (OAT). GAT flights are conducted in accordance with the same ICAO rules as the civil airliners discussed above. Over the N. Atlantic, and in many other areas, both civil and military GAT traffic is handled by a joint civil-military control centre. There may be minor differences in the way military aircraft communicate with ATC, but the above account remains equally applicable to both civil and military.

OAT flights comply with whatever rules and procedures are laid down by the appropriate authorities. Such flights may involve activities having no analogue in civil aviation, such as in-flight refuelling or practice combat. In most countries involved there is close coordination between civil and military authorities, with the military accepting responsibility for keeping their traffic clear of conflict with civil flights. Details of the military ATC organisation and its methods of operation may not, however, be so readily available as for their civil counterparts. Many conflicts are avoided by declaring regions of airspace out-of-bounds to civil traffic, either at specified times or permanently.

3.3 Controlled Flight Along Airways and Upper Air Routes.

3.3.1. Airspace Management

3.3.1.1. ICAO practice is to designate airspace along major routes and around major airports as controlled airspace. Minor differences between national practices and ICAO rules are no more than slightly relevant to the present discussion. Unless otherwise stated, the discussion that follows will be based on UK airspace. Strictly speaking, little airspace above FL 245 is "controlled" in the formal sense, and airways normally have a ceiling at this flight level. Above FL 245 there is a Special Rule which requires all civil traffic to be under air traffic control, and a series of Mandatory Radar Areas oblige military traffic to take a similar service from military controllers. The airways are, in effect, extended upwards to form Upper Air Routes.

3.3.1.2. In the vicinity of airports, the traffic pattern is dependent on the landing direction and too complex to be fitted into an airways structure. Terminal Control Areas (TMA's) are defined around major civil airfields, and roughly similar rules apply as for other controlled airspace. There is a lower height limit to the TMA, usually increasing with distance from the airfields, and eventually coinciding with the bottom of the airways to which it is connected. Within the TMA, the immediate vicinity of the airfield has a Control Zone or Special Rules Zone, extending down to ground level. Conflicts in TMA's will be dealt with in Section 3.5

3.3.1.3. ICAO divides traffic into that flying under Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). The UK permits flight by civil aircraft in airways or in the upper airspace (above FL245, generally) only under IFR. These require the aircraft to be under the command of a pilot with an instrument rating. The aircraft must have SSR and carry suitable instruments and navigational equipment. Traffic operating under VFR must conduct the flight under visibility conditions better than some defined minima, and flight is permitted only between the hours of sunrise and sunset. The requirement for an IFR pilot to have an Instrument Rating in effect debars most private fliers from entry into controlled airspace, although flight in TMA's may be permitted under special rules. Outside TMA's the aircraft need carry neither radio nor nav aids. In other States, e.g. the USA, VFR traffic flying under ATC control is allowed to mix with IFR traffic on airways.

3.3.1.4. Traffic in level flight on airways or in the upper air space is required to cruise at defined levels. ICAO lay down rules which require IFR traffic at heights up to FL 290 to use levels which are an odd integer multiple of 1000 ft., for aircraft whose track is between 000° and 179°. If the track is between 180° and 359°, the levels are even multiples of 1000 ft. VFR traffic is to fly 500 ft. above the IFR levels, but such traffic is not admitted to UK airways. For flights above FL 290, the rules call for IFR flight at 29,000 ft. plus an integer multiple of 4000 ft. for tracks between 000° and 179°, otherwise at 31,000 ft. plus an integer multiple of 4000 ft.. In areas where VFR traffic is permitted, levels are 1000 ft. higher than for their IFR counterparts.

The UK departs from these rules for traffic outside controlled airspace at or below 24,500 ft., effectively assigning the "VFR" levels to IFR traffic on tracks between 090° and 179°, (odd multiple plus 500 ft.) and between 270° and 259° (even multiple plus 500 ft) VFR flights are advised, but not obliged, to follow the same convention as their IFR counterparts. Aircraft planning to fly in controlled airspace should normally file flight plans in advance of takeoff. Traffic wishing ATC clearance to cross an airway may supply the flight plan data by radio at any time up to 10 mins. before crossing. Military controllers, often seated next to their civil counterparts, usually take their own aircraft across airways.

3.3.2 The Function of ATC

3.3.2.1 In broad principle, the methods used by ATC for control of cruising traffic are the same for the N. Atlantic as for other controlled airspace. The first step, by the planning authorities, is to lay down a framework of rules and procedures. The controllers, working within these rules, draw up relatively long-term plans for individual flights. These, if accurately followed, would lead to safe movement of the traffic without further ATC intervention. The next step, by ATC is to monitor that each flight is following the agreed plan. If not, or if some unplanned event should make it necessary, the plan will need revision. There may even be a need for some short-term collision avoidance action of the type discussed in section 2. When any immediate threat has been dealt with, it will be necessary to take steps to restore the aircraft to some orderly and expeditious agreed trajectory, by revision of the earlier plan where necessary.

3.3.2.2. In regions where there are reliable communications, the planned separation between aircraft may be reduced below the N. Atlantic track limits, but the difficulty of predicting the departure time of aircraft still on the ground often results in aircraft getting an initial clearance that apparently condemns them to flight at a level much lower than requested. An important task of ATC, once the traffic is airborne and under radar surveillance, is to lift these restrictions, whenever possible, thus enabling the aircraft to achieve a more economical cruising level. Although the earlier discussion of conflict detection and resolution may have given a different impression, controllers do not usually spend their time in a life-or-death struggle to avert collisions. Most controller effort is devoted to achieving efficient movement of traffic, although safety must be paramount and it is essential never to plan a situation from which there are no adequate escape routes.

3.3.3. Conflicts at Cruising Level

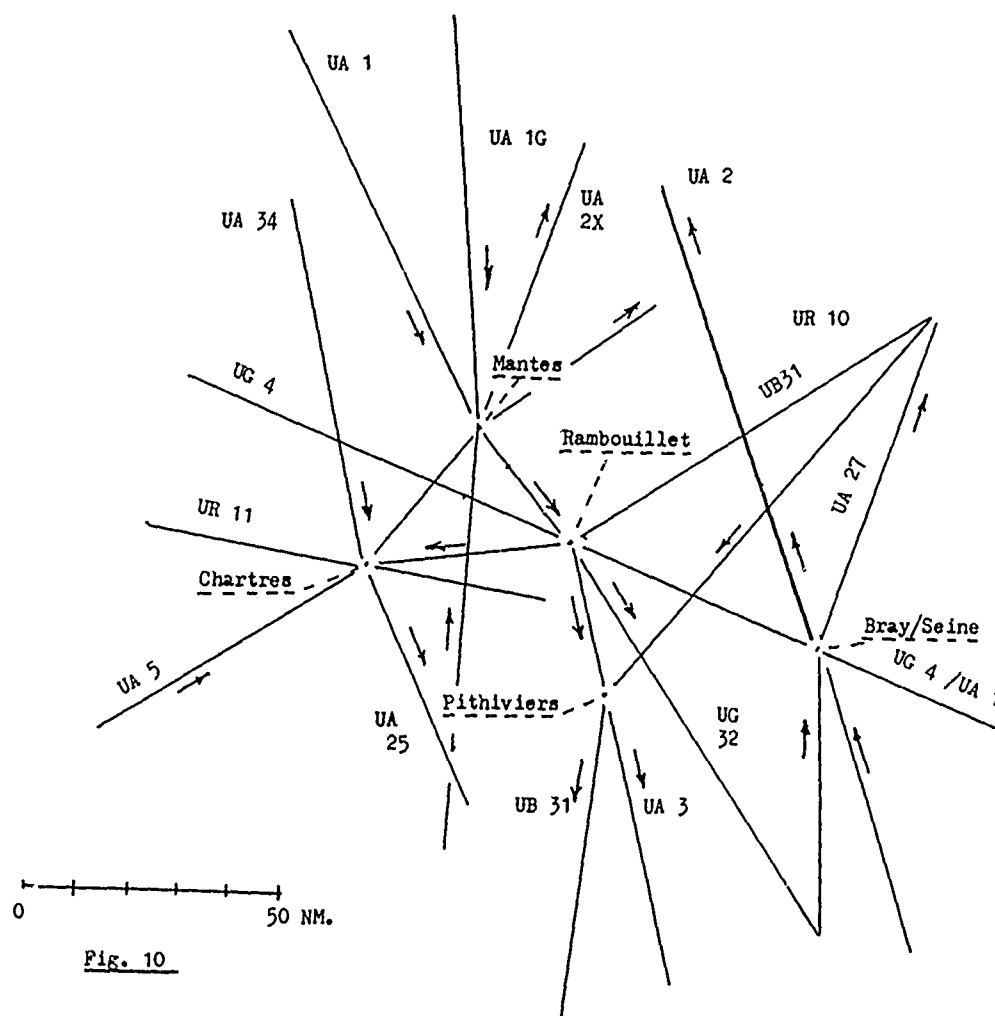
3.3.3.1. Since the height rules, if obeyed, effectively separate traffic cruising in opposite directions, the situation on airways or upper air routes in some aspects resembles an organised track on the N. Atlantic. In regions where there are good communications it is possible to have more frequent position reports from the aircraft. Even in the absence of radar cover, the minimum longitudinal spacing between aircraft can be reduced to 10 mins. i.e. about 80 NM. for jets in cruise (where speed differences will be small). As with oceanic traffic, the controller enters times and heights at reporting points on his flight progress display, and uses the data to test for potential conflicts.

The advent of radar permits the longitudinal spacing to be reduced from 80 NM. to 5 NM., thus offering a considerable increase in the traffic capacity of any airway or upper air route. A limitation on the use of radar may arise at national boundaries. It is now usual, in countries having a network of radars, to process the totality of the radar data to give one integrated "air picture". This makes it possible, for example, to use an equipment at one radar site to substitute for a failed equipment at another, or to work through gaps in the coverage from a particular site. The normal method of achieving this situation is to convert the measured slant range and height data (taking some default values when no height is available) into the trace of the aircraft on the ground, and then to map this data, along with any necessary geographical information, from the whole area covered by the radar onto some plane surface. Usually, stereographic projection is used to transfer the ground traces onto a plane tangential to Earth's surface at some central point. Unfortunately, there is a limit to the area over which this stereographic representation can be used. In consequence of this and other problems, adjacent ATC authorities often use different frames of reference for their data, and may be obliged to insist on procedural (i.e. non-radar) separation rules at the boundary with some other airspace.

With or without radar, however, the airway capacity is considerably less than the account so far would suggest. In Western Europe, many flights spend much of their time in climb or descent, when the height rules are not applicable. The resulting failure of these rules to segregate traffic into small, easily handled, subsets, introduces problems to be discussed in section 3.3.4. Even in level flight, aircraft trajectories are often obstructed by crossing traffic. Fig 9 and para 2.5.1.2 showed that, if two busy streams of traffic are crossing in level flight, under radar control and at the same level, the effect of the intersection is to increase the minimum spacing between adjacent aircraft from 5 NM. to more than 14 NM. Even with that spacing, the margin of safety would be low, given a relative velocity of 700 Knots, and aircraft whose radius of turn is at least 20 NM.

3.3.3.3. Detection of impending conflicts, on the assumption that both aircraft are in straight line flight, is not difficult. The controller can judge the situation by eye, using the "constant bearing" criterion, or he can be assisted by a radar display which uses velocity data to draw a prediction-line ahead of the track. Resolution of conflicts is less simple. A change in the flight level of one of the aircraft would have to be at least 2000ft. to satisfy the separation rules, and to guarantee that this change could be achieved before the crossing, the reclearance would have to be issued minutes in advance. The alternative solution exploits the fact that the upper air routes do not have defined boundaries and the crossing aircraft may be handled by diverting one or other of the aircraft in search of a gap in the traffic stream. This manoeuvre also requires time to implement, and there needs to be a longer time-horizon than those used in the automatic warning systems described in sections 2.5.2 and 2.5.3.

3.3.3.2. Many countries in W. Europe have a network of airways and upper air routes in which intersections are numerous. Rambouillet, shown in Fig. 10, has 7 upper air routes converging on the VOR, and most of these routes pass through one or more other junctions within 50 NM.



Saint Prex VOR, in Fig. 11, has 13 converging routes. Air route maps of Europe, even when printed in several colours, are not easy to read. For simplicity, figures 10 and 11 are not complete, they show only routes immediately relevant to the present discussion. Routes, other than those marked with an arrow, are used in both directions. Note that, in fig 10, the proximity of Mantes, Rambouillet, Chartres and Pithiviers is such that there is unlikely to be time for changes in flight level or for horizontal manoeuvres between one intersection and the next. For most purposes these three intersections must be handled as a single problem. Note also in fig 11, drawn to the same scale as fig 10, the proximity of St. Prex to the boundary of Swiss airspace and to the triple junction of French, Italian and Swiss ATC jurisdiction. The cumulative effect of the obstructions to traffic resulting from multiple route intersections, such as those just illustrated, is to make necessary flow restrictions which aim to ensure that the capacity of the route structure is not exceeded by the traffic offering. This "flow-control" process is outside the scope of the present paper, but the effect is to impose conditions that must be met by traffic crossing interfaces such as the FIR boundary between the UK and France. Since the delays necessary to meet these conditions, at peak periods, can be most economically be taken on the ground, there are interactions between the constraints at the airfield runway and the time-slot at the FIR boundary.

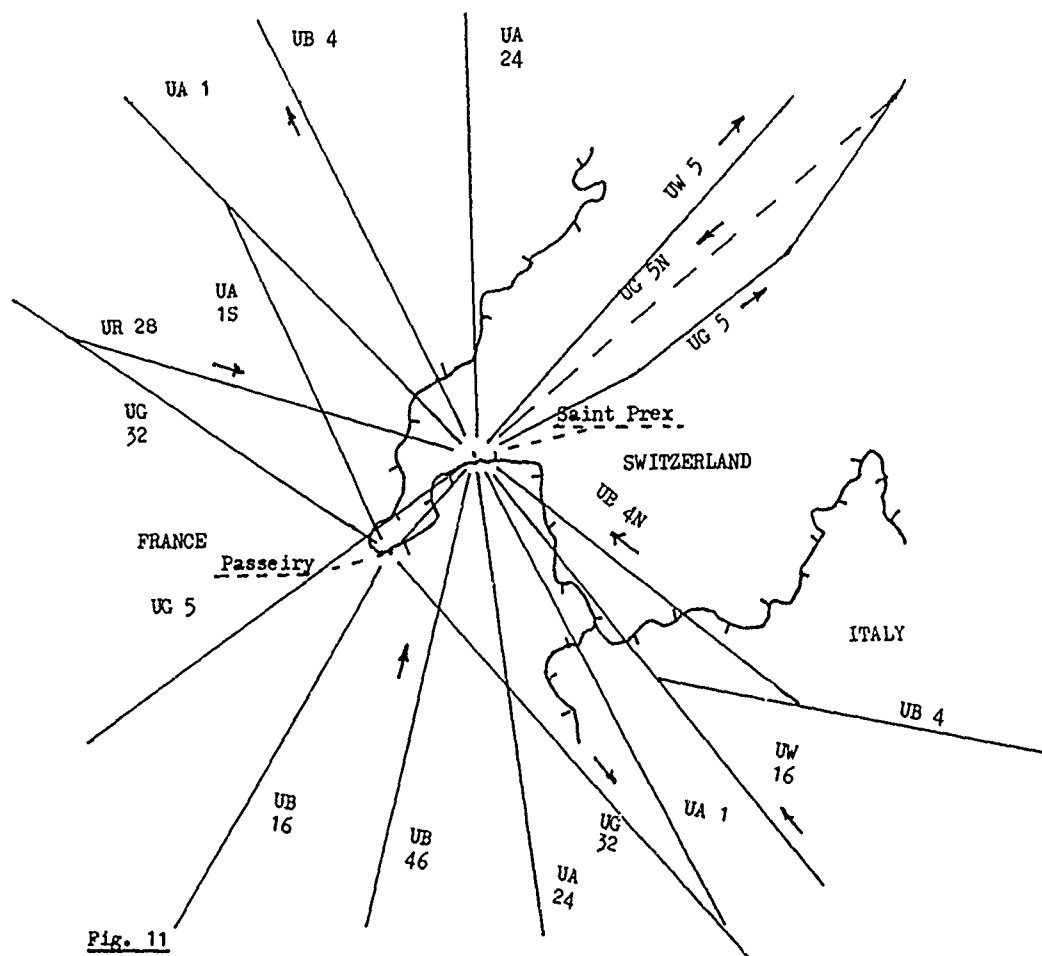


Fig. 11

3.3.4 Aircraft in Climb and Descent

3.3.4.1. When aircraft are in cruising flight, long-term predictions use the airspeed/Mach number given in the flight plan, and assume that the vertical separation standard offers adequate protection against minor fluctuations in height. When aircraft are in climb or descent, forward prediction of aircraft height and position is more difficult. Under present-day ATC, the aircraft flight plan gives cruising level and speed, but no data on airspeed or vertical rate during climb or descent. ATC clears an aircraft to climb or descend to a given flight level, but, except in TMA's, the trajectory is not defined in greater detail. The most economical rate of climb for a civil jet is probably closely related to the maximum that can be achieved. This, in turn, is subject to outside air temperature and to limits on indicated airspeed, Mach number, and jet pipe temperature. It will also be heavily influenced by the all-up weight of the aircraft, since the thrust available from the power plant is only a small fraction of the aircraft weight.

The rate of descent may be limited by bounds on airspeed or Mach number, the need to maintain thrust at or above the "flight idle" limits (in order to maintain supplies of electrical and hydraulic power and of air at adequate levels), and perhaps by the acceptable rate of rise of cabin pressure. In practice, for traffic inbound to a congested airport, the problem is not that of achieving the most economical descent from cruise level to runway, but that of achieving a descent which brings the aircraft to the runway at a given time.

3.3.4.2. It is interesting to note that, whilst the accuracy with which aircraft navigate in plan has been the subject of the numerous studies, comparable work on the accuracy of navigation in the vertical plane by aircraft in climb or descent is very sparse (except for aircraft in the approach phase). In controlled airspace, aircraft are expected to follow a precise track in the horizontal, so that any independent and accurate surveillance system can readily yield data on errors. When the trajectory to be followed in the vertical plane has not been defined, discussion of accuracy is meaningless. Trails are possible using aircraft flight simulators (Benoit, Swierstra and de Wispelaere, 1986), but there will always be doubts that only real-world data can dispel.

It is hard to believe that ATC could not achieve better use of airspace capacity if they had access to the better predictions of climb performance that should be possible given access to data available on the flight deck. Perhaps the first need is to demonstrate that improved prediction would make possible better strategies for the control of the traffic through complex route structures. If a significant payoff can be demonstrated, the next step might be to consider how adequate data could be made available to ATC. It is regretted that FANS studies, which contemplate a dramatic improvement in horizontal navigation accuracy as well as automatic data links between aircraft and ATC, do not appear to have addressed many of the real limitations on traffic capacity of complex route networks.

3.4 Other Traffic in the Vicinity of Airways and Upper Air Routes

3.4.1 A detailed account of all the varieties of airspace and the arrangement for ATC in even a single European state could easily overflow this AGARDOGRAPH. The present section will be concerned only with three problems in which there is some element of long-term planning.

The U.K. divides its airspace into regions above and below FL245. Other States use similar divisions. The boundary between Flight Information regions (below FL245) and Upper Flight Information Regions (above the FIR's) roughly corresponds to the operating ceiling of sporting or executive aircraft not equipped with pressure cabins. The result is that most upper airspace traffic not flying fixed routes is military OAT, whereas much of the traffic in off-route FIR's is civil. Requests for permission to cross the airways (mainly from civil aviation) or upper air routes (mainly from military traffic) cause complications in the longer-term planning of on-route traffic. One other problem for discussion, that is more a matter of management than of control, is to reduce the risk of civil or military traffic accidentally straying, without warning, into controlled airspace.

3.4.2. In the U.K., most of the UIR is covered by a Military Mandatory Radar Service Area. Military aircraft between FL245 and FL660 are required to operate under a radar and procedural control service. Outside this area, military aircraft are not obliged to stay in touch with ATC. ATC cannot, therefore, predict their behaviour although they will warn traffic under their jurisdiction of the proximity of any such, to them, unknown traffic.

Military aircraft crossing upper air routes do so either under control of an approved ATC radar unit or under a positive ATC clearance, issued by the Upper Air Route controllers. Aircraft are normally required to cross in level flight, at right angles to the established Air Route, and to give ATC at least 10 mins. warning of their intended crossing point, the crossing level and their estimated time of crossing. Para. 3.3.3.1 has already discussed the problems of using radar to direct a high-speed aircraft through a traffic stream. There may be circumstances where neither radar nor procedural clearance is possible in the time available, e.g. if a high-performance aircraft is returning to base with minimal fuel. In this situation, the UK permits military traffic to cross airways without ATC clearance, at a height which is 500 ft. greater than an integer multiple of 1000 ft.

If a military aircraft wishes to cross a busy air route where traffic is in climb or descent, it will present a significant obstruction to the main traffic flow. Sec. 3.3.4 pointed out that ATC clearances to climb or descend do not normally define the profile to be followed. It may be necessary, therefore, for ATC to arrest the climb/descent of one or more of the on-route aircraft at some standard level differing from that planned for the crossing. If, for any reason, the on-route aircraft failed to obey this revised clearance, several minutes would be required safely to abort the crossing manoeuvre.

It is therefore necessary for this restriction to be planned to take effect some time before the crossing is due and it must persist until the crossing aircraft is clear.

Below FL245 and away from ATC-controlled airspace, aircraft are free to operate without any contact with ATC. Some airborne vehicles, such as gliders, may not even carry radio. Powered aircraft are encouraged to maintain radio contact with the appropriate ATC organisation. During the day, and in VMC, the U.K. allows gliders to cross airways at will. Powered aircraft may, without ATC clearance, cross airways at or below the base of any en-route section. Aircraft wishing to cross an airway at a higher flight level under Instrument Flight Rules, must follow a similar procedure to that used in UAS. Crossings are normally at right angles to the airway, and in level flight at an approved altitude. IFR rules require not only that the aircraft carries navigational aids meeting a prescribed standard, but also that the pilot has an instrument rating. Under VMC conditions, the UK rules are more relaxed, the navigational equipment rules no longer apply, but the pilot still needs an instrument rating, a serious constraint on amateur aviators.

3.4.3 There is an uneasy compromise between the desire to allow members of the public the right to use non-controlled airspace for training or pleasure flying, and the pressure for safety in public transport. Light aircraft in Europe do not usually carry SSR transponders, and even fewer have the relatively expensive Mode C capability. Around major cities there is often a great deal of light aircraft activity, clear of the terminal area and below the base of the airways. ATC can usually see the traffic on primary radar but has no means of measuring height, except, perhaps a rough estimate based on observed groundspeed. It is therefore usual to assume the unknown traffic whose plan position falls within airway boundaries is obeying the rules and remaining below the base of the airway. It is therefore usually ignored by ATC. In regions near a TMA where much of the air transport traffic is climbing or descending en-route to major airports, this situation is perhaps more hazardous than is otherwise desirable.

The difficulty is that it would be prohibitively expensive to force light aircraft to carry and maintain complex navigation systems, and pilots under training, often preoccupied with handling their aircraft, could not be relied on, with or without such nav aids, to obey the complex rules which apply to controlled airspace. It is easy to draw precise lines on a map to define the boundary of a city or of a TMA, but neither of these boundaries are visible from the air. Perhaps the day will come when a reasonably priced satellite-based navigation system can be combined with stored data to give an automatic warning that the boundary of controlled airspace is being infringed.

3.5.1 Conflicts in Terminal Areas

3.5.1. Fig. 12 shows an idealised terminal area surrounding an airport having two parallel runways, one for takeoffs and the other for landing. Traffic to and from the airport is distributed between six two-way airways. The wind-dependent direction of landing and takeoff is assumed in the figure to be from right to left. Landing traffic is merged into a common stream at 12 NM. or so from the threshold and thereafter descends at 300 ft./NM. The diagram shows six points at which climbing outbound traffic crosses descending inbound traffic. These intersections are unavoidable, although the route structure may make them more, or less, convenient.

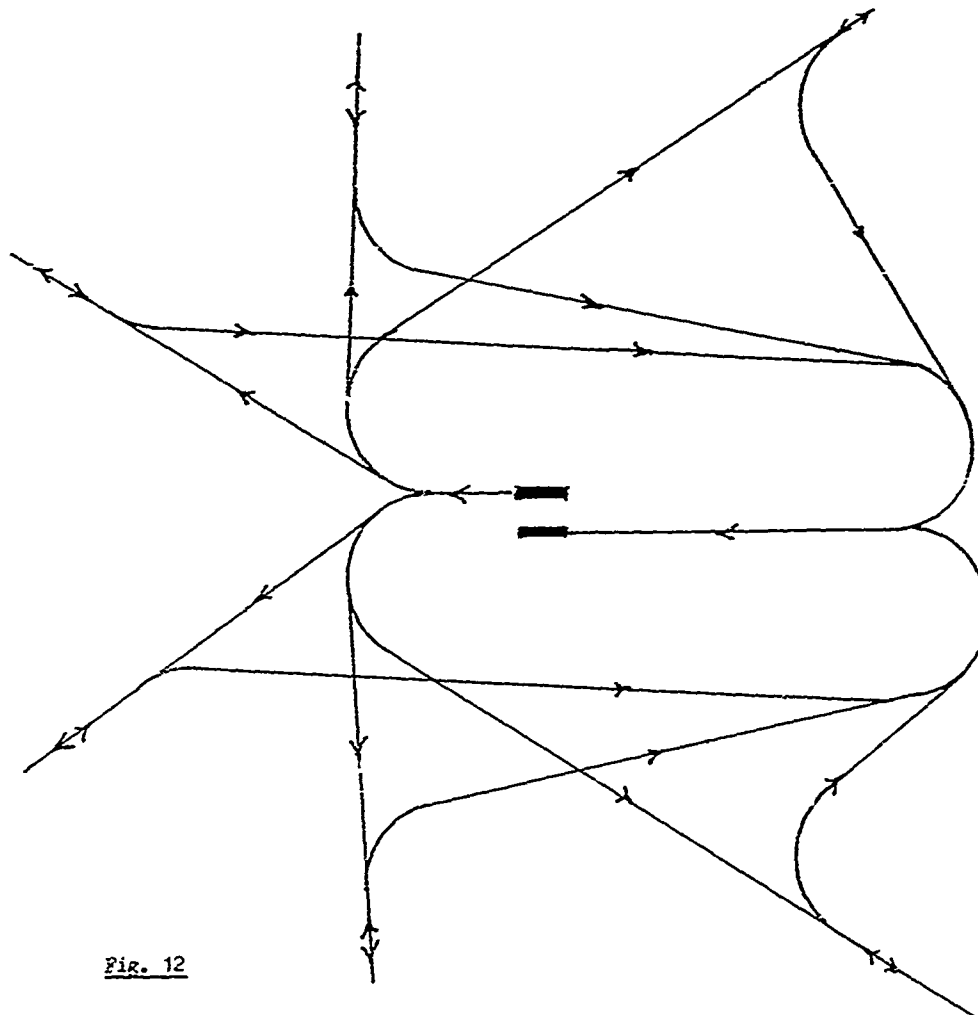


Fig. 12

The major congestion in such a TMA usually arises, not in the airspace but on the runways. Runway rules of operation are complicated by vortex wake problems, but there is a minimum interval between successive takeoffs or successive landings that is not likely to be less than 90 secs.. Present-day TMA's deal with delays to inbound traffic by directing them to a "stack", probably about 30 NM. from the runway, to fly a time-wasting racetrack-shaped holding pattern, each aircraft being allocated its own flight-level. Between the holding-pattern and the runway, fine adjustment of the time of arrival is possible by modifying the aircraft path till the length matches the desired time of arrival. This results in a much greater diversity of inbound tracks than fig. 12 might suggest.

3.5.2. Very large TMA's, of which London is probably the busiest in Europe, though quite peaceful by comparison with New York or Los Angeles, have to make provision for several major airports, inconveniently close to each other because of the need to locate them near the city centre. London has two major airports, Heathrow and Gatwick, together with other peripherals such as Stansted, Luton and Southend. These airports need access to all the airways, and do not, at a given time, necessarily wish to use the same landing direction. The U.K. Air Pilot devotes 15 arrival and departure charts to description of the TMA routes used by Gatwick, Heathrow and Luton traffic. The TMA contains holding patterns, primarily for Heathrow, at Ockham, Biggin, Lambourne and Bovingdon, at Willo and Eastwood for Gatwick, and at Barkway for Stansted and Luton. Since traffic in these holding patterns must frequently descend from one level to the next as landing aircraft are withdrawn from the bottom of the pattern, they can, at peak periods, constitute a serious obstacle to departing traffic. If two additional airports were added to the structure shown in Fig. 12, each of which had traffic to all six routes, the minimum number of crossing routes increases from 6 to 36 (Attwooll, 1974).

3.5.3. Clearly, the avoidance of conflict between traffic on the various routes will present problems for ATC. All flights begin or terminate at the same height. Inbound traffic is constrained by the need to complete its flight at a standard descent angle for the last 10NM. or so, down the glide slope, and must have slowed down to landing speed on arrival at the runway. Departing traffic may be heavily loaded and is subject to engine noise constraints. Speeds are not likely to be far above stall, and therefore there are limits on the ability of the aircraft to manoeuvre. It has also been earlier pointed out that uncertainties in departure time present difficulties for long-term planning. The situation is made slightly simpler by the fact that runways require minimum time intervals between successive landings or successive departures. Since most large TMA's impose an upper limit of 250 knots or so on airspeed, the limited range of speeds ensures that, for aircraft arriving at, or departing from, the same airfield, a spacing of several miles must persist for some distance from the runway. For example, in fig. 12, if arrivals and departures were separated from the preceding aircraft by 1 minute, and if the traffic was distributed between the six airways in turn, the aircraft going through a crossing would be 6 mins., about 20 NM., apart. This is an optimistic scenario, and the runway constraints will not help against traffic from the other airports in the TMA.

3.5.4. The solution adopted in most large TMA's is to define Standard Instrument Departures (SID's) for normal departure routes and Standard Terminal Arrival Routes (STAR's) for arrivals. These ensure vertical separation between arriving and departing traffic, at the expense of considerable restrictions on climb by departing traffic, since the usual principle is to keep departures below arrivals. This policy results in flight at inefficient levels, aggravates problems of interaction with traffic from other airports, and increases the noise nuisance to city dwellers. It is, however, probably the only safe solution to the problems of planning traffic, given an uncertain time-table. Controllers, using radar and working on a short time-scale, lift the height restrictions whenever the traffic situation allows them to overrule the SID clearance. At Heathrow, probably only about 30% of outbound traffic are seriously restricted in their climb whilst in the TMA.

3.5.5. TMA planning was originally based on the assumption that, since one airport, e.g. Heathrow, carried most of the traffic, the object was to optimise the flow of traffic for that airport whilst providing other airports with safe SID's and STAR's that had efficiency only as a secondary consideration. The growth of traffic, combined with serious limits to the possibility of further increase in the capacity of the present airports, means that TMA planning must, in future, look for an integrated plan concerned with efficient movement of the traffic as a whole.

Although, as this paper has more than once pointed out, there is little scope for control of the groundspeed of a jet aircraft at cruise level, this situation changes as the aircraft begins its descent. Over the last hundred miles or so of the flight, it is possible to adjust the flight trajectory so as to achieve a given time of arrival at the runway with greater fuel economy than a system which imposes most of the delay at low flight levels. An account of experimental work on a control technique that uses a "zone of convergence" of radius 100NM. or so to adjust arrival times at the runway will be described separately elsewhere in this AGARDOGRAPH.

4. Interception and Evasion Manoeuvres.

4.1 Introduction.

In its simplest form, an aerial military encounter involves two aircraft one of which, here termed the "pursuer", P, has the objective of destroying the other. The second aircraft, here termed the "evader", E, has some objective that does not directly involve P and which may not be known to him. Clearly, E must evade destruction by P if his objective is to be achieved. There are more complicated situations possible, where more than one aircraft launch a concerted attack on a single E, where there are a number of E from whom P can select a target, or the two-way combat situation where each aircraft is attempting to destroy the other. Pursuit by P may involve a number of phases. For example, a ground- or sea-based radar controller may select a target for P and attempt to guide him into a situation where P can continue the engagement using his own resources, such as airborne radar or pilot vision. P then attempts to achieve a position relative to E such that he can launch some armament that makes its own way to E, possibly guided by some missile-borne sensor. Each of these stages may require separate analysis, but only if P achieves all these objectives can E be destroyed.

4.2 Game Theory.

4.2.1. E may be initially unaware of P's activity but the situation will probably develop into what the operational research analyst term a "two-person zero-sum game". Zero-sum, because a win for P is a loss for E and vice-versa. In such a "game", the object of each player is to devise a strategy that maximises his chance of success even if his opponent is seeking to minimise the same probability. This is the "minimax" problem. Note that this situation, from E's viewpoint, is similar to the collision-avoidance problem discussed elsewhere in part II of this AGARDOGRAPH:- E attempts to avoid the encounter on the basis of a worst-case assumption about P's unknown intentions.

The mathematical theory of such games (Isaacs, 1985) has been the subject of a collection of papers (Yavin, Pachter et al., 1987), many of them specifically dealing with aerial combat. This collection includes an extensive bibliography. In what follows, an attempt will be made to sketch no more than an introduction to the theoretical approach to the problem, and to indicate, in general terms, some of the limitations with which the theory cannot easily deal.

4.2.2. Classical game theory is concerned with a static situation in which each player decides on an "optimal" strategy based on the information available at the start of the game. In a more dynamic version of the problem, players amend their strategy as the game is played out, using information on the state in play to exploit any error by the adversary. The desired strategy is one that optimises some performance index, defined for the whole time extent of the game. An important class of problems involves a dynamic system which can be modelled by a differential equation, some of the parameters of which are under the control of each player. Players attempt to change the parameters, as far as lies within their power, to optimise the performance index of the game. Clearly, optimal for one player is minimal for the other. Most discussion of pursuit/evasion problems is based on such "differential games". In modern aerial warfare, considerable efforts are made to blind or mislead the opponent as to the true situation, and both players may be taking their decisions on the basis of fuzzy data.

Differential games are normally based on the concept of a "state vector" which describes the present state of the two aircraft in adequate detail for subsequent analysis. Such a vector might, for instance, comprise the relative three dimensional position, velocity and acceleration of the two aircraft. The development of this state vector with time gives the relative trajectory of the two aircraft. For full definition of the system state, we require a mathematical "space" having as many dimensions as are involved in defining the state vector, 9 in the example just given. As in the Kalman filtering problem discussed in section 2.2, the choice of the coordinate system may involve some careful compromises.

4.2.3. It is commonly found that there exists some form of "barrier" in state space which one aircraft must avoid or the other penetrate in order to achieve the desired outcome. Consider the extremely simple example illustrated in Fig. 13. Two aircraft A and B are in level flight at fixed speeds V_A , V_B proportional to AX and BX respectively. If the aircraft follow the tracks AX and BX they are on course for collision at X, since they will reach this point at the same time.

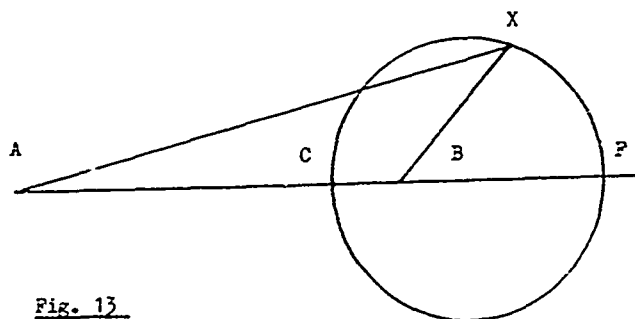


Fig. 13

For any heading chosen by B, the slower of the two aircraft, there is a heading which A can adopt that ensures collision. The earliest moment at which interception is possible is when they both proceed head-on to C, and the latest moment is after a tail-chase to F. It can be shown, by Apollonius' theorem, that the locus of X is a circle, defined by V_A and V_B . The positions S and F are easily computed. B is not at the centre of the circle. Having fixed V_A and V_B , so long as A is capable of a rate of turn not less than B, B has no escape strategy available to him, since any change in his heading can be dealt with by a suitable heading change by A. If B is the pursuer and A the evader, it is sufficient for A to avoid the circle CFX.

Note that, in Fig. 13, the lengths AX and BX are fixed by the velocities V_A and V_B which do not change with time. In so far as AB represents a distance, however, the scale changes with time to collision. If $V_A = V_B$, the circle CFX degenerates into a straight line, the perpendicular bisector of A and B, and either aircraft can avoid collision by keeping clear of this boundary.

In this problem, we were concerned with trajectories in 4-dimensional state-space, say in x, y, \dot{x}, \dot{y} , and the boundary is in \dot{x} and \dot{y} , extending indefinitely in x and y . In a slightly more complex version of the game (Bryson and Ho, 1969), the pursuer has a minimum radius of turn.

4.2.4. TCAS

Another example of a barrier, this time more complex, arises in the TCAS collision warning device discussed in section 2.4. The role of TCAS can be considered that of enabling an equipped aircraft to avoid collision with some threat that, in the worst case, can be assumed to have inadvertently adopted an efficient pursuit trajectory. TCAS provides warnings of collision risk at various levels, the sensitivity of the alarm being under pilot control. Ignoring, for the present, some minor discontinuities in the rules at FL180, TCAS has two subsets of alarm criteria, one based on the range, r , between aircraft, and on r 's rate of change with time. The other set is based on height difference, h , and on relative height rate.

For greater detail, see section 2.4 and the references there quoted. Ignoring the FL180 region, the behaviour of TCAS can be specified in terms of four quantities, r , \dot{r} , h , and \dot{h} . In the state space defined by these quantities, the TCAS alarm boundaries are simply defined, but the path of a threat, even when in straight line flight, is complex (Ratcliffe, 1982). In more orthodox coordinates (Ford, 1986), the motion of the threat is relatively simple but the TCAS alarm boundary has a complex shape.

Strictly speaking the alarm thresholds set by TCAS are not barriers in the sense used by the game theorists, but are surfaces which should, ideally, enclose such barriers, so that there is always opportunity for threatened aircraft to escape by appropriate evasive manoeuvres initiated after TCAS has issued a warning.

In practice, the TCAS rules have evolved by a process of trial and error, and it is possible that further modifications may be made before TCAS2 is adopted. It is a striking feature of the draft specification that it defines in detail the rules to be obeyed but never gives, in quantitative terms any account of the problems they are meant to solve. There may be a case for the application of a "game" model to study the problem facing a TCAS-equipped aircraft facing a determined pursuer. This should give some better feel for the worst-case situations that can arise for aircraft having different levels of performance and manoeuvre capability.

4.2.5. The Real World

Although theoretical study of the pursuit/evasion problem can provide valuable insights, and should, in theory, make possible a completely automatic interceptor, by the time the full range of factors has been fed into the model, the computational problem may be very serious. For example, a model based on relative position may need only half the number of dimensions needed to discuss absolute positions, and will need considerable expansion to cope with factors such as limitations on the endurance of the participants, or on the coverage of ground-based radars or ECM devices.

Since many "evaders" are in pursuit of some objective other than providing exercise for the pursuers, any knowledge, or even a guess, about the evader's objective must be relevant to the choice of pursuit strategy, although the pursuer's intuition may not fit too well into the mathematics. It should further be noted that, in the real world, there is no agreement between two combatants about the game being played. The "evader" may be attempting to lead the pursuer into some kind of trap, or to distract attention from some other activity. It is probable that, on a short time-scale, logic based on even a simple model may be useful to either party, but the overall strategy is likely to remain in the hands of the military commanders. Elaborate off-line simulation of the larger-scale aspects of an encounter may nevertheless be useful as a means of testing and refining simpler rules or mechanisms that may be useful in the real world.

5. Automation of Conflict Detection and Resolution."

5.1 Introduction

5.1.1. Of the relatively few practical applications of computing to conflict detection and to ATC planning in general, the majority have been added-on to existing computers originally designed to assist with radar and other data-processing problems. The design of the conflict detection systems, for example, may be heavily influenced by the existing data structure, the capabilities of the existing displays to the controllers, and the computing power and storage space that is available for additions to the existing system.

5.1.2. Until the advent of machine-intelligence that can be trusted with such a sensitive task as the control of air traffic, there is no possibility of building a completely automatic system for conflict detection and resolution. Present day software can provide no more than rules for identifying possible situations that can arise and a set of solutions for dealing with each of them. Even if such software were totally reliable under the circumstances envisaged when it was designed, constructed and tested, there is no way to guarantee, to the level of confidence needed by air transport, that all possible combinations of circumstances have been foreseen and incorporated in the validation software. The problem is made more acute by the steady stream of modifications to the ATC rules, often minor, but still significant to the software, that arise during the construction, validation and operation of the system. At present, only the human controller is sufficiently flexible to detect that a novel situation is arising, or to improvise an immediately applicable solution.

5.1.3. Given a task within its capabilities, however, a computer can work much faster than a human controller, and does not tire or suffer from loss of concentration. At the very least, the mistakes made by a computer are not likely to coincide with those made by a controller. An automatic aid to ATC, based on elegant algorithms for problem solving will succeed only if it is of real value to the controllers, a value that they perceive as justifying any additional tasks, such as keyboard operations, that the "automatic" aid imposes on them. No doubt the day will come when most interchange of data between pilots and controllers takes place by way of a digital link. Given easy access to this data, the application of computer aids to ATC will be greatly simplified.

5.2. Short-Term Problems

5.2.1. It will be convenient to consider separately the application of computers to assist with the short-term problems described in Section 2 and with the long-term problems of Section 3. Short-term conflict detection is characterised by the need to work with simple but bulky and frequently updated radar data, and on a time scale that means that there can be little relevant manual input by the controllers. The computational task is heavy. If there are N aircraft in the system, then $N(N-1)/2$ tests are necessary to examine all pairs of possibly conflicting aircraft.

If the traffic flow is structured in accordance with some strategic plan, e.g. separated tracks for different classes of traffic, and if this plan is embedded in the software or otherwise accessible to the computer, then the task may reduce to that of monitoring that each of the N aircraft is conforming to its assigned track, with adequate longitudinal separation from its neighbours, and then performing some more general test only on aircraft not falling into this convenient pattern.

It is usual to apply not one, but a whole hierarchy of conflict tests, beginning with crude procedures that will rapidly trap the conflicts along with many false alarms. Such a test will serve to eliminate most pairs of aircraft without more detailed study, a succession of more elaborate tests then being applied to the dwindling population of pairs of aircraft not rejected at an earlier stage. For example, suppose we are given the position of each aircraft in Cartesian coordinates and wish to pick out all pairs whose separation in the horizontal plane is less than S . If the X coordinates of two aircraft differ by more than S the pair can be rejected at once. The test can be repeated, if necessary, for the Y coordinates, and only if the pair has failed both these tests will it be necessary to compare S^2 with the sum of the squares of the two differences.

5.2.2. Where the majority of aircraft do not have intentions known to ATC, it is usual to structure the data in a manner calculated to simplify the comparison process. The conflict tests are best applied, not to the area as a whole, but to a series of segments. For simplicity, suppose that the area of interest is a square having sides of length L , and that the area divided up into square segments having sides of length kL , where k is not greater than unity. The aircraft population will be assumed to be randomly distributed over the entire area of interest, and the average population of any given sector is proportional to the area of the sector, P_K say, where $P_K = k^2 L^2$. Taking the computation effort as proportional to the number of comparisons to be made, the number of comparisons in one segment as proportional to $(P_K)^2$, and the number of sectors to be dealt with as $1/k^2$, the whole computing task is approximately proportional to C_K , where

$$C_K = P_K^2 / k^2 = L^4 k^2 \quad (13)$$

If k becomes small, an increasing number of conflicts will be overlooked, because the two aircraft are in different segments. If the segments are made to overlap, this difficulty can be overcome. Suppose that an adequate overlap is available if each side of the segment is $(kL+b)$ say, and the number of segments remains unchanged at $1/k^2$, P_K is now equal to $(kL+b)^2$ and the total computing task is given by

$$C_K = (kL+b)^4 / k^2 \quad (14)$$

It can be shown that C_K has a minimum when $k=b/L$, giving $C_K = 16b^2 L^2$. In the absence of sectorisation, $C_K = L^4$.

5.2.3. In connection with the ACARS proposal discussed in section 2.5.3, it is clear that the software designers found processing time to be a serious constraint (Lentz et al. 1981). A complex scheme was therefore adopted for the conflict tests. ACARS was designed to rely on a Mode S data link which required the mechanically rotating antenna to be pointing to the aircraft when an alarm was issued. This means that there is necessarily a delay, corresponding to the time needed for a full rotation of the antenna, between the radar observation of the situation and the alarm being issued. This involves a delay of about 6 seconds. The ACARS designers faced the need to ensure that the data could be processed within this period, since the next opportunity to warn the aircraft would be one more rotation later.

The ACARS data structure for the conflict test is stored in a track file which is physically separate from, and different in organisation to, the radar sensor track files from which the data is derived. (ACARS could only issue warnings to Mode S equipped aircraft, but it tracked both Mode S and Mode A/C aircraft, as well as those visible only to primary radar. This would probably have required separate but co-rotating radar heads, and certainly the three sets of data would require separate processing). Data was stored in x, y, z coordinates in one central Track Store. Several sets of pointers were provided to string together various categories of aircraft into separate lists for ease of access during processing. One such set of lists divided the total population of aircraft into sub-groups, based, not on Cartesian coordinates as implied in the scheme in sec 5.2.2, but on the bearing of the aircraft from the radars. 32 sectors were provided, data being processed sector by sector. This organisation ensured that messages to the various aircraft were derived in the approximate time order in which they needed to be dispatched down the Mode S data link, and incidentally made it possible to ensure that conflict tests were never carried out on data that was in the process of being updated by the radars. Separate sets of pointers were provided to enable the radar data (identified by the Mode S address or other discrete SSR code, or, for aircraft without this facility, by some reference given to the track in the radar data processor) to be delivered to the corresponding addresses in the main track file. Further pointers split the traffic into two lists. All aircraft whose altitude is below some threshold level, and whose ground speed is below a specified limit, are placed on the "X-list", all others go on the "Ex-list". Separate conflict test mechanisms are used for the two categories of aircraft and for possible conflicts between pairs of aircraft whose members are split between the X and Ex lists. Radar data updates may give rise to transfers of aircraft between the X and Ex lists. These two lists are ordered, by way of their pointers, according to the x -coordinate of each aircraft, so that the differences in this coordinate can be used as an efficient first means of locating possible conflicts. Separate procedures, with different search limits, are used for "controlled aircraft" and "uncontrolled aircraft", since only the controlled aircraft have known intentions.

The algorithms designed for the ACARS software are given by Lentz(1981). Although ACARS was never implemented, it has been here discussed at some length because it is a system having a detailed description of the algorithms in a document freely available to interested readers.

It should perhaps be remarked that, since the broad design of the software in 1980, the cost of storage and computing has fallen considerably, whilst the cost of software development and subsequent modification continues to rise. It is probable that any future system on the lines of ACARS, similarly free from the constraints imposed by the need to share a host with some large existing software system, would be designed with more generous hardware intended to simplify the software design.

5.2.4. The conflict resolution techniques used by ATARS were briefly discussed in para.2.5.3.2. In ATARS, there was no alternative to machine resolution of conflicts. In a system intended to assist, rather than replace the controller, the case for automating the resolution problem may be weaker. In practice, controllers or software must choose from the limited repertory of available short-term alternatives. For conventional aircraft, the only possible decisions involve, for either or both of the aircraft in conflict, a choice between:-

(i) stopping or initiating a climb or descent.

and/or (ii) stopping or initiating a turn to right or left.

In controlled airspace, the human controller is very likely to have background knowledge of the manoeuvre capability and the intentions of two or more aircraft who may be involved in the resolution of a conflict. If an automatic data-link is in use, the controller faces the task of using some input mechanism to compose the data link message. A better alternative might be to allow the computer to assemble a list of feasible alternative solutions, from which the controller can choose, using for example a VDU with a touch-sensitive screen. Having indicated his choice he can leave the computer to compose and launch the data link message or messages.

5.3. Long-Term Problems.

5.3.1 From the discussion in section 3, it should be clear that the strategy e.g. the assignment of routes and flight levels, is based on decisions by management, using historical data on traffic offering on analogous occasions in the past. Within civil ATC, tasks are divided up between controllers largely on a geographical basis, so that the load on an individual controller at a given moment is determined by the number of aircraft at that time within the fixed geographical bounds of his sector. Admittedly, under conditions of light traffic, it is sometimes possible to give a pair of adjacent sectors into the jurisdiction of a single sector team, and similar simplifications of the control structure are possible in a large TMA. It remains true that, as a whole, ATC controllers work within a framework of constraints that can only with difficulty be modified in the light of traffic demand at a given instant. The advantage of a detailed set of formal rules is that it makes it possible for controllers in a particular sector to perform most of their tasks without time-consuming efforts to ensure that their decisions are coordinated and compatible with those taken by their neighbours.

5.3.2. It is easy to argue that such a system leads, at best, to the piecemeal optimisation of traffic flow in limited regions of airspace. There is, in effect, little opportunity for the in-flight optimisation of the trajectory of an aircraft flying across even one country in Europe. This is not a criticism of either air traffic management or controllers. At a given time, there may be 70 aircraft or so in climb or descent out of, or into, the London TMA. It is out of the question for one controller to hold in his mind the present status and intentions of all these aircraft, still less to consider all possible permutations of their respective trajectories, as well as issuing several control instructions per minute for the implementation of the strategy.

If one controller cannot consider the permutations possible with a population of 70 aircraft, a committee of about 20 controllers who are, under the present system, collectively responsible for movements in and around the London TMA, is even less capable. In practice, in order to minimise coordination problems, the activities of different controllers are, as far as possible, decoupled from one another. Complete decoupling is not possible. Consider, for example, traffic outbound from Gatwick and Heathrow. Control of the traffic requesting clearance to taxi and, subsequently, for takeoff, is in the hands of Ground Movement Planning (GMP) and aerodrome controllers in the airfield tower. At a runway dedicated to departures only, the tower must ensure a spacing between departures giving adequate protection against vortex wake and other factors to be discussed later. At single-runway airports, departing aircraft must fit into gaps in the landing pattern, as well as satisfying the constraints arising from the other departures.

Inside the TMA, there may be congestion problems at waypoints such as Midhurst, where traffic streams from London airports either merge or cross. This traffic, as it continues to climb, will eventually merge with other flights originating outside London. The combined traffic must satisfy any flow control constraints at the transfer points where traffic passes to other jurisdiction, France in this example. Traffic overflying London, and therefore airborne at an earlier time, has in effect booked slots at the transfer point ahead of takeoff by the London traffic. Takeoff clearance from London airports has to satisfy constraints imposed at the transfer point, in addition to those arising near the runway. There may also be restrictions on traffic flow within the TMA, through Midhurst, say. In a purely "manual" system, at busy times, every departure may involve the aerodrome controllers in negotiations with the Departure Flow Regulator (DFR) or the TMA Flow Controller (TFC), neither of whom are located at the aerodrome.

5.3.3. Clearly, little computing is needed to deduce the approximate relationships between the time at which an aircraft takes off, passes through some waypoint in the TMA, arrives at some transfer point or, for that matter, any other point of interest. Unpublished work involving laboratory trials of one possible system for the mechanisation of much of the coordination task involved in the organisation sketched above, using a simulated London TMA, has drawn favourable comment from London controllers. In this simulation, Ground Movement Planners (GMP's) at the airports had interactive displays which held details of departing aircraft prior to their request for startup.

On request, the GMP's could be offered slot-times for the transfer point, if any, at which flow constraints applied, as well as target take-off times from the TFR. Interactive displays were also available for the aerodrome controllers and the TFC. The TFC also had a schematic PPI, displaying the planned situation, and the TMA outbound controllers also had displays showing flight data on intended departure traffic, to supplement their radar data.

When an aircraft requested start-up, the GMP signalled the event to the computer. Knowing the aircraft type, route, stand number and runway in use, the computer calculated the earliest time at which the aircraft could be airborne, together with its estimated time at the transfer point. A message could be sent, when necessary, to the DFR requesting an allocated slot time. TFC's display also showed that the aircraft was bidding for a slot. If the DFR found it necessary to delay the arrival at the transfer point, the start-up and departure times were revised, and the TFC and GMP displays were updated accordingly. Decisions on slot times by DFR were binding on the TFC. If the aircraft did not fall under DFR jurisdiction, the TFC was free to accept or modify the proposed target takeoff time.

If the aircraft then took off as planned, an acceptable situation would exist in both the TMA and at the subsequent transfer point. As the aircraft approached the holding point for take-off, the aerodrome controller, who is responsible for planning and controlling events on the runway, took his final decisions on take-off order and timing in the light of his data, which included an indication of the time constraints to be satisfied to meet the DFR flow plans. On take-off, this controller notified the computer of the actual departure time. In the trials, the system offered smooth coordination of the various activities, normally without the need for telephone discussions.

The hardware involved in implementing such a system would be quite extensive. The main role of the computer is in switching data between displays, the computation task being, by computer standards, quite light. The introduction of such an installation might open the door to the subsequent adoption of more elaborate aids to TMA planning.

5.3.4. Section 5.2.2 pointed out the difficulties human controllers could experience in devising a flexible and efficient plan for the movement of traffic through a large TMA, not to mention W. Europe as a whole. The difficulty may not be overcome even by the purchase of a large computer and software. Consider one apparently simple problem. Six aircraft are to pass through a waypoint in some order yet to be decided. Each aircraft can be assigned to one of two flight levels. Delays experienced will depend on the way levels are assigned and on the order in which the aircraft are taken. Suppose that ATC wishes to find the levels and in which the aircraft should arrive so as to minimise total delays.

If the delay experienced by a given aircraft is determined only by its immediate predecessor at the same level, this is a slight elaboration of the "Travelling Salesman" problem which, for many years has been the subject of considerable study by research workers, mostly in universities. No algorithm has yet been designed that does more than speed-up the trial-and-error method of testing each alternative in turn. In the example given above, a decision about six aircraft and two flight levels could involve examination of 46,080 options. Doubling the number of aircraft increases the list to about 1.96×10^{12} . In this situation, the ATC planner falls back, rather thankfully perhaps, on the ICAO ruling that aircraft should be handled on a first-come first-served basis, whatever the expression is taken to mean. There is little doubt, though, that where a machine uses the available time to search for "better" rather than ideal solutions, it may well, under simulation conditions at least, considerably out-perform the human controllers.

The software used in such a game often takes the form of an elaborate framework of rules, partly based on formal ATC instructions, partly on techniques which controllers have evolved in the light of experience, and partly on rules devised, and often extensively revised, during the software development. The rules are often implied, rather than explicitly stated, in the software, and the end product is a mechanism that may be found to be very sensitive to software changes arising out of situations outside the programmers control.

6. Conclusion.

6.1 Since this is an AGARD paper, it should not be out of place to draw attention to a few areas where R&D might profitably be employed in a study of problems that do not appear to be receiving adequate attention. It is being argued by other writers that further "Automation" in ATC, often meaning automatic conflict detection, will enable a reduction in the large and expensive controller workforce. It is interesting to ask how reliable automatic conflict detection must be before a significant saving in controller workload can be achieved. If a totally automatic system could achieve fewer airmisses than a human controller, the economic argument might be worth careful study, but there may be little material in the present paper to encourage the belief that present-day sensors and software technology make possible an adequately reliable automatic system. The question is, given a system that acts as an aid to the controller, how reliable must it be to do more good than harm? For the present purposes, the problems arising from false alarms will be ignored, the question was directed at errors of the other kind;- failures to alarm in adequate time to deal with a genuinely hazardous situation.

Suppose that the alarm detects 90%, 99%, or even 99.9% of all hazards, and that the controller's task has been reduced(?) to that of dealing with the remainder. Even a 99.9% success rate is clearly too low, without such back-up. Will the machine with an inadequate performance to operate unaided, actually simplify the controller's task, or will it induce a false sense of security in management or controllers? Existing conflict-alert packages, such as the French system outlined in para. 2.5.2 or the roughly equivalent system at Maastricht, are intended to back-up the controller rather than to replace him. Such systems, despite an appreciable false alarm rate, appear to work to the satisfaction of all concerned. This is understandable, since if such a device detected even 50% of a controller's rare oversights, it would be serving a very useful purpose.

A similar argument to TCAS, or where ATARS proposed to provide radar-derived warnings to aircraft that are, at present, relying on "see and avoid". It is when, in the words of Hunt and Zellweger (1987), "planning and control functions migrate to the computer system", that the reliability problem becomes more stringent.

6.2. It is not clear how the performance of a very reliable conflict predictor can be measured. Simulation tests have dubious value since problems overlooked in the system design may well also be overlooked in the simulation. One approach, suggested in para 4.2.4 is to use the "game" techniques developed for the study of pursuit-evasion problems. It can be assumed that one aircraft in normal flight under ATC control is "pursued" by a second aircraft which, due to some system failure or other, is flying in obedience to Murphy's Law rather than to ATC. In the game, "Murphy" will attempt to minimise the escape time available to its target when the conflict warning was issued. It was earlier pointed out that the extensive theoretical studies on TCAS have been almost entirely concerned with aircraft in straight line flight. It is possible that "Murphy" might detect loopholes in the detection logic that "straight-line" studies have overlooked.

6.3 It is, perhaps, a surprising feature of ATC that, whilst traffic in controlled airspace is required accurately to maintain a defined track, in the horizontal, and to maintain accurate height in cruise, little attempt is normally made to define the aircraft trajectory in climb or descent. One exception is when aircraft are descending on a glideslope, another, under special conditions, is where ATC requires an aircraft to achieve a specified height before arrival at a given waypoint. Otherwise, even in controlled airspace, ATC may have knowledge of current height but no means, other than linear extrapolation, of predicting future behaviour in the vertical plane.

Since the traffic capacity of a volume of airspace is, to a good approximation, proportional to the number of flight levels that can be independently assigned to the traffic, improved ability to forecast aircraft behaviour in climb or descent should make possible an increase in the traffic capacity of congested airspace, particularly in and around TMA's.

It is therefore suggested that two topics that might be usefully studied are:-

- (i) the effect on airspace capacity and control workload of the possession by ATC of better means of predicting the vertical component of aircraft trajectories.
- (ii) means, such as the greater use of data-links, whereby this improvement might be achieved.

Acknowledgments

The author is indebted to British Aerospace for permission to use their data in para. 2.1, to the U.K. Civil Aviation Authority for permission to quote results from various unpublished works, and to his former colleagues in the U.K. Min. of Defence and the Civil Aviation Authority for advice and assistance too extensive to particularise.

AIRCRAFT DYNAMICS FOR AIR TRAFFIC CONTROL

by

P.-Y. Willems

Université Catholique de Louvain, Département de Mécanique
Bâtiment Stévin
B - 1348 Louvain-la-Neuve, Belgique

0. Introduction

The aim of the paper is to discuss the equations of motion of airplanes in the context of ATC. The basic laws of mechanics will be recalled together with a mathematical model of mechanical systems which is suitable for airborne systems, this will allow us to point out the generally accepted (but often implicit) assumptions of usual models.

A simplified description of the main dynamical effects (gravity and aerodynamical interactions) will be given together with a complete kinematical description of the system. The coherence with ISO norms (ISO - 1985) will be respected as far as possible, some dynamical shortcomings of these norms will be mentioned.

1. Mechanics

We will start from the following statement: *Applied Mechanics is based on experimental physics, uses mathematical models and tools and its goal is to solve technical problems.*

Here, the technical goal is quite clear: provide the equations of motions of an airplane flying in normal conditions, under a form which reasonably describes the main features of the behaviour, remains simple enough to be incorporated in an ATC model and is capable of providing the required accuracy.

Experimental evidence

From physical experiments, we know that for any material system observed in (non relativistic) mechanics, we can define a mass function which is additive on the set of bodies under consideration and constant with respect to time.

Once a *fixed or inertial axis system* (a fixed point O and fixed axis directions) has been chosen, we can define, for each "point" of the system, a position vector \tilde{x} (this function is assumed to be measurable with respect to the mass). The time derivative of the position is the velocity vector $\dot{\tilde{x}}$ (i.e. the velocity with respect to the fixed axis system).

From these notions, two vectorial functions, the momentum, \tilde{N} , and the angular momentum with respect to O , \tilde{H}^O can be defined for each body A as

$$\tilde{N}(A) = \int_A \dot{\tilde{x}} dm \quad \tilde{H}^O(A) = \int_A \tilde{x} \times \dot{\tilde{x}} dm \quad (1)$$

The momentum \tilde{N} is thus the weighted sum of the velocities of the points making up body A , with the weighting made according to the mass distribution. The angular momentum (or moment of momentum) with respect to point O , \tilde{H}^O , is the corresponding weighted sum of moments (vectorial product with position). This form excludes systems with internal distributions of mass or energy circulation but such systems are not considered here.

From physical observations, it appears that the interactions between bodies can be characterized by their rates of exchange of momentum (forces) and angular momentum (torques), obey principles of action and reaction and have additive properties. This allows us to write

$$\dot{\tilde{N}}(A) = \tilde{F}(A) \quad \dot{\tilde{H}}^O(A) = \tilde{L}^O(A) \quad (2)$$

where

$$\begin{aligned} \tilde{F}(A) &= \int_A d\tilde{F} && \text{is the resultant (sum) of all the forces acting on } A \text{ and produced by external bodies,} \\ \tilde{L}^O(A) &= \int_A \tilde{x} \times d\tilde{F} + \int_A d\tilde{M} && \text{is the resultant of the moments of these forces together with the sum of pure torques produced on } A. \end{aligned}$$

The interactions can be described by functions related to the history of the motion (constitutive equations).

As the forces and torques have additive properties (resulting from their relation to \tilde{N} and \tilde{H}^O), the constitutive equations must have a form which allow us to write

$$\tilde{F}(A) = \int \tilde{f} dm \quad \tilde{L}^O = \int \tilde{x} \times \tilde{f} dm + \int \tilde{g} dm \quad (3)$$

where

\tilde{f} is the corresponding force density and represents the distribution of resultant of force per unit mass in the body,
 \tilde{g} is the corresponding density of pure torque.

In general a distinction is made between field forces directly described by force densities in the body - gravity of a typical example - \tilde{g} is nothing but the gravitational force density i.e. the weight per unit mass - and contact forces described by surface densities \tilde{t} acting on the boundaries - here the pressure is a typical example (the corresponding force density results from the divergence theorem).

From equations (1) (2) and (3), we can conclude that locally, at each point in the system, the following relations hold

$$\dot{\tilde{x}} = \tilde{f} \quad \dot{\tilde{g}} = 0$$

(From a mathematical point of view these relations may be violated on a set of points where total mass is zero.)

This is the local form of the equations of motion which is well known in continuum mechanics.

Constant mass systems

The equations (2) apply to a material body A i.e. to a system made up of specific material points. If these points are always confined in a given surface S , the body A can also be defined as the material system included in S and equations (2) apply.

For airborne systems, the fixed point can be far from the body and a local reference point can be useful. This point, say P , does not necessarily belong to the system but an adequate choice is very important as we shall see. The position vector \tilde{x} of a material point can be written as the sum of the relative

position vector of the point with respect to P , \underline{p} , and the position vector of P (with respect to O), \underline{P} .

i.e.

$$\underline{x} = \underline{P} + \underline{p}$$

If the centre of mass of the body is defined as the mean position vector of the system i.e.

$$\underline{R} \triangleq \frac{1}{m} \int \underline{x} \, dm,$$

the momentum can be written as

$$\underline{N} = \int \dot{\underline{x}} \, dm = m \dot{\underline{R}}$$

and its derivative as

$$\dot{\underline{N}} = \int \ddot{\underline{x}} \, dm = m \ddot{\underline{R}}.$$

The position vector of the centre of mass with respect to P will be denoted \underline{p}_o with $\underline{p}_o = \underline{R} - \underline{P}$ and

$$m \underline{p}_o = \int \underline{p} \, dm.$$

The translational equations can be written as

$$m \ddot{\underline{R}} = m(\ddot{\underline{P}} + \ddot{\underline{p}}_o) = \underline{F}.$$

Similarly

$$\dot{\underline{H}}^O = \int \underline{x} \times \ddot{\underline{x}} \, dm = \int (\underline{P} \times \underline{p}) \times (\dot{\underline{P}} \times \dot{\underline{p}}) \, dm = \underline{P} \times m \ddot{\underline{R}} + \underline{p}_o \times m \ddot{\underline{P}} + \dot{\underline{H}}^P$$

where $\dot{\underline{H}}^P \triangleq \int \underline{p} \times \dot{\underline{p}} \, dm$ is defined as the angular momentum with respect to P .

The equations (2) are the equivalent to the system

$$m \ddot{\underline{R}} = \underline{F} \quad \dot{\underline{H}}^P = \underline{L}^P - \underline{p}_o \times m \ddot{\underline{P}} \quad (4)$$

where $\underline{L}^P = \int \underline{p} \times d\underline{F} + \int d\underline{M}$ is the moment of external interactions with respect to P .

It should be noted that these equations are equivalent to the system

$$\int \underline{x} \, dm = \int \underline{f} \, dm \quad \text{and} \quad \int \underline{p} \times \ddot{\underline{x}} \, dm = \int \underline{p} \times \underline{f} \, dm \quad (5)$$

If the point P coincides with the centre of mass ($\underline{p}_o \equiv 0$) these equations reduce to

$$m \ddot{\underline{R}} = \underline{F} \quad \dot{\underline{H}} = \underline{L}$$

(when the subscript is absent, the reference point is supposed to be the mass centre).

If further the body is rigid, the distances between points remain constant and one may define a body (fixed) axis system with origin P and axis directions fixed with respect to the body. The relative position vectors \underline{p} will have constant components in this axis system. It follows that the angular momentum vector \underline{H} can be expressed in terms of the body inertia matrix and the components of the angular velocity vector (of the body axis system with respect to the inertial axis system). This greatly simplifies the rotational equations which are generally expressed in body axis. The choice of axes is not so obvious for the translational equations. These topics will be analyzed in the section devoted to kinematics.

Variable mass systems

In this case the body $B(t)$ will be defined as the material system which at time t lies inside a certain surface $S(t)$. It will be assumed that mass can flow through two separated exchange surfaces N^+ and N^- corresponding to input and output flows respectively.

The equations (2) no longer hold but one can still write relations in a form equivalent to equation (5) as the local form of equations remains valid.

$$\int_{B(t)} \underline{x} \, dm = \int_{B(t)} \underline{f} \, dm \quad \int_{B(t)} \underline{p} \times \ddot{\underline{x}} \, dm = \int_{B(t)} \underline{p} \times \underline{f} \, dm$$

The right hand sides are none other than the resultants of forces and torques (with respect to P) acting on $B(t)$. It should be noted that the interactions on the exchange surfaces are included in these terms, but this is generally not a major difficulty.

For the translational equation the integral of the acceleration is no longer the time derivative of the momentum of the body. However, by using the transport theorem (see for instance (M. Decuyper *et al.*, 1981)) this equation can be written under the form:

$$m \ddot{\underline{R}} = \underline{F} + \underline{F}_j$$

where m is the current mass of the system and is thus a function of time that must be given – the mass balance of an airplane can normally be estimated without difficulty;
 \underline{F} is the resultant of external forces and includes aerodynamical and gravity terms;
 \underline{F}_j is often called the "propulsion force" but corresponds to the momentum flow through the exchange surfaces.

In the case of jet propulsion, the propulsion force is dominated by the effect of mass ejection through the nozzle and the equation is written under the form

$$m \ddot{\underline{R}} = m \underline{g} + \underline{F}_a + \underline{F}_j^* \quad (6)$$

where \underline{F}_a is the resultant of aerodynamical forces but generally does not include the interactions on the exchange surfaces;

\underline{F}_j^* is the "effective propulsion force expressed as $\underline{F}_j^* = \dot{m} \underline{V}^*$

where \dot{m} is the time derivative of mass of the system and corresponds to the mass flow through the nozzle – this function is negative;

\underline{V}^* is the "effective" velocity of the ejected mass with respect to the nozzle – this velocity is generally an experimental datum and includes interactions on the exchange surface.

Similarly the rotational equation can be written under the form

$$\dot{\underline{H}}^P = \underline{L}^P - \underline{p}_o \times m \ddot{\underline{P}} + \underline{L}_j^P$$

where $\dot{\tilde{H}}^P$ has a form similar to the corresponding term for a rigid body but includes time varying inertia parameters ;
 \tilde{L}^P is the external torque
 \tilde{L}_j^P is called the "propulsive torque" but corresponds to the moment of momentum flow through the exchange surfaces.

Here too the "propulsion torque" is generally dominated by the moment of the "propulsion force" even if other terms may have significant effects, for instance on the stability of the system (jet damping terms) ; nevertheless these terms are more important for the design of the systems and they are generally neglected or "incorporated" in similar terms (by adapting the coefficients) for simulation purposes. The equations are then written under the form

$$\dot{\tilde{H}}^P = \tilde{L}_a^P + \underline{p}_O \times m(\underline{\ddot{g}} - \underline{\ddot{P}}) + \tilde{L}_j^{P*} \quad (7)$$

where \tilde{L}_a^P is the resultant aerodynamical torques ;
 \tilde{L}_j^{P*} is the effective propulsion torque :

$$\tilde{L}_j^{P*} = \underline{p}_N \times \dot{\tilde{m}} \underline{V}^*$$

where \underline{p}_N is the effective relative position of the nozzle with respect to P and is generally determined from experiments.

For most problems, one can consider that the inertial configuration varies slowly (during a given manoeuvre) and the inertia coefficients are then considered as constants.

It should be clear that the deformation of the system are not considered here, but again their influence is more important for design purposes. The various expression of inertia coefficients and interactions can be estimated for the corresponding elastic equilibrium configurations – this configuration may vary with time –. It is then implicitly accepted that the coupling between the general behaviour and the deformation modes is weak.

For systems with propellers a similar form of equations is obtained by separating the aerodynamical interactions in conventional terms and "propulsive forces".

It may be concluded that the motion of a well designed airplane in normal flight conditions can be essentially described by equations (6) (7) for quasi-rigid bodies associated with a mass time history and an appropriate description of propulsive interactions. The evaluation of the other terms will be described in the following sections.

II. Kinematics

An axis system will be denoted $x y z$ and, when necessary, subscripts permit to distinguish between frames. This triplet denotes three orthogonal directions. A vector base can be defined from the axis system concept. We can align three unit vectors along these directions, the "length" of these vectors is chosen equal to a given standard unit. It is then follows that any vector of the geometrical space, say \tilde{X} , can be described by its components "along" the axes as a linear combination of the unit vectors \tilde{x} , \tilde{y} and \tilde{z} :

$$\tilde{X} = X \tilde{x} + Y \tilde{y} + Z \tilde{z}.$$

Formally this vector can be represented by the triplet of its components $\tilde{X} = \{X, Y, Z\}$ i.e. by a triplet of real numbers. This triplet \tilde{X} is a vector of the R^3 -space. As R^3 -space has the appropriate mathematical structure for integration and treatment of differential equations, the vectorial quantities will always be represented by the corresponding vectors of R^3 . In particular vectors x , y and z will be represented by vectors $\tilde{x} = \{1, 0, 0\}$, $\tilde{y} = \{0, 1, 0\}$ and $\tilde{z} = \{0, 0, 1\}$ respectively (the circumflex accent indicates that the norm of the vector is unity – it corresponds to one standard unit). It is seen that $\tilde{x}, \tilde{y}, \tilde{z}$ is an orthogonal base of R^3 , namely the canonical base, and the vector \tilde{X} can also be written as

$$\tilde{X} = X \tilde{x} + Y \tilde{y} + Z \tilde{z}.$$

If one formally defines the arrays

$$[X] = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \text{ and } [\tilde{x}] = \begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{bmatrix}$$

the vector \tilde{X} can be written as

$$\tilde{X} = [\tilde{x}]^T [X]$$

if the rules of matrix products are extended to arrays with vector elements.

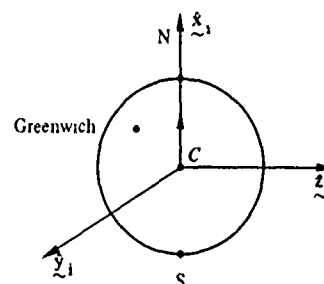
Operations on vectors are described in the appendix.

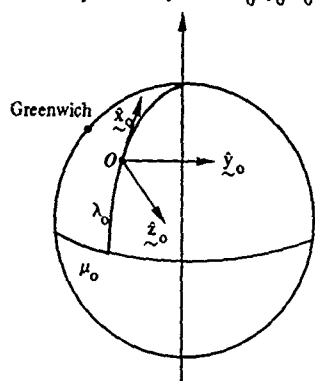
Axis systems

The following axis system will be used

1. Inertial axis system : $x_1 y_1 z_1$

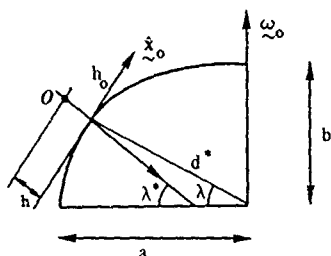
The origin of this axis system coincides with the centre of the earth C and the directions $x_1 y_1 z_1$ are fixed with respect to the stars. We will arbitrarily choose x_1 aligned with the North-South axis. The corresponding inertial base is denoted $\{\tilde{x}_1, \tilde{y}_1, \tilde{z}_1\}$ and is the canonical base.



2. Normal earth fixed axis system : x_o, y_o, z_o (ISO 1.1.2)*

The origin of this axis system is fixed with respect to the earth, we will choose a given point O of the earth surface localized by the geographical coordinates μ_o, λ_o and its altitude h_o . The z_o axis is oriented according to the downward vertical passing through the origin. We choose x_o oriented to the North and y_o to the East. The corresponding earth-fixed base will be denoted $\{\tilde{x}_o, \tilde{y}_o, \tilde{z}_o\}$.

The transition from the inertial base to the earth-fixed base is obtained by rotations through an angle $(\omega_o t + \mu_o)$ about the \tilde{x}_i axis followed, for spherical earth, by a rotation through an angle $-\lambda_o$ ($\lambda_o > 0$ in the northern hemisphere) about an intermediate y -axis (ω_o is the angular velocity of the earth around its axis).



If the earth is considered to be an ellipsoid, the direction of the vertical is aligned with the normal to the ellipsoid (this direction also corresponds to the "apparent" gravity density which includes "centrifugal" and earth oblateness effects). If a is the semi-major axis and b the semi-minor axis of the ellipsoid the rotation of the earth-fixed base will be $\lambda_o^* = \lambda_o + \frac{a-b}{a} \sin 2\lambda_o$ - the accuracy of this formula being of the same order as the ellipsoidal approximation, i.e. within 10^{-5} .

We thus have

$$[\tilde{x}_o] = [A_{oi}] [\tilde{x}_i] \text{ with } [A_{oi}] = [A^{(b)}(-\lambda_o^*)] [A^{(a)}(\omega_o t + \mu_o)]$$

The angular velocity of the earth fixed base (with respect to inertial space) is the angular velocity of the earth around its axis

$$\omega_{oi} = \omega_o \tilde{x}_i = \omega_o \cos \lambda_o^* \tilde{x}_o - \omega_o \sin \lambda_o^* \tilde{z}_o \quad \text{or} \quad \omega_{oi} = [\tilde{x}_i]^T [\omega_o] = [\tilde{x}_o]^T [A_{oi}] [\omega_o] \quad \text{with} \quad [\omega_o] = [\omega_o \ 0 \ 0]^T.$$

This angular velocity is considered to be constant and in most situations it may be considered to have a negligible influence on the dynamics.

Within the same approximation the distance from the centre of mass of the earth and the ellipsoid is given by

$$d_o^* = a - (a-b) \sin^2 \lambda_o$$

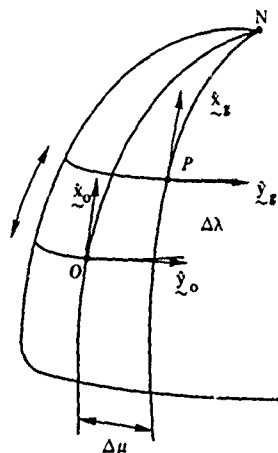
and the position vector from the centre of the earth to the reference point O is given in the earth fixed base with the same accuracy as

$$R_O = -d_o^* \sin(\lambda_o^* - \lambda_o) \tilde{x}_o - [d_o^* \cos(\lambda_o^* - \lambda_o) + h_o] \tilde{z}_o \approx -(a-b) \sin 2\lambda_o \tilde{x}_o - [a + h_o - (a-b) \sin^2 \lambda_o] \tilde{z}_o = [\tilde{x}_o]^T [R_O].$$

2bis. Aircraft carried normal earth axis system x_o, y_o, z_o

The origin of this frame is fixed in the aircraft (usually the centre of mass) [ISO]. This origin is the point P . The directions are the same as for 2.

The position vector of point P with respect to point O can be expressed in the earth fixed base and the corresponding coordinates can be related to the geographical coordinates of P .

3. Aircraft carried local earth axis system x_g, y_g, z_g (ISO 1.1.4 with 1.0 § 3)

The origin of the axis system (point P) is fixed in the aircraft and usually coincides with the centre of mass. This point is localized by its real geographical coordinates μ, λ and by its altitude h . The z_g axis is oriented according to the local downward vertical (passing through P). The x_g axis will be oriented northwards and y_g eastwards. When $\lambda \sim \lambda_o$ and $\mu \sim \mu_o$ (short term motions) this axis-system coincides with the one defined in 2bis. The direction of the axes are the same as the corresponding direction of a local normal earth fixed axis system whose origin coincides with point P (at a given time t). With this interpretation - which implies the definition of a local normal earth fixed axis system for each instant - this axis system is defined by (ISO 1.1.4).

The corresponding local base will be denoted $\{\tilde{x}_g, \tilde{y}_g, \tilde{z}_g\}$. The transition from the inertial base to this local base is obtained as for the normal earth fixed base by rotations through angles $\omega_o t + \mu$ and $-\lambda^*$ with

$$\lambda^* = \lambda + \frac{a-b}{a} \sin 2\lambda$$

and

$$[\tilde{x}_g] = A_{gi} [\tilde{x}_i]$$

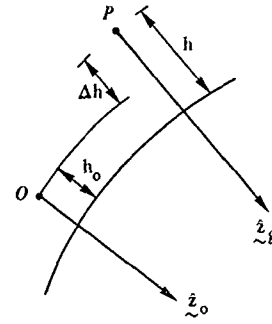
with

$$[A_{gi}] = [A^{(b)}(-\lambda^*)] [A^{(a)}(\omega_o t + \mu)].$$

The angular velocity of the base is given by

$$\begin{aligned}\omega_{gi} &= (\omega_o + \dot{\mu}) \hat{x}_i - \dot{\lambda}^* \hat{y}_g \\ \text{or} \quad \omega_{gi} &= (\omega_o + \dot{\mu}) \cos \lambda^* \hat{x}_g - \dot{\lambda}^* \hat{y}_g - (\omega_o + \dot{\mu}) \sin \lambda^* \hat{z}_g = [\hat{x}_g]^T [\omega_{gi}] \\ \text{with} \quad [\omega_{gi}] &= [\cos \lambda^* \ 0 \ -\sin \lambda^*]^T (\omega_o + \dot{\mu}) + [0 \ -1 \ 0]^T \dot{\lambda}^* \\ \text{and} \quad \dot{\lambda}^* &= \dot{\lambda} (1 + 2 \frac{a-b}{a} \cos 2\lambda).\end{aligned}$$

In many situations this angular velocity is considered to have negligible dynamical influence i.e. the g-axis system is considered to be inertial.



The position vector of point P with respect to the centre of the earth written R_P is given by (with $d^* = a - (a-b)\sin^2\lambda$)

$$R_P = -d^* \sin(\lambda^* - \lambda) \hat{x}_g - [d^* \cos(\lambda^* - \lambda) + h] \hat{z}_g \approx - (a-b) \sin 2\lambda \hat{x}_g - [a + h - (a-b) \sin^2\lambda] \hat{z}_g = [\hat{x}_g]^T [R_P].$$

Its position vector with respect to point O , $P_O = R_P - R_O = [\hat{x}_o]^T [X_o]$ with $[X_o] = [X_o \ Y_o \ Z_o]^T$ can be expressed in the earth fixed base.

$$\text{If} \quad [\hat{x}_o] = [A_{og}] [\hat{x}_g] = [A_{oi}] [A_{ig}] [\hat{x}_g] = [A^{(g)}(-\lambda_o^*)] [A^{(x)}(-\Delta\mu)] [A^{(y)}(\lambda^*)] [\hat{x}_g]$$

with $\Delta\mu = \mu - \mu_o$ we obtain the relation

$$[X_o] = [A_{og}] [R_P] - [R_O] = [X_o(\Delta\mu, \lambda, h)]. \quad (8)$$

Various approximations of this relation are available but they are limited to short range motion (see below).

With the same accuracy the velocity of the aircraft with respect to inertial space is expressed in the local base as

$$\dot{R}_P = [a + h - (a-b)\sin^2\lambda] \dot{\lambda} \hat{x}_g + [a + h - (a-b)\sin^2\lambda] \cos \lambda \dot{\mu} \hat{y}_g - \dot{h} \hat{z}_g$$

and its velocity with respect to the ground $V_K = \dot{R}_P - \omega_o \times R_P$ as

$$V_K = [a + h - (a-b)\sin^2\lambda] \dot{\lambda} \hat{x}_g + [a + h - (a-b)\sin^2\lambda] \cos \lambda \dot{\mu} \hat{y}_g - \dot{h} \hat{z}_g$$

or

$$V_K = d \dot{\lambda} \hat{x}_g + d \cos \lambda \dot{\mu} \hat{y}_g - \dot{h} \hat{z}_g$$

where $d = [a + h - (a-b)\sin^2\lambda]$ is - with the same accuracy - the distance to the centre of the earth. It must be noted that this expression depends on λ (and not on λ^*). This vector can also be written (ISO 2.2.2 with 1.1.4 and 1.0.3)

$$V_K = v_{Kx} \hat{x}_g + v_{Ky} \hat{y}_g + v_{Kz} \hat{z}_g = V_K \hat{x}_k$$

where \hat{x}_k is the flight path axis (in the direction of the flight velocity (ISO 2.1.1)).

4. Body axis system : $x \ y \ z$ (ISO 1.1.5)

This is a frame fixed in the aircraft with origin at the point P and consisting of the following axes

- x : the longitudinal axis, located in the reference plane (plane of symmetry)
- y : the transverse axis, normal to the reference plane and positive to starboard
- z : the normal axis, completing the frame (positive in the ventral sense).

The corresponding body-base will be denoted $\hat{x}_b, \hat{y}_b, \hat{z}_b$. The transition between the local base and the body base is obtained by three, successive (positive) rotations about z - y - and x -axis, the corresponding angles being respectively the local azimuth angle Ψ , the local elevation angle Θ and the local bank angle Φ . The definitions correspond to the axes given in (ISO 1.2.2) with the adjunction of the word local (ISO 1.0.3) and an appropriate interpretation for local earth fixed axis systems.

Two intermediate bases are defined during this procedure but they will not be used explicitly here.

We have the following relation between the body and local bases

$$[\hat{x}_b] = [A_{bg}] [\hat{x}_g] \quad \text{where} \quad [A_{bg}] = [A^{(x)}(\Phi)] [A^{(y)}(\Theta)] [A^{(z)}(\Psi)].$$

Further the relative angular velocity of the body base with respect to the local base $\omega_{bg} = [\hat{x}_b]^T [\omega_{bg}]$ can be obtained under the form $[\omega_{bg}] = [B_{bg}] [\dot{\theta}_b]$. The matrices $[A_{bg}]$ and $[B_{bg}]$ are the matrices $[A_{gi}]$ and $[B_{gi}]$ gives in appendix (see P22 and P23) with

$$i = b, \quad i = g, \quad \theta_x = \Phi, \quad \theta_y = \Theta, \quad \theta_z = \Psi \quad \text{and} \quad [\theta_b] = [\Phi \ \Theta \ \Psi]^T.$$

The angular velocity of the body with respect to inertial space is thus

$$\omega_{bi} = \omega_{bg} + \omega_{gi} = [\hat{x}_b]^T [[B_{bg}] [\dot{\theta}_b] + [A_{bg}] [\omega_{gi}]].$$

this vector is generally written

$$\omega_{bi} = p \hat{x}_b + q \hat{y}_b + r \hat{z}_b = [\hat{x}_b]^T \begin{bmatrix} p \\ q \\ r \end{bmatrix} = [\hat{x}_b]^T [\omega]$$

(ISO 1.3.6) $p \ q \ r$ being the components of the correspond vector $\vec{\omega}$ (ISO 1.3.5) of geometrical space. We thus have the matrix relation

$$[\omega] = [B_{bg}] [\dot{\theta}_b] + [A_{bg}] [\omega_{gi}].$$

5. Air-path axis system : $x_a \ y_a \ z_a$ (ISO 1.1.6)

This is also an axis system fixed in the aircraft usually at the centre of mass and consisting of the following axes :

- x_a : the air-path axis in the directory of the aircraft velocity (velocity of the origin of the body axis system) with respect to the atmosphere
 y_a : the lateral air-path axis on cross-stream axis, normal to x_a and z_a positive to starboard ;
 z_a : the normal air-path axis, located in the reference plane (and normal to x_a).

The corresponding air-path (or aerodynamical) base will be denoted $\{\hat{x}_a, \hat{y}_a, \hat{z}_a\}$. The transition between the local base and the aerodynamical base is obtained (as in 4.) by three successive (positive) rotations about z y and x-axis the corresponding angles being respectively the air-path track angle χ_a , the air-path climb angle γ_a and the air-path bank angle μ_a (ISO 1.2.3). The relations between air-path and local angle bases are given by

$$[\hat{x}_a] = [A_{ag}] [\hat{x}_g] \quad \text{where} \quad [A_{ag}] = [A^{(x)}(\mu_a)] [A^{(y)}(\gamma_a)] [A^{(z)}(\chi_a)].$$

Further the relative angular velocity of the air-path base with respect to the local base $\omega_{ag} = [\hat{x}_a]^T [\omega_{ag}]$ can be obtained under the form: $[\omega_{ag}] = [B_{ag}] [\dot{\theta}_a]$.

The elements of the matrices $[A_{ag}]$ and $[B_{ag}]$ are given in appendix with $l \equiv a \quad i \equiv g$

$$\theta_z = \chi_a \quad \theta_y = \gamma_a \quad \theta_x = \mu_a \quad \text{with} \quad [\theta_a] = \begin{bmatrix} \mu_a \\ \gamma_a \\ \chi_a \end{bmatrix}$$

The angular velocity of the air-path base with respect to inertial space is then

$$\omega_{ai} = \omega_{ag} + \omega_{gi} = [\hat{x}_a]^T \{ [B_{ag}] [\dot{\theta}_a] + [A_{ag}] [\omega_{gi}] \}.$$

This vector is generally written

$$\omega_{ai} = p_a \hat{x}_a + q_a \hat{y}_a + r_a \hat{z}_a = [\hat{x}_a]^T \begin{bmatrix} p_a \\ q_a \\ r_a \end{bmatrix} = [\hat{x}_a]^T [\omega_a]$$

and in matrix form we have

$$[\omega_a] = [B_{ag}] [\dot{\theta}_a] + [A_{ag}] [\omega_{gi}]. \quad (9)$$

6. Intermediate axis system : x_e, y_e, z_e (ISO 1.1.7)

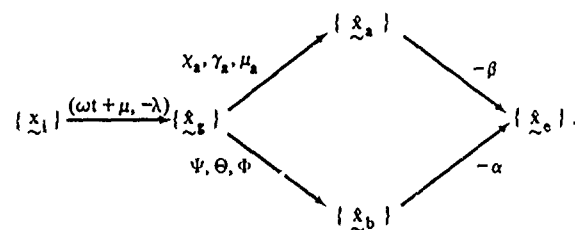
This axis system is also fixed in the aircraft. The transition between the body axis system and the air-path axis system can be obtained by a sequence of two rotations. A direction can indeed be defined by two angles and this is the case for the relative aircraft velocity \vec{V} (ISO) which is represented by $\vec{V} = V \hat{x}_a$.

The sequence of rotation (taken arbitrarily as a y - z sequence) defines an intermediate axis frame. This frame is sometimes called the experimental frame (from the german experimentales Achsenkreuz). Indeed the frame can be chosen in such a way that the external forces (aerodynamical or aerodynamical plus gravity) have zero components along the y and z-axis for a given equilibrium configuration.

The corresponding experimental base will be denoted $\{\hat{x}_e, \hat{y}_e, \hat{z}_e\}$. The transition between the experimental base and the body base is obtained by a rotation through an angle α around the y-axis i.e. $[\hat{x}_b] = [A^{(y)}(\alpha)] [\hat{x}_e]$ the angle α is called the angle of attack (ISO 1.2.1.2). The corresponding relative angular velocity is $\omega_{be} = \dot{\alpha} \hat{y}_e = \dot{\alpha} \hat{y}_b$.

The transition between the experimental base and the air-path base is obtained by a rotation through an angle β around the z-axis $[\hat{x}_a] = [A^{(z)}(\beta)] [\hat{x}_e]$ the angle β is called the angle of sideslip (ISO 1.2.1.1). The corresponding angular velocity is $\omega_{ae} = \dot{\beta} \hat{z}_e = \dot{\beta} \hat{z}_a$. It should be noted that $\hat{y}_e \equiv \hat{y}_b$ and $\hat{z}_e \equiv \hat{z}_a$.

The transition between inertial space and the experimental base can be obtained via two paths.



In particular we can write $[\hat{x}_e] = [A^{(y)}(-\alpha)] [A_{bg}] [\hat{x}_a] = [A^{(z)}(-\beta)] [A_{ag}] [\hat{x}_a]$ and obtain three independent algebraic relations between $\Psi, \Theta, \Phi, \alpha, \beta, \mu, \gamma_a$ and χ_a under the form

$$[A^{(y)}(-\alpha)] [A_{bg}] = [A^{(z)}(-\beta)] [A_{ag}].$$

One can also express the angular velocity of the experimental base under the form

$$\omega_{ei} = \omega_{eb} + \omega_{bi} = \omega_{ea} + \omega_{ai} \quad \text{or} \quad -\dot{\alpha} \hat{y}_e + \omega_{bi} = -\dot{\beta} \hat{z}_e + \omega_{ai}.$$

These last relations can be expressed as

$$\begin{bmatrix} 0 \\ -\dot{\alpha} \\ 0 \end{bmatrix} + [A_{eb}] \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -\dot{\beta} \end{bmatrix} + [A_{ea}] \begin{bmatrix} p_a \\ q_a \\ r_a \end{bmatrix} \quad \text{with} \quad [A_{eb}] = [A^{(y)}(-\alpha)] \quad \text{and} \quad [A_{ea}] = [A^{(z)}(-\beta)]$$

or

$$\dot{\alpha} = q - \sin \beta p_a - c \gamma \beta q_a$$

$$\dot{\beta} = r_a + \sin \alpha p - \cos \alpha r$$

$$p_a = \tan \beta q_a + \frac{\cos \alpha}{\cos \beta} p + \frac{\sin \alpha}{\cos \beta} r$$

(10)

It should be noted that $[\hat{x}_b] = [A_{ba}] [\hat{x}_a]$ with $[A_{ba}] = [A^{(y)}(\alpha)] [A^{(z)}(-\beta)]$.

Velocity with respect to the air and Wind models requirements

In section 3, we expressed the absolute velocity of the aircraft and its velocity with respect to the ground and in section 5 we aligned the \hat{x}_a -axis along the velocity of the aircraft with respect to the atmosphere; these various velocities will now be related.

The velocity with respect to the ground (\vec{V}_K) is in fact the sum of the velocity with respect to the atmosphere \vec{V} and of the velocity of the atmosphere with respect to the ground, the latter being the wind velocity \vec{V}_w (ISO 2.2.3) represented here by the vector \vec{W} . We can write $\vec{V}_K = \vec{V} + \vec{W}$. Here we will depart from ISO norms and express the wind velocity in the local base as

$$\vec{W} = W_x \hat{x}_g + W_y \hat{y}_g + W_z \hat{z}_g = [\hat{x}_g]^T [W]$$

and consider that the components are functions of the location (λ, μ) and the altitude h i.e. $W_\alpha = W_\alpha(\lambda, \mu, h)$; $\alpha = x, y, z$.

The components of wind velocity are measured at specific locations and altitudes. Appropriate interpolation functions and updating procedures are necessary. Furthermore, in order to be useful for ATC operations, the accuracy on the wind velocities have to be of the order of one metre per second (~ 2 knots). This seems to be a severe requirement but, as we shall see the equations of motion are linear in the wind parameters and one can take advantage of this fact to identify the wind values during ATC operations, in order to improve the overall accuracy and obtain a valuable wind description along the main approach trajectories.

Using the relation $\vec{V} = V \hat{x}_a$ and $[\hat{x}_a] = [A_{ag}] [\hat{x}_g]$ as $\vec{V} = [\hat{x}_g]^T [A_{ga}] [V]$ with $[V] = [V \ 0 \ 0]^T$ the vector \vec{V} can be expressed in the local base as

$$\vec{V} = V \cos \gamma_a \cos \chi_a \hat{x}_g + V \cos \gamma_a \sin \chi_a \hat{y}_g - V \sin \gamma_a \hat{z}_g.$$

Together with the expressions of \vec{V}_K obtained in section 3, this allows us to obtain the following kinematical relations

$$\begin{aligned} u_{Kg} &= W_x + V \cos \gamma_a \cos \chi_a & \dot{\lambda} &= \frac{1}{d} [W_x + V \cos \gamma_a \cos \chi_a] \\ v_{Kg} &= W_y + V \cos \gamma_a \sin \chi_a & \dot{\mu} &= \frac{1}{d \cos \lambda} [W_y + V \cos \gamma_a \sin \chi_a] \\ w_{Kg} &= W_z - V \sin \gamma_a & \dot{h} &= -W_z + V \sin \gamma_a \end{aligned} \quad (11)$$

$$\text{with } d = a + h - (a - b) \sin^2 \lambda.$$

Acceleration

The velocity of the aircraft can be written under the form $\dot{\vec{R}}_P = \omega_o \times \vec{R}_P + \vec{W} + \vec{V}$. Taking the time derivative of this expression the acceleration is obtained under the form

$$\ddot{\vec{R}}_P = \dot{\omega}_o \times \vec{R}_P + \omega_o \times \dot{\vec{R}}_P + \dot{\vec{W}} + \dot{\vec{V}} = \dot{\vec{W}} + \dot{\vec{V}} + \omega_o \times \omega_o \times \vec{R}_P + \vec{a}_r$$

where $\vec{a}_r = \dot{\vec{W}} + \omega_o \times \vec{W} + \omega_o \times \vec{V}$.

The vector \vec{V} being expressed in the air-path base as $\vec{V} = V \hat{x}_a$ its time derivative is given by

$$\dot{\vec{V}} = \dot{V} \hat{x}_a + \omega_{ai} \times \vec{V} = \dot{V} \hat{x}_a + r_a V \hat{y}_a - q_a V \hat{z}_a. \quad (12)$$

The residual acceleration \vec{a}_r can easily be expressed in the local base with

$$\begin{aligned} \omega_o &= [\hat{x}_g]^T [A_{gi}] [\omega_o] & \vec{W} &= [\hat{x}_g] [W] & \dot{\vec{W}} &= [\hat{x}_g]^T [\dot{W}] + [\hat{x}_g]^T [\omega_{gi}] \tilde{[W]} & \text{and } \vec{V} &= [\hat{x}_g]^T [A_{ga}] [V] \text{ as} \\ \vec{a}_r &= [\hat{x}_g]^T \left\{ [\dot{W}] + [\omega_{gi}] \tilde{[W]} + \left[[A_{gi}] [\omega_o] \right] \tilde{[W]} + [A_{gi}] [\omega_o] \tilde{[A_{ga}] [V]} \right\} \end{aligned}$$

and in the air-path base we have $\vec{a}_r = [\hat{x}_a]^T [a]$ with $[a] = [a_x \ a_y \ a_z]^T$. (13)

It may be checked that the matrix

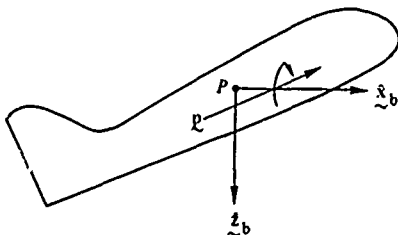
$$[a] = [A_{ag}] \left[[\dot{W}] + [\omega_{gi}] \tilde{[W]} + [A_{gi}] [\omega_o] \tilde{[W]} + [A_{gi}] [\omega_o] \tilde{[A_{ga}] [V]} \right]$$

is a function of the variables $\lambda, \chi_a, \gamma_a, \mu, V, \dot{\lambda}$ and of the parameters derived in the previous section $\omega_o, W_x, W_y, W_z, \dot{W}_x, \dot{W}_y, \dot{W}_z$. It should be noted that by use of the expression (6) the variable μ and λ can be expressed in term of the remaining variables $\lambda, \chi_a, \gamma_a$ and V .

Finally we can write

$$\ddot{\vec{R}}_P = [\hat{x}_a]^T \begin{bmatrix} \dot{V} + a_x \\ r_a V + a_y \\ -q_a V + a_z \end{bmatrix} + \omega_o \times \omega_o \times \vec{R}_P.$$

Angular momentum



The angular momentum of the body with respect to point P was defined as

$$\vec{H}^P = \int \vec{p} \times \dot{\vec{p}} dm.$$

If the structure is rigid the vector \vec{p} has constant components in the body base i.e.

$$\vec{p} = x \hat{x}_b + y \hat{y}_b + z \hat{z}_b = [\hat{x}_b]^T [x]$$

with $[x] = [x \ y \ z]^T$.

The vector $\dot{\vec{p}}$ is then equal to $\dot{\vec{p}} = \omega_{bi} \times \vec{p}$ with $\omega_{bi} = [\hat{x}_b]^T \begin{bmatrix} p \\ q \\ r \end{bmatrix}$

We have $\dot{\vec{p}} = [\hat{x}_b]^T [\omega] \tilde{[x]} = -[\hat{x}_b]^T [x] \tilde{[\omega]}$.

The angular momentum can then be written $\mathbf{H}^P = [\mathbf{x}_b]^T [\mathbf{I}^P] [\boldsymbol{\omega}]$ where the matrix $[\mathbf{I}^P]$ is the inertia matrix of the rigid body with respect to point P , expressed in the body base and can be computed from the relation

$$[\mathbf{I}^P] = - \int [\mathbf{x}] \tilde{[\mathbf{x}]} dm = \begin{bmatrix} \int x_2^2 + x_3^2 dm & -\int x_1 x_2 dm & -\int x_1 x_3 dm \\ -\int x_1 x_2 dm & \int x_1^2 + x_3^2 dm & -\int x_2 x_3 dm \\ -\int x_1 x_3 dm & -\int x_2 x_3 dm & \int x_1^2 + x_2^2 dm \end{bmatrix}$$

when the point P is the centre of mass this matrix will be written $[\mathbf{I}]$ and called the central inertia matrix. The elements of this matrix are the moments and products of inertia.

Probably due to a tradition dating from the time when the tensor properties of the inertia matrix were not well known, ISO standards define the product of inertia *without* the minus sign and the corresponding inertia matrix is then written

$$[\mathbf{I}^P] = \begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{xy} & I_y & -I_{yz} \\ -I_{xz} & -I_{yz} & I_z \end{bmatrix} \quad (\text{ISO 1.4.2, 1.4.3})$$

When the system includes "fast rotating" parts such as motors, the circulation of mass slightly modifies the expression of the angular momentum. The effects of these parts can be represented by adding to the contribution of the rigid (frozen) body an internal angular momentum vector \mathbf{h}_M which for balanced systems is aligned with the relative angular velocity $\boldsymbol{\omega}_M$ of the rotating parts and has an amplitude equal to the product of this relative angular velocity by the moment of inertia of the rotating part around its axis, $\mathbf{h}_M = I_M \boldsymbol{\omega}_M$. If the system includes several motors, the total internal angular momentum is simply the vectorial sum of the individual momenta $\mathbf{h} = [\mathbf{x}_b]^T [\mathbf{h}]$. The angular momentum will then be given under the form

$$\mathbf{H}^P = [\mathbf{x}_b]^T \{ [\mathbf{I}^P] [\boldsymbol{\omega}] + [\mathbf{h}] \}$$

and its derivative is given by

$$\dot{\mathbf{H}}^P = [\mathbf{x}_b]^T \left[[\mathbf{I}^P] [\dot{\boldsymbol{\omega}}] + [\dot{\mathbf{I}}^P] [\boldsymbol{\omega}] + [\boldsymbol{\omega}] \tilde{[\mathbf{I}^P]} [\boldsymbol{\omega}] + [\dot{\mathbf{h}}] + [\boldsymbol{\omega}] \tilde{[\mathbf{h}]} \right]. \quad (14)$$

It is seen that $\dot{\mathbf{H}}^P$ is a function of the angular velocities p, q, r and of the components of the inertia matrix and of the internal angular motion (and possibly their time derivative). In practice some of the rotations are inverted in order to cancel the total internal angular momentum. When it remains, the internal angular momentum is parallel to the plane of symmetry and we will write

$$\mathbf{h} = h_M \cos \alpha_M \hat{\mathbf{x}}_b - h_M \sin \alpha_M \hat{\mathbf{z}}_b \quad (15)$$

with h and α_M (tilt positive for rotation around $\hat{\mathbf{y}}_b$ of the motors) considered as constants. Similarly we will generally assume that this plane of symmetry is also symmetrical for the mass distribution which implies $I_{xy} = I_{yz} = 0$.

III. Dynamics

The principal interactions on an aircraft originate from aerodynamical and propulsive effects as well as from the gravitational field. Further torque (moment) description implies the choice of a reference point – but it should be noted that the change of reference point is not a major problem – we have seen that the resultant moment with respect to a point P with position vector \mathbf{p} is given by

$$\mathbf{L}^P = \int \mathbf{p} \times d\mathbf{F} + \int d\mathbf{M}$$

and is the resultant of the moments of the various forces and of pure torques (interactions with zero force resultant but providing a resultant moment).

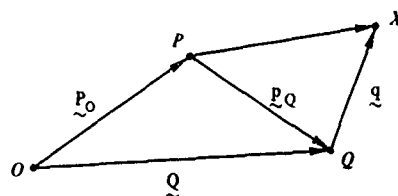
If we wish to determine the moment with respect to a point Q with position vector \mathbf{q} , we can consider that the position vector of a material point X with respect to Q is given by

$$\mathbf{q} = -\mathbf{Q} + \mathbf{P} + \mathbf{p}.$$

The resultant moment $\mathbf{L}^Q \triangleq \int \mathbf{q} \times d\mathbf{F} + \int d\mathbf{M}$ can then be written as

$$\mathbf{L}^Q = \mathbf{L}^P + (\mathbf{P} - \mathbf{Q}) \times \mathbf{F} = \mathbf{L}^P - \mathbf{p}_Q \times \mathbf{F}$$

where \mathbf{p}_Q is the position vector of Q with respect to P and \mathbf{F} is the resultant force.



In particular, if Q is the centre of mass $\mathbf{P} - \mathbf{Q} = -\mathbf{p}_O$ and we write

$$\mathbf{L} = \mathbf{L}^P - \mathbf{p}_O \times \mathbf{F} \quad \text{or} \quad \mathbf{L} = \mathbf{L}^Q + (\mathbf{p}_Q - \mathbf{p}_O) \times \mathbf{F}.$$

As already mentioned the separation between propulsive and aerodynamical interactions is not always obvious and further "propulsive forces" are generally not real forces (interactions between material systems) but rather include terms expressing an exchange of momentum. Nevertheless we will separate the two at least in a first stage.

Propulsive "interactions"

The resultant of "propulsive forces" (thrust) vector \vec{F} in (ISO)) will be easily expressed in the body axis as

$$\mathbf{F}_j^* = F_x \hat{\mathbf{x}}_b + F_y \hat{\mathbf{y}}_b + F_z \hat{\mathbf{z}}_b \quad \text{or} \quad \mathbf{F}_j^* = [\mathbf{x}_b]^T [\mathbf{F}_x].$$

In general this vector will be in the plane of symmetry of the aircraft and we can then write $F_x = F_j^* \cos \alpha_j$, $F_y = 0$ and $F_z = -F_j^* \sin \alpha_j$ (α_j represents the tilt of the "propulsive force"). This vector can be expressed in the airpath base by

$$\mathbf{F}_j^* = [\mathbf{x}_a]^T [\mathbf{F}_{xa}] = [\mathbf{x}_a]^T [\mathbf{A}_{ab}] [\mathbf{F}_x]$$

with

$$[\mathbf{A}_{ab}] = [\mathbf{A}^z(\theta)] [\mathbf{A}^y(-\alpha)]$$

but in general we will be able to write

$$[F_{xa}] = [A^2(\theta)] [A^2(-\alpha - \alpha_j)] [F_j^* \ 0 \ 0]^T$$

or

$$[F_{xa}] = F_j^* [\cos(\alpha + \alpha_j) \cos \beta \quad -\cos(\alpha + \alpha_j) \sin \beta \quad -\sin(\alpha + \alpha_j)]^T \quad (16)$$

where F_j^* is a control variable which depends inter alia on the temperature, the density (altitude) and the pilot controls. The jet torque will be given by $L_j^* = p_N \times F_j^*$ with $p_N = [\hat{x}_b]^T [p_N]$ the point N being the equivalent point of application of the resultant "propulsive forces" and the corresponding moment around the centre of mass will be given by

$$L_j^* = (p_N - p_O) \times F_j^* = [\hat{x}_b]^T [p_N - p_O] \sim [F_x] \quad (17)$$

In general the vector $p_N - p_O$ is also located in the plane of symmetries and consequently the moment L_j^* is aligned with \hat{y}_b or $L_j^* = M^F \hat{y}_b$.

Aerodynamical interactions

In principle, the aerodynamical interactions (resultant aerodynamical force and resultant aerodynamical moment) can be obtained by integrating the aerodynamical interaction on the complete surface of the airplane. The resultant of aerodynamical forces (\vec{R}^A in ISO) will be represented by the vector

$$F_a = X^A \hat{x}_b + Y^A \hat{y}_b + Z^A \hat{z}_b = X_a^A \hat{x}_a + Y_a^A \hat{y}_a + Z_a^A \hat{z}_a = [\hat{x}_b]^T [X^A] = [\hat{x}_a]^T [X_a^A] \quad \text{with} \quad [X^A] = [A_{ba}] [X_a^A]. \quad (18)$$

The resultant moment with respect to the centre of mass will generally be expressed in the body base as

$$L_a = L^A \hat{x}_b + M^A \hat{y}_b + N^A \hat{z}_b = [\hat{x}_b]^T [L^A].$$

Some of these components have particular names and are normalized :

- $-X_a^A$ is the drag (D)
- $-Z_a^A$ is the lift (L)
- Y_a^A is the cross-stream or lateral force (Y_a)
- Y^A is the transverse or sideforce (Y) with $Y^A = \sin \beta X_a^A + \cos \beta Y_a^A$ (or $Y \approx Y_a - D\beta$)
- X^A and Z^A are the axial and normal force (A and N)
- L^A is the rolling aerodynamical moment
- M^A is the pitching aerodynamical moment with respect to the centre of mass (usually the centre of gravity ISO 1.5.4. - see below).
- N^A is the yawing aerodynamical moment

If S is a reference area (generally an equivalent wing area S_L) (ISO 6.6.16) l a reference length (generally the overall length of the aircraft l_R) (ISO 6.2. 1), ρ the density (which must be given as a function of altitude and temperature), the aerodynamical forces and moments can be normalized as

$$\begin{aligned} X_a^A &= \frac{1}{2} \rho V^2 S C_{Xa}^A & \text{where} & \quad -C_{Xa}^A (= C_L) \text{ is the lift coefficient} \\ Z_a^A &= \frac{1}{2} \rho V^2 S C_{Za}^A & \text{where} & \quad -C_{Za}^A (= C_D) \text{ is the drag coefficient} \\ Y_a^A &= \frac{1}{2} \rho V^2 S C_{Ya}^A & \text{where} & \quad C_{Ya}^A \text{ is the cross stream coefficient or } Y^A = \frac{1}{2} \rho V^2 S C_Y^A \text{ with } C_Y^A (= C_Y) \text{ the transverse force coefficient} \\ L^A &= \frac{1}{2} \rho V^2 S l C_L^A & \text{where} & \quad C_L^A \text{ is the rolling moment coefficient} \\ M^A &= \frac{1}{2} \rho V^2 S l C_m^A & \text{where} & \quad C_m^A \text{ is the pitching moment coefficient} \\ N^A &= \frac{1}{2} \rho V^2 S l C_n^A & \text{where} & \quad C_n^A \text{ is the yawing moment coefficient.} \end{aligned}$$

In general the aerodynamical coefficients are functions of the follow quantities

$$C^A = C^A(\alpha, \dot{\alpha}, (\alpha), \beta, (\beta), p, q, r, M, \delta_\rho, \delta_m, \delta_n)$$

where M is the Mach number

$\delta_\rho, \delta_m, \delta_n$ are, respectively, the deflections of the roll pitch and yaw motivators (ISO 1.8.3.11, 12 and 13). For classical systems we have

- $\delta_\rho = \frac{1}{2}(\delta_{aL} - \delta_{aR})$ where δ_a are the rotations of the left and right ailerons (positive around the y axis - aileron down)
- $\delta_m = -\delta_e$ where δ_e is the rotation of the elevator (positive around the y axis - elevator down)
- $\delta_n = -\delta_r$ where δ_r is the rotation of the rudder (positive around the z axis - rudder to the left).

Aerodynamical interactions are also "easily" expressed with respect to the structure and particular points are sometimes chosen to express the moments for instance the aerodynamical centre (A) which is a point around which the pitching moment is constant (does not vary with the angle of attack). The corresponding moments will be written $L_a^A = L^{AA} \hat{x}_b + M^{AA} \hat{y}_b + N^{AA} \hat{z}_b$ and the position of the aerodynamical centre will be given by $p_A = [\hat{x}_b]^T [p_A]$.

The corresponding moment around the centre of mass will be given by

$$L_a = L_a^A + (p_A - p_O) \times F_a = [\hat{x}_b]^T [L^{AA}] + [p_A - p_O] \sim [A_{ba}] [X_a^A] \quad (19)$$

Gravity

The local gravity density \underline{g}^* is obtained by integrating the effects of gravitational attraction produced on a unit mass by the earth mass distribution. If the earth were spherical the resultant would be directed towards the centre of the earth. As the earth is neither spherical nor homogeneous, the local gravity density is not directed towards this centre, moreover it is not aligned with the local normal to the earth ellipsoid. Nevertheless if we combine \underline{g}^* with the centripetal acceleration due to earth rotation we can see that the vector $\underline{g} = \underline{g}^* - \underline{\omega}_0 \times \underline{\omega}_0 \times \underline{R}_p$ is normal to the earth ellipsoid with a very good accuracy for points on the earth surface, this simply expresses the fact that material points left on the earth surface (at sea level) have no tangential *relative* acceleration (this corresponds to an equilibrium for perfect liquids). Higher order effects can be expected, but they have a negligible influence for the motions we are considering and they will be neglected. In the vicinity of the earth surface the vector \underline{g} can be given by the expression

$$\underline{g} = (1 - \frac{2h}{a})\underline{g}_0 (1 + \epsilon \sin^2 \lambda) \underline{z}_g = \underline{g} \underline{z}_g = [\underline{x}_g]^T [\underline{g}] \quad \text{with} \quad \underline{g} = [0 \ 0 \ g]^T \quad g \approx (1 - \frac{2h}{a})(1 + \epsilon \sin^2 \lambda)g_0$$

where h is the altitude with respect to the earth ellipsoid
 g_0 is the value of g at sea level on the equator $g_0 \sim 9,780$ [N/kg]
 ϵ is a coefficient which is related to the eccentricity of the ellipsoid, the difference of moments of inertia of the earth and its angular velocity (with $\epsilon \approx 0,00528$).

The (apparent) weight is then given by

$$\begin{aligned} \underline{F}_g &= m \underline{g} = m [\underline{x}_b]^T [\underline{A}_{bg}] [\underline{g}] = m [\underline{x}_a]^T [\underline{A}_{ag}] [\underline{g}] \\ &= mg [-\sin \gamma_a \underline{x}_a + \sin \mu_a \cos \gamma_a \underline{y}_a + \cos \mu_a \cos \gamma_a \underline{z}_a] \\ &= mg [-\sin \Theta \underline{x}_b + \sin \Phi \cos \Theta \underline{y}_b + \cos \Phi \cos \Theta \underline{z}_b] \end{aligned} \quad (20)$$

The moment of gravitational force around the centre of mass, which coincides with a very good accuracy with the centre of gravity, is zero and the corresponding moment with respect to a point P is given by

$$\underline{L}_g^P = \underline{p}_o \times m \underline{g}.$$

IV. Equations of motion

Choice of reference point

In principle we may choose a point P fixed with respect to the structure (for instance at the location of the instruments, on the pilot's seat ...). The position of the centre of mass with respect to this point can vary with time (fuel consumption, transfer of fluid between tanks ...) but can generally be estimated with sufficient accuracy as $\underline{p}_o = [\underline{x}_b]^T [\underline{p}_o]$.

For dynamical purposes we will transfer all the moments to the centre of mass as the rotational equations of motion then reduce to

$$\underline{\dot{H}} = \underline{L}_a + \underline{L}_j^* = \underline{L}$$

where \underline{L} is the resultant moment and can be written as

$$\underline{L} = L \underline{x}_b + M \underline{y}_b + N \underline{z}_b = [\underline{x}_b]^T [\underline{L}] \quad (21)$$

where $L \ M \ N$ are the rolling pitching and yawing moments (ISO 1.5.5) which are obtained by summing (17) and (19).

Further

$$\underline{H} = [\underline{x}_b]^T [\underline{I}] [\underline{\omega}_b]$$

where $[\underline{I}]$ is the inertia matrix with respect to the mass centre and is related to $[\underline{I}^P]$ by

$$[\underline{I}^P] = [\underline{I}] - m[\underline{p}_o][\underline{p}_o]^T \quad (\text{Steiner's theorem})$$

The vector \underline{p}_o is then given by

$$\begin{aligned} \underline{p}_o &= [\underline{x}_b]^T [\underline{p}_o] + 2 \underline{\omega}_{b1} \times [\underline{x}_b]^T [\underline{p}_o] + \underline{\omega}_{b1} \times \underline{\omega}_{b1} \times \underline{p}_o + \dot{\underline{\omega}}_{b1} \times \underline{p}_o \\ &= [\underline{x}_b]^T [\underline{p}_o] + 2[\underline{\omega}] \underline{\omega} [\underline{p}_o] + [\underline{\omega}] \underline{\omega} [\underline{p}_o] + [\dot{\underline{\omega}}] \underline{\omega} [\underline{p}_o] \end{aligned}$$

or

$$\underline{p}_o = [\underline{x}_a]^T [\underline{a}^P]$$

$$\text{with } [\underline{a}^P] = [\underline{a}_x^P \ \underline{a}_y^P \ \underline{a}_z^P]^T \quad \text{and} \quad [\underline{a}^P] = \underline{A}_{ab} \left[[\underline{p}_o] + 2[\underline{\omega}] \underline{\omega} [\underline{p}_o] + [\dot{\underline{\omega}}] \underline{\omega} [\underline{p}_o] + [\underline{\omega}] \underline{\omega} [\underline{p}_o] \right]. \quad (22)$$

The translational equations can now be written under the form

$$\begin{aligned} m \underline{\ddot{R}} &= \underline{F} \\ m(\underline{\ddot{R}}_p + \underline{\ddot{p}}_o) &= m \underline{g} + \underline{F}_a + \underline{F}_j^* \\ m(\underline{\dot{V}} + \underline{\omega}_0 \times \underline{\omega}_0 \times \underline{R}_p + \underline{a}_r + \underline{\ddot{p}}_o) &= m \underline{g} + \underline{F}_a + \underline{F}_j^* \\ m \underline{\dot{V}} &= -m(\underline{a}_r + \underline{\ddot{p}}_o) + \underline{F}_g + \underline{F}_a + \underline{F}_j^*. \end{aligned}$$

The various vectors appearing in this relation have been expressed in the airpath base.

Now it remains to assemble the results of the previous sections and to present them in a sequence that can be programmed and is suitable for numerical integration. From the previous discussions, it is clear that the rotational equations will be expressed in the body frame and that their reference point will be the centre of mass. The translational equations will relate the motion of the centre of mass to the interactions; they can be expressed in body or air-path. In fact the "x and z equations" have a simplest form if they are expressed in the air-path base; the y equation may also be expressed in the body frame but this choice would somewhat modify the structure of the system of equations. Here we will express the translational equations in the air-path base.

Equation of translation

Using (12) (13) (16) (18) (20) and (22) the equation of translation expressed in the air-path-base can be written as :

$$\begin{aligned} m\dot{V} &= -m(a_x + a_x^P) + F_j^* \cos(\alpha + \alpha_j) \cos\beta + X_a^A - mg \sin\gamma_a \\ m r_a V &= -m(a_y + a_y^P) - F_j^* \cos(\alpha + \alpha_j) \sin\beta + Y_a^A + mg \sin\mu_a \cos\gamma_a \\ -m q_a V &= -m(a_z + a_z^P) - F_j^* \sin(\alpha + \alpha_j) + Z_a^A + mg \cos\mu_a \cos\gamma_a \end{aligned}$$

Equation of rotation

Using (14) and (21) the equation of rotation expressed in the body base can be written as

$$[I] \{\dot{\omega}\} + [\dot{I}] \{\omega\} + [\omega] \sim [I] \{\omega\} + \{\dot{h}\} + [\omega] \sim \{h\} = [L].$$

Kinematics relations

This set of equations will be completed by the kinematical relations (9) (10) and (11).

Variables of the problem

μ	actual longitude of the aircraft
λ	actual latitude of the aircraft
h	altitude with respect to the ground (see level)
V	velocity with respect to the atmosphere
α	angle of attack
β	sideslip angle
μ_a	air path bank angle
X_a	air path track angle
γ_a	air path climb angle
p	rate of roll
q	rate of pitch
r	rate of yaw
t	time independant variable)

Control variables

δ_R	deflection of roll motivators	or $\delta_{a_L}, \delta_{a_R}, \delta_e, \delta_r$ (deflections of ailerons, elevation and rudder)
δ_m	deflection of pitch motivators	
δ_n	deflection of yaw motivators	
$F_i^* = F_i^* $	effective propulsion force.	

Data to be provided

Earth	a, b	earth axes
	g_0, ϵ	local gravity density parameters
	ω_0	angular velocity of the earth (around its axis)
	h_0, μ_0, λ_0	localisation of earth reference point.
Meteorology	W_x, W_y, W_z	wind velocity as a function of μ, λ, h and t
	$\dot{W}_x, \dot{W}_y, \dot{W}_z$	wind acceleration as a function of μ, λ, h and t
	(T)	temperature).

Aircraft configuration

m	mass (as function of time)
\dot{m}	mass flow as function of time and/or controls
$[P_0]$	position of the centre of mass with respect to the body axis system
(\dot{P}_0)	relative velocity of the centre of mass when appropriate)
(\ddot{P}_0)	relative acceleration of the centre of mass when appropriate)
$[I^P]$	inertia matrix with respect to the body axis sytem
(\dot{I}^P)	time derivative of inertia matrix when appropriate)
$[h]$	internal angular momentum (or h_M and α_M)
(\dot{h})	time derivative of the internal angular momentum (or \dot{h}_M)
α_j	direction of propulsive force (or $\frac{[F_x]}{ F_j^* }$)
$[P_N]$	position of effective propulsive force application point with respect to body axis system
l	reference length (or l_R)
S	reference surface (or S_L)

Aerodynamic Parameters

ρ air density (to be given or computed from altitude and temperature)
 (M) mach number)

The following parameters have to be given as function of $\alpha, \dot{\alpha}, \beta, p, q, r, \delta\ell, \delta m, \delta n, (M)$

$-C_{xa}^A$ drag coefficient
 $-C_{za}^A$ lift coefficient
 C_{ya}^A cross stream formce coefficient (or C_y^A transverse force coefficient)
 C_ℓ^A aerodynamic rolling moment coefficient (with respect to the centre of mass)
 C_m^A aerodynamic pitching moment coefficient (with respect to the centre of mass)
 C_n^A aerodynamic yawing moment coefficient (with respect to the centre of mass)

Aerodynamic and propulsions functions to be computed

$$X_a^A = \frac{1}{2} \rho V^2 S C_{xa}^A \quad Z_a^A = \frac{1}{2} \rho V^2 S C_{za}^A \quad Y_a^A = \frac{1}{2} \rho V^2 S C_{ya}^A \quad (= \frac{1}{2} \frac{\rho V^2 S}{\cos \beta} [C_y^A - \tan \beta C_x^A])$$

$$L^A = \frac{1}{2} \rho V^2 S \ell C_\ell^A \quad M^A = \frac{1}{2} \rho V^2 S \ell C_m^A \quad N^A = \frac{1}{2} \rho V^2 S \ell C_n^A$$

$$[F_x] = F_j^* \begin{bmatrix} \cos \alpha_j \\ 0 \\ -\sin \alpha_j \end{bmatrix} \quad [L^A] = \begin{bmatrix} L^A \\ M^A \\ N^A \end{bmatrix}$$

$$[L] = [[p_N] - [p_0]]^T [F_x] + [L^A]$$

When the aerodynamic moments are given as moments with respect to the aerodynamic centre

$$\tilde{L}_a^A = [\tilde{x}_b]^T [L^A] \quad \text{with} \quad \tilde{p}_A = [\tilde{x}_b]^T [p_A]$$

we must be consider the additional relation

$$[L^A] = [L^A] + [[p_A] - [p_0]]^T [X^A]$$

with

$$[X^A] = [A_{ba}] [X_a^A] = \begin{bmatrix} \cos \alpha \cos \beta & -\cos \alpha \sin \beta & -\sin \alpha \\ \sin \beta & \cos \beta & 0 \\ \sin \alpha \cos \beta & -\sin \alpha \sin \beta & \cos \alpha \end{bmatrix} \begin{bmatrix} X_a^A \\ Y_a^A \\ Z_a^A \end{bmatrix}$$

Parameters to be computed

$$d = d^* + h = a - (a-b) \sin^2 \lambda + h \quad d_o = d_o^* + h_o = a - (a-b) \sin^2 \lambda_o + h_o$$

$$\mu_p = \frac{1}{d} [W_x + V \cos \gamma_a \cos \chi_a], \quad \lambda_p = \frac{1}{d \cos \lambda} [W_y + V \cos \gamma_a \sin \chi_a]$$

$$\lambda^* = \lambda + \frac{a-b}{a} \sin 2\lambda, \quad \lambda_p^* = \lambda_p (1 + \frac{2(a-b)}{a} \cos 2\lambda)$$

$$[A_{gi}] [\omega_o] = \omega_o \begin{bmatrix} \cos \lambda^* \\ 0 \\ -\sin \lambda^* \end{bmatrix}, \quad [\omega_{gi}] = (\omega_o + \mu_p) \begin{bmatrix} \cos \lambda^* \\ 0 \\ -\sin \lambda^* \end{bmatrix} + \lambda_p^* \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$$

$$[A_{ag}] = \begin{bmatrix} \cos \gamma_a \cos \chi_a & \cos \gamma_a \sin \chi_a & -\sin \gamma_a \\ -\cos \mu_a \sin \chi_a + \sin \mu_a \sin \gamma_a \cos \chi_a & \cos \mu_a \cos \chi_a + \sin \mu_a \sin \gamma_a \sin \chi_a & \sin \mu_a \cos \gamma_a \\ \sin \mu_a \sin \chi_a + \cos \mu_a \sin \gamma_a \cos \chi_a & -\sin \mu_a \cos \chi_a + \cos \mu_a \sin \gamma_a \sin \chi_a & \cos \mu_a \cos \gamma_a \end{bmatrix}$$

$$[B_{ag}]^1 = \frac{1}{\cos \gamma_a} \begin{bmatrix} \cos \gamma_a & \sin \mu_a \sin \gamma_a & \cos \mu_a \sin \gamma_a \\ 0 & \cos \mu_a \cos \gamma_a & -\sin \mu_a \cos \gamma_a \\ 0 & \sin \mu_a & \cos \mu_a \end{bmatrix}$$

$$[a] = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = [A_{ag}] \left\{ \begin{bmatrix} \dot{W}_x \\ \dot{W}_y \\ \dot{W}_z \end{bmatrix} + [\omega_{gi}]^T \begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} + [A_{gi}] [\omega_o] \sim \begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} + [A_{ag}]^T \begin{bmatrix} V \\ 0 \\ 0 \end{bmatrix} \right\}$$

$$[\omega_p] = \begin{bmatrix} p_p \\ q_p \\ r_p \end{bmatrix} = -[I]^1 \left\{ \begin{bmatrix} p \\ q \\ r \end{bmatrix} + \begin{bmatrix} p \\ q \\ r \end{bmatrix}^T [I] \begin{bmatrix} p \\ q \\ r \end{bmatrix} + [h] \right\} + [\dot{h}] - \begin{bmatrix} L \\ M \\ N \end{bmatrix}$$

$$[A_{ab}] = \begin{bmatrix} \cos\alpha \cos\beta & \sin\beta & \sin\alpha \cos\beta \\ -\cos\alpha \sin\beta & \cos\beta & -\sin\alpha \cos\beta \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix}$$

$$[a^p] = \begin{bmatrix} a_x^p \\ a_y^p \\ a_z^p \end{bmatrix} = [A_{ab}] [\bar{p}_0] + 2 \begin{bmatrix} p \\ q \\ r \end{bmatrix} [\dot{p}_0] + \begin{bmatrix} p_p \\ q_p \\ r_p \end{bmatrix} [p_0] + \begin{bmatrix} p \\ q \\ r \end{bmatrix} [\dot{p}_0] + \begin{bmatrix} p \\ q \\ r \end{bmatrix} [p_0]$$

$$r_a = \frac{1}{V} [-a_y - a_z^p - \frac{F_j^*}{m} \cos(\alpha + \alpha_j) \sin\beta + \frac{Y_a^A}{m} + g \sin\mu_a \cos\gamma_a]$$

$$q_a = \frac{1}{V} [a_z + a_z^p + \frac{F_j^*}{m} \sin(\alpha + \alpha_j) - \frac{Z_a^A}{m} - g \cos\mu_a \cos\gamma_a]$$

$$p_a = \tan\beta q_a + \frac{\cos\alpha}{\cos\beta} p + \frac{\sin\alpha}{\cos\beta} r$$

$$[I] = [I^p] + m [p_0]^\sim [p_0]^\sim \quad \quad \quad [\dot{I}] = [\dot{I}^p] + \dot{m} [p_0]^\sim [p_0]^\sim + 2m [\dot{p}_0]^\sim [p_0]^\sim$$

Equation of motion

$$\begin{aligned} \dot{V} &= -a_x \dot{\lambda} + \frac{F_j^*}{m} \cos(\alpha + \alpha_j) \cos\beta + \frac{X_a^A}{m} - g \sin\gamma_a \\ \dot{\alpha} &= q - \sin\beta p_a - \cos\beta q_a \quad (\text{or } \dot{\alpha} = q - \frac{1}{\cos\beta} q_a - \tan\beta (\cos\alpha p + \sin\alpha r)) \\ \dot{\beta} &= r_a + \sin\alpha p - \cos\alpha r \end{aligned} \quad \left. \begin{aligned} & \\ & \\ & \end{aligned} \right\} \text{dynamical equations}$$

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = -[I]^{-1} \left\{ [\dot{I}] \begin{bmatrix} p \\ q \\ r \end{bmatrix} + \begin{bmatrix} p \\ q \\ r \end{bmatrix}^\sim [\dot{I}] \begin{bmatrix} p \\ q \\ r \end{bmatrix} + [h] + [\dot{h}] - \begin{bmatrix} L \\ M \\ N \end{bmatrix} \right\}$$

$$\begin{bmatrix} \dot{\lambda}_a \\ \dot{\gamma}_a \\ \dot{\chi}_a \end{bmatrix} = [B_{ag}]^{-1} \begin{bmatrix} p_a \\ q_a \\ r_a \end{bmatrix} - [A_{ag}] [\omega_{gj}] \quad \left. \begin{aligned} & \\ & \end{aligned} \right\} \text{kinematical equations}$$

$$\begin{aligned} \dot{\lambda} &= \frac{1}{d} [W_x + V \cos\gamma_a \cos\chi_a] \\ \dot{\mu} &= \frac{1}{d \cos\lambda} [W_y + V \cos\gamma_a \sin\chi_a] \\ \dot{h} &= -W_z + V \sin\gamma_a \end{aligned}$$

Position with respect to the normal earth fixed axis system

$$A_{og} = \begin{bmatrix} \cos\lambda^* \cos\lambda_o^* + \cos\Delta\mu \sin\lambda^* \sin\lambda_o^* & \sin\lambda_o^* \sin\Delta\mu & -\sin\lambda^* \cos\lambda_o^* + \cos\Delta\mu \cos\lambda^* \sin\lambda_o^* \\ -\sin\Delta\mu \sin\lambda^* & \cos\Delta\mu & -\sin\Delta\mu \cos\lambda^* \\ -\cos\lambda^* \sin\lambda_o^* + \cos\Delta\mu \sin\lambda^* \cos\lambda_o^* & \cos\lambda_o^* \sin\Delta\mu & \sin\lambda^* \sin\lambda_o^* + \cos\Delta\mu \cos\lambda^* \cos\lambda_o^* \end{bmatrix}$$

$$R_p = \begin{bmatrix} -d^* \sin(\lambda^* - \lambda) \\ 0 \\ -d^* \cos(\lambda^* - \lambda) - h \end{bmatrix} = \begin{bmatrix} -(a-b) \sin 2\lambda \\ 0 \\ -d \end{bmatrix} \quad \quad R_o = \begin{bmatrix} -d_o^* \sin(\lambda_o^* - \lambda_o) \\ 0 \\ -d_o^* \cos(\lambda_o^* - \lambda_o) - h_o \end{bmatrix} = \begin{bmatrix} -(a-b) \sin 2\lambda_o \\ 0 \\ -d_o \end{bmatrix}$$

$$\begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} = [A_{og}] [R_p] - [R_o]$$

$$\underline{p}_o = X_o \underline{\hat{x}}_o + Y_o \underline{\hat{y}}_o + Z_o \underline{\hat{z}}_o$$

V. Simplified models and Conclusions

The equations of motion reduce to simpler forms when additional assumptions are used.

• Motions of centre of mass

One can assume that the aircraft reference point coincides with its centre of mass. In this case $\underline{p}_0 = 0$ and consequently $\underline{\dot{a}}^P = 0$. The equation of motion then provide the motion of the centre of mass.

• Dynamically controlled systems

It should be noted the dynamical equations (equations in $\dot{V}, \dot{\alpha}, \dot{\beta}, \dot{p}, \dot{q}, \dot{r}$ together with the algebraic relations in p_a, q_a, r_a), relate the relative velocity of the system (with respect to the atmosphere) and its angular velocity to the control variables ($F_j^*, \delta_c, \delta_m, \delta_n$). It may often be considered that the motion of the aircraft is perfectly controlled by the pilot or automatically controlled. i.e. that the vectors \underline{V} and $\underline{\omega}$ have assigned values (given as a function of time). Alternatively, one may consider that the components of these vectors are measured during the motion and are thus available as functions of time.

It should be noted that the components of the \underline{V} vector in the body axis system with (ISO 1.3.4.)

$$\underline{V} = u \underline{\hat{x}}_b + v \underline{\hat{y}}_b + w \underline{\hat{z}}_b = [\underline{\hat{x}}_b]^T \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

are related to the V, α and β variables by

$$u = V \cos \alpha \cos \beta \quad v = V \sin \beta \quad w = V \cos \beta \sin \alpha$$

If V and ω are known as functions of time so are the variables V, α, β, p, q and r . In these cases, the dynamical equations do not provide useful information (besides the actual values of the control variables) and they can be discarded. One is left with a purely kinematical system consisting of the kinematical equations and relations between p_a, q_a, r_a and α, β, p, q, r ; these latter relations are usefully written under the form

$$p_a = -\sin \beta \dot{\alpha} + \cos \alpha \cos \beta p + \sin \beta q + \sin \alpha \cos \beta r$$

$$q_a = -\cos \beta \dot{\alpha} - \cos \alpha \sin \beta p + \cos \beta q - \sin \alpha \sin \beta r$$

$$r_a = \dot{\beta} - \sin \alpha p + \cos \alpha r$$

The variables p_a, q_a and r_a are also given functions of time. (This confirms the fact that the kinematical equations are sufficient to describe the motion).

• Airpath controlled systems

For most (elementary) trajectories (en route, constant climbing and descent, perfect turning) one can consider that the variables γ_a and χ_a (air-path climb and track angles) are also known as function of time. The motion is then described by

$$\dot{\lambda} = \frac{1}{d} [W_x + V \cos \gamma_a \cos \chi_a]$$

$$\dot{\mu} = \frac{1}{d \cos \lambda} [W_y + V \cos \gamma_a \sin \chi_a]$$

$$\dot{h} = -W_z + V \sin \gamma_a$$

$$d = a - (a-b) \sin^2 \lambda + h \quad \lambda^* = \lambda + \frac{a-b}{a} \sin 2\lambda$$

$$\Delta \mu = \mu_o + \Delta \mu \quad \lambda_o^* = \lambda_o + \frac{a-b}{a} \sin 2\lambda_o$$

$$\begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} = [A_{og}] [R_p] - [R_o]$$

$$[A_{og}] = [A^{(v)}(-\lambda_o^*)] [A^{(h)}(\Delta \mu)] [A^{(v)}(\lambda^*)]$$

For large range (> 300 km) the components of the relative position vector must be computed without further approximation.

• Non rotating earth approximation

In this case, the normal earth fixed axis system is assumed to be inertial, the point O and the $\{\underline{\hat{x}}_o\}$ frame are fixed ($\dot{R}_o = 0 \quad \omega_{oi} = 0$).

• Flat earth approximation

If the earth is considered to be flat (and fixed) the aircraft carried earth axis system always coincides with $\{\underline{\hat{x}}_o\}$ i.e. $\{\underline{\hat{x}}_g\} \equiv \{\underline{\hat{x}}_o\}$ and consequently $\underline{\omega}_{gi} = 0$. Furthermore the vector \underline{a}_i reduces to the wind acceleration. The velocity with respect to earth $\underline{V}_K = u_{Kg} \underline{\hat{x}}_g + v_{Kg} \underline{\hat{y}}_g + w_{Kg} \underline{\hat{z}}_g$ is now expressed in an inertial base and is equal to the time derivative of the relative position vector

$$\underline{P}_o = X_o \underline{\hat{x}}_g + Y_o \underline{\hat{y}}_g + Z_o \underline{\hat{z}}_g$$

i.e.

$$u_{Kg} = \dot{X}_o \quad v_{Kg} = \dot{Y}_o \quad w_{Kg} = \dot{Z}_o$$

Finally the kinematical equations reduce to the system

$$\dot{X}_o = W_x + V \cos \gamma_a \cos \chi_a$$

$$\dot{Y}_o = W_y + V \cos \gamma_a \sin \chi_a$$

$$\dot{Z}_o = W_z - V \sin \gamma_a = -\dot{h}$$

$$\begin{bmatrix} \dot{\mu}_a \\ \dot{\gamma}_a \\ \dot{\chi}_a \end{bmatrix} = [B_{ag}]^{-1} \begin{bmatrix} p_a \\ q_a \\ r_a \end{bmatrix}$$

For dynamical controlled systems these equations are sufficient describe the motion, but it must also be assumed that the controls are able to compensate for wind accelerations as well as for the acceleration produced by the earth rotation.

• *Middle range position approximations*

The compositions of the position of the aircraft with respect to a fixed point on the earth

$$\begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix} = [A^{(y)}(-\lambda_o^*)][A^{(x)}(\Delta\mu)][A^{(y)}(\lambda^*)][R_p] - [R_o]$$

are expressed as function of trigonometric functions of the variables $\lambda, \lambda^*, \lambda_o^*$ and $\Delta\mu = \mu - \mu_o$.

These functions can be developed in Taylor series around their values for λ_o (for the variables λ, λ_o^* and λ^*) and μ_o (for μ) with

$$\begin{aligned} \lambda &= \lambda_o + \Delta\lambda & \lambda_o^* &= \lambda_o + \frac{a-b}{a} \sin 2\lambda_o \\ \mu &= \mu_o + \Delta\mu & \lambda^* &= \lambda_o^* + (1 + 2 \frac{a-b}{a} \cos 2\lambda_o) \Delta\lambda \\ \Delta h &= h - h_o & R_o &= d_o \\ \sin \Delta x &= \Delta x & \cos \Delta x &= 1 - \frac{(\Delta x)^2}{2} \\ d &= R_o + \Delta h - (a-b) \sin 2\lambda_o \Delta\lambda. \end{aligned}$$

Up to quadratic terms in $\Delta\lambda, \Delta\mu$ and $\frac{a-b}{a}$ (double products are neglected) the following relations are obtained

$$\begin{aligned} X_o &= R_o \Delta\lambda + \Delta h \Delta\lambda + R_o \sin \lambda_o \cos \lambda_o \frac{(\Delta\mu)^2}{2} \\ Y_o &= R_o \cos \lambda_o \Delta\mu + \cos \lambda_o \Delta h \Delta\lambda - R_o \sin \lambda_o \Delta\mu \Delta\lambda \\ Z_o &= -\Delta h + R_o \left[\frac{(\Delta\lambda)^2}{2} + \frac{(\cos \lambda_o \Delta\mu)^2}{2} \right] \end{aligned}$$

It should be noted that these relations depend only on the coordinates of the reference point and of the geographical latitude and longitude of the aircraft. This approximation is quite satisfactory for ranges up to the order of 250 km.

When quadratic terms are neglected, these equations reduced to

$$X_o = R_o \Delta\lambda \quad Y_o = R_o \cos \lambda_o \Delta\mu \quad Z_o = -\Delta h$$

By derivation with respect to time, one obtains a result equivalent to the flat earth approximation.

For ranges up to 25 km, this approximation leads to error on touch down times of the order of a few seconds (~ 5 s.). These errors are of the same order as those due to an uncertainty of 3 m/s (5 knots) on the wind velocities.

For similar ranges an error of the order of one second could, in principle, be forthcoming if the uncertainty on wind components falls to one knot and if the second order approximation is used. The same accuracy could also be obtained for range of the order of 250 km but in this case a (small) number of corrections on the dynamical parameters should be carried out along the trajectory. The main difficulty remains the determination of in route wind velocities. It is clear that one can take advantage of the values of these corrections to improve the wind knowledge in particular in the neighborhood of the reference point (when the traffic is sufficiently heavy).

It can be concluded that for accurate ATC operations, flat earth approximation is not sufficient except for range of the order of 5 km. But the second order approximation provides useful results for much large ranges (up to 250). For longer trajectories (re-entry for instance) the complete non linear equations must be implemented.

The complete set of equations is available under the form of an alphanumerical subroutine under development at the University of Louvain, in collaboration with M.J. Lemaître and Eurocontrol. The corresponding computer programme written in PASCAL, provides the equation of motion (in fully developed form or via intermediate parameters). These outputs can be used as subroutines in FORTRAN programmes.

Persons interested in these programmes are welcome to contact the author.

Appendix : Useful vector and matrix operations

Scalar and vector products

P1. The scalar product of two vectors expressed in the same base $\underline{\tilde{X}}_1 = [\underline{\tilde{x}}]^T [X_1]$ and $\underline{\tilde{X}}_2 = [\underline{\tilde{x}}]^T [X_2]$

with
$$\underline{\tilde{x}} = \begin{bmatrix} \underline{\tilde{x}} \\ \underline{\tilde{y}} \\ \underline{\tilde{z}} \end{bmatrix}, [X_1] = \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}, [X_2] = \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix}$$
 is given by

$$\underline{\tilde{X}}_1 \cdot \underline{\tilde{X}}_2 = X_1 X_2 + Y_1 Y_2 + Z_1 Z_2 = [X_1]^T [X_2] = [X_2]^T [X_1];$$

where the subscript ()^T means "transposed"

P2. their vector products is

$$\underline{\tilde{X}}_1 \times \underline{\tilde{X}}_2 = (Y_1 Z_2 - Y_2 Z_1) \underline{\tilde{x}} + (Z_1 X_2 - Z_2 X_1) \underline{\tilde{y}} + (X_1 Y_2 - X_2 Y_1) \underline{\tilde{z}} = [\underline{\tilde{x}}]^T [X_1] \tilde{[X_2]} = - [\underline{\tilde{x}}]^T [X_2] \tilde{[X_1]}$$

where a "tilded" matrix is a skew-symmetric matrix formed from the elements of the corresponding matrix

$$[X] = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \text{ as } [X] \tilde{=} \begin{bmatrix} 0 & -Z & Y \\ Z & 0 & -X \\ -Y & X & 0 \end{bmatrix}.$$

Change of base

Several bases can be used in a problem; they will be written $\{\underline{\tilde{x}}_i \underline{\tilde{y}}_j \underline{\tilde{z}}_k\}$, $\{\underline{\tilde{x}}_j \underline{\tilde{y}}_i \underline{\tilde{z}}_j\}$, $\{\underline{\tilde{x}}_k \underline{\tilde{y}}_k \underline{\tilde{z}}_k\}$.

P3. The base $\{\underline{\tilde{x}}_i \underline{\tilde{y}}_j \underline{\tilde{z}}_k\}$ will be assumed to be the canonical base. The elements of other bases being vectors can be expressed as :

$$\underline{\tilde{x}}_j = a_{11} \underline{\tilde{x}}_i + a_{12} \underline{\tilde{y}}_j + a_{13} \underline{\tilde{z}}_i, \underline{\tilde{y}}_j = a_{21} \underline{\tilde{x}}_i + a_{22} \underline{\tilde{y}}_j + a_{23} \underline{\tilde{z}}_i, \underline{\tilde{z}}_j = a_{31} \underline{\tilde{x}}_i + a_{32} \underline{\tilde{y}}_j + a_{33} \underline{\tilde{z}}_i.$$

P4. This linear relations can be written in matrix form as $[\underline{\tilde{x}}_j] = [A_{ji}] [\underline{\tilde{x}}_i]$ with $A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$.

P5. As the vector $\underline{\tilde{x}}_j$, $\underline{\tilde{y}}_j$ and $\underline{\tilde{z}}_j$ are orthogonal (their scalar product is zero and their norm are equal to one) the matrix $[A_{ji}]$ is an orthogonal matrix and has the following properties :

$$\text{determinant } [A_{ji}] = 1 \quad [A_{ji}]^{-1} = [A_{ji}]^T.$$

P6. We can also write $[\underline{\tilde{x}}_i] = [A_{ij}] [\underline{\tilde{x}}_j] = [A_{ji}]^{-1} [\underline{\tilde{x}}_j]$ and it follows that $[A_{ij}] = [A_{ji}]^T$.

P7. If we write $[\underline{\tilde{x}}_k] = [A_{kj}] [\underline{\tilde{x}}_j] = [A_{ki}] [\underline{\tilde{x}}_i]$ we can verify the following transition property : $[A_{ki}] = [A_{kj}] [A_{ji}]$.

P8. We can partition the matrix A_{ji} in rows and columns as $A_{ji} = [X_j^T \ Y_j^T \ Z_j^T]^T = [X_i \ Y_i \ Z_i]$ and thus allows us to write

$$\underline{\tilde{x}}_j = [\underline{\tilde{x}}_i]^T [X_j], \underline{\tilde{y}}_j = [\underline{\tilde{x}}_i]^T [Y_j], \underline{\tilde{z}}_j = [\underline{\tilde{x}}_i]^T [Z_j]$$

and also

$$\underline{\tilde{x}}_i = [\underline{\tilde{x}}_j]^T [X_i], \underline{\tilde{y}}_i = [\underline{\tilde{x}}_j]^T [Y_i], \underline{\tilde{z}}_i = [\underline{\tilde{x}}_j]^T [Z_i].$$

The rows of the matrix A_{ji} represent the components of the j-base vectors in the i-base and the columns of A_{ji} are the components of the i-base vectors in the j-base.

P9. If a vector $\underline{\tilde{X}}$ is expressed in two different bases as

$$\underline{\tilde{X}} = [\underline{\tilde{x}}_j]^T [X_j] = [\underline{\tilde{x}}_i]^T [X_i]$$

the relations above lead to the following relation

$$[X_j] = [A_{ji}] [X_i];$$

the components of a vector are transformed in the same way as the corresponding vector bases (vectors are first order tensors). Similarly "tilded" matrices are transformed according to the relation

$$[X_j] \tilde{=} = [A_{ji}] [X_i] \tilde{=} [A_{ji}]^T [X_i] \tilde{=} [A_{ji}] [X_i] \tilde{=} [A_{ji}]$$

(tilded matrices correspond to second order tensors).

Time derivative

P10 The time derivative of a vector $\underline{\tilde{X}} = [\underline{\tilde{x}}_i]^T [X_i]$ expressed in the canonical base is by definition $\dot{\underline{\tilde{X}}} = [\dot{\underline{\tilde{x}}}_i]^T [\dot{X}_i]$.

The time derivative of a vector expressed in another base can be obtained by the following procedure. First the vector can be expressed in the canonical base for which the definition holds i.e. $\underline{\tilde{X}} = [\underline{\tilde{x}}_j]^T [X_j] = [\underline{\tilde{x}}_i]^T [A_{ji}]^T [X_j]$.

Then

$$\dot{\underline{\tilde{X}}} = [\dot{\underline{\tilde{x}}}_i]^T \frac{d}{dt} ([A_{ji}]^T [X_j]) = [\dot{\underline{\tilde{x}}}_i]^T [\dot{[A_{ji}]}^T [X_j] + [A_{ji}]^T [\dot{X}_j]].$$

The derivative can be expressed in the j-bases as

$$\dot{\tilde{X}} = [\tilde{x}_j]^T [\dot{\tilde{X}}_j] + [\tilde{x}_j]^T [A_{ji}] [\dot{A}_{ji}]^T [X_j].$$

The first term in this expression is called the relative time derivative indeed this would have been the time derivative of the vector if the j-base were the canonical base.

P11 As we have $[A_{ji}] [A_{ji}]^T = [E]$, where E is the unit-matrix, whence $\frac{d}{dt} [A_{ji}] [A_{ji}]^T = 0$, it can be checked that the matrix $[A_{ji}] [\dot{A}_{ji}]^T$ is a skew symmetrical matrix and can be written as $[A_{ji}] [\dot{A}_{ji}]^T = [\omega_{ji}]^\sim$.

This is equivalent to the relation $[\dot{A}_{ji}] = -[\omega_{ji}]^\sim [A_{ji}]$.

P12 The vector defined as $\tilde{\omega}_{ji} = [\tilde{x}_j]^T [\omega_{ji}]$ is called the angular velocity of the j-base with respect to the canonical base.

P13 Using the definition of the vector product, the time derivative of \tilde{X} can be written as

$$\dot{\tilde{X}} = [\tilde{x}_j]^T [\dot{\tilde{X}}_j] + \tilde{\omega}_{ji} \times \tilde{X}.$$

P14 Similarly one can be defined relative angular velocities of the k-base with respect to the j-base from the relations $[A_{kj}] [\dot{A}_{kj}]^T = [\omega_{kj}]^\sim$ as $\tilde{\omega}_{kj} = [\tilde{x}_k] [\omega_{kj}]$

P15 It can be checked that the angular velocities have the following additive property :

which implies

$$\begin{aligned} \tilde{\omega}_{ki} &= \tilde{\omega}_{kj} + \tilde{\omega}_{ji} \\ [\omega_{ki}] &= [\omega_{kj}] + [A_{kj}] [\omega_{ji}]. \end{aligned}$$

P16 With $[\omega_{kj}] = [\omega_{ki}] - [A_{kj}] [\omega_{ji}]$ and then $[\omega_{kj}]^\sim = [\omega_{ki}]^\sim - [A_{kj}] [\omega_{ji}]^\sim [A_{kj}]^T$ the relation $[\dot{A}_{kj}] = -[\omega_{kj}]^\sim [A_{kj}]$ leads to usefull relation :

$$[\dot{A}_{kj}] = [A_{kj}] [\omega_{ji}]^\sim - [\omega_{ki}]^\sim [A_{kj}].$$

P17 These relations also imply that $\tilde{\omega}_{ji} = -\tilde{\omega}_{ij}$ which is equivalent to

$$[\omega_{ij}] = -[A_{ij}] [\omega_{ji}] \quad \text{and} \quad [\omega_{ji}]^\sim = -[A_{ji}] [\omega_{ij}]^\sim [A_{ji}].$$

P18 The elementary rotation matrices $[A_{kj}^{(x)}]$, $[A_{kj}^{(y)}]$ and $[A_{kj}^{(z)}]$ correspond to rotations around the axes $\tilde{x}_k \equiv \tilde{x}_j$, $\tilde{y}_k \equiv \tilde{y}_j$ and $\tilde{z}_k \equiv \tilde{z}_j$ respectively, the corresponding rotation angles $\theta_x, \theta_y, \theta_z$ being positive if the rotation respects the cyclic permutation

$$\begin{array}{ccc} & \tilde{x} & \\ \nearrow & & \searrow \\ \tilde{z} & - & \tilde{y} \end{array}$$

P19 The relative angular velocities corresponding to these elementary rotations have an obvious interpretation as these vectors are aligned with the rotation axis with an amplitude equal to the time derivative of the rotation angle.

$$\begin{aligned} \tilde{\omega}_{kj}^{(x)} &= \dot{\theta}_x \tilde{x}_k = \dot{\theta}_x \tilde{x}_j & \tilde{\omega}_{kj}^{(y)} &= \dot{\theta}_y \tilde{y}_k = \dot{\theta}_y \tilde{y}_j & \tilde{\omega}_{kj}^{(z)} &= \dot{\theta}_z \tilde{z}_k = \dot{\theta}_z \tilde{z}_j. \end{aligned}$$

P20 An arbitrary orientation can be obtained by a sequence of three elementary rotations around independant axes.

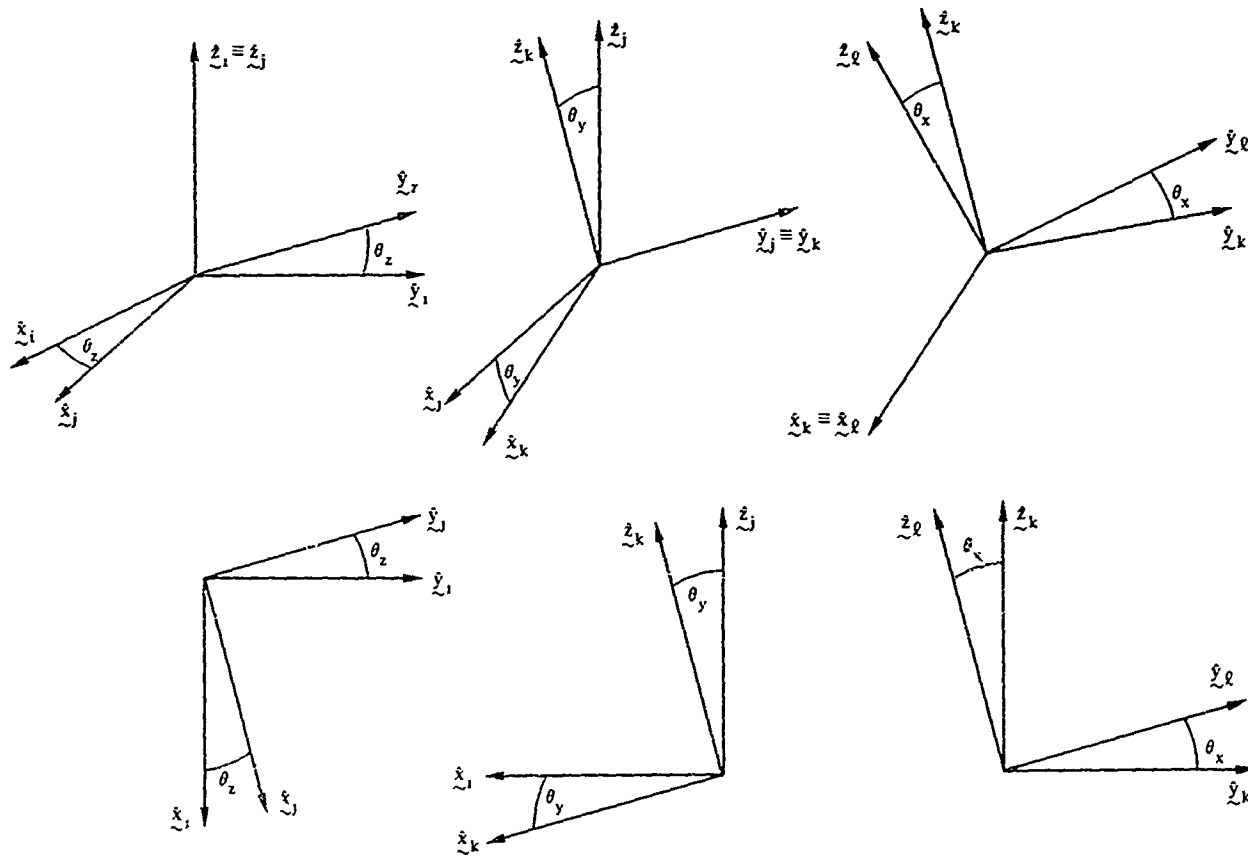
P21 If we write

$$[\tilde{x}_j] = [A_{ji}^{(\alpha)}(\theta_\alpha)] [\tilde{x}_i] \quad [\tilde{x}_k] = [A_{kj}^{(\beta)}(\theta_\beta)] [\tilde{x}_j] \quad [\tilde{x}_\ell] = [A_{\ell k}^{(\gamma)}(\theta_\gamma)] [\tilde{x}_k] \quad \text{and} \quad [\tilde{x}_\ell] = [A_{\ell i}](\tilde{x}_i)$$

we obtain the relation

$$[A_{\ell i}] = [A_{\ell k}^{(\gamma)}] [A_{kj}^{(\beta)}] [A_{ji}^{(\alpha)}] = [A_{\ell i}(\theta_\alpha, \theta_\beta, \theta_\gamma)].$$

The matrix $[A_{\ell i}]$ is a function of the three elementary rotation angles. This matrix being orthogonal there are six constraints between its nine elements and three independant variables suffices to completely describe the matrix, as an example let us consider a sequence of rotations around the z- y- and x-axes respectively ($\alpha = z, \beta = y, \gamma = x$).



$$[\tilde{x}_j] = [A_{ji}^{(z)}(\theta_z)] [\tilde{x}_i]$$

$$[A_{ji}^{(z)}] = \begin{bmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\omega_{ji}^{(z)} = \dot{\theta}_z \tilde{z}_i = \dot{\theta}_z \tilde{z}_j$$

$$[\tilde{x}_k] = [A_{kj}^{(y)}(\theta_y)] [\tilde{x}_j]$$

$$[A_{kj}^{(y)}] = \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{bmatrix}$$

$$\omega_{kj}^{(y)} = \dot{\theta}_y \tilde{y}_j = \dot{\theta}_y \tilde{y}_k$$

$$[\tilde{x}_l] = [A_{lk}^{(x)}(\theta_x)] [\tilde{x}_k]$$

$$[A_{lk}^{(x)}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{bmatrix}$$

$$\omega_{lk}^{(x)} = \dot{\theta}_x \tilde{x}_k = \dot{\theta}_x \tilde{x}_l$$

P22 It should be noted that the elementary rotation matrices have the following property

$$[A_{ij}^{(\alpha)}] = [A_{ji}^{(\alpha)}]^T = [A_{ji}^{(\alpha)}](-\theta_\alpha).$$

We can also write

$$[\tilde{x}_k] = [A_{kj}^{(y)}] [A_{ji}^{(z)}] [\tilde{x}_i] = [A_{ki}] [\tilde{x}_i]$$

$$[\tilde{x}_l] = [A_{lk}^{(x)}] [A_{kj}^{(y)}] [\tilde{x}_j] = [A_{lj}] [\tilde{x}_j] = [A_{lk}^{(x)}] [A_{kj}^{(y)}] [A_{ji}^{(z)}] [\tilde{x}_i] = [A_{li}] [\tilde{x}_i]$$

with

$$[A_{ki}] = [A_{kj}^{(y)}] [A_{ji}^{(z)}] = \begin{bmatrix} \cos\theta_y \cos\theta_z & \cos\theta_y \sin\theta_z & -\sin\theta_y \\ -\sin\theta_z & \cos\theta_z & 0 \\ \sin\theta_y \cos\theta_z & \sin\theta_y \sin\theta_z & \cos\theta_y \end{bmatrix}$$

$$[A_{lj}] = [A_{lk}^{(x)}] [A_{kj}^{(y)}] = \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ \sin\theta_x \sin\theta_y & \cos\theta_x & \sin\theta_x \cos\theta_y \\ \cos\theta_x \sin\theta_y & -\sin\theta_x & \cos\theta_x \cos\theta_y \end{bmatrix}$$

$$[A_{li}] = [A_{lk}^{(x)}] [A_{kj}^{(y)}] [A_{ji}^{(z)}] = \begin{bmatrix} \cos\theta_y \cos\theta_z & \cos\theta_y \sin\theta_z & -\sin\theta_y \\ -\cos\theta_x \sin\theta_z + \sin\theta_x \sin\theta_y \cos\theta_z & \cos\theta_x \cos\theta_z + \sin\theta_x \sin\theta_y \sin\theta_z & \sin\theta_x \cos\theta_y \\ \sin\theta_x \sin\theta_z + \cos\theta_x \sin\theta_y \cos\theta_z & -\sin\theta_x \cos\theta_z + \cos\theta_x \sin\theta_y \sin\theta_z & \cos\theta_x \cos\theta_y \end{bmatrix}$$

$$\omega_{ki} = \omega_{kj}^{(y)} + \omega_{ji}^{(z)} = \dot{\theta}_y \tilde{y}_j + \dot{\theta}_z \tilde{z}_j$$

$$\omega_{li} = \omega_{lk}^{(x)} + \omega_{kj}^{(y)} + \omega_{ji}^{(z)} = \dot{\theta}_x \tilde{x}_k + \dot{\theta}_y \tilde{y}_j + \dot{\theta}_z \tilde{z}_j = [\tilde{x}_l] [\omega_{li}]$$

P23 In order to obtain the elements of the matrix $[\omega_{li}]$ we require the components of \tilde{y}_j and \tilde{z}_j in the l -base i.e. the second and third column of the matrix A_{lj} .

Finally

$$[\omega_{qi}] = \begin{bmatrix} 1 & 0 & -\sin\theta_y \\ 0 & \cos\theta_x & \sin\theta_x \cos\theta_y \\ 0 & -\sin\theta_x & \cos\theta_x \cos\theta_y \end{bmatrix} \begin{bmatrix} \dot{\theta}_x \\ \dot{\theta}_y \\ \dot{\theta}_z \end{bmatrix} = [B_{qi}] [\dot{\theta}] \quad \text{with} \quad [\theta] = \begin{bmatrix} \theta_x \\ \theta_y \\ \theta_z \end{bmatrix}.$$

P24 This relation can be inverted when determinant $[B] \neq 0$ i.e. when $\cos\theta_y \neq 0$ ($\theta_y \neq \pm \frac{\pi}{2}$) under the form

$$[\dot{\theta}] = \begin{bmatrix} \dot{\theta}_x \\ \dot{\theta}_y \\ \dot{\theta}_z \end{bmatrix} = \frac{1}{\cos\theta_y} \begin{bmatrix} \cos\theta_y & \sin\theta_x \sin\theta_y & \cos\theta_x \sin\theta_y \\ 0 & \cos\theta_x \cos\theta_y & -\sin\theta_x \cos\theta_y \\ 0 & \sin\theta_x & \cos\theta_x \end{bmatrix} [\dot{\omega}_{qi}] = [B_{qi}]^{-1} [\omega_{qi}].$$

P25 If the matrix $[A_{qi}]$ is given one can determine the angles $\theta_x, \theta_y, \theta_z$ (except when the elements 11, 12, 32 and 33 of this matrix are zero, the elements 13 being equal to ± 1).

In the general case we have

$$\theta_y = \sin^{-1} [-[A_{qi}]_{31}] \quad \text{i.e. } \theta_y = \theta_y^* \text{ or } \theta_y = \pi - \theta_y^*$$

$$\theta_x = \sin^{-1} \left[\frac{[A_{qi}]_{32}}{\cos\theta_y} \right] = \cos^{-1} \left[\frac{[A_{qi}]_{33}}{\cos\theta_y} \right] \quad \text{i.e. } \theta_x = \theta_x^* \text{ or } \theta_x = \pi + \theta_x^*.$$

$$\theta_z = \sin^{-1} \left[\frac{[A_{qi}]_{12}}{\cos\theta_y} \right] = \cos^{-1} \left[\frac{[A_{qi}]_{11}}{\cos\theta_y} \right] \quad \text{i.e. } \theta_z = \theta_z^* \text{ or } \theta_z = \pi + \theta_z^*.$$

One can not switch from one solution to the other without crossing through the singular solution $\theta_y = \pm \frac{\pi}{2}$.

In this case the matrix $[A_{qi}]$ is given by

$$[A_{qi}] = \begin{bmatrix} 0 & 0 & \mp 1 \\ \pm \sin(\theta_x \mp \theta_z) & \cos(\theta_x \mp \theta_z) & 0 \\ \pm \cos(\theta_x \mp \theta_z) & -\sin(\theta_x \mp \theta_z) & 0 \end{bmatrix}.$$

and it is not possible to distinguish between θ_x and θ_z — indeed in this case the first and third axes of elementary rotation coincide (they are not independent). Such a situation must be avoided — this can be done by changing the sequence of elementary rotations or by defining the problem in other terms. Another solution is to define the orientation by use of Euler parameters (quaternions) but this problem will not be considered here.

THE APPLICATION OF TRAJECTORY PREDICTION ALGORITHMS FOR
PLANNING PURPOSES IN THE NETHERLANDS ATC-SYSTEM

by

J.N.P. Beers, T.B. Dalm, J.M. ten Have
National Aerospace Laboratory (NLR)
Anthony Fokkerweg 2
1059 CM Amsterdam
THE NETHERLANDS

H. Visscher

The Netherlands Department of Civil Aviation (RLD)
P.O. Box 7601
Havenmeesterweg
1118 ZJ Schiphol
THE NETHERLANDS

SUMMARY

The paper first describes briefly some relevant aspects of the Netherlands ATC-environment, it then gives the basic set-up of the trajectory prediction module, the improvements that have been realised so far and the performance figures. Furthermore it lists the applications of the trajectory prediction results in the system. Some of these applications such as data distribution rules, presentation of Estimated Times of Arrival (ETA's), Boundary Estimates etc. are only briefly mentioned. Others are given more attention; among these are: long-term detection of conflicts for overflying aircraft, planning of inbound traffic for Schiphol Airport and planning of departure times for an efficient engine start-up procedure.

LIST OF ABBREVIATIONS

ABR	Abeam Bergen RP
ACC	Area Control Centre
AFL	Assigned Flight Level (level at which aircraft are handed over to an adjacent centre)
ARK	Arkon RP
ATA	Actual Time of Arrival
ATC	Air Traffic Control
ATD	Actual Time of Departure
ATS	Air Traffic Services
BLF	Blufa RP
CFL	Current Flight Level (level at which aircraft are accepted from an adjacent centre)
CP	Calculation Point
DEST	Airport of Destination
DFT	Distance from Touchdown
EAT	Expected Approach Time
ETA	Estimated Time of Arrival
FIR	Flight Information Region
FMS	Flight Management System
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organisation
IFL	Intermediate Flight Level (level at which aircraft will pass the SPY-area)
KST	Korte Estimate (Short Estimate)
LAS	Latest Assigned Slottime
LIV	Landing Interval
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)
NM	Nautical Mile
NYK	Nyke RP
PAM	Pampus RP
RETD	Revised Estimated Time of Departure
RFL	Requested Flight Level (pilot's requested flight level according to the flight plan)
RLD	Rijksluchtvaartdienst (Department of Civil Aviation)
ROC	Rate of Climb
ROD	Rate of Descent
RP	Reporting Point
RNAV	Area Navigation
SARP	Signaal Automatic Radar data Processing
SPL	Schiphol Airport
SPY	Spijkerboor RP
STAR	Standard Arrival Route
TAS	True Airspeed
TMA	Terminal Manoeuvring Area
VOR	Very high frequency omni directional radio range

1. INTRODUCTION

The Netherlands air traffic control system is characterized by its typical ATS-route structure and by the high level of support for the controller from the computer system. Speaking about trajectory prediction therefore means elaborating briefly on these characteristics first. In the field of flight plan processing the Netherlands have a long history, dating back to the first automation efforts in the fifties. These older systems basically performed a flight plan processing task that already included a rudimentary form of trajectory prediction and a simple conflict search. It is on the basis of a long development that the present sophisticated trajectory prediction method and its various applications for other functions, could evolve.

The ATS-route structure for area control over the Netherlands is depicted in figure 1. Each of the five "legs" or sectors of this star-like routesystem is served by one executive, one planning and one assistant air traffic controller. Hand-off from one sector to another sector takes place "somewhere" in the complicated crossing area over the SPY and PAM VOR's, depending on the traffic situation. It has always been considered obvious that to maintain an efficient flow of air traffic in this area, one has to rely on a proper conflict free planning of the traffic. So, the need for accurate ETA's for SPY and PAM arises. This planning task is carried out by a special planning controller for the SPY-PAM crossing area, who also coordinates between the sector controllers. This controller has no executive task, the execution of tactical control in this area being performed by the five sector radar controllers. The task of the SPY-sector planning controller is relieved by adequate support from the computer system. Part of this support is an automated planning conflict detection function.

Approach control mainly serves in- and outbound traffic to and from Schiphol Airport (fig. 1). Inbound aircraft typically pass the FIR-boundary some twenty to thirty minutes before their actual landing time at Schiphol; their arrival order being planned by approach control shortly after this passage has occurred. They eventually may use one of the three holding areas (LAK, SEA, RIV) as depicted in fig. 1. Hand-off from area control takes place at the TMA-boundary.

The computer and display system presently in use is called SARP, for Signaal Automatic Radar data Processing. It employs a.o. automated radar data processing and flight plan processing. This system, serving both approach control and area control, was commissioned in 1981.

Tracks are built up for primary as well as secondary radar data, originating from the terminal area radar at Schiphol or from the long range radar at Leerdam. Secondary as well as combined primary/secondary tracks are automatically correlated with the proper flight plan data, while the sporadic primary tracks are to be correlated manually. Presentation on displays is basically synthetic and inputs are made using keyboards and lightpen.

The present paper describes the trajectory prediction method and gives figures for its quality. Short descriptions are given of the various functions in the SARP system that make use of the estimated times as computed by the trajectory module. The paper concludes with a discussion of the possible future developments of the trajectory prediction method and its applications.

It may be stressed that the subject of this paper relates to an operational system i.e. a system that is working today after having gone through numerous evaluation steps.

2. THE TRAJECTORY PREDICTION METHOD

2.1 General methodology

In the SARP trajectory prediction module as presently implemented, a diversity of input data is used. The following groups of data can be distinguished:

- Flight plan data
- SARP database with fixed aircraft performance and route geometry data
- Meteorological data
- Radar data

The Flight plan contains information like: aircraft type, planned route, ETA for the entry route point, requested flight level and associated cruising speed. This information is the basic data source for the trajectory computation, and in quite a number of ATC-systems this flight plan information (combined with wind data) is the sole tool for computing ETA's in order to apply time separation.

The SARP database contains pre-stored aircraft performance data (see table 1) as well as route geometry information. The aircraft performance information is available for 34 performance categories. Each performance category represents one or more different aircraft types. The "route geometry"-information contains basically the x/y co-ordinates of the route points (computed from Lat/Long co-ordinates by stereographic projection). However, also strings of subsequent co-ordinates are stored like for instance standard approach routes (STAR's). For every route point the co-ordinates are given together with a meteo code. This meteo code is used, in combination with the meteorological data, to determine the windvector and the temperature on the route segment defined by two successive points on the route.

The meteorological database contains upper air wind data as well as temperature data as provided by the Meteorological Office each 6 hours. If necessary these meteo data are updated more frequently. For 5 different pressure altitudes and for 6 so-called meteo-areas these wind/temperature clusters are stored in the SARP system.

The radar data are obtained from the long range radar and the terminal area radar. The mode C altitudes as well as the horizontal positions of the aircraft (track positions) are used for trajectory prediction purposes.

How are the afore mentioned data combined and by what kind of strategy are the trajectory computations executed?

To explain this, the Flight Category-concept has to be introduced firstly. This flight category functionally defines in SARP one out of some 60 specific flight types such as transit flights, outbound Schiphol flights, inbound Schiphol flights and so on. For each specific flight type a unique trajectory prediction scenario is valid.

Three flight scenario's viz. transit flights, outbound flights and inbound flights are described in more detail in the following.

The transit flight scenario

For illustrative reasons in figure 2 a schematic representation of a possible although rather unusual transit flight profile on route Upper Blue 1 (UB1) is sketched. Some characteristic events with respect to the trajectory prediction are depicted by the small circles and will be referred to as case 1 to case 6.

In this example, trajectory computations are performed at the moments indicated by the small circles. The transit flight profile is defined in the vertical sense by means of 4 planning flight levels denoted respectively as RFL, CFL, IFL and AFL (see fig. 2 for legenda) and where possible, the radar derived Mode C flight level is used.

Let us assume for case 1 that the only available information is the flight plan. The data which are used in the trajectory computation are:

from the flight plan - Cruising speed (at RFL)
 - ETA-BLF
 - Route points BLF...ARK

from the SARP-data - Co-ordinates and meteocoding of the route points

from the meteo-data - Wind vector and temperature at the subsequent route points

The ETA's in this rather elementary case are determined by computing the ground speeds (cruising speed and wind) and the interval distances between the route points. It is assumed that the whole flight is executed at the RFL.

Case 2 shows the situation that the air traffic controller, on the basis of the preliminary ETA-computation of case 1 and time separation criteria, has assigned three new planning flight levels, i.e. CFL, IFL and AFL. The most significant effect as shown in figure 2 is, that these levels in this case are different from the RFL. So, a solution must be found for level flight segments not equal to RFL and also for climb- and descent- profiles. Here the use of the SARP performance data base comes into focus to fill the "white spots" not covered by the standard ICAO flightplan (see table 1 for the performance data of the wide body category).

An important assumption is made in SARP, that there exists only one single IAS/Mach-transition level, i.e. FL 260. So, above FL 260 the aircraft are supposed to fly constant Mach and below FL 260 the aircraft are supposed to fly constant IAS. For climb-, descent- and horizontal flight segments different IAS- and Mach-values are used as will be explained furtheron.

Now, using the physical relations between flight level, IAS-value, Mach-number and also the ambient static temperature difference (ΔT) from the ICAO-standard, the true airspeed can be computed at any altitude (see table 2 for conversion formulae).

As indicated in figure 2, a descent is executed in the computation from CFL to IFL as soon as BLF is crossed (note: aircraft is still at position 2). The rate of descent is computed with the relations from table 2 and the numerical performance values from table 1 at the mean flight level between CFL and IFL. So, the time to descent from CFL to IFL is known now. The true airspeed during the descent is also computed with the relations from table 2 and the numerical performance values of table 1 on the mean height. Also the meteo data must be known (wind and temperature). As explained in the foregoing each route point is labeled with a meteo code providing the necessary correlation with the meteorological data base. In this concrete case, the meteo data are found in the meteo area file to which BLF belongs (always the first route point on a segment determines the meteo area) on an altitude halfway CFL and IFL. Using the true airspeed and wind data, the ground speed during the artificially computed descent directly after passing BLF is determined. After combining with the time-to-descent, also the horizontal distance flown is known.

The time-to-fly after levelling off, to the subsequent route points ABR, PAM and NYK during a horizontal cruise at IFL is again computed on the basis of the cruising speed as filed in the flight plan. However, using the common IAS/Mach- transition assumption and the formulae from table 2, the true airspeed at RFL can be "scaled" to that speed at IFL. With additional wind information, the ground speeds at the segments BLF-ABR, ABR-PAM and PAM-NYK can be estimated and subsequently the ETA's for these route points. In the scenario for case 2 a climb is assumed directly after passing NYK. The rate of climb (ROC) is computed with the assistance of additional performance information of the aircraft type involved and the linearised rate of climb expressions of table 2 (formulae h, i and j). In analogy with the descent, the true airspeed is obtained via the performance data base during the climb from IFL to AFL. After levelling off at AFL, the ground speed is again computed with a "scaled" true airspeed from the flight plan like that was the case for the horizontal segment preceeding NYK.

In case 3 the situation is given where the aircraft has been correlated and tracked for at least 2 minutes. Based on the x/y-positions 2 minutes apart, a so-called radar derived ground speed can be determined. The ETA-BLF is computed by extrapolating this ground speed to BLF, using the last x/y-track position as a reference. The remaining flight parts after passing BLF are identical with those of case 2 and the interval time lapses don't need to be recalculated.

In case 4 the trajectory prediction is triggered by the time stamp "ETA-PAM minus 10 minutes". In the example of figure 2, the descent from CFL to IFL is delayed somewhat. Mode C information, combined with the latest x/y-position as measured by radar, is the starting point of the computation. The horizontal and vertical speeds are determined in conformity with the strategy as described in case 2, i.e. no radar derived speeds are used for a re-calculation starting with a climb- or descent status, only performance- and flight plan data are used in this case.

Case 5 represents the passage of route point ABR by the aircraft. This is automatically detected by means of the radar track positions relative to the route point co-ordinates. At that moment a new trajectory prediction calculation is carried out, starting from the actual aircraft position and making use of the latest received Mode C flight level. In general every time an aircraft passes an RP this will be automatically detected and a subsequent update will be executed.

Case 6 shows the situation that the aircraft is for some 4 minutes in a level flight at AFL. The trajectory prediction to ARK is executed with the most recent radar derived speed and x/y-position.

The outbound flight scenario

In figure 3 a schematized outbound profile for Schiphol is depicted. The horizontal profile of the flight consists of two distinct parts, i.e. a TMA-phase (Schiphol departure runway, CP_a, CP_b, CP_c, TMA-exit) and an exit sector phase (TMA-exit, Sector exit). The points denoted as CP_a, CP_b and CP_c are the so-called "calculation points". These points are not actually flown by the aircraft, but they serve merely to represent the curved flight segments as SARP only makes use of straight horizontal flight segments. They are located in such a way that the end result of the trajectory prediction becomes as accurate as possible.

The calculation of the true airspeed (TAS) is done on the basis of the pre-set performance data (see table 1) only. So, no flight plan cruising speed is used whatsoever. During the climb to 4000 ft, a fixed rate of climb (c_1) and a fixed true airspeed (TAS-climb) are applied. Above 4000 ft the computation during the climb is comparable with the transit flight strategy.

The only updates which are made for outbound flights, are the "actual time of departure"-update and the ETA/ATA-corrections (by radar) at the TMA-exit and Sector-exit (compare case 5 of the transit flight).

The inbound flight scenario

Figure 4 represents the inbound flight profile for Schiphol. The calculation points CP_a, CP_b and CP_c have the very same background as was the case for the outbound flight. The true-airspeed for the inbound flight is determined from the performance data base only. After leaving the holding RP it is assumed that the aircraft descent to one common height of 2000 ft for the last stretch of the trajectory. ETA/ATA-updates (by radar) are done at the Sector entry and the holding RP. When a holding delay is pertinent, an equivalent ETA-shift is incorporated in the calculation. Every radar scan a Distance-from-Touch down computation (DFT) is made for aircraft in the final approach phase (starting 15 NM from touch down). The DFT-values are used to calculate an updated ETA for the touch down point.

2.2 Accuracy aspects

2.2.1 General

Since the introduction of the SARP system in 1981, the trajectory prediction module has been adapted several times. The various evaluations have given more insight in the error sources that lead to inaccuracies of the results.

Two techniques were used basically, viz. the evaluations based on system recordings and an extensive study based on aircraft performance questionnaires which were sent out to the different companies operating in the Netherlands airspace.

The evaluations concentrated upon the following basic elements:

- Input data accuracy and reliability
- Accuracy and reliability of the prediction methodology proper.

In this chapter some findings will be highlighted.

2.2.2 Discussion on some factors which determine the prediction quality

- The filed flight plan is the cornerstone for the initial calculations. Each discrepancy can be translated directly into a prediction error. The non-adherence of the pilot to the filed cruising speed can be regarded as one of the main error sources for the initial computation. Notwithstanding the so-called "5-percent ICAO rule", a number of aircraft show much larger deviations from their intended speed. The non-adherence of the pilot to the filed route (shortcuts) or the deliberate deviations as instructed by the controller can cause significant prediction errors. Any deviation from the filed route must be notified to the SARP prediction module in the proper stage of the flight; especially in quiet periods the controllers initiate "direct-to"-clearances which must be accounted for. The unreliability of the predicted wind values sometimes leads to large errors. In a number of cases the 6-hourly updates are not fitting well the actual weather variations.
- Differences between estimated performances and actual aircraft performances. Because of a much higher amount of aircraft types than performance categories, it is clear that some aircraft types don't fit well within their category division. Even when the performance category for an individual aircraft type would be correct, differences between expected and actual performances arise. This is because aircraft are operated in different ways, either caused by pilot-behaviour or company-instructions. The given values in each performance category must therefore be considered as average values. The number of performance categories presently amounts to 34.
- Inaccuracies are also caused by simplifications in the calculation methodology. For instance the top-of-descent or the bottom-of-climb is situated in the calculations exactly overhead a reporting point. In practice however, delayed descents and climbs are observed. Also the common transition level of FL 260 doesn't fit well to some of the different aircraft types. Furthermore the IAS/Mach-strategy is not valid for all aircraft types. For instance, "low performance"-jets as well as turbo-props sometimes tend to decrease speed with altitude to realise an acceptable rate of climb margin. The calculation of the rate of climb and the rate of descent is simplified in SARP. The effects of the aircraft weight and the air temperature are omitted.
- Notwithstanding the attractive aspects of the radar derived ground speed it must be recognized that this strategy requires straight and level flights without accelerations or decelerations, combined with adequate radar performance. If the flight is not straight, the along track wind component will change and if the aircraft initiates a climb or a descent, the actual aircraft speed will change also. For this reason at present no radar derived ground speed is used in SARP during climb and descent. After leveling-off, distinct deceleration or acceleration effects can be observed and the use of the radar derived ground speed shows a delayed reaction.

2.2.3 Operational results

In fig. 5 a histogram is shown of the results of 542 overflying aircraft which have been observed. Over a stretch of 10 to 15 minutes flying time, the difference between ETA and ATA (for SPY/PAM) was determined for all aircraft. As can be seen, the mean value of the difference between ETA and ATA amounts -2 seconds at a standard deviation of 46 seconds. A number of 8 aircraft have an extreme value for ETA minus ATA of more than 3 minutes (1.5%).

A comparable investigation has been done also for 393 inbound flights. The differences between ETA and ATA were determined 10 minutes before the expected passage of the holding RP. In fig. 6 a histogram is shown of the results. In this sample, the mean value of ETA-ATA is 11 seconds at a standard deviation of 84 seconds.

Also a similar investigation has been done for 522 outbound flights. The prediction of the ETA for TMA-exit was executed at take-off. The mean value of ETA and ATA was -1 second at a standard deviation of 52 seconds.

3 APPLICATION OF THE TRAJECTORY PREDICTION IN THE SARP SYSTEM

3.1 General

In this paragraph a number of examples is given of the application of the trajectory prediction results in the SARP-system. Before doing so, some general statements have to be made.

Predicted times (ETA's) over specific points are used in different ways in the system. They can be considered as data items for the controller and printed on paper strips or shown in the strips on Electronic Data Displays. They can also be used as triggering moments for system activities such as data distribution, automatic conflict search and planning. A very important aspect is their use as input to these various automated functions.

The usefulness of ETA's will increase with their accuracy. To this reason an indication is given in the strips on the tabular displays whether or not an actual time (ATA) was measured/given for a specific flight. Doing so, the controller gets more valuable ETA's and can for example use this extra information to update the planning.

Also, some automatic actions will only start when an actual time is available. An example of such an action is the distribution of boundary estimate information for outbound aircraft. This information will be generated after the actual time of departure (ATD) has been input into the system.

3.2 General data distribution rules

For all categories of flights which are to be handled by the SARP-system, so called time action diagrams have been set up. These diagrams define at which moments information has to be distributed to different users of the system. In figure 7 an example is given of such a diagram. The vertical axis indicates which ATC functions and which users are involved in the flight. The horizontal axis represents the significant inputs/events and the triggering moments for automatic data distribution. For each of those moments an indication is given on the required activity. It says for example that 25 minutes prior to the ETA at the boundary entry RP, strip data will be sent to the controller of the entry sector and 6 minutes before the same ETA, a label will be shown on the radar screen. The distribution of data can of course also be triggered by a manual input.

The distributed data contains always ETA's for one or more reporting points plus the planned flight levels at which those points will be passed.

One of the users outside ATC are the airport-authorities. This user receives strip data in the form of an airfield estimate as soon as one actual time is available (mostly radar derived) and the boundary estimate has been received for the specific inbound flight. The time element in the airfield estimate is regularly updated during the rest of the flight. As soon as the ATA distinction of the destination is available an arrival message (containing the actual time of arrival) is generated.

3.3 Automatic planning of inbound traffic for Schiphol airport

All IFR traffic which will land on the main landing runway of Schiphol airport will be subject to an automatic planning. This planning is based on the first come first served principle and makes use of the momentary runway capacity. This capacity depends mainly on the weather conditions and is manually fed into the system in the form of a landing interval (LIV).

For the planning of an inbound flight three time elements are important i.e. the ETA for Schiphol, the landing interval and the latest assigned planned landing time or slottime (LAS) for the runway.

Just before the planning for the flight starts, a new trajectory prediction is carried out in order to obtain the best possible ETA's.

At the planning moment (which is 7 minutes prior to ETA Stack; see figure 7) the ETA for Schiphol of the flight is compared with the latest assigned slottime for the runway. In case $ETA_{Schiphol} \geq LAS + LIV$, there is no delay and a slottime equal to the ETA for Schiphol will be allocated to the flight. The LAS for the runway will also be equal to $ETA_{Schiphol}$.

In case the $ETA_{Schiphol} < LAS + LIV$, the aircraft has to be delayed. The first available slot for the aircraft is $LAS + LIV$ and that time slot will be allocated. The delay will be presented on the tabular displays of the controllers in the form of an expected approach time (EAT). This EAT indicates at which moment the aircraft is allowed to leave the holding RP and enter the terminal manoeuvring area.

In itself the planning mechanism is rather straight forward. A complicating factor is caused by the fact that the automated planning is only allowed for aircraft which have an actual time (radar-correlation or manual input). For aircraft which do not fulfill this condition, slottimes are reserved automatically in advance. At a later stage a final planning will be carried out.

Although being rather simple, this planning mechanism is very effective. This effectiveness is illustrated by the following properties:

- it brings the randomly arriving aircraft from different sectors into one planning scheme, thus performing a sort of coordination function;
- it has simple "manual override" functions thus providing for operational flexibility. For instance when traffic demand is high the controller can manually resequence, for example to minimise the effect of large separations due to wake vortices;
- when a traffic peak is due to arrive, delays can be minimised by accelerating the first aircraft of that peak by means of tactical control. The planning mechanism adjusts itself to this situation by planning two aircraft at the same landing slot. This is done automatically when there is a large difference between the last and one but last slottime or in other words when a quiet period precedes the traffic peak. It is up to the executive radar controller whether to accelerate the first or delay the second aircraft to guarantee for separation in that case.

3.4 Planning of outbound aircraft

The proper planning of outbound aircraft is a procedure requiring coordination activities between ATC-units and, under certain conditions, with adjacent centres (flow-control), before the actual clearance is given to the pilot. The automated departure planning function supports these coordination activities and makes use of trajectory prediction results. The aim of the function is to reduce the use of fuel and consequently the nuisance of noise and exhaust gases at the airport. The function can be described as follows:

As soon as the pilot reports to be ready to taxi to the runway, the start-up controller in the Tower inserts a revised estimated time of departure (RETD) in the system. This RETD is the earliest time that the aircraft can be airborne taken into account the pushback procedure and the taxi time to the take-off runway. The system carries out the trajectory prediction using the standard instrument departure information plus the route/level data as filed in the flight plan. This all results in time and level conditions for one or more significant points, among with the boundary exit RP is predominant.

For boundary points an automatic conflict search is done by which the new flight is compared with all other flights which are to pass these points. In this conflict search a number of criteria are defined for each RP (FL, aircraft on same track or crossing etc.) which on their turn are used to check whether the aircraft can pass the specified RP conflict-free. The ETA for the boundary exit RP, together with conflict search information is presented to the sector en-route controller.

The en-route controller may inform the system by means of a simple input (RETD-acknowledge) that the aircraft is cleared to pass the sector on the proposed conditions. In case a conflict was detected or flow control restrictions are applicable, the controller modifies the RETD and/or the FL-condition(s) by means of an input into the system. The acknowledgement or the new RETD is then shown to the start-up controller in the Tower.

The procedure ends by delivering the clearance to the pilot. From that moment onwards, the pilot as well as air traffic control will be in charge to keep -at least within reasonable limits- to the agreed time of departure.

3.5 Conflict search for overflying aircraft

The route structure as depicted in figure 1 shows that traffic overflying the Amsterdam FIR, will pass an area in which a large number of crossing routes are located. In order to make it possible to use that area efficiently, ATC is supported by the system by means of a conflict search routine.

This routine compares each flight that will pass this so-called SPY-area with all other overflying traffic. The comparison consists of a "route check" (crossing or non crossing routes), "horizontal separation check" and a "level check". This level check is possible since for each aircraft a level or levelband (in case of climbing- or descending traffic) is allocated for the SPY-area.

A conflict is detected when the aircraft are on crossing routes while both the height separation will be insufficient and the horizontal separation will become less than 10 NM under the most unfavourable circumstances. These worst-case circumstances are a result of an allowable lateral deviation of 10 NM from the routes and possible time errors in the trajectory prediction.

Conflict search is started at an early stage (some 25 minutes before actually passing the area) and repeated when the level and/or time conditions change. When a conflict is detected, the frequency of the conflict search is changed to once per radar scan, which means every 10 sec. Use will be made of the radar derived mode C FL to determine whether the conflict still exists.

When a conflict is detected this is shown to the controller being responsible for the planning of traffic through the SPY-area. Conflicts are indicated on the radar screen with flashing C's near the track symbols of the flights. The controller has a number of options available to solve the conflict. Replanning by modifying the FL is one possibility. Another possibility is to inform the sector controllers about the conflict and let them solve the problem by tactical control.

The required accuracy of the predicted ETA's is high, especially as the operational use of the conflict search is such that a conflict warning indicates that there might be a conflict but no warning means that absolutely no conflict will occur. It is mainly therefore that during the lifetime of the SARP system much attention has been given -and still is- to the quality of the predicted ETA's.

4 PRESENT ACTIVITIES AND FUTURE DEVELOPMENTS

There is a tendency for operational trajectory prediction modules to deteriorate in quality. This stems from the fact that operational circumstances change, viz. new aircraft types, changes in routes, ATC-practices, aircraft flying-procedures, aircraft type mix etc. Therefore a continuous effort is devoted to the maintenance of these modules in SARP, as a form of quality assurance. Thorough statistical analyses on a regular base are part of this effort. To obtain statistically significant data, also of rare aircraft types and situations, large samples are necessary.

Apart from this maintenance aspect there is a constant need for further improvements, since trajectory predictions are the backbone of many automated functions as described in chapter 3. Such improvements will, as experience shows, come along gradually and evolutionary. Of course this effort can be easily combined with the afore mentioned practice of analysis and adjustments for maintenance purposes.

A factor complicating the use of trajectory predictions already now is the increasing use of direct-to-routes. Modern RNAV systems enable aircraft to fly any route defined by waypoints thus making it increasingly difficult to provide the controller with adequate system support. An arbitrary route must be completely defined and fed into the system. But even if done so, problems may arise because of uncertainties in the vertical profile especially on the resulting longer stretches between RP's. This problem is one that should be resolved on rather short notice.

Several ideas on further improving trajectory prediction quality exist. To mention a few that could be worked on at short notice:

- upgrading of the automatic monitoring of adherence to the planned route;
- further integration of radar derived data, viz. the use of mode C and ground speed in the trajectory prediction for climbing and descending aircraft;
- use of better winddata which will become available through improvement in wind forecasting by the meteorological offices;
- the introduction of performance parameters per aircraft type instead of per category.

In the future a need for significantly better predictions might arise depending on the future scenario one adopts. A certain shift to more strategic control requiring longer term predictions, however, seems to be inevitable. On the other hand introduction of an air-ground-air datalink, in combination with sophisticated FMS's, at least offers the technical possibilities to obtain significant improvements.

Depending on the outcome of international discussions one could foresee on the longer term:

- direct transmission from the aircraft FMS to the ground via datalink of actual wind and temperature;
- direct transmission via datalink to the aircraft of accurate and detailed weather forecasts for its route;
- "negotiations" via datalink between air and ground about detailed 4-D profiles to be flown, thus laying the responsibility for accurate trajectory predictions at the airborne side for those aircraft that are properly equipped.

5 CONCLUDING REMARKS

The trajectory prediction algorithm, which is operational in the Netherlands ATC-system, has been described in this article. Emphasis has been laid on its application in an automated system and a brief outlook into the future has been given.

The development of the trajectory prediction algorithm has been made possible by a close cooperation between system designers from the Civil Aviation Administration and researchers from the National Aerospace Laboratory. After implementation by the national industry, the evaluation of the algorithm has significantly profitted from the very cooperative way the various airline companies responded to a possibly unique inquiry into flight procedures that has been set up by the civil aviation authorities.

6 REFERENCES

1. Aeronautical Information Publication, Department of Civil Aviation (RLD), the Netherlands, 1985.
2. Procedures for Air Navigation Services, Rule of the Air and Air Traffic Services. ICAO Doc. 4444-RAC/501/10, 1970.
3. RLD, SARP II programmatuur specificaties (in Dutch, release 16 included), 1986.
4. Beers, J.N.P., The Planning Conflict Detection Method for SARP, (in Dutch), NLR Report TR 81153, 1981.
5. Have, J.M. ten, Proposal for the trajectory prediction in SARP II (in Dutch), NLR Memorandum VG-73-013, 1973.
6. Have, J.M. ten, Trajectory prediction updating using filtered track speed data, NLR Memorandum VG-80-037 L, 1980.
7. Beers, J.N.P., Evaluation and adaptations of the SARP trajectory prediction model, NLR Memorandum VG-84-004 L, 1984.
8. Visscher, H. and Blokland, W. van, Improvements in computing flight paths and flight times for air traffic control, The International Journal of Aviation Safety, Sept. 1984 (p. 152-157).

TABLE 1
Performance parameters of class J

Description	Dimension	Value	Remarks
Mach-L	Mach	0.84	Mach during cruise above FL 260
IAS-2-L	kts	325	IAS during cruise between FL 100/260
IAS-1-L	kts	275	IAS during cruise below FL 100
Mach-D	Mach	0.84	Mach during descent above FL 260
IAS-2-D	kts	305	IAS during descent between FL 100/260
IAS-1-D	kts	250	IAS during descent below FL 100
Mach-C	Mach	0.82	Mach during climb above FL 260
IAS-2-C	kts	320	IAS during climb between FL 100/260
IAS-1-C	kts	250	IAS during climb below FL 100
d ₁	ft/min	2695	ROD above FL 260
d ₂	ft/min	2280	ROD between FL 080/260
d ₃	ft/min	1331	ROD below FL 080
c ₁	ft/min	1620	ROC during climbout FL 000/040
c ₂	ft/min	1961	ROC-parameter below FL 100
c ₃	ft/min/FL	+ 4.68	ROC-parameter below FL 100
c ₄	ft/min	2650	ROC-parameter between FL 100/260
c ₅	ft/min/FL	- 3.89	ROC-parameter between FL 100/260
c ₆	ft/min	1985	ROC-parameter above FL 260
c ₇	ft/min/FL	- 2.17	ROC-parameter above FL 260
IAS (init)	kts	240	Approach speed Holding/CP _b
IAS (intm)	kts	180	Approach speed CP _b /Threshold
TAS-climb	kts	190	Climbout speed FL 000/FL 040
TAS-min	kts	300	Lower TAS-check value
TAS-max	kts	510	Upper TAS-check value

TABLE 2
Conversion formulae for horizontal and vertical speeds

Horizontal speed (see table 1)

Below FL 100; TAS = IAS (0.998 + 0.00158 x FL + 0.002 x ΔT) (a)

Between FL 100 and FL 200; TAS = IAS (0.963 + 0.00198 x FL + 0.0025 x ΔT) (b)

Between FL 200 and FL 260; TAS = IAS (0.893 + 0.00219 x FL + 0.0033 x ΔT) (c)

Between FL 260 and FL 361; TAS = Mach (665.2 - 0.253 x FL + 1.28 x ΔT) (d)

Above FL 361; TAS = Mach (573.6 + 1.37 x ΔT) (e)

- Below FL 361; ΔT = T (actual) - (288.15 - 0.1981 x FL) Kelvin (f)

- Above FL 361; ΔT = T (actual) - 216.65 Kelvin (g)

Rate of climb (see table 1)

Below FL 100; ROC = c₂ + c₃ x FL ft/min (h)

Between FL 100 and FL 260; ROC = c₄ + c₅ x FL ft/min (i)

Above FL 260; ROC = c₆ + c₇ x FL ft/min (j)

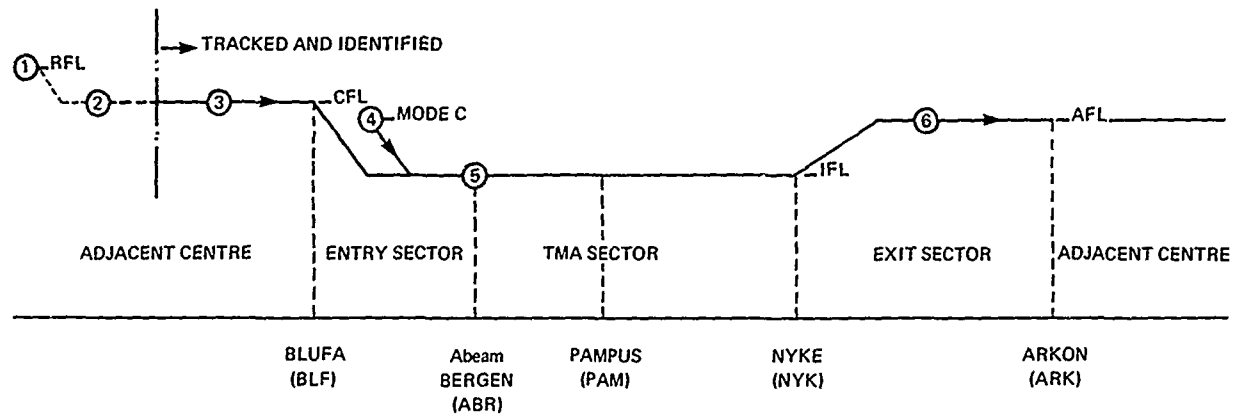
Rate of descent (see table 1)

Below FL 080; ROD = d₃ ft/min (k)

Between FL 080 and FL 260; ROD = d₂ ft/min (l)

Above FL 260; ROD = d₁ ft/min (m)

Note: TAS and IAS in kts



LEGENDA

AFL: Assigned Flight Level
 CFL: Current Flight Level
 IFL: Intermediate Flight Level
 RFL: Requested Flight Level

Fig. 2 Schematic presentation of transit flight profile on route Upper Blue 1 (UB1)

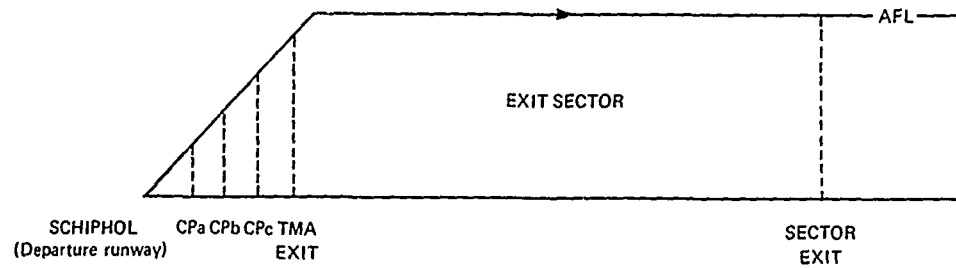


Fig. 3 Outbound Schiphol schematization

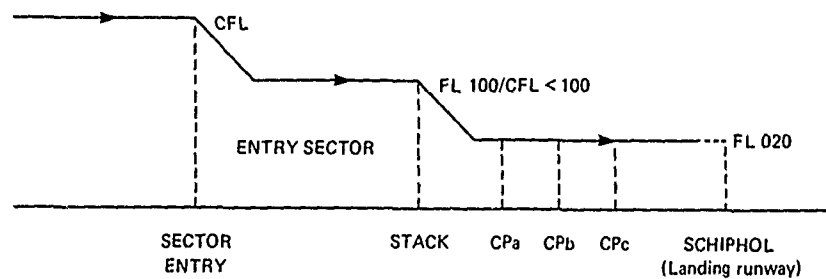


Fig. 4 Inbound Schiphol schematization

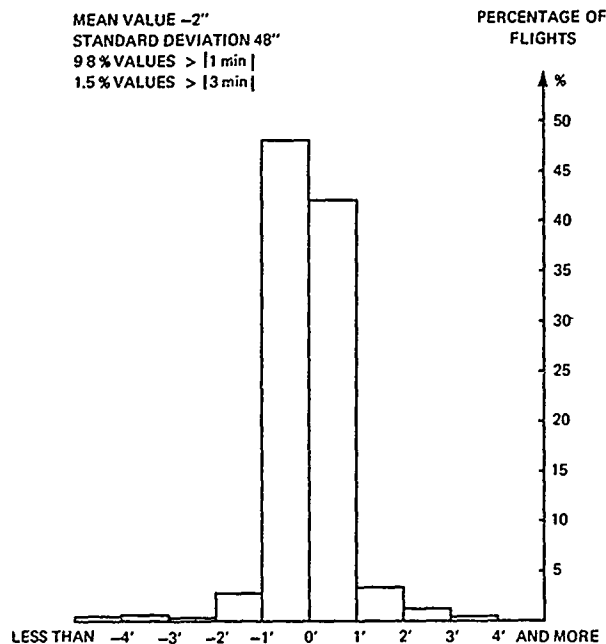


Fig. 5 (ETA-ATA) differences for
542 transit flights

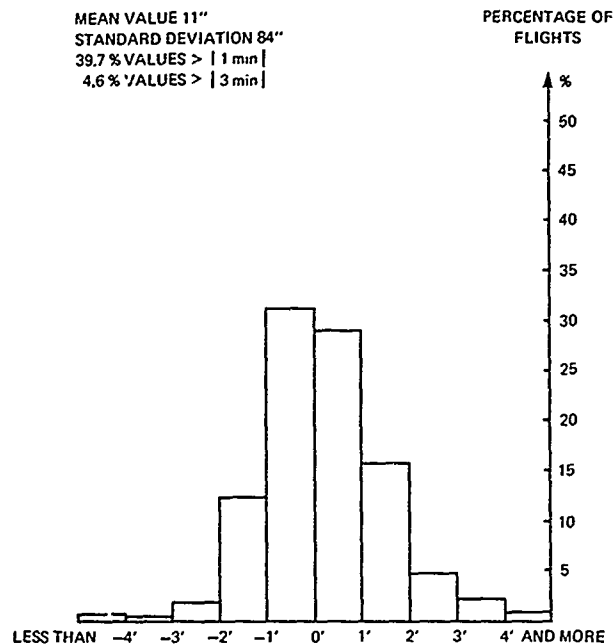


Fig. 6 (ETA-ATA) differences for
393 inbound flights

	ESTIMATE INPUT	ETA BOUNDARY	FIRST ATA *)	ETA STACK	ATA SCHIPHOL
FLIGHT DATA ASSISTANT	STRIP				
ENTRY SECTOR		25' 6' STRIP LABEL			
STACK SECTOR	STRIP				
APPROACH		5' STRIP		2' LABEL	
TOWER				5' STRIP	
AIRPORT AUTHORITIES			STRIP		ARRIVAL MESSAGE
AUTOMATIC PLANNING				7' PLANNING	

General note: Data distribution will only be allowed after
the estimate input has been made.

*) Mostly "radar derived" however it also can be the result of a manual input (e.g. ATA BOUNDARY)

Fig. 7 Time-action scenario of an inbound flight to Schiphol

GENERATION OF AIRCRAFT TRAJECTORIES FOR ON-LINE OPERATION

Methods - Techniques - Tools

by

André Benoît and Sip Swierstra

EUROCONTROL
European Organisation for the Safety of Air Navigation
Engineering Directorate
72, Rue de la Loi, B-1040 Bruxelles

SUMMARY

An appreciable amount of work has been conducted at the EUROCONTROL Agency's Engineering Directorate in the division engaged in the Study of Long-Term Air Traffic Control (ATC) System Requirements in order to generate accurate aircraft trajectory predictions for use in both ATC on-line operation and real-time simulations in current and realistic conditions, human interfaces included.

This paper will outline the basic approach developed for two distinct classes of application : on the one hand, the on-line generation of predictions for use in actual operation and, accessorially, real-time ATC simulations, on the other the introduction of realistic aircraft response and motion into ATC simulations, with pilot/auto-pilot interfaces included.

1. INTRODUCTION

In the aircraft/ATC system the problems to be solved by the trajectory calculation function are all contained in the same basic question : "At what time and, possibly, at which altitude, will an aircraft pass a predefined point?". For air traffic management purposes the question may take a different form : "What should be done in order to ensure that an aircraft arrives at a selected time over that predefined point?". With an appropriate guidance and control function, the second is only a variant of the first question.

Inevitably, the accuracy with which these questions can be answered will depend on the standard of information available to the trajectory calculation function. Also the actual applications may vary considerably from pre-flight planning and the computation of Estimated Times of Arrival (ETA) in current, automated on-line flight plan processing systems, to future on-line Air Traffic Management (ATM) systems.

A trajectory calculation function is essential not only to air traffic control systems, but also in a simulation environment where these systems can be assessed. This application requires in particular correct modelling of the aircraft behaviour in all phases of flight, but is less demanding on absolute profile accuracy.

Last but not least, a trajectory calculation function is found in tools which allow the testing and validation of ATC procedures and the study of their impact on fuel consumption, noise patterns, etc. For such applications, besides accurate modeling of the aircraft operation, detailed aircraft performance data are also of great importance.

It is clear that this last application is the most demanding as regards the absolute accuracy of aircraft performance data and realism of the control of the flight. On the other hand, in an on-line air traffic management system (ATM) the level of accuracy of the predicted profiles needs only to be commensurate with the errors resulting from the perturbations in the operational environment. However, calculation speed is very important in this case as the computation time required for a trajectory directly affects the number of alternative solutions the ATM system can investigate to find an optimum solution within the real time constraints.

2. TRAJECTORY COMPUTATION - GENERAL APPROACH

Following a top-down approach, the predicted future flight path of our aircraft comprises a series of 4-D positions (t, x, y, h), which may cover all phases of flight from brake-release until touchdown, in some cases extended by the ground movements to and from the stand. The real time, t , is the reference common to all trajectories computed ; (x, y) describe the horizontal position of the aircraft projected on the ground and h its altitude above the ground.

The flight profile is computed by a trajectory calculation function of which the basic data bases and processing modules and their interrelationships are illustrated in Figure 1.

The trajectory generation module constitutes the kernel. The series of 4-D positions (t, x, y, h) in the computed flight profile results from a two-step generation process :

In the first step, the position of the aircraft is known and the following values determined :

- horizontal and vertical components of the speed ;
- horizontal and vertical components of the acceleration ;
- geographical heading of the aircraft ;
- bank angle ;
- aircraft mass ;
- fuel flow.

In the second step these parameters are integrated over time t under local meteorological conditions to provide the next computed 4-D position of the flight profile.

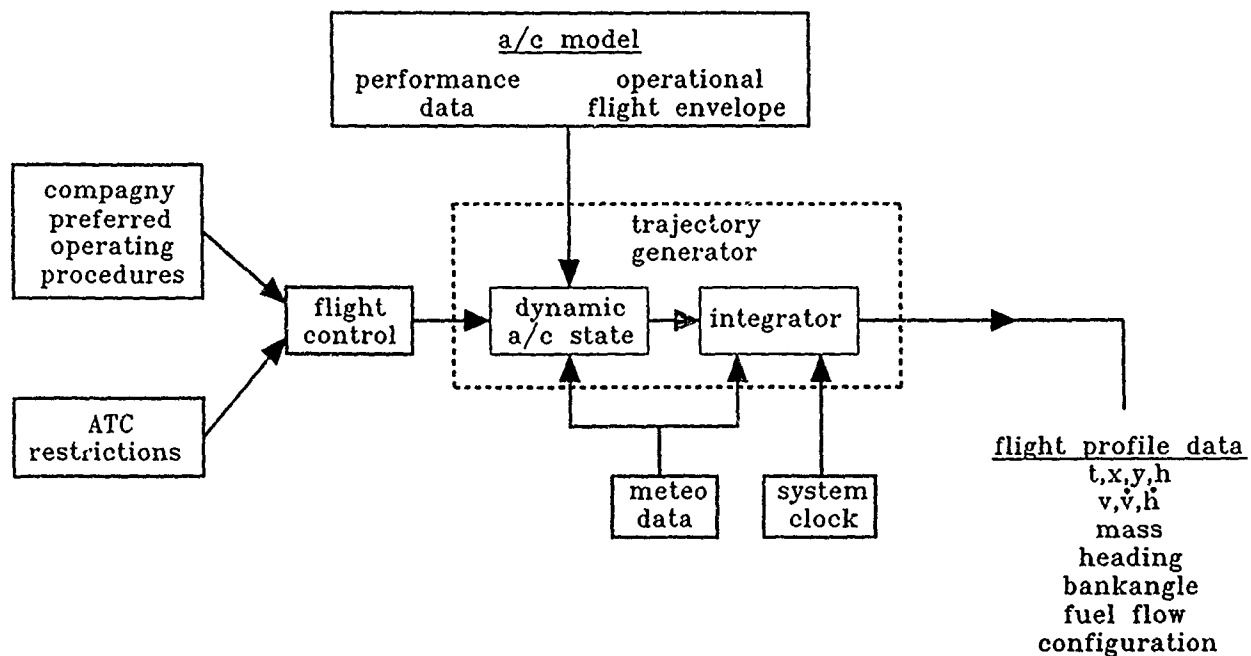
The sequence of vertical and horizontal manoeuvres to be computed is defined by the flight control module. This includes a detailed description of the route and the speed profiles to be followed and how the transition from one phase to the other should be made. The flight description in the flight control module is a compilation of the preferred company operation procedure and the current active ATC restrictions, whether at the planning level, such as Standard Instrument Departure (SID), Standard Arrival (STAR) procedures, runway in use, etc., or at the executive level, such as en-route altitude and speed restrictions.

The aircraft model contains two sets of data, namely the operational flight envelope and the basic aircraft performance data.

The operational flight envelope data defines - as a function of aircraft configuration and instantaneous mass - the speed and altitude limits within which the aircraft can be safely operated.

The content of the aircraft performance data section depends heavily on the type of modelling. In any case it must allow the definition of horizontal acceleration, vertical speed, bank angle and fuel flow during any flight phase to be computed.

Before discussing aircraft modelling techniques, let us first investigate the requirements during the various individual phases of flight and their impact on the overall reliability of the computed flight paths.



Calculation of aircraft trajectories

Figure 1

3. FLIGHT CONTROL

3.1 Take-off and climb

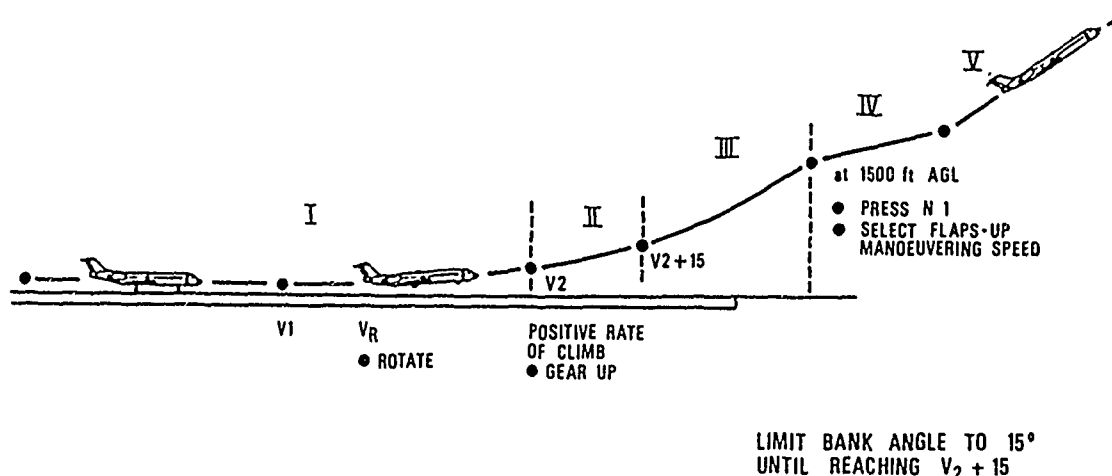
As an example, the normal take-off and climb procedure for a typical short-haul jet aircraft is shown in Figure 2. The initial phases (I-III) are flown with the engines at take-off power and comprise the take-off run until V_2 and 35 ft above ground (I), followed by an acceleration to initial climb speed $V_2 + 15$ (II) and initial climb until 1500 ft above ground (III). Then the aircraft accelerates to en-route climb speed whilst changing the aircraft configuration following the flap retraction schedule. As an example, for most B737 aircraft the economic en-route climb speed schedule is 280 kt IAS/Mach .74, often with a speed limitation of 250 kt below FL 100.

The initial part of the climb consists of a series of phases of flight of relatively short duration. Accordingly when the take-off is in the direction of the destination airport, the absolute accuracy of each individual phase is not very relevant compared to the total climb to cruise level. However, when the destination airport is in the opposite direction, the modelling of the take-off performance requires considerably more attention, in particular when the wind is strong and a noise abatement procedure prohibits turning below a certain altitude.

The operational flight envelope data section of the aircraft model dictates the take-off flap setting considering runway length, take-off mass and meteorological conditions. Subsequently the take-off configuration and aircraft mass define the V_2 vertical speed. Together with the standard instrument departure procedure, the initial part of the flight is completely defined from a procedural point of view.

With respect to aircraft performance data, the most critical phases include the average acceleration rate on the ground from brake-release until V_2 (Phase I) and the rate of climb in non-clean configuration at take-off power during Phase III. For completeness, it should be possible to consider non-standard take-off procedures, e.g. use of derated take-off thrust and impact of a wet runway or the presence of slush on it.

During the en-route climb, the aircraft normally proceeds in clean configuration with the engines' power set to maximum climb thrust. When undisturbed by ATC restrictions, a fixed speed schedule will be followed, although when the aircraft is equipped with a Flight Management and Control System (FMCS) small deviations may be observed to optimise efficiency. Other factors affecting the climb profile include the occurrence of turbulence, which may have an impact on the climb speed, and icing conditions, which may affect the climb performance.



FLAP RETRACTION SPEED SCHEDULE			
	Flap Setting for Take-off		
	15	5	1
SELECT FLAPS 5 at	$V_2 + 15$		
SELECT FLAPS 1 at	170	$V_2 + 15$	
SELECT FLAPS UP at	190	190	190

Illustration of nominal take-off and climb procedure

Figure 2

3.2 Cruise

When undisturbed by ATC, the aircraft will cruise at its recommended level and speed. The operational flight envelope is defined by the maximum cruise altitude, the minimum clean speed and the maximum speed and/or the maximum continuous thrust available from the engines.

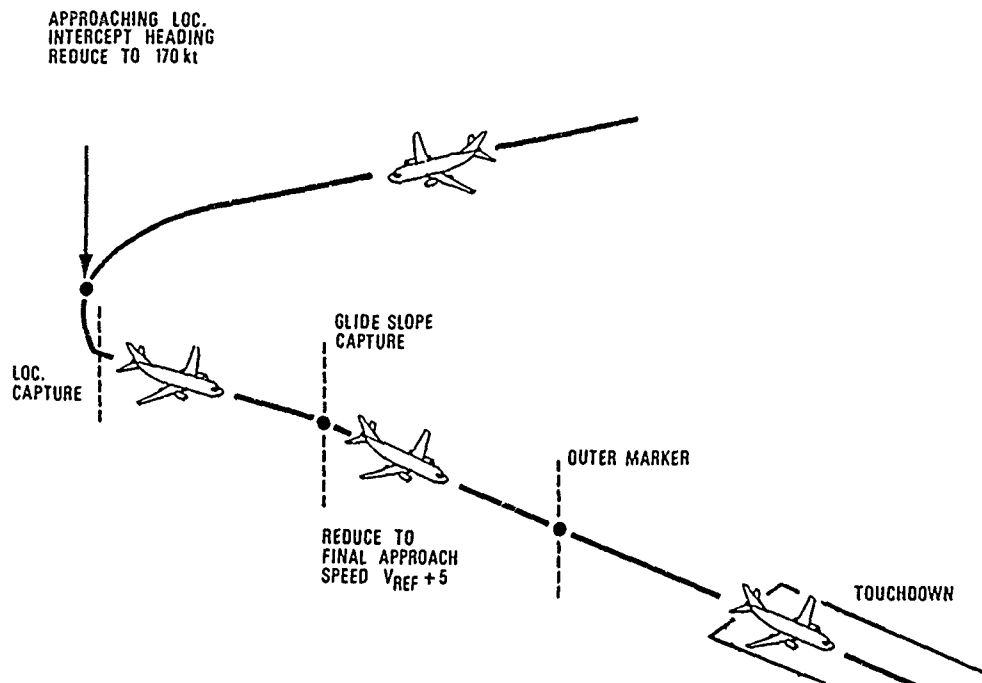
Again, turbulence may affect the cruise speed. As long as the cruise thrust setting remains below maximum continuous thrust, the impact of icing conditions will serve to increase only the fuel flow.

3.3 Descent, approach and landing

Accordingly, during take-off and climb phases and, to a lesser extent, cruise, the flight profile is greatly affected by the performance of the engines. This is not the case during descent.

In principle the descent is conducted with the engines set to "flight idle" power and as a result, the vertical speed is mainly determined by the aerodynamic drag.

For the en-route descent part, an optimum descent speed schedule can be defined on the basis of an economic criterion. However, the recommended speed profiles for the approach and landing phases are defined in such a way as to allow the pilot safely to navigate to the localizer/glide slope and to prepare the aircraft for final touchdown. It is obvious that the meteorological conditions at the arrival airport will have a great impact on the procedures followed. Moreover, as all inbound traffic is converging towards the airport ATC will often have to enforce speed restrictions and impose route deviations in the form of radar vectors.



FLAP EXTENSION SPEED SCHEDULE		
FLAP POSITION	FIXED SPEED	SELECT FLAPS
UP	210	1
1	190	5
5	170	15
15	150	25
25	140	30 / 40

Illustration of an approach procedure

Figure 3

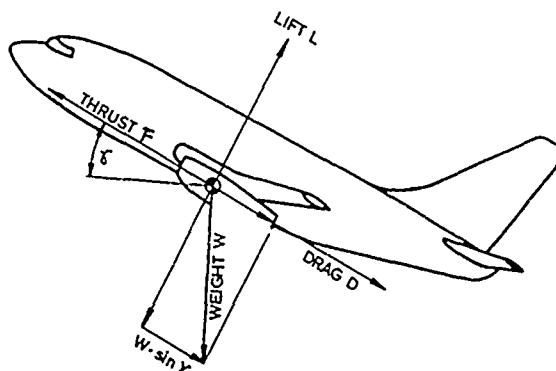


Figure 4

Given the numerous possible perturbations which may affect the traffic flow, it would be very difficult to define the inbound profile in great detail. Fortunately, the pilot has ample means to adapt the flight path to the evolving traffic situation. By using speed brakes or lowering the landing gear or extending the flaps he can increase the drag with an associated increase in rate of descent or, conversely, by selecting a power setting above "idle", he may reduce the vertical speed.

Other sources of perturbation may affect the nominal preferred or selected inbound profile. Among these, two factors should be mentioned specifically :

- severe icing conditions may require the pilot to increase the power setting to above "idle" level, resulting in a reduction of the descent rate ;
- cabin pressurisation limitations may require a reduction in descent rate at high altitudes. In particular, depending on the aircraft type, cruise level and descent speed profile, the "cabin-rate-of-descent" limitation may have a considerable impact on the top-of-descent planning.

A typical approach procedure is illustrated in Figure 3. First the pilot will aim to align the aircraft with the landing runway direction on the localizer beam. By then the aircraft will have descended to an altitude below the 3-degree glide slope and the speed will be slowly reduced to final approach speed, which should be obtained at the "outer marker". Subsequently, the glide slope is followed until touchdown. During the deceleration from en-route descent speed to final approach speed the aircraft configuration is adapted according to the flap extension speed schedule. The landing gear will be lowered in line with the distance to the touchdown point.

In general, during the en-route descent, the operational speed envelope is defined by the minimum clean speed and maximum operating speed, possibly restricted by turbulence conditions. During the approach phase the lower speed limit would be equal to the final approach speed, at the cost, however, of a considerable increase in fuel flow. The maximum speed is defined in the first place not by the aircraft's capabilities but by the safety aspects considered by the pilot. Remaining distance to go, meteorological conditions and pilot experience play an important role in the definition of the maximum speed.

For the last 4 nm before touchdown the aircraft speed is equal to the final approach speed. The absolute value depends only on the aircraft's landing weight and configuration, possibly increased by a safety factor which depends on the wind.

3.4. Selection and implementation of flight control modules

Obviously the practical implementation of the flight control module is completely different depending on whether it is to be included in a flight simulator environment* or in an ATC operational or simulated environment.

For a **flight simulator**, the sequence of 4-D positions of the aircraft is generated in **real time**. This calls for a level of flight control compatible with, for instance, the autopilot / flight director operation onboard the real aircraft. By contrast, in an **Air Traffic Control system**, future flight paths are to be predicted : hence the flight control needs to be defined on a **procedural level**, taking into account, of course, the best available knowledge of local atmospheric conditions and ATC restrictions.

In a **flight simulator application**, the sequence of 4-D positions of the aircraft - which constitutes the flight profile flown - results from a straightforward integration of the aircraft state in real time. For such application the flight control should be compatible with auto-pilot and flight director operation in a real aircraft.

* In this context, "flight simulator" refers to a model of the type described in Paper 38.

By contrast, in an **Air Traffic Control system** - simulated or operational - instantaneous aircraft position is obtained through radar observations. It is the predicted future flight profile which is of interest. Hence the flight control will be defined in terms of procedures taking into account the best available knowledge of local atmospheric conditions and ATC restrictions. For computer efficiency the number of integration steps required to compute the complete profile will be minimized. What in practice results is a dynamic integration step magnitude depending on the phase of flight or manoeuvre computed.

4. BASIC ASPECTS OF FLIGHT PATH CALCULATION

4.1 Fundamentals

For **air traffic handling purposes**, it is sufficient to control the 4-D position of the aircraft. Indeed, it may be taken for granted that the pilot controls the motion around the centre of gravity and ensures the overall stability of the aircraft. Accordingly, it is reasonable to consider the **3-dimensional translational motion of the aircraft**, the mass being concentrated at the centre of gravity (Figure 4., representation in the wind trihedral).

The general problem of aircraft translational motion is discussed extensively in a variety of textbooks and papers*. Depending on the application considered - design of a new aircraft, operational capabilities of an existing aircraft, integral or point performance determination, etc. - the degree of complexity of the system of equations to be used may vary appreciably. Further, the type of flight considered, i.e. the nature of acceptable simplifications, has a great impact on the type of data, numerical techniques, algorithms and other tools required.

For instance, in the case of a civil or military aircraft where the following may reasonably be assumed :

- the aircraft has a plane of symmetry which is vertical when the aircraft is standing on the runway ;
- the engine is fixed with respect to the aircraft ;
- the direction of the thrust is in the plane of symmetry and fixed with respect to the aircraft ;
- the aircraft and engine controls are independent and no interaction ensues ;
- the quasi-steady approach is followed for deriving the aerodynamics and engine description ;

the equations describing and governing the translational motion and the control of the vehicle in terms of the independent time variable include a set of 7 first-order differential equations - the **equations of motion** -

- 3 scalar **kinetic** relations ;
- 3 scalar **dynamic** relations ;
- 1 scalar relation expressing the **variation of mass** in terms of the engine mass flow ;

completed by a set of 4 relations usually given in a tabular form or approximated by algebraic expressions, providing a description of the **aircraft aerodynamics and power plant**, namely

- 2 scalar relations giving the aerodynamic **drag** and **lift** in terms of speed, altitude and angle of attack ;
- 2 scalar relations expressing the **thrust** and **engine mass flow** in terms of speed, altitude and power setting, this last value being also referred to as a thrust or engine control parameter.

Accordingly, the description of the aircraft's translational motion under these assumptions includes

- 1 set of 7 first-order differential equations completed by
- 2 sets of 4 equations, usually algebraic ;
- 7 dependent derived-state variables, namely
 - . position (3)
 - . speed (3)
 - . mass (1)
- 3 dependent non-derived control variables, namely
 - . geographical heading (1)
 - . angle of attack (1)
 - . power setting (1)

which results in a differential system with 3 degrees of freedom, reflecting the availability of two main control surfaces, ailerons and elevator, and one engine power setting.

* See for instance P. Willems, Paper 15 and A. Miele "Flight Mechanics-1, Theory of flight paths", Addison-Wesley Publishing Company, Inc., Reading, Mass, USA, 1962

4.2 Integration of the equations of motion : Approaches versus applications

Given the acceptable operational range of the non-derived control variables, their time history could be determined to meet particular economy or other operational criteria. Whether these are determined on-line, onboard or on the ground, or available from previous optimisation processes, if the aircraft heading or, more practically, the ground speed heading, the angle of attack and the engine power setting are given as functions of time, the state variables result - for given initial conditions - from the time integration of the equations of motion.

Two cases are of particular interest, flights conducted in a vertical plane, and horizontal or level flights. In the **vertical plane**, the determination of the control variables as functions of time to meet particular criteria (minimum time, minimum consumption of fuel, minimum cost) results in a climb/cruise/descent speed profile currently approximated by a sequence of phases conducted at constant indications of speed, as discussed in Section 3. The analysis of a flight conducted in a **horizontal plane** is convenient for the determination of the turn characteristics of the aircraft.

The preceding analysis suggests two fundamentally different approaches for the calculation of aircraft trajectories for use for **air traffic handling application purposes**, viz :

- (a) All information pertaining to aircraft aerodynamics, powerplant and philosophy of operation is available and the variational calculus is applied to determine the time dependency of the control variables.
- (b) The time dependency of the control variables has been determined **previously** - by the manufacturer and/or the operator -, or **possibly on-line** - using the computational facilities available on board - and the resulting nominal speed profile is used - if only as a recommended or preferred profile for particular missions - for the purposes of direct integration of the remaining kinematic and mass equations.

In this project, for a number of practical reasons, the authors have selected the second approach, duly tailored to the two classes of applications considered, namely

- (a) real-time operation in the flight simulator and
- (b) on-line computation of possible trajectories in the tactical and strategic planning functions, and in the regulation and guidance modules for the scheduling and sequencing of inbound traffic.

The reasons which lead us to select this approach are essentially based on practical considerations, viz :

- the availability of basic information ;
- the implementation in operational life on a short to medium-term basis ;
- the relative impact of various sources of uncertainty on the conduct of flights.

5. COMPUTATION OF AIRCRAFT TRAJECTORIES FOR AIR TRAFFIC HANDLING APPLICATIONS

5.1 Principles

Consideration of a flight flown in a **vertical plane** will illustrate the simplicity of the approach followed. In the case of such a flight, on the assumptions listed in Section 4.1, the set of equations of motion is composed of

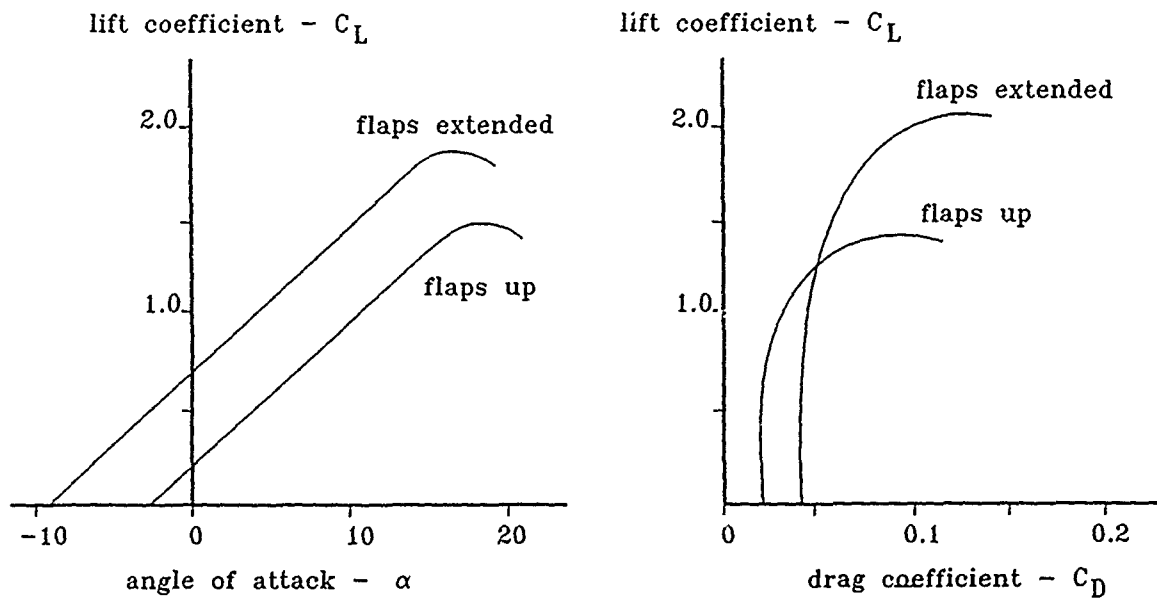
- 2 scalar kinetic equations ;
- 2 scalar dynamic equations ;
- 1 scalar equation giving the fuel mass flow in terms of thrust rating.

Formally, the trajectory results from the integration of the horizontal and vertical speed components and the mass variation from the integration of the fuel mass flow, the control variables considered being the angle of attack and the power setting.

Practically, the approach required for the applications considered in the field of air traffic handling may be appreciably simplified. Nevertheless, such simplifications often leave the approach much more accurate than a classical process, because of the nature of the fundamental data used. It is based on the following considerations :

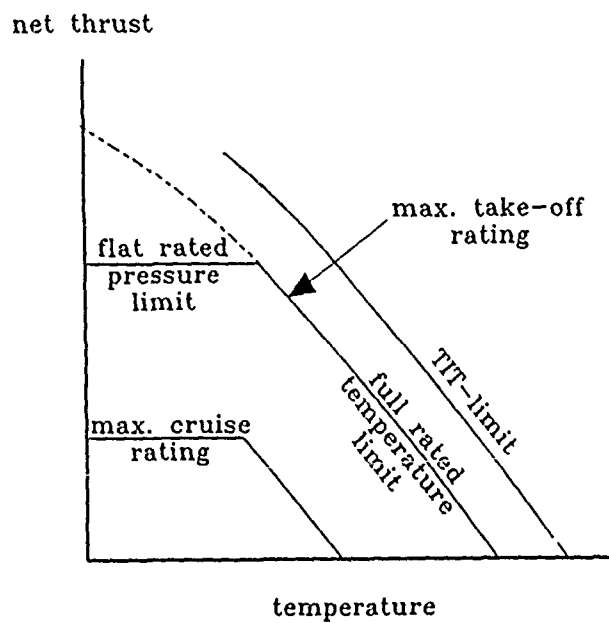
- (i) The aircraft's safe operation speed range is available from the aircraft manufacturer and/or operator.
- (ii) A speed schedule is selected in terms of operator's recommendations or in terms of the mission - phase(s) of flight - considered.
- (iii) For commercial transport, the acceleration along the principal normal to the flight path is generally slight and in most instances, can be neglected.

The tangential speed and tangential acceleration result from (i) and (ii). Accordingly, the essential problem consists in determining the vertical speed as a function of altitude and other parameters



Aerodynamics description as used - when available - in flight simulator type of application

Figure 5



Power plant description as used - when available - in flight simulator type of application

Figure 6

(mass, temperature, thrust rating and/or tangential speed). If the vertical speed is available, the climb gradient or slope of the trajectory results from the kinematic equations. The first dynamic equation yields the tangential acceleration force, thrust minus drag, while the second dynamic equation with assumption (iii) provides a good approximation of the thrust. Once the thrust has been determined, the mass fuel flow results from the last remaining equation. If the vertical speed is not available, it will result from the kinetic relations combined with the tangential dynamic equation. Furthermore, if the flight is conducted without a pre-determined speed schedule, approximation (iii) provides the trajectory slope through the normal dynamic equation and the tangential acceleration results from the tangential dynamic equation.

In short, two basic approaches can be followed for the computation of the trajectories in the field of applications considered :

- A speed profile is introduced, for example in IAS/Mach form, and the first associated vertical speed is available as a separate function (EROCOA*/PARZOC**). In this case, a separate function similar to EROCOA can also be introduced to represent the fuel mass flow. As a result, all information needed is readily available from aircraft manufacturers and airlines in an integrated form, which is an appreciable advantage. Further, the performance term, namely the thrust minus drag over weight ratio, can be derived and the computation module extended for any acceptable speed selection. This approach appears fully adequate for all air traffic control and management applications involving on-line computation of aircraft trajectories.
- Nevertheless, in the flight simulator type of applications, it may be desirable to assess various types of procedure involving a range of speed profiles and/or to reproduce the aircraft response in a most realistic manner. In this second case, the aerodynamics and powerplant of the aircraft are used in their original forms (see Figures 5 and 6).
- To complete the description of the flight in a 3-space dimension, it has proved sufficient to introduce the maximum bank angle in terms of a linear function of the indicated airspeed and assume a constant rate-of-change of bank angle, such that the maximum value would be obtained in a given period of time of the order of 5 to 10 seconds.

5.2 Techniques

The computation of a trajectory and the interface with the ATC environment are illustrated in Figure 1. In actual operations, the flight path computation module must exhibit a high level of flexibility to cope with all aspects reflecting in particular to aircraft type, airline operating procedures, requested routes, ATC and other possible constraints.

The model used for aircraft to compute the aircraft motion in the vertical plane for en-route climb, cruise and descent phases is based on the EROCOA* and PARZOC** techniques.

The EROCOA coefficients define the vertical speed during climb phases at a given thrust setting (e.g. maximum climb thrust).

$$\dot{h} = f_1(h, m, DT)$$

where h = altitude;
 m = aircraft mass;
 DT = deviation of ambient temperature from the standard ISA profile.

Thus 16 coefficients define the climb performance for IAS/Mach climb speed laws.

The PARZOC coefficients define the vertical speed during descent at idle power, M representing the Mach number :

$$\dot{h} = f_2(h, IAS/M)$$

A total of 6 coefficients are required to define this phase.

The aircraft performance during the acceleration and deceleration phases can also be computed from the EROCOA/PARZOC coefficients. For the normal operating range of commercial aircraft the vertical speed may be approximated by :

$$\dot{h} = \frac{T-D}{m \cdot g} \cdot f$$

T = installed net thrust
 D = aerodynamic drag

* "Aircraft trajectory prediction data for ATC purposes"

A. Benoît and E. Evers, AGARDograph AG-209, Vol-I, pp. 327-367, July 1975

** "Simulations of air traffic operation in a Zone of Convergence
 Aircraft PARZOC performance data"

A. Benoît and S. Swierstra, EUROCONTROL Report 812031-2, April 1982.

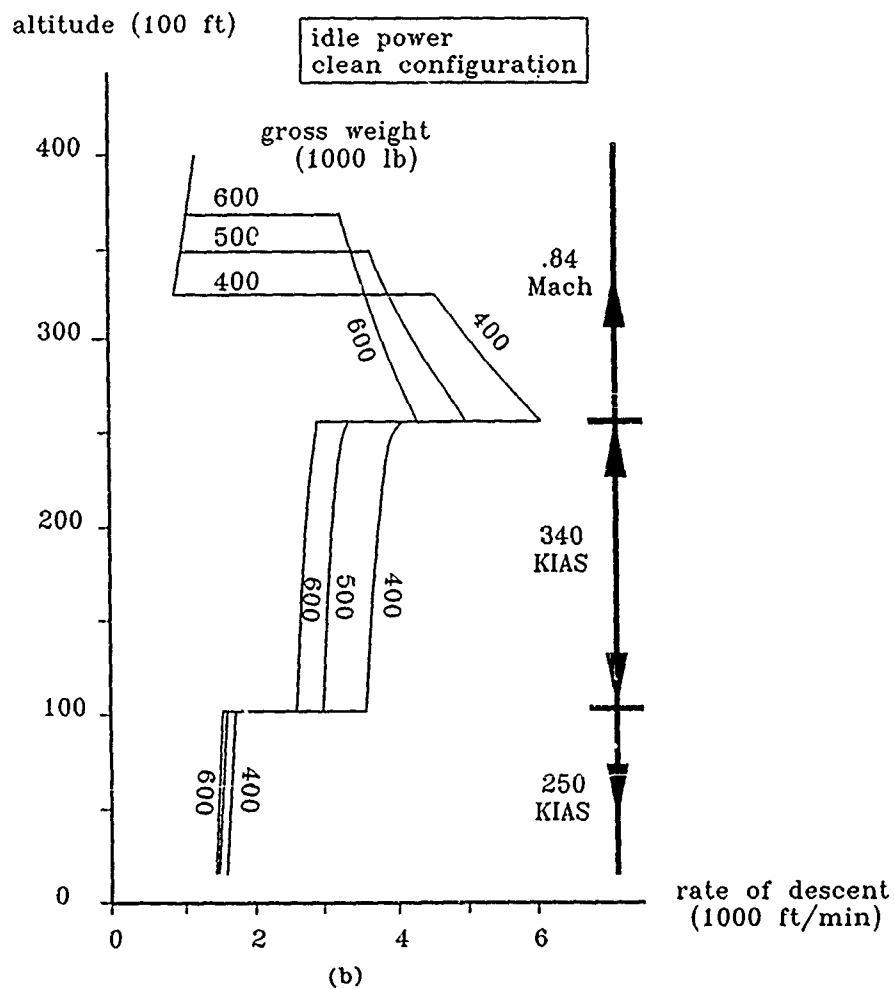
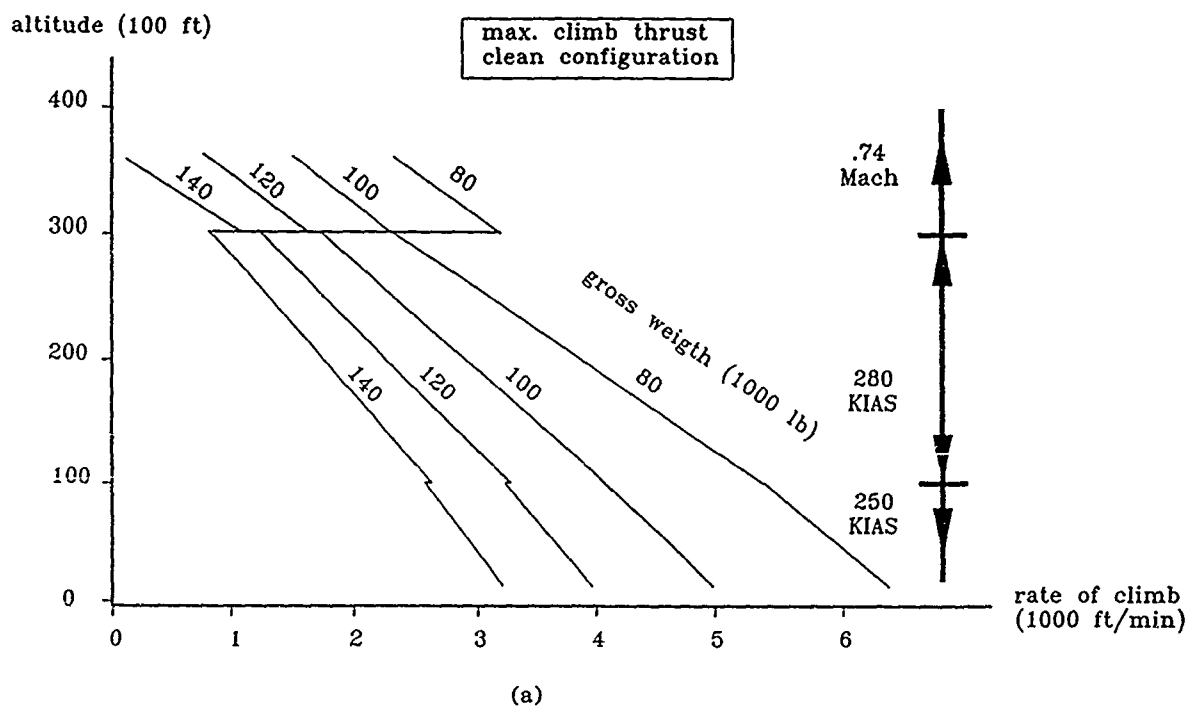


Illustration of rate-of-change of altitude
(EROCOA and PARZOC)

Figure 7

The "performance" term $(T-D)/mg$ corresponds to the climb gradient, \dot{h}/v , for a non-accelerated climb and f represents the effect of the acceleration associated with the speed law followed, either constant IAS or Mach number ; the tangential speed is noted v

$$f = \frac{\dot{v}}{1 + \frac{v}{g} \cdot \frac{dv}{dh}}$$

The following expressions constitute adequate approximations of f :

$$f_I = \frac{v}{1 + 0.567 M^2 - 0.17 M^4} \quad \text{for constant IAS ;}$$

$$f_M = \frac{v}{1 - 0.133 M^2} \quad \text{for constant Mach number (below the tropopause).}$$

Accordingly, through a simple calculation, EROCOA or PARZOC approximation also provides the slope of the trajectory and the tangential acceleration required for the integration.

Approximating the aircraft performance by reference to EROCOA and PARZOC coefficients has proved convenient and accurate. The coefficients can be generated direct from reference flight profiles readily available from aircraft manufacturers and operators with no extra need for detailed thrust and drag data. The output appears as illustrated in Figures 7 (a) and (b) for climb at maximum climb thrust, and descent at idle power - clean configuration in both cases.

By using a small set of additional coefficients, corrections can be obtained to compute the vertical speed (\dot{h}) and fuel flow (k_w) for non-clean aircraft configurations. Further, the use of EROCOA can be extended to compute the take-off run, possible take-off thrust modifications included ; similarly, the impact of mass and cabin rate of descent is readily introduced in the PARZOC descent modelling.

5.3 Applications

The integration using the EROCOA/PARZOC approach is ideal for profile calculations for all on-line ATC/ATM applications, when only reasonable estimates of fuel burn are necessary.

However, besides the flight profile, specific parametric studies involving the flight simulator i.e. to investigate noise patterns, economic aspects of certain aircraft operating procedures, etc. will also require the instantaneous thrust value and an accurate estimate of the fuel burn. To this effect, basic performance information (thrust, drag and specific fuel flow) is required, in a tabular form, for instance. The subsequent calculation remains the same as discussed above, leading to extremely realistic flight data at the cost, however, of some computation overhead.

5.4 Environment

The computation techniques and tools designed have been successfully implemented in the following environments :

- flight simulator used autonomously and based in individual IBM-compatible computers (XT and AT types) ;
- on-line regulation of traffic and 4-D guidance of flight systems such as ROSAS/CINTIA ;
- simulations of guidance of aircraft techniques and procedures involving one or two full-scale flight simulators operated by professional pilots ;
- full-scale ATC simulations conducted at the Agency's Experimental Centre ;
- SMART, the radar data plot simulator jointly sponsored by the FAA and the EUROCONTROL Agency.

6. CONCLUSIONS

For air traffic control applications, there is a need for reliable models and data to predict accurately the future paths of aircraft. The field of interest includes fast-time and real-time aspects, off-line and on-line applications.

The selection of models and, as a result, the basic data needed - to be provided by aircraft manufacturers and/or operators - is based on practical considerations such as

- (a) operational implementation on a short to medium-term basis ;
- (b) relative influence of the range of factors influencing the quality of a prediction ;
- (c) availability of data for all aircraft of concern to ATC.

Within this framework, the approach selected is based on the availability of speed characteristics directly available or readily derived from manufacturers' and operators' data presented in integrated

form. This confirmed the choice made previously, namely the introduction of expressions for the rate of change of altitude versus altitude in terms of mass, speed and power setting.

This approach constitutes an extension of the EROCOA/PARZOC method developed previously. It proves fully adequate - in terms of input data, computer time, maintenance, update of aircraft data bank, accuracy and flexibility - for real-time ATC simulations and on-line control operations. Its use has been extended to the design and operation of a flight simulator facility suitable to reproduce the 4-D translational motion of aircraft and possibly the response of the aircraft/pilot couple in ATC simulations, as well as to assess the impact of proposed aircraft operational procedure on the traffic situation, economy aspects included.

Such techniques were introduced in the control of a trajectory module. The tests conducted to date show control quality fully compatible with the most advanced techniques suggested for the on-line regulation and control of arrivals (See Paper 23 and 30).

OPTIMIZATION MODELS AND TECHNIQUES TO IMPROVE AIR TRAFFIC MANAGEMENT

by
Lucio Bianco

Director, Progetto Finalizzato Trasporti and Istituto di Analisi dei Sistemi ed Informatica
Consiglio Nazionale delle Ricerche, Viale Manzoni, 30 - 00185 - Roma - Italy

SUMMARY

In this paper a survey of earlier works of ours is given with particular emphasis on optimization models and solution techniques. Firstly, in section 2, a multilevel model of the different ATC functions is proposed. Then, in the successive sections 3, 4, and 5, attention is devoted to the on-line control functions (flow control, on-line strategic control of flights and aircraft sequencing in the terminal area); for each problem, an optimization model is established and a solution technique is illustrated. The numerical behaviour is also discussed.

1. INTRODUCTION

The current Air Traffic Control (ATC) systems are mainly conceived to ensure, with short term interventions, safety of flights. This depends on the difficulty of accurately foreseeing the future traffic evolution so that planes are often penalized more than strictly necessary with the real traffic conditions. In fact, in such a situation, safety standards are redundant and the single airplane can be forced to fly non optimal routes and unnecessary holding patterns.

This management philosophy, probably, will not be allowable in the future, when congestion phenomena will occur more often in the most important terminal areas. Therefore, it seems necessary to introduce in the future ATC systems not only more automated procedures to keep adequate safety levels, but also planning functions to increase the system capacity and reduce total cost. In this manner it is possible to improve system efficiency.

In recent years, several scientists have carried out studies in these two directions, consequently, they have introduced new control concepts and developed some optimization models and algorithms to improve airtraffic management.

In earlier papers (Bianco and others, 1978, 1979, 1980; Andreussi and others, 1981, Bianco 1985, 1986) I dealt with these problems and suggested specific approaches and solutions.

In this paper a survey of my previous works in this field is reported, placing emphasis on the optimization methods and techniques. In particular, in the following, firstly a multilevel model of air traffic control is proposed and discussed. Then the functions corresponding to on-line control (flow-control, strategic control of flights and aircraft sequencing in the terminal area) are examined and the optimization models and solution algorithms are illustrated.

2. A MULTILEVEL MODEL OF AIR TRAFFIC CONTROL

The Air Traffic Control (ATC) problem is a typically large scale problem characterized by:

- high number of variables and constraints;
- numerous sub-systems and strong interactions;
- numerous control objectives also conflicting;
- limitations and complexity of models used to forecast the movement of airplanes and traffic evolution;
- fast dynamics and real-time interventions;
- presence of several human operators in the system (pilots, controllers, etc.), each having a certain independence on taking decision.

To approach this problem it seems right to resort to the possibility of decomposing the overall problem in sub-problems solvable in a simpler manner (Mesarovic and others, 1970; Wismo., 1971). Typically, each control function can be decomposed in different levels; each level deals with a specific problem that can be solved by known methods and techniques. Moreover each level can be viewed as a multilevel system of the global process.

In the ATC field an appropriate decomposition criterion is that based on a hierarchy of control functions, each related to a different time horizon.

Fig. 1 represents a possible scheme where both the available resources and a long term air traffic demand are supposed to be known.

The higher level is associated with the planning of the air space structure, routes and ATC procedures and generally with the evolution of the overall control system. The second level represents the planning activity of flights carried out within a time horizon of some months in connection with the estimated traffic demand. The level called "strategic control" represents a planning activity of medium-long term interventions to organize traffic flows and/or define amendments to single flight plans. Finally, tactical control is a real-time control action to satisfy short-term requirements and/or to solve emergency situations.

At present, the actions relative to the first two levels are not being carried out on the basis of optimization criteria. For example, in general, there is no coordination in the decision of the airlines; then, it is not a priori possible to prevent the congestion situations.

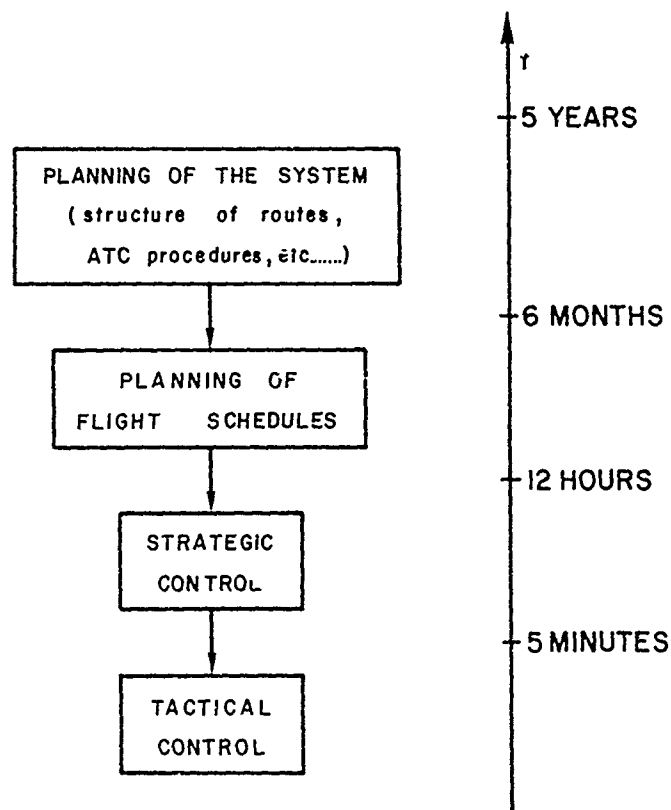


Fig.1- MULTILEVEL MODEL OF AIR TRAFFIC CONTROL

Available studies refer especially to the two lowest levels of the mentioned hierarchy or, more precisely, to sub-functions of these levels. In particular, strategic control, up to now, has only been utilized in a partial and limited manner; in fact, the current ATC systems are still mainly based on tactical control actions. On the contrary, we feel that a systematic introduction of a strategic function could constitute the most relevant and revolutionary innovation in air traffic control. In fact, this approach seems to be, in theory, the only one able to minimize the operational cost and, at the same time, improve safety standards in ATC (Erwin 1974, 1975). In practice, the implementation of a control function that optimizes planning of flights, implies considerable difficulties depending on the necessity of long-term right forecasts and inadequacy of the available methodologies to solve problems of such complexity. Therefore, it seems convenient to decompose the strategic control function, in its turn, on the basis of a multilevel model of distinct sub-functions.

A first decomposition criterion could be a distinction between "off-line" and "on-line" control. For off-line control, we mean a planning activity carried out before interested planes enter the system (generally, before planes departure) and based exclusively on traffic forecasts. Instead, for on-line control, we mean a control activity based mainly on observations of the current state of the system and worked out in a rather short period (in comparison with dynamics of flights) to allow subsequent interventions on the controlled traffic.

A second criterion could be based on a distinction between control on aggregate variables (traffic flows) and control on variables relative to single planes (flight plans).

Fig. 2 represents a multilevel decomposition of strategic control corresponding to the above criteria. To completely understand the meaning of this model, one must point out that the hierarchical order of the various levels refers mainly to the different time horizon and generally doesn't express a decisional hierarchy in the control actions. More precisely, we can say that higher levels basically ought to simplify decisional problems relative to the lower levels. In the following, functions associated to each level and relative operations are illustrated.

Flow Planning

The flow planning function should be carried out within a few hours, comparing the expected traffic demand with an estimate of the system capacity (airways, terminal areas). Then, a distribution of traffic flows in the airspace should be determined to relate the demand to the capacity.

Planning of Flights

On the basis of flow planning and of the same time horizon, this off-line activity should determine amendments for the requested flight plans. These amendments should have the aim both of reducing the a priori conflict probability and satisfying a somewhat optimal criterion. We must also specify that many random factors affect the above process; so we represent the flights by utilizing a simplified model made up, for example, of passing times and altitudes at the way-points of the planned route.

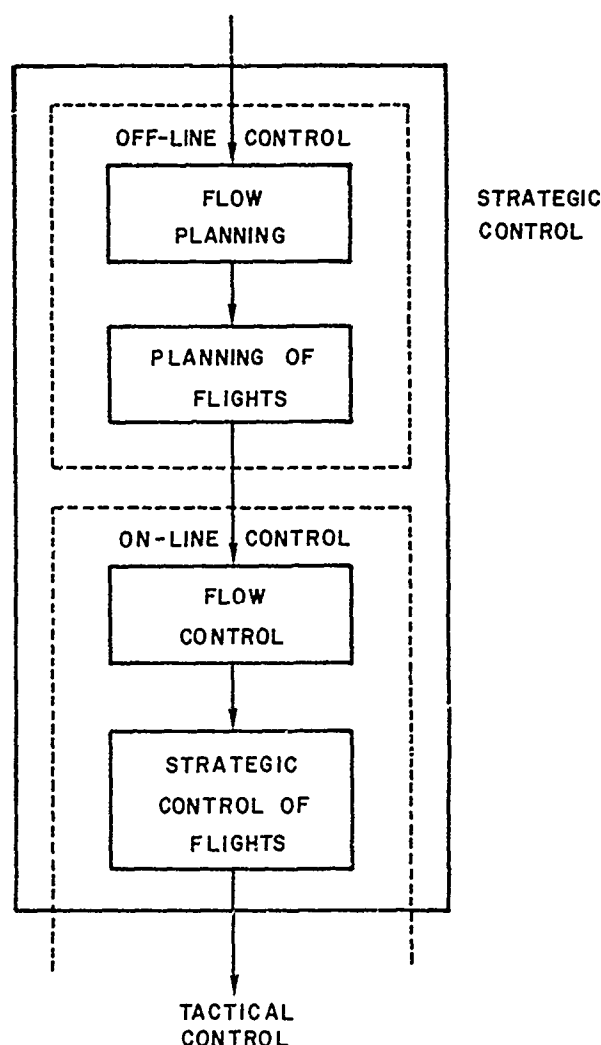


Fig.2 - MULTILEVEL MODEL OF STRATEGIC CONTROL

Flow Control

The on-line flow control refers to a time horizon of about 15-30 minutes and, in particular, it should forecast local and short-period traffic peaks and reduce possible effects on the system. This can occur both by imposing delays on the flows upstream of the traffic congestion and planning a different distribution of the traffic in adjacent sectors.

Strategic Control of Flights (SCF)

This function has the same time horizon as the on-line flow control. It should plan free conflict trajectories on the basis of observation of the current state of the system in order to satisfy the constraints on the airplane performances, space structures and possible flow limitations.

Once a hierarchical structure of an ATC system has been defined, it seems worthwhile to develop specific mathematical models to support the optimization of semi/fully automatic air traffic control and management systems at different levels of intervention.

In the following sections we consider in detail only those functions related to the on-line ATC problem.

3. FLOW CONTROL

Whenever a traffic congestion is present or is likely to originate in the controlled area, a flow control action must be taken. This means, essentially, to match traffic demand with capacity of the ATC system facilities.

The flow control activity can be, conceptually, decomposed into two different phases:

- 1) Congestion forecast: This refers to the evaluation of where and when a congestion is likely to arise and the corresponding overload order of magnitude.
- 2) Congestion prevention: Whenever an overload is forecasted, a control action, possibly optimal, must follow so as to prevent congestion development.

The first phase is the basis for an efficient ATC system; in particular, it requires accurate evaluation of air traffic capacity and demand. These two characteristics show random variations with space and time. Capacity varies for several reasons: (a) airport and airspace structure, communication, control and aid to navigation facilities used; (b) workload of controllers; (c) weather; (d) special events: incorrect functioning or out-of-order of control facilities, etc.

The traffic demand depends on time-varying characteristics of air transport, on delays etc.

Once traffic demand and capacity associated to the controlled region have been fully evaluated, congestion prevention can be taken into consideration. It can be performed by means of certain typical control actions: take-off delays, holdings, re-routing and upstream flow restrictions. Take-off delays may only be imposed on the airports located within the controlled region. Holding is used whenever an aircraft cannot start its landing procedure, because of an airport congestion. In this case, the aircraft is instructed to join a waiting line which is called a "holding stack" because aircraft are "stacked" at different altitude levels above a check point, called feeder fix point. The re-routing action involves a flow reassignment on a path different from the normal one, constrained to the same destination point. Upstream flow restrictions consist of limitations imposed on the "flow rate" at the boundary points of the region under control.

In this paper, attention is essentially devoted to the prevention of congestion. As a consequence, a constrained optimization model based on an airspace and traffic model can be established so as to perform the control actions, aforementioned, in an efficient way. The objective is that of minimizing an overall cost function, respectively fuel consumption and/or total delay in the system, taking into account capacity and safety constraints.

3.1 Airspace and Traffic Flow Optimization Model

The airspace under control is defined by a structure of a given set of standard routes and waypoints, corresponding to navigational aids and check point locations, and by the associated flights procedures. In modelling it, one must take into account the subdivision of the airspace into several control sectors and, in general, the associated rule of operation (Ratcliffe, 1974).

The airspace structure can be represented in a straightforward way as a directed network of arcs and nodes. The nodes are of the following types:

- Source nodes, representing terminal areas, generating departing traffic, or boundary points of the airspace where traffic arriving from outer regions is "generated";
- Intermediate nodes, representing routes intersections or given check points;
- Sink nodes, representing points of arrival into terminal areas, or boundary points where traffic "disappears" to outer regions.

The arcs represent route segments connecting a couple of nodes. Furthermore, different arcs can be associated to different groups of altitude flight levels along the same route. The control sectors, which are parts of the airspace controlled by one controller team, are represented by non-overlapping subnetworks connected by nodes representing the points of transfer of control from one sector to another.

Finally, as a controlled region is, in general, affected by different kinds of traffic (departure, arrival, overflight) and by different aircraft speed classes, they can be modeled by different commodities, each one characterized by its origin-destination pair. In general, when dealing with traffic congestion problems, it can be necessary to consider time-varying flows on the network. So, a dynamic traffic model can give a more precise description of the real environment (Bianco and others, 1980; Bielli and others, 1980). In this case, one needs to specify arc-transit times so as to represent dynamic evolution of traffic patterns entering the network. The planning horizon T is subdivided into elementary time intervals of suitable length δ , so as to establish a discrete-time model.

Then the following assumptions have been made:

- 1) All the variables have been discretized (that is, they are supposed not to change appreciably within the elemental time period δ fixed),
- 2) To each commodity-flow on each arc an average transit time is assigned (the greater the mix of aircraft speed and trajectories are considered the less this assumption is valid).
- 3) Each average transit time τ_{ij}^k is chosen as a multiple integer of δ .

Network flow equations assume an orderly and regular flow. To take into consideration any congestion situation one has to consider some waiting lines, according to the procedures actually employed by ATC controllers. These waiting lines are modelled as arcs closed on the nodes that represent the associated check points.

Once the network $G(N,A)$ and the set of commodities are defined, the optimal control strategy to solve traffic congestion can be obtained by setting up a constrained optimization model. It has been defined in the following way:

$$\max \sum_{t=1}^{T/\delta} \sum_{k=1}^K \left[c_s^k D^k(t) - \sum_{(i,j) \in A} c_{ij}^k x_{ij}^k(t) \right] \quad (3.1)$$

subject to:

$$\sum_{j \in A(i)} x_{ij}^k(t) - \sum_{j \in B(i)} x_{ji}^k(t - \tau_{ji}^k) = \begin{cases} D^k(t), & i = s^k \\ -E^k(t), & i = p^k \\ 0, & \text{otherwise} \end{cases} \quad (3.2)$$

$$t = 1, \dots, T/\delta; i \in N; k = 1, \dots, K$$

$$\sum_{k=1}^K x_{ij}^k(t) \leq h_{ij}(t), \quad t = 1, \dots, T/\delta; (i,j) \in A \quad (3.3)$$

$$\sum_{t=1}^{T/\delta} \sum_{(i,j) \in S_r} \sum_{k=1}^K x_{ij}^k(t) \leq h_r, \quad r = 1, \dots, R \quad (3.4)$$

$$0 \leq \sum_{q=1}^t D^k(q) \leq \sum_{q=1}^t D_0^k(q), \quad t = 1, \dots, T/\delta; k = 1, \dots, K \quad (3.5)$$

$$E^k(t) \leq E_0^k, \quad t=1, \dots, T/\delta; \quad k=1, \dots, K \quad (3.6)$$

$$\sum_{(i,j) \in A} x_{ij}^k(0) + \sum_{t=1}^{T/\delta} D^k(t) = \sum_{(i,j) \in A} x_{ij}^k(T) + \sum_{t=1}^{T/\delta} E^k(t), \quad k=1, \dots, K \quad (3.7)$$

$$x_{ij}^k(t) \geq 0 \text{ and integer, } t=1, \dots, T/\delta; (i,j) \in A; k=1, \dots, K \quad (3.8)$$

where

- A = set of arcs; $A = \{1, \dots, m\}$
- $A(i)$ = set of nodes j "after" node i ; $A(i) = \{j \in N \mid (i,j) \in A\}$
- $B(i)$ = set of nodes j "before" node i ; $B(i) = \{j \in N \mid (j,i) \in A\}$
- c_s^k = cost associated to the flow generated by the source s^k
- c_{ij}^k = cost associated to the k -commodity flow on arc (i,j)
- $D_0^k(t)$ = k -commodity forecasted flow in the time interval t
- $D^k(t)$ = feasible k -commodity flow in the time interval t
- $E_0^k(t)$ = k -sink capacity in the time interval t
- $E^k(t)$ = k -sink flow in the time interval t
- $h_{ij}(t)$ = arc (i,j) capacity in the time interval t
- h_r = r -sector capacity
- K = set of commodities; $K = (1, \dots, K)$
- N = set of nodes; $N = (1, \dots, n)$
- p^k = k -commodity sink
- R = number of sectors
- S_r = r -sector
- s^k = k -commodity source
- T = control time interval
- $x_{ij}^k(t)$ = k -commodity flow on arc (i,j) in the time interval t
- δ = elemental time interval
- τ_{ij}^k = k -commodity arc-flow average transit time on arc (i,j) , multiple of δ .

The objective function is made up of two terms: a weighted sum of the source-generated flows and a weighted sum of the arc flows. The first term involves maximization of the source-generated flows, so as to better match traffic demand with system capacity. Different weight coefficients can be assigned to different commodities, according to the priorities established. The second term concerns a better management in the traffic assignment on the network. In this way, weight coefficients can be assigned to different arcs, so that they can represent priorities in selecting the routes and flight levels or they can be directly associated to delays and/or fuel consumptions, associated with different paths. Hence, the system can analyse different objectives, i.e. maximal flow, minimum cost rerouting and holding delays, etc.

As regard to constraints, equations (3.2) represent flow continuity at the various nodes. Since, for safety reason, the aircraft have to maintain given in-trail standard separations, a maximum rate-flow on each arc can never be exceeded. This is expressed by arc capacity constraints (3.3). In each control sector, a maximum controller workload is defined. Here, it is approximated by the maximum number of aircraft in the sector during the period T . This is represented by sector capacity constraints (3.4). Upstream flow restrictions or source restrictions are given by constraints (3.5). The limitation both on airport acceptance rates and on overflight traffic to outer regions is taken into account by sink capacity constraints (3.6). Total flow conservation on the network, over the period T , is expressed by equations (3.7). Finally the natural nonnegativity and integrity constraints (3.8) are to be included.

The proposed mathematical model has been supposed to be linear. As a matter of fact, the relationship between cost coefficients and flows and the controllers' workload dependence (over a period T) on the flows are not exactly known and there is a need for further research in this field. However, since the purpose of this study is mainly to establish a suitable basis for working out more refined flow control models, the aforementioned hypotheses are acceptable. The dynamic problem (3.1) + (3.8) can be changed into a static one, by considering the network replicated in a multiperiod context (Fig. 3) i.e. each arc is repeated according to the number of time periods selected (Bielli and others, 1982). It becomes an equivalent linear static problem, belonging to the class of multicommodity network flow programming.

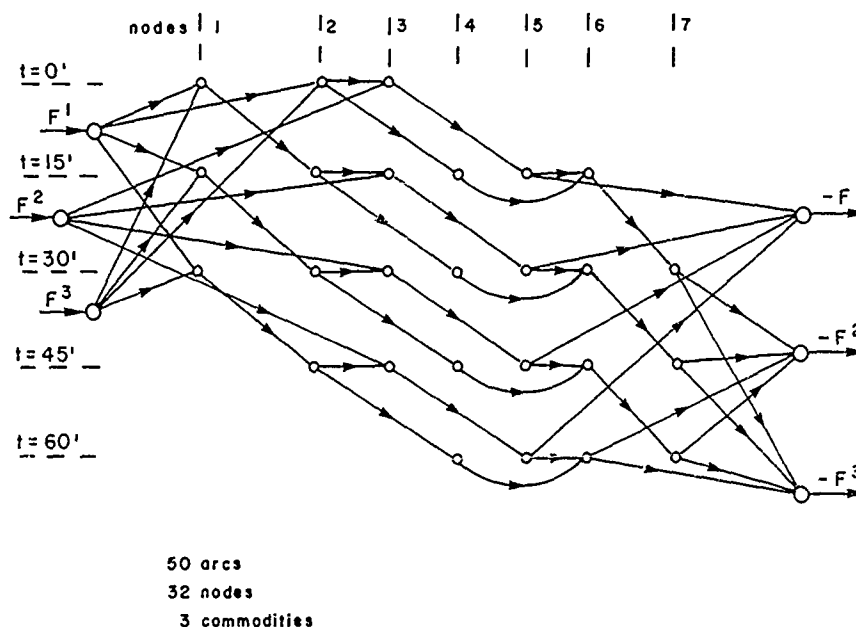


Fig. 3 - EXAMPLE OF TIME-SPACE REPLICATED NETWORK

3.2 Decomposition Techniques and Computation Algorithms

The resolution of the problem can be more or less complex, depending on the accuracy required to represent the airspace structure and dynamic traffic evolution. If the controlled region is wide and includes several airports and a complex route and flight levels structure, one has to deal with a network, with a large number of arcs, nodes, commodities. Solving such a large-scale problem can become a rather heavy task if detailed airspace and traffic representation over space and time is required. In this case, simulation models appear to be a more suitable tool, especially for traffic analysis and management problems (EUROCONTROL, 1977). On the other hand, if a certain level of aggregation in the flows and airspace structure is acceptable, then the problem can be solved by suitable mathematical programming decomposition techniques. For instance, from a general point of view the resource-directive decomposition method (as that developed by Assad, 1976) looks promising, in spite of some computation difficulties.

This method is based on the distribution of the arc capacities among the single commodities. Once solved the resulting one commodity ("local") subproblems, the initial ("master") problem can also be considered solved, if the aggregate solution satisfies a given optimality criterion. Otherwise, the arc capacities are redistributed and the process repeated. To redistribute the arcs capacities one can apply in a suitable way an optimization method, based on the subgradient algorithm. The advantage of this approach lies in the fact that many efficient algorithms are available for solving the one-commodity problems like the out-of-kilter algorithm. However, the "bundle" constraints (3.4) make peculiar the problem considered in this paper.

Thus, an approach, suitable for implementing an operative flow control technique, is presented (Bielli and others, 1981). From an operative point of view, real-time flow control is aimed to cope with traffic peaks exceeding an acceptable demand level by optimally re-distributing the traffic flows over the network. Moreover, the capacity constraints to be absolutely respected are, generally, the sector workloads and only a few arc capacity constraints (stacks of aircraft waiting for landing over the airports, departure and landing acceptance rates).

The former constraints measure the total flow over all arcs of the sector that can be handled by the associated team of controllers. Let us remark that these constraints are more restrictive, in the sense that they become binding before all individual arcs of the sector are full to capacity. Thus the problem can be seen as one of choosing how to redistribute this workload among the arcs of the sector to optimize the objective function. Then the approach can be summarized as follows:

- (1) Smooth the traffic peaks and then set fixed capacity values on some arcs and an initial capacity distribution h_0 to all other arcs. This initial distribution satisfies the sector workloads constraints and insures a starting feasible flow on the network.
- (2) Find capacities increments on the latter arcs satisfying workload constraints and optimizing the objective function.

On the other hand if one deals with a strategic flow control, only aggregated flows between sectors, rather than flows on specific route legs, can be considered. In this way, the route network can be suitably aggregated: the constraints on the controllers' workload become upper bounds on the capacity of the arcs connecting two sectors. Also the integrity constraints can be relaxed, considering only continuous flows, if the traffic volume is sufficiently large. Under the preceding hypotheses, the computational difficulties of the problem are greatly reduced (Bielli and others, 1981).

4. STRATEGIC CONTROL OF FLIGHTS

As previously mentioned, the task of on-line SCF is to optimize flight plans of single airplanes in a prefixed region with a time horizon of about 15-30 minutes. The sub-system associated with the SCF functions can be outlined as in fig. 4 where both inputs and outputs are indicated. The inputs are the flight plans of the airlines, the information relative to the state of the system and the limitations imposed by flow control.

The outputs are the amendments to the flight plans that represent control interventions on the planes of the system and can be useful information for tactical control.

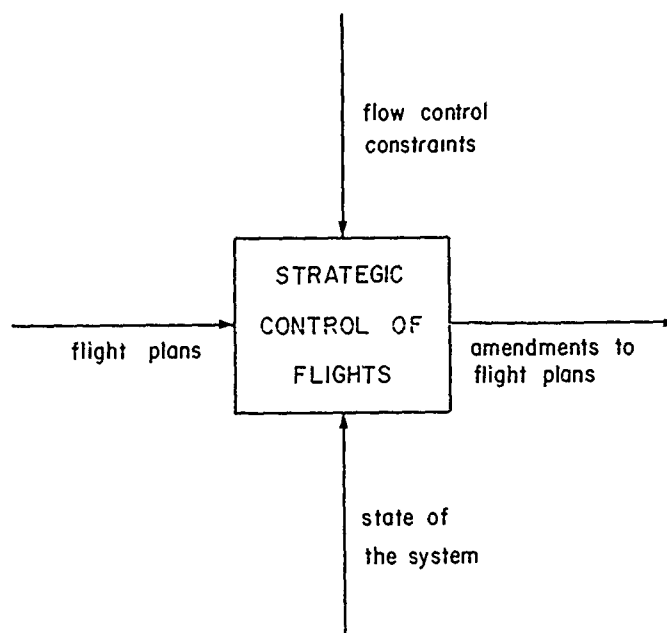


Fig. 4 - REPRESENTATION OF THE SCF FUNCTION

More in detail, the requested flight plans should be optimal from the point of view of fuel and/or time consumption if each plane were alone in the system. Instead information on the state of the system, concerns radar data on the flights evolution, short and medium term meteorological forecasts and state of the ATC infrastructures. As for restrictions imposed by flow control, these limit the control action on the single plane according to the flow planning in the control region. In particular such limitations can refer to the maintaining of appropriate separations when the planes fly over prefixed points of the controlled airspace. Finally, for amendments to flight plans we mean:

- variations of altitude levels in comparison with the nominal flight plans;
- imposing route delays through the speed control;
- imposing reroutings and/or holding patterns;
- imposing departure delays.

Now to build a mathematical model of the SCF, we must first establish a control region, a time horizon and a representation of the airways network and the trajectories of planes; then we must define control variables, constraints and the objective function to optimize.

Control Region

The possibility to carry on a strategic action on the single plane depends greatly on the extent of the region where a coordinating intervention is possible. In fact, SCF generally aims to follow an efficient profile during all phases of the flight (take-off, cruise, landing). Therefore, the more flight plans (compared with global traffic) refer to the prefixed control region, the more significant SCF is. Nevertheless, even not considering political, normative and organization difficulties, an upper bound to the extent of the control region is derived because of the limited performances both of mathematical methodologies and real time computation systems. In fact, the problem complexity increases if also the dimensions of the control region increase.

Time Horizon

The time horizon is mainly determined by the maximum time interval in which it is possible to accurately predict future traffic situation in the control region. At present, the available models seem to be able to provide adequate forecasts for look-ahead times of about 15-30 minutes. This limit could also bring to a spatial decomposition of the control action in the fixed region.

Airspace and Planes Trajectories Representation

Given a control region R, the representation of the space and planned trajectories must be accurate enough to make a meaningful control action and, at the same time, simple enough to permit real-time data processing. To this end, in the following, airspace is described through a network representing both the airways and the terminal areas. More in detail, the network nodes represent:

- the intersection of the airways with the R boundary;
- the intersection of the airways with the terminal areas boundary;
- the intersection of two or more airways;
- the waypoints fixed on each airway.

Obviously, the arcs represent all possible connections of the nodes.

A set of discrete altitude levels is also associated with each node so that constraints on vertical separation, imposed by safety requirements, are respected.

As for the representation of flights, we utilize a discrete model which trajectories are defined by the set of nodes subsequently crossed, by the corresponding altitude levels and by the passing times on each node. In this model we don't consider the dynamics of flights between the following nodes and within the terminal area; nevertheless, the problem solutions are forced to be consistent with the performances of airplanes.

In the following section we suggest a mathematical formulation of SCF, such as it has been previously stated. In particular the problem is formulated as an optimization problem with the hypothesis that the nodes, subsequently crossed, are fixed on the basis of the nominal flight plan. In this framework one must determine altitude levels and passing times on the trajectories nodes, so that an appropriate constraints set is satisfied and a cost function is minimized.

4.1 Mathematical Model

Notations

R: strategic planning region;

$[t_0, t_0 + T]$: strategic planning interval;

$I = \{1, \dots, i, \dots, N\}$: set of representative indexes of flights in R in the interval $[t_0, t_0 + T]$;

$K = \{1, \dots, k, \dots, N\}$: set of representative indexes of nodes in R;

$K^i = \{k_0^i, \dots, k_f^i\} \subseteq K$: set of nominal trajectory nodes crossed in R by plane i in the interval $[t_0, t_0 + T]$;

\tilde{k} : node following k in K^i ;

\bar{t}_k^i : nominal passing time of plane i on node k;

t_k^i : actual passing time of plane i on node k;

H: set of representative indexes of altitude levels allowable in nodes of R;

$H_k^i \subseteq H$: set of indexes of altitude level allowable for plane i on node k;

z_h , $h \in H$: altitude level h;

q_{kh}^i , $h \in H_k^i$: binary variable indicating whether the plane i occupies or not the altitude level h of node k;

\bar{q}_{kh}^i , $h \in H_k^i$: binary variable indicating whether the plane i occupies or not the altitude level h of node k in the nominal trajectory;

$P_{kh}^i \subset H_k^i$: set of indexes of altitude levels allowed in node \tilde{k} , when plane i starts from level h of node k.

Altitude Constraints

First of all, we must specify the set H_k^i of altitude levels allowable for plane i in each node of the trajectory. With reference to the definition of P_{kh}^i we have

$$H_k^i = \bigcup_{h \in H_k^i} P_{kh}^i, \quad \tilde{k}, k \in K^i$$

To correctly determine P_{kh}^i , we must consider that a speed range, consistent with the performance of plane i, corresponds to each allowable level. Then, knowing the distance between \tilde{k} and k, we can determine, for each speed, the altitude levels reachable in \tilde{k} . Among these levels, we will only consider levels satisfying eventual control needs in \tilde{k} and/or limitation on the maximum shifting of the actual altitude level from the nominal one. Therefore, if we introduce the binary variables q_{kh}^i , the altitude constraints can be expressed as

$$\sum_{h \in H_k^i} q_{kh}^i = 1, \quad \forall k \in K^i, \forall i \in I \quad (4.1)$$

$$\sum_{h \in H_k^i} q_{hk}^i \sum_{j \in P_{\tilde{k}}^i} q_{kj}^i = 1, \quad \forall k, \tilde{k} \in K^i, \forall i \in I \quad (4.2)$$

The first states that plane i can occupy only one of the allowable levels of node k . The second concerns altitude variations when plane i goes from k to \tilde{k} . It states that if plane i is in level h of k , it can occupy only one level of $P_{\tilde{k}}^i$ in node \tilde{k} .

Transit Time Constraints

As regards the transit time on nodes, denoted with t_k^i , we must consider constraints depending on planes performances, safety standards and possible restrictions of traffic flows on the airways network. Constraints on planes performances can be expressed as

$$t_{\tilde{k}}^i \leq t_k^i + \sum_{h \in H_k^i} \sum_{j \in P_{\tilde{k}}^i} q_{kh}^i q_{kj}^i \tau_{khj}^{Mi}, \quad \forall k, \tilde{k} \in K^i, \forall i \in I \quad (4.3)$$

$$t_{\tilde{k}}^i \geq t_k^i + \sum_{h \in H_k^i} \sum_{j \in P_{\tilde{k}}^i} q_{kh}^i q_{kj}^i \tau_{khj}^{mi}, \quad \forall k, \tilde{k} \in K^i, \forall i \in I \quad (4.4)$$

$$T_{om}^i \leq t_{k_o}^i \leq T_{oM}^i, \quad \forall i \in I \quad (4.5)$$

$$T_{fm}^i \leq t_{k_f}^i \leq T_{fM}^i, \quad \forall i \in I \quad (4.6)$$

where τ_{khj}^{Mi} and τ_{khj}^{mi} denote, respectively, maximum and minimum time intervals from level h of node k to level j of node \tilde{k} ; T_{om}^i and T_{oM}^i indicate limits on the initial node; T_{fm}^i and T_{fM}^i indicate limits on the final node.

Moreover, as regards the safety constraints and possible further restrictions caused by flow control, we can state, for every two planes, the following condition

$$\left| t_k^i - t_k^r \right| \geq \left[\sum_{h \in H_k^i \cap H_k^r} q_{kh}^i q_{kh}^r \right] \Delta T_k^{i,r} \quad (4.7)$$

$$\forall k \in K^i \cap K^r, \forall (i,r) \in I, i \neq r$$

where $\Delta T_k^{i,r}$ is the minimum time separation. (4.7) ensures that if planes i and r cross node k at the same level, they have a minimum separation time $\Delta T_k^{i,r}$.

Transit Time Intervals

Exact definition of transit times in each node can be meaningless, especially for those nodes far from the initial one. To improve this model it is convenient to associate an interval of transit times, consistent with plane performances and assigned standard separations, with each plane and each node instead of a transit time. To this end constraints (4.3) + (4.6) must be modified.

Now let $[t_k^i - \Delta t_k^i, t_k^i + \Delta t_k^i]$ be transit times interval of plane i on node k , the expressions (4.3) + (4.6) become, respectively

$$t_{\tilde{k}}^i \leq t_k^i - \Delta t_k^i + \sum_{h \in H_k^i} \sum_{j \in P_{\tilde{k}}^i} q_{kh}^i q_{kj}^i \tau_{khj}^{Mi} - \Delta t_k^i, \quad \forall k, \tilde{k} \in K^i, \forall i \in I \quad (4.3^*)$$

$$t_{\tilde{k}}^i \geq t_k^i + \Delta t_k^i + \sum_{h \in H_k^i} \sum_{j \in P_{\tilde{k}}^i} q_{kh}^i q_{kj}^i \tau_{khj}^{mi} + \Delta t_k^i, \quad \forall k, \tilde{k} \in K^i, \forall i \in I \quad (4.4^*)$$

$$T_{om}^i + \Delta t_{k_o}^i \leq t_{k_o}^i \leq T_{oM}^i - \Delta t_{k_o}^i, \quad \forall i \in I \quad (4.5^*)$$

$$T_{fm}^i + \Delta t_{k_f}^i \leq t_{k_f}^i \leq T_{fM}^i - \Delta t_{k_f}^i, \quad \forall i \in I \quad (4.6^*)$$

(4.3*) and (4.4*) ensure that any transit time on node \tilde{k} , relative to plane i and included in the interval $[t_k^i - \Delta t_k^i, t_k^i + \Delta t_k^i]$ is always consistent with plane performances, while transit time on node k assumes any value in the interval $[t_k^i - \Delta t_k^i, t_k^i + \Delta t_k^i]$.

(4.5*) and (4.6*) are similar to (4.5) and (4.6) and extend to intervals the limitations on the initial and final nodes.

Obviously, system (4.3*) + (4.6*) is meaningful if conditions

$$\tau_{khj}^{Mi} - \tau_{khj}^{mi} \geq 2 [\Delta t_k^i + \Delta t_k^r], \quad \forall h \in H_k^i \text{ and } \forall j \in P_{\tilde{k}}^i$$

$$T_{OM}^i - T_{om}^i \geq 2\Delta t_{k_0}^i, \quad T_{FM}^i - T_{om}^i \geq 2\Delta t_{k_f}^i$$

are satisfied.

As far as separation constraints are concerned, (4.7) becomes

$$|t_k^i - t_k^r| \geq [\Delta t_k^r + \Delta t_k^i + \Delta T_k^{ir}] \left[\sum_{h \in H_k^i \cap H_k^r} q_{kh}^i q_{kh}^r \right] \quad (4.7^*)$$

$$\forall k \in K^i \cap K^r, \forall i, r \in I, i \neq r$$

Waiting Times

The suggested model may have no feasible solution because of transit times constraints. To avoid this circumstance, we can increase a freedom degree of the system providing a waiting possibility on prefixed nodes. To this end it is sufficient to introduce in (4.3) or in (4.3*) a term presenting waiting times. In detail (4.3*), could be replaced by

$$t_k^i \leq t_k^i - \Delta t_k^i + \sum_{h \in H_k^i} \sum_{j \in P_{kh}^i} q_{kh}^i q_{kh}^j \tau_{khj}^i - \Delta t_k^i + \tau_k^i$$

$$a_i \mu_k^i \leq \tau_k^i \leq b_i \mu_k^i, \quad \forall k, \tilde{k} \in K^i, \forall i \in I$$

where μ_k^i is a binary variable equal to 1 if plane i waits on node k a time $\tau_k^i \neq 0$ and equal to zero otherwise.

Objective Function

We may consider several objective functions. The first possibility is to minimize total delay of planes in the control region. In this case the objective function can be expressed as

$$J_1 = \sum \alpha_{k_f^i}^i t_{k_f}^i$$

where $\alpha_{k_f^i}^i$ are weight coefficients depending on the plane class and the terminal mode.

In particular, J_1 seems meaningful in the terminal area, where, because of operating reasons, the main objective is to minimize the final delay.

When we consider larger airspace regions, we must also take into account the cost connected with deviations from the nominal flight profile. In this case, the objective function could be expressed as

$$J_2 = \sum_{i \in I} \sum_{k \in K^i} \left\{ \sum_{h \in H_k^i} \sum_{j \in H_k^i} \alpha_{khj}^i q_{kh}^i q_{kj}^i |t_k^i - t_k^j - \tau_{khj}^i| + \beta_k^i \left| \sum_{h \in H_k^i} (q_{hk}^i - \bar{q}_{hk}^i) z_h \right| \right\}$$

where τ_{khj}^i represents, for plane i , the transit time from level h of node k to level j of the subsequent node following minimum consumption profile; α_{khj}^i and β_k^i are appropriate weight coefficients. The first term of J_2 represents the total shifting of transit times between couples of adjacent nodes from the corresponding times in the minimum consumption profile; the second term represents the total deviation of altitude levels from the nominal ones. Therefore, J_2 could be utilized as a cost index related to the total final consumption.

In this model one must also notice that, if delay costs and costs of deviations from the nominal flight profile were evaluable in homogeneous quantitative terms, we could take as an objective function $J_3 = J_1 + J_2$, where arrival times and fuel consumptions are simultaneously considered.

On the basis of this model, the minimization of whichever objective function with the previous constraints, is a non linear mixed variables optimization problem.

4.2 Problem Decomposition

The use of the general model above illustrated involves several computational and operational difficulties. In fact, mathematical complexity increases with the number of planes to be controlled; moreover, the provided control methodology may conflict with current ATC procedures. With regard to these problems, we must consider that the suggested control philosophy may require, for every new plane entering the control region, an intervention on all planes previously planned. Consequently, this could involve heavy operational difficulties. To partially overcome these difficulties, in the following, we shall consider a simplified model of SCF based on the hypothesis that flights planning is carried out according to the FIFO (first in, first out) discipline. More in detail, we decide that planning action for each new plane entering the control region is carried out assuming, as constraints, the flight plans of airplanes still in the system.

This hypothesis obviously reduces solution optimality, but it reduces also mathematical complexity (variables relative to only-one plane must be taken into account). Moreover, the suggested control method becomes consistent with the current ATC procedures. On this basis the mathematical model can be simplified considering planning of only-one plane.

Since minimization of $J_3 = J_1 + J_2$ remains a problem which difficulty increases with the number of nodes of the trajectory, in the following, a decomposition algorithmic procedure of the control problem is illustrated. In such a way, in general, a sub-optimal solution of global problem can be obtained. More in detail, the solution method consists in two sequential steps:

- 1) determine a solution satisfying constraints (4.1) + (4.7) and minimizing only deviations of altitude levels from the nominal ones:
- 2) for the levels fixed in the first step, determine a solution satisfying constraints (4.3) – (4.7) and minimizing transit times deviations from the those relative to the nominal flight path (or delay on terminal node).

Thus, we obtain two different sub-problems that can be denoted, respectively, as “altitude control” and “speed control”.

In the following we recall only the fundamental mathematical aspects of each problem and the techniques utilized to solve them. More details on the mathematical models and solution algorithms can be found in an earlier paper (Andreussi and others, 1981).

4.2.1 Altitude Control

Let $K = \{1, 2, \dots, k, \tilde{k}, \dots, N\}$ be the ordered set of nodes subsequently crossed by a plane and denote with \tilde{t}_k^r the transit times of planes already planned on the node k ; constraints (4.1) + (4.7) become the following

$$\sum_{h \in H_k} q_{kh} = 1, \quad \forall k \in K \quad (4.1')$$

$$\sum_{h \in H_k} q_{kh} - \sum_{j \in P_{kh}} q_{kj} = 1, \quad \forall k < N \quad (4.2')$$

$$\tilde{t}_k^{\sim} \leq t_k + \sum_{h \in H_k} \sum_{j \in P_{kh}} q_{kh} q_{kj}^{\sim} \tau_{khj}^M, \quad \forall k < N \quad (4.3')$$

$$\tilde{t}_k^{\sim} \geq t_k + \sum_{h \in H_k} \sum_{j \in P_{kh}} q_{kh} q_{kj}^{\sim} \tau_{khj}^m, \quad \forall k < N \quad (4.4')$$

$$t_{om} \leq t_1 \leq t_{oM} \quad (4.5')$$

$$t_{fm} \leq t_N \leq t_{fM} \quad (4.6')$$

$$|t_k - \tilde{t}_k^r| \geq \left(\sum_{h \in H_k \cap H_k^r} q_{kh} q_{kh}^r \right) \Delta T_k^r, \quad \forall r \in I_k \text{ and } \forall k \in K \quad (4.7')$$

where m and M , as denoted before, indicate, respectively, the minimum and the maximum values of the time parameters and I_k is the set of indexes of planes already planned passing on node k .

The problem corresponding to step 1) and referred to as “altitude control” is, therefore, that of determining altitude levels so that the function

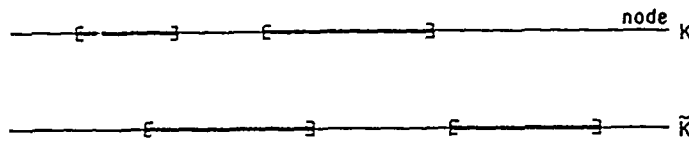
$$J_q = \sum_{k \in K} \beta_k \left| \sum_{h \in H_k} (q_{kh} - \tilde{q}_{kh}) z_h \right|$$

is minimized and constraints (4.1') + (4.7') are satisfied.

The problem, thus defined, is one with mixed variables, h_k and t_k , where variables t_k are not present in the objective function and constraints on t_k impose that at least a sequence of time intervals, by twos consistent according to what is represented in fig. 5, exist. It follows that given the altitude levels h_k , we can verify their feasibility by a definite number of comparisons. Therefore, the optimal solution h_k^* can be determined by a classical branch and bound algorithm.

REMARK 1. If nominal altitudes are feasible (according to planes performances, separation constraints and possible limitations on available altitude levels) the optimal solution is determined in the first cycle of the algorithm.

REMARK 2. Corresponding to each feasible solution found a sequence $\{V_k\}$ of consistent time sets, with $k = 1, 2, \dots, N$, is also determined. Thus, a sequence of transit times on each node satisfying all constraints, can be easily defined.



a) Feasible time windows: the case of one altitude level for each node

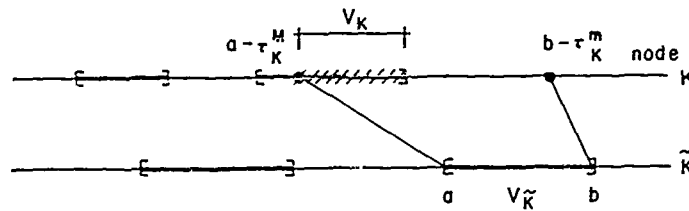
b) Reflection of feasible time windows of node \tilde{K} and representation of consistent time intervals $(V_K, V_{\tilde{K}})$

Fig. 5 - EXAMPLES OF FEASIBLE TIME WINDOWS OF TWO SUBSEQUENT NODES AND CORRESPONDING CONSISTENT TIME INTERVALS

4.2.2 Speed Control

The problem referred to as "speed control" is to determine transit time on each node so that the function

$$J_V = \alpha_N t_N + \sum \alpha_k |t_k^{\sim} - t_k - \bar{r}_k|$$

is minimized and constraints on performances of the controlled airplane and safety, are satisfied. Since, in this problem, we assume that the altitude levels are the nominal ones or those computed by the algorithm of altitude control, then the control action carried out is equivalent to the control of the plane speed.

With these hypotheses, constraints (4.3) + (4.7) can be further simplified by eliminating altitude variables. Therefore, they become

$$t_k^{\sim} \leq t_k + \tau_k^M, \quad \forall k < N \quad (4.3'')$$

$$t_k^{\sim} \geq t_k + \tau_k^m, \quad \forall k < N \quad (4.4'')$$

$$t_1^m \leq t_1 \leq t_1^M \quad (4.5'')$$

$$t_1^m \leq t_N \leq t_N^M \quad (4.6'')$$

$$|t_k^{\sim} - t_k| \leq \Delta t_k^{\sim}, \quad \forall r \in \bar{t}_k \text{ and } k \in K \quad (4.7'')$$

The problem, thus formulated, is a linear programming one with mixed variables where the combinatorial aspect is due to constraints (4.7''). To solve this problem, we have carried out a hybrid algorithm that utilizes dynamic programming and branch and bound techniques. Dynamic programming is used to transform a problem with mixed variables into a problem with only discrete variables. The latter is then solved by an enumerative procedure.

An important aspect of this method is that, since no discretization of the continuous variables t_k is necessary, the optimal solution can be reached.

4.3 Computational Results

The algorithms relative to altitude and speed control, previously described, have been implemented in a UNIVAC 1100/82 computer and different series of tests have been performed. More in detail, in a first step, the altitude levels have been determined; subsequently, transit times on the prefixed nodes have been computed. With this approach, the altitude levels and the consistent time intervals, determined by the first algorithm, are utilized as input data for the second algorithm.

The numerical tests were carried out by considering an increasing number of nodes $N = 5, 10, 15, 17, 20$ for a total of 400 tests. For each test, the input variables supposedly have been uniformly distributed over fixed intervals and the relative values have been randomly generated. Moreover, appropriate limits to ensure reciprocal consistency and operational meaningfulness have been imposed. For example, the number of levels in each node is five and upper and lower bounds for τ , τ^m , τ^M are derived from the speed/altitude aeroperformance diagrams.

The simulation results are fully reported in Table 1 where, for each value of N , the most significant computation times are indicated. In particular, t_a is the time required to determine altitudes and it coincides with the time necessary to find the first global feasible solution; t_o is the time relative to the optimal solution and t_c is the global computation time. The results shows that the more time-consuming algorithm is the altitude control algorithm. Little computation effort is requested, on the contrary, by speed control.

Table 1

Number of nodes	5	10	15	17	20
Number of tests	150	110	100	40	10
t_a (sec)	.014	.27	6.2	17	102
t_o (sec)	.014	.27	7.2	17	102
t_c (sec)	.014	.37	7.4	19	112

Besides the computation times values suggest that the proposed approach can be used as a tool to on-line provide free-conflict four dimensional paths until the number of nodes of trajectory is less than 20. For $N = 20$ the algorithm behaviour begins to look unsatisfactory.

These results demonstrate that the algorithm could be used, for example, in a strategic control system of large Terminal Areas.

However, one must also notice that computation times strongly depend both on the number of nodes N and on the number of feasible windows corresponding to the various levels. This indicates that the tests mostly increasing the mean computation times are those that simulate traffic congestion situations which occur only in special operational conditions.

5. TACTICAL CONTROL

Today the air traffic controller uses radar to assess the traffic situation and speed, altitude and heading instructions to separate and space aircraft. This is the "tactical" system using relative - position separation in which the planning horizon is very short and the situation is allowed to develop before solutions are offered. The pilot does his own navigation only when there are no nearby aircraft. As the flight encounters traffic of increasing density, ATC intervenes more and more until, in a busy terminal area, the controller is vectoring the airplane continuously in all three dimensions and in airspeed. This control system is manpower intensive, uses relatively inefficient flight paths to solve traffic situations and is at or near its capacity in handling traffic and supporting increased runway operations. This management philosophy is not adequate in congestion situations and, in particular, near the main airports where, owing to users requirements, traffic distribution is highly concentrated.

The effects of this situation are felt mostly in the arrival and departure phases. In fact, in the last years it has been assessed that only 10% of the delays occurs along the aircraft routes, while the corresponding percentages for arrivals and departures are, respectively, about 60% and 30%. For this reasons, in the last years, specific attention has been devoted to the management of Terminal Area (TMA) where the overall system efficiency becomes nearly as important as safety. Moreover, a reduction of human intervention in the operations management is needed and, consequently, more automated system have been proposed. From this point of view the TMA problem is "the automation of the aircraft flow control and sequencing in the proximity of the airport so as to satisfy an optimality criterion".

As a consequence, the need arises to define a model which can be dealt with mathematically and to analyze all those elements which constitute a semi or fully automated control system.

To contribute in solving the TMA control problems, in this paper, we consider in particular the Aircraft Sequencing Problem (ASP).

5.1 The Aircraft Sequencing Problem

During traffic peak periods, the control of aircraft arrivals and departures in a TMA becomes a very complex task. Air traffic controllers, among other things, must guarantee that every aircraft, either waiting to land or preparing to take off in such a congested area, maintains the required degree of safety. They have to decide also what aircraft should use a particular runway, at what time this should be done and what manoeuvres should be executed to achieve this. The viable accomplishment of such a task becomes more difficult in view of the fact that aircraft are continuously entering and leaving the system and that, at peak periods, the demand for runway occupancy may reach, or even exceed the capabilities of the system. It is at such periods that excessive delays are often observed, resulting in passenger discomfort, fuel waste and disruption of the airlines' schedules.

Under such "bottleneck" conditions, an increase in collision risk can logically be expected as well. As a consequence, because of safety considerations, the structure of TMA is rigidly defined and all aircraft must fly satisfying prefixed procedural constraints.

To simplify the understanding of the problem we refer to a TMA as shown in fig. 6 and fig. 7 and we consider only landings, even if the approach proposed in the following allow, to simultaneously take into account takeoffs.

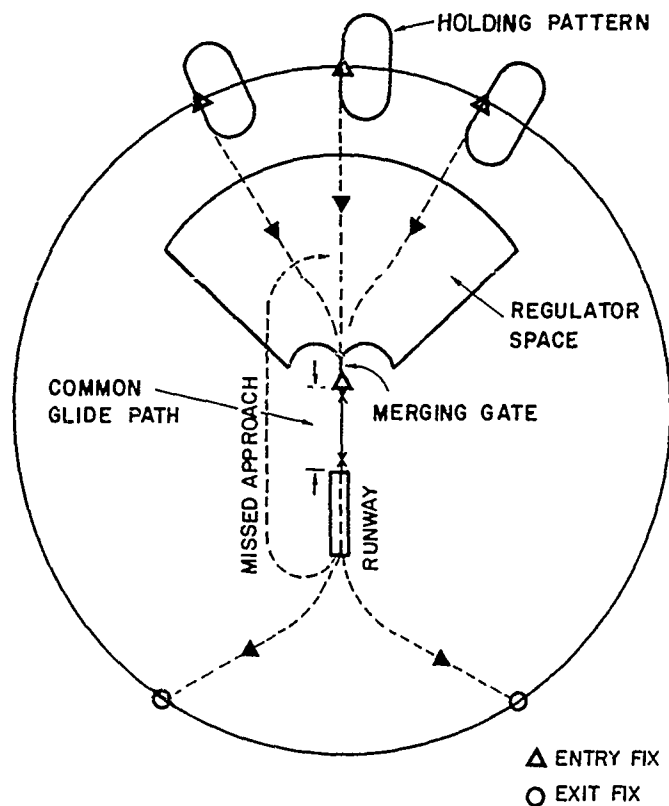


Fig.6- STRUCTURE OF TMA

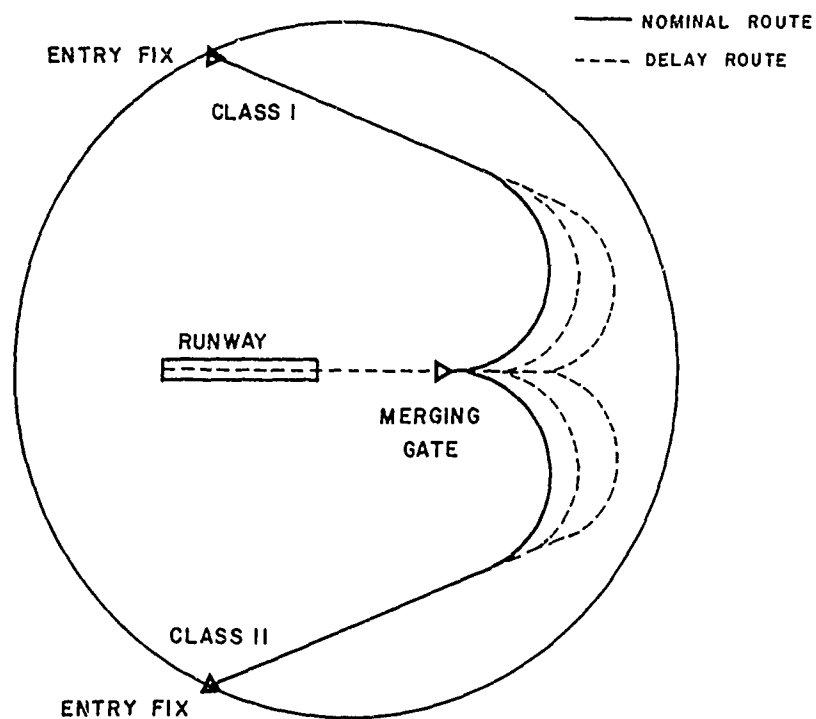


Fig. 7- DELAY ROUTES

Then the following aspects must be underlined:

- a) every aircraft must approach the runway for landing, flying along one of the prestructured paths of TMA;
- b) the runway can be occupied by only one aircraft at a time;
- c) every aircraft must fly along the common approach path following a standard descent profile;
- d) during all the approach phases a separation standard between every couple of subsequent aircraft must be maintained;
- e) the sequencing strategy used by almost all major airports of the world is still today the "First-Come First-Served" (FCFS) discipline.

As it is well known, FCFS strategy is very simple to implement, but it is likely to produce excessive delays. Therefore, any effort must be made to minimize the delay or optimize some other measure of performance related to the passenger discomfort, without violating safety constraints.

Consequently the TMA problem can be stated as follows: "Given a set of aircraft entering the TMA and given, for each aircraft, the Preferred Landing Time (PLT), the runway occupancy time, the cost per unit time of flight, the geometry of the approach path and glide path and the corresponding aircraft speeds, assign to each aircraft the starting time from the fix and the approach path in such a way that the procedural constraints are satisfied and a system performance index is optimized".

With the TMA operating in the aforementioned way, the TMA problem can be decomposed into the two following sub-problems.

- 1) given the constraints on the aircraft performances, the initial and final states (position and speed) and the pre-established flight time, determine the optimum trajectories which connect these states with the specified flight time;
- 2) given a set of PLT and the maximum admissible delay, determine the Actual Landing Times (ALT) sequence which satisfies the procedural constraints on the runway and the glide path and optimizes a system performance index.

To a large extent these two problems are independent. In fact, as the required controls to follow the approach paths can be calculated in advance, it is possible to predetermine the optimal flight path. Therefore, the need of "real-time" calculations is limited only to sub-problem 2, called Aircraft Sequencing Problem (ASP), which is the topic discussed here. The goal of solving the ASP is, at least theoretically, achievable for two reasons.

First, safety regulations state that any two coaltitudinal aircraft must maintain a "minimum horizontal separation", which is a function of the types and relative positions of these two aircraft.

Second, the "landing speed" of an aircraft is generally different from the landing speed of another aircraft.

A consequence of the variability of the above parameters (minimum horizontal separation and landing speed) is that the "minimum permissible time interval" between two successive landings is a variable quantity.

Thus, it may be possible, by rearranging the initial position of the aircraft, to take advantage of the above variability and obtain a landing sequence that results in a more efficient use of the runway as compared with that obtainable by using the FCFS discipline. In fact, an optimal sequence does exist; it is theoretically possible to find it by examining all sequences and selecting the most favorable one.

The method suggested above to determine the optimal sequence is safe, but extremely inefficient, because the computational effort associated with it is a factorial function of the number of aircraft and it is not possible to evaluate all combinations in a short time interval (as the nature of ASP requires) even on the fastest computer. To give an idea of the difficulty, it is sufficient to consider that, with only 10 aircraft, we would have to make 3,628,000 comparisons and with 15 aircraft 1,307,674,368,000 comparisons.

It should be also pointed out that while the main factor that suggests the existence of an optimal landing sequence is the variability of the minimum permissible time interval between two successive landings, it is the same factor that makes the determination of this optimal sequence a nontrivial task.

Moreover, the real world problem involves many other considerations, especially as far as the implementation of sequencing strategies is concerned.

For these reasons, the relevant literature on the subject has been, till now, considerable and growing [see for example Odoni, 1969; Tobias, 1972; Park and others, 1972, 1973; Bianco and others, 1978, 1979; Trivizas, 1985.].

Three papers, in particular, seem to offer an adequate solution to the operational needs.

In the first (Dear, 1979), an excellent investigation of the ASP was carried out. In particular the author points out that, in order to determine the landing order, we need to consider all aircraft currently in the system. As this number can be very large (20 or even more simultaneously), he puts forward serious doubts on the possibility of reaching an optimal solution in real-time even with pseudo-enumerative techniques. Therefore, he resorts to a simulation model where identical arrival streams, under various sequencing strategies, are compared. In particular he proposes a "Constrained Position Shifting" (CPS) strategy instead of FCFS strategy. That is, no aircraft may be sequenced forward or rearward more than a prespecified number of positions (Maximum Position Shifting) from its FCFS position.

The second paper (Psaraftis, 1979, 1980) takes into account Dear's proposal about the CPS management concept, but he develops an exact optimization algorithm based on the dynamic programming approach and referring to the "static" case when all aircraft are supposed to wait to land at a given time. In reality, every aircraft entering TMA has an earliest landing time (which is the PLT) depending on the characteristics of TMA, the aircraft speed, pilot preferences and so on. Therefore, the aircraft to be sequenced wait to land at different times. Fig. 8 shows an example of a real world situation. In this case the Psaraftis approach cannot be easily utilized.

In a third paper (Bianco and others, 1987) a new combinatorial optimization approach, more consistent with the real environment, is proposed.

In the following, the basic idea of this last work and an outline of the optimization model and of the solution algorithm are reported and discussed.

5.2 A Job-Scheduling Formulation of the ASP

Suppose that the air traffic controller is confronted with the following problem. A number n of aircraft are waiting to land at different PLT_i at a single runway airport. His task, then, is to find a landing sequence for these aircraft, so that a certain measure of performance is optimized, while all problem constraints are satisfied.

We now make the problem statement more specific:

- 1) It is assumed that the pilots of all aircraft are capable and willing to execute the instructions of the controller given enough prior notice.

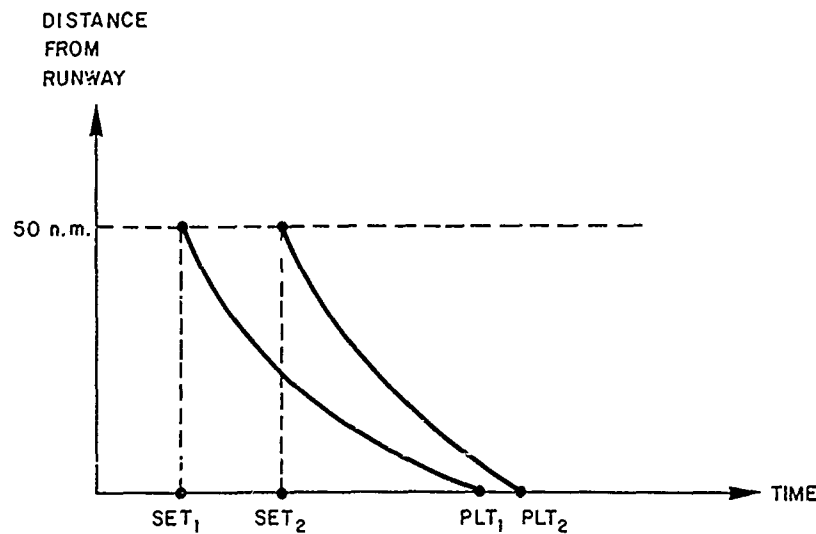


Fig. 8-EXAMPLE OF AIRCRAFT CONFLICTING ON THE RUNWAY

- 2) The measure of performance selected is the "Last Landing Time" (LLT). The corresponding objective is then to find a landing sequence such that the aircraft that lands last does this as quickly as possible.
- 3) Concerning the problem constraints, only the satisfaction of the "minimum inter-arrive time" constraints is required. This means that the time interval between the landing of an aircraft i , followed by the landing of an aircraft j , must not be less than a known time interval t_{ij} .
- 4) The composition of the set of aircraft waiting to land is, of course, assumed to be known. For each ordered pair (i, j) of aircraft, the minimum time interval t_{ij} is also known.
- 5) At any stage of sequencing procedure, the air controller is free to assign the next landing slot to any of the remaining aircraft. This means that we ignore the initial positions which the aircraft had when they arrived at TMA.

At this point it is not difficult to see that the problem described above can be represented by means of a particular "job-machines scheduling" model. In fact, with the aforementioned assumptions, the following analogy may be established:

- a) to each landing operation is associated a job;
- b) the runway corresponds to a machine with capacity one;
- c) the PLT_i of aircraft i corresponds to the ready time r_i of job i ;
- d) the ALT_i of aircraft i corresponds to the start time t_i of job i ;
- e) the LLT corresponds to the maximum completion time C_{max} of the schedule;
- f) the minimum time interval t_{ij} between the landing of aircraft i , followed by the landing of aircraft j , corresponds to the processing time p_{ij} of job i when it depends on job j following in the sequence.

Therefore, the ASP, as defined here, can be mathematically reformulated as the $n||r_i|seq-dep|C_{max}$ scheduling problem. For this problem the following approach (Bianco et others 1985) can be utilized.

5.3 The $n||r_i|seq-dep|C_{max}$ Model

Let $J = \{1, 2, \dots, n\}$ be a set of n jobs to be processed on a single machine, and denote by r_i the ready time of the job i . A matrix (p_{ij}) , with $i, j \in J = J \cup \{0\}$, is given where p_{ij} ($i \neq 0$) is the "processing time" of the job i if job j is the successor of i in the sequence ($0 = 0$, if i is the last job in the sequence) and p_{0i} is the "setup time" of the machine when the sequence starts with job i .

The $n||r_i|seq-dep|C_{max}$ problem can be formulated using the following integer programming model:

$$\min (s + \sum_{i \in J \cup \{0\}} \sum_{j \in J \cup \{0\}} p_{ij} x_{ij}) \quad (5.1)$$

subject to

$$t_i + \sum_{j \in J_0} p_{ij} x_{ij} - \sum_{k \in J_0} \sum_{j \in J_0} p_{kj} x_{kj} - s \leq 0, \quad i \in J_0 \quad (5.2)$$

$$r_i - t_i \leq 0 \quad i \in J_0 \quad (5.3)$$

$$(p_{ij} + T_{ij}) x_{ij} + t_i - t_j - T_{ij} \leq 0, \quad i \in J_0, j \in J, j \neq i \quad (5.4)$$

$$\sum_{j \in J_0} x_{ij} = 1, \quad i \in J_0 \quad (5.5)$$

$$\sum_{i \in J_0} x_{ij} = 1, \quad j \in J_0 \quad (5.6)$$

$$s \geq 0, \quad (5.7)$$

$$t_0 = 0, \quad (5.8)$$

$$x_{ij} \in \{0,1\}, \quad i \in J_0, j \in J, j \neq i \quad (5.9)$$

$$t_i \geq 0, \quad i \in J_0 \quad (5.10)$$

where:

$x_{ij} = 1$ if job i directly precedes job j

$x_{ij} = 0$ otherwise

t_i is the start time of job i

s is the machine idle time

T_{ij} are chosen to make constraints (5.4) redundant whenever $x_{ij} = 0$

REMARK 1. This problem is NP hard and in the case of zero ready times it reduces to the asymmetric travelling salesman problem (ATSP). Moreover constraints (5.4) both prevent sub-tours in the ATSP solution and avoid two jobs to be simultaneously processed.

REMARK 2. The above formulation can be considered as an ATSP with unlimited time windows ($r_i \leq t_i < +\infty$).

5.4 Outline of the Solution Algorithm

The solution of the above problem can be obtained by a pseudo enumerative procedure exploiting both some peculiar properties of the problem and efficient lower and upper bound.

Branching Phase

Denote by $C(\sigma)$ the completion time of a subsequence σ , the following two dominance criteria, (see Bianco others, 1985), are utilized for tree pruning.

Theorem 1: A subsequence $\sigma\pi k$ is dominated if there exists a permutation π' of π such that

$$C(\sigma\pi k) > C(\sigma\pi'k)$$

Theorem 2: A subsequence $\sigma j \sigma' i$ is dominated if

$$\begin{aligned} \text{a) } r_i &> \max \{ r_i, C(\sigma) \} + p_{ij} \\ \text{b) } p_{ki} + p_{ih} &\geq p_{hk}, \quad \forall h, k \in J \setminus \{i\} \end{aligned}$$

Then the following branching strategy can be stated.

At each node of the enumeration tree is associated a partial sequence σ in which the first k jobs have been fixed. As first step theorem 2 is used to define, among the unscheduled jobs, a set of candidates to the $(k+1)$ -th position in the optimal sequence. Subsequently, for each candidate i , the procedure checks whether or not it is dominated according to theorem 1. If it is dominated, a new candidate is examined, otherwise the lower bound is computed and, if it is less than an upper bound of the optimal solution, a new node, representing the subsequence σi , is generated.

At this point the ready times of the unscheduled jobs which are smaller than $C(\sigma i)$ are set to $C(\sigma i)$.

Backtracking takes place whenever a complete sequence has been produced or all the candidates at a given level have been examined.

Bounding Phase

At each node of the enumerative tree we have a new problem with job-set $J \setminus \{\sigma\}$, new ready times and new set-up times. To this problem two lower bounds and an upper bound are applied.

1) Lagrangean Lower Bound (LLB)

It is obtained as the solution of the lagrangean problem obtained by dualizing constraints (5.2) and (5.3), and dropping constraints (5.4) in the original model.

2) Alternative Lower Bound (ALB)

As the LLB tends to be weak in case of small variations in the matrix $\{p_{ij}\}$, the following heuristic rule can be utilized:

$$(i) \text{ to each job } i \in J \text{ associate the processing time } p_i = \min_j \{p_{ij}\};$$

(ii) schedule the jobs using the FCFS rule and take the completion time as the ALB of the original problem.

REMARK. Observe that ALB is the optimal solution of our problem when processing times do not depend on the sequence, and hence, in the general case, ALB is a lower bound on the optimal solution.

3) Upper Bound (UB)

As observed in the previous remark, EST (Earliest Start Time) rule is optimal if the processing times are sequence-independent. Consequently, a reasonably good feasible solution can be obtained by associating to each job an average processing time $p_h = (\sum_{j \in J} p_{ij})/n$ and sequencing the jobs according to the EST rule. The upper bound UB is then obtained by computing the completion time of the EST sequence using the original processing times. Next we improve the UB value by applying two procedures based on Theorem 1.

The first one performs exchange among pairs of adjacent jobs till a 2-exchange local optimum is reached.

To the resulting sequence, a second procedure is applied. It works as follows: Given a parameter m , for $i=0, \dots, n-m$, the current sequence is replaced by the best among the sequences obtained by permuting the jobs in the positions from $i+1$ to $i+m$. Notice that the resulting sequence is not in general an m -exchange local optimum.

5.5 Computational Results

To test the efficiency of the algorithm when applied to real-world problems, we must consider that aircraft, waiting to land, can be classified into a relatively small number m of distinct "categories" according to speed, capacity, weight and other technical characteristics.

As a consequence, the minimum interarrival times between two successive aircraft is a function only of the categories they belong to.

We have exploited this clustering of aircraft into categories to drastically reduce the size of the enumeration tree. In fact, it can be easily seen that, at the k -th iteration, only the earliest aircraft of each category, is eligible to be scheduled at position $(k+1)$ -th.

The following table 4 represents the minimum interarrival times relative to the main categories of commercial aircraft, while tables 5 and 6 illustrate the results of two realistic large scale problems with 30 and 44 aircraft, respectively.

The CPU times required to find the optimal solution with the algorithm coded in Pascal and tests carried out on a Vax - 11/780, have been respectively 373 sec. and 1,956 sec. Even though those times might seem not compatible with real time requirements, we want to point out that our code is experimental and very little has been spent to improve its efficiency.

Nevertheless we believe that the algorithm could be implemented to fit into real-time environment by using a faster machine, more sophisticated data structures and implementation techniques.

On the other hand, we want to stress that, as shown in tables 5 and 6, the optimal solution allows the saving up to about 20% on the runway utilization.

Table 2 - t_{ij} (sec); $m=4$

1 = B 743 ; 2 = B 727 ; 3 = 707 ; 4 = DC 9

$i \backslash j$	1	2	3	4
1	96	200	181	228
2	72	80	70	110
3	72	100	70	130
4	72	80	70	90

Table 3 (n=30)

Aircraft Number	Category	Nominal Landing Time (sec.)	FCFS Landing Time (sec.)	Optimal Sequence	Optimal Landing Time (sec.)
1	1	0	0	1	0
2	1	79	96	2	96
3	1	144	192	3	192
4	2	204	392	5	288
5	1	264	464	6	384
6	1	320	560	4	584
7	2	528	760	8	656
8	1	635	832	11	752
9	2	730	1032	7	952
10	2	766	1112	9	1032
11	1	790	1184	12	1104
12	1	920	1280	14	1332
13	3	1046	1461	10	1412
14	4	1106	1591	15	1492
15	2	1136	1671	16	1572
16	2	1166	1751	13	1642
17	2	1233	1831	18	1714
18	1	1642	1903	19	1810
19	1	1715	1999	20	1991
20	3	1770	2180	17	2091
21	1	2074	2252	23	2201
22	1	2168	2348	21	2273
23	4	2259	2576	22	2369
24	2	2427	2656	25	2465
25	1	2481	2728	24	2665
26	2	2679	2928	26	2745
27	3	2883	2998	27	2815
28	2	2982	3098	28	2915
29	1	3046	3170	29	2987
30	1	3091	3266	30	3083

Table 4 (n = 44)

Aircraft Number	Category	Nominal Landing Time (sec.)	FCFS Landing Time (sec.)	Optimal Sequence	Optimal Landing Time (sec.)
1	1	0	0	1	0
2	1	79	96	2	96
3	2	144	296	3	296
4	2	204	376	4	376
5	2	264	456	6	448
6	1	320	528	7	544
7	1	528	624	8	640
8	1	635	720	5	840
9	2	730	920	9	920
10	1	766	992	11	1000
11	2	790	1192	13	1080
12	1	920	1264	14	1160
13	2	1046	1464	16	1240
14	2	1106	1544	17	1320
15	1	1136	1616	19	1400
16	2	1166	1816	10	1472
17	2	1226	1896	12	1568
18	1	1233	1968	15	1664
19	2	1286	2168	18	1760
20	2	1418	2248	21	1856
21	1	1642	2320	22	1952
22	1	1715	2416	24	2048
23	2	1744	2616	29	2144
24	1	1770	2688	30	2240
25	2	1809	2888	32	2236
26	2	1869	2968	34	2432
27	2	1929	3048	35	2528
28	2	1989	3128	20	2728
29	1	2074	3200	23	2808
30	1	2168	3296	25	2888
31	2	2229	3496	26	2968
32	1	2259	3568	27	3048
33	2	2326	3768	28	3128
34	1	2427	3840	31	3208
35	1	2481	3936	33	3288
36	2	2488	4136	36	3368
37	2	2565	4216	37	3448
38	2	2657	4296	38	3528
39	1	2679	4368	44	3608
40	1	2883	4464	39	3680
41	1	2982	4560	40	3776
42	1	3046	4656	41	3872
43	1	3091	4752	42	3968
44	2	3153	4952	43	4064

6. CONCLUSIONS

In conclusion, a new manner of looking at the ATC system can be derived. In particular, the multilevel model proposed shows that the ATC is well depicted by a control functions hierarchical structure. Thus, a more correct balance between planning actions and operational actions can be established. Moreover, in this framework, for each on-line function, the corresponding optimization models and the solution techniques seem to be helpful tools to better understand the involved phenomena, to increase the ATC system automation level and, therefore, to improve air traffic management.

ACKNOWLEDGMENTS

The author is indebted with all colleagues mentioned in the references who cooperated with him in the previous works.

OPTIMIZATION MODELS AND TECHNIQUES TO IMPROVE AIR TRAFFIC MANAGEMENT

Bianco L.

REFERENCES

1969

Odoni A.R. "An Analytical Investigation of Air Traffic in the Vicinity of Terminal Area". Technical Report n. 46, Operations Research Center MIT, Cambridge, 1969.

1970

Mesarovic M.D., Macko D., Tokamata Y. "Theory of Hierarchical Multilevel System". Academic Press, 1970

1971

Wismor D.A. "Optimization Methods for Large-Scale System with Applications". Mc Grow-Hill, 1971

1972

Park S.K., Straeter T.A., Hogge J.E. "An Analytic Study of Near Terminal Area Optimal Sequencing and Flow Control Techniques". AGARD CP. 105, 1972

Tobias L. "Automated Aircraft Scheduling Methods in the Near Terminal Area". AIAA Paper n. 72. 120, 1972.

1973

Park S.K., Straeter T.A. "Near Terminal Area Optimal Sequencing and Flow Control as a Mathematical Programming Problem". Symposium on Non Linear Programming, George Washington University, 1973.

1974

Erwin R.L. and others "Strategic Control Algorithm Development" U.S. Department of Transportation, Report n. DOT-TSC-OST 74-3, Vol. I-IV, 1974.

Ratliffe S. "Computer Representation of Air Traffic Route Structure" Royal Radar Establishment Memorandum N. 2880, Malvern, 1974

1975

Erwin R.L. "Strategic Control of Terminal Area Traffic". AGARD Conference Proceedings n. 188, Plans and Developments for Air Traffic Systems 3-1, 3-13, 1975.

1976

Assad A.A. "Multicommodity Network Flows — Computational Experience". Working Paper OR 058-76, Operations Research Center, MIT, Cambridge, 1976

Dear R.G. "The Dynamic Scheduling of Aircraft in the Near Terminal Area". FTL R76.9, Flight Transportation Laboratory, MIT Cambridge, 1976

1977

Eurocontrol "Traffic Flow Investigation System Progress Report". International Air Transport Association. 6th Meeting of the ATM Group, Paris, 1977.

1978

Bianco L., Nicoletti B., Ricciardelli S. "An Algorithm for Optimal Sequencing of Aircraft in the Near Terminal Area". Optimization Techniques (Stoer J. Ed.). Lecture Notes in Control and Information Science, Springer Verlag, 1978.

Bianco L., Cini M., Grippo L. "Pianificazione e Controllo Strategico del Traffico Aereo". Istituto di Automatica - Università di Roma and CSSCCA-CNR-R 78-28, December 1978.

Psarafitis H.N. "A Dynamic Programming Approach to the Aircraft Sequencing Problem" FTL R78-4, Flight Transportation Laboratory, MIT, Cambridge, 1978.

1979

Bianco L., Ricciardelli S., Rinaldi G., Sassano A. "The Aircraft Optimal Sequencing as a N Job-One Machine Scheduling Problem" Istituto di Automatica - Università di Roma and CSSCCA-CNR-R79-36, 1979.

Bianco L., Cini M., Grippo L. "A Strategic Approach to Air Traffic Control". 9th IFIP Conference on Optimization Techniques, Warsaw, September 1979.

18-22

1980

Bianco L., Bielli M., Cini M., Grippo L., Ricciardelli S. "New Approaches to Air Traffic Control and Management". Invited Paper to the World Conference on Transport Research. London, 1980.

Bielli M., Calicchio G., Nicoletti B., Ricciardelli S. "Flow Control of Large Scale Air Traffic Systems". 2th Symposium IFAC, Large Scale Systems (Titli A and Singh M.G. Eds), Pergamon Press, 1980.

Psaraftis H.N. "A Dynamic Programming Approach for Sequencing Group of Identical Jobs". Ops. Res. 6, 1980.

1981

Andreussi G., Bianco L., Cini M., Grippo L. "Un Approccio Strategico per il Controllo in Linea del Traffico Aereo" IASI-CNR-RI-7, 1981.

Bielli M., Calicchio G., Iozzia S., Nicoletti B. "Air Traffic Control Systems. Modelling and Evaluation". IFAC Control Science and Technology - Kyoto (Akashi H., Ed.) Pergamon Press, 1981.

1982

Bielli M., Calicchio G., Nicoletti B., Ricciardelli S. "The Air Traffic Flow Control Problem as an Application of Network Theory". Computers and Operations Research - Vol. 9, 1982.

1985

Bianco L., Ricciardelli S., Rinaldi G., Sassano A. "Sequencing Tasks with Sequence Dependent Processing Times" TMS XXVI International Meeting, Copenhagen, 1985. To appear also on Naval Research Logistic Quarterly.

Bianco L. "A Multilevel Approach to the ATC Problem. the On-Line Strategic Control of Flights". Seminar CEE-CNR-PFT on Informatics in Air Traffic Control, Capri, October 1985.

Trivizas D. "Optimization of Runway Operations". Working Paper. Flight Transportation Laboratory, MIT, Cambridge, 1985

1986

Bianco L. "Strategic Control to Improve Efficiency of Air Traffic Management" AGARD CP-410.

1987

Bianco L., Rinaldi G., Sassano A. "A Combinatorial Optimization Approach to Aircraft Sequencing Problem". Flow Control of Congested Networks (Odoni A.R., Bianco L., Szego G., Eds) Springer Verlag, 1987.

THE HIGH-RESOLUTION GRAPHIC DISPLAY :

A possible man/machine interface for a computer assisted
ATC management system.

by

Carlos Garcia Avello.

Engineering Directorate
EUROCONTROL
European Organisation for the Safety of Air Navigation
72, Rue de la Loi - B-1040 Brussels

SUMMARY.

This article describes an application of high-resolution graphic display in the field of management and control of air traffic in an extended area including a major terminal, the radius of the area being liable to vary from 150 to 300 nm.

Reference is made to air traffic management and 4-D guidance techniques for individual aircraft in a Zone of Convergence, ZOC, in the knowledge that the graphic display techniques are applicable virtually to all systems affording the controller assistance at the decision-making level.

For the purpose of presenting data to the controller we employ a graphic rectangular display having a resolution of 1280 by 1024 points, capable of displaying 16 colors. A circular display similar to most existing radar scopes could of course be used if it had equivalent resolution and colour characteristics.

The management directives and orders for guidance are presented to the operator, area manager or controller of an individual sector as part of the set of data displayed on the radar surveillance and control scope without the use of additional special tabular displays.

1. INTRODUCTION

Increasing air traffic delays in recent years have highlighted dramatically the bottlenecks in existing air traffic control system in Western Europe. Proposed solutions range from upgrading ATC computer systems to increase data processing capacity, to constructing new runway facilities or even new airports, all supported by gruesome stories in the media about airmissses, etc.

Obviously, the availability of more "concrete" might ease at least certain aspects of the critical situation; but from a practical point of view many of these proposals have little chance of realisation owing to the complex environmental conditions around the cities involved. Further, upgrading ATC computing capacity may provide relief for a while, but "more of the same" is probably not an adequate solution for the next generation of ATC systems. Indeed, the current problems have been epitomised by the airline captain who said : "The sky is empty, only the radar screens are full"!

This situation has come about gradually. Initially, the total airspace was divided into sectors which were sufficiently large to allow a controller to execute his tasks more or less autonomously. With the increase in air traffic, control sector volumes have had to be reduced in order to restrict the maximum number of aircraft in a given sector to a level compatible with an acceptable workload. Consequently, the number of sectors has had to be increased and, in many areas, the limit has now been reached, as any further increase in the number of sectors would lead to a disproportional rise in coordination workload with other sectors. In addition, general flow control restrictions have been introduced and have to be complied with.

Today, the consensus is to aim for a computer-based air traffic management system which, as a first step, integrates all en-route and terminal area (TMA) control sectors of an air traffic control centre or group of centres. However, such a system produces information which has firstly to be assimilated by the controller and secondly to be reacted to. Accordingly, it will in itself constitute a certain workload for the controller. Consequently, if an overall controller workload reduction and/or an increase in air traffic capacity is to be obtained, an efficient ergonomic man-machine interface is an absolute necessity.

The paper summarises the state of the art as regards the air traffic management system developed at EUROCONTROL Headquarters in Brussels which is referred to as the Zone of Convergence (ZOC) concept. It goes on to discuss how modern high-resolution raster scanning displays may be used to design an efficient and ergonomic replacement of conventional analogue radar vector scanning radar screens.

2. THE ZONE OF CONVERGENCE CONCEPT

2.1. General Philosophy

The Zone of Convergence (ZOC) concept provides the executive controller with tools to optimise the general flow of traffic in an extended area (100-300 nm) whether inbound, outbound or overflying, through the integration of all ATC sectors (en route and approach) in a given area of jurisdiction.

Three main system components can be identified, viz :

a. The air traffic management component

The system modules involved define optimum take-off and landing sequences according to traffic demand and available resources. Optimisation criteria may vary dynamically with the expected traffic load from minimum flight cost operation to maximum utilisation of runway facilities.

This component of the Zone of Convergence concept is referred to as ROSAS (Regional Optimised Sequencing And Scheduling).

b. The ground based 4D-trajectory prediction system

After sequence optimisation by the ROSAS air traffic management component, the controller must have tools available to maintain the planned traffic flow.

In the ZOC system this software module is referred to as CINTIA (Control of Individual Trajectories of Inbound Aircraft).

For each flight handled by the air traffic management system, whether inbound, outbound or overflying, CINTIA will compute a flight path which meets the specific constraints. As for inbound flights the landing time is a constraint, the CINTIA module provides a ground based 4D trajectory calculation capability which, in order to ensure maximum system throughput, has a delivery accuracy at touch-down of about 10 seconds.

c. Automatic conflict detection system

After definition of traffic streams by the management component and definition of possible flight paths and procedures by the 4D-trajectory prediction system, the resulting trajectories can be checked against potential conflicts.

Rather than automating the complete air traffic control function, the Zone of Convergence concept merely aims at providing the controller with automatic tools to allow him to make optimum use of the available resources whilst ensuring maximum safety.

The three closely interacting system components provide an automatic on-line, real-time planning function which is sufficiently flexible to maintain the controller 100% in the loop. The radar screen has been selected as the main ZOC controller interface since the controller's attention should be distracted as little as possible from the overall picture of the traffic situation in his sector. The presentation of the information is discussed below.

2.2. CINTIA control directive advices

In modern ATC systems labels are associated with plotted aircraft positions on the radar screen (Figure 2.1.). Many formats are in use, each adapted to its specific environment. However, in general, the first line contains the aircraft identification expressed by its callsign. In the experimental ZOC system this is followed by the weight class (heavy, medium or light) and, for inbound aircraft only, the planned number in the landing sequence.

The second line most often shows the current flight level as received from the mode C returns of the secondary radar system (SSR). In the example this is followed by the cleared flight level and the ground speed obtained from the radar tracker algorithm.

Radar labels comprising these two lines are used in most modern ATC systems. In the Zone of Convergence concept the control directives as generated by the CINTIA module are also directly displayed on the radar screen, on a third line appended the standard radar label. In the example of Figure 2.1 the information reads :

"At 12 nm DME distance from beacon "KOKSY" start descending at a speed profile defined by Mach number .80 or an indicated airspeed of 280 kt".

Figure 2.1.

SAB597K	H05
350 100	48
-12 K	.80/28

On standard vector scanning radar screens the status of the information is encoded through the mode in which the third line is displayed.

normal intensity : advises to the controller of the current plan ,

blinking : the aircraft is within 1 minute of flight from the indicated point. If traffic conditions allow, the aircraft should be cleared to descend at the speed law indicated. The controller will be expected to communicate the directive through R/T or a data-link channel to the aircraft.

In this way, the ZOC system will constantly inform the controller in respect of each flight what the next control advice will be and alert him when to send it to the aircraft. Perturbations of the ideal stable situation caused by differences between actual and predicted wind and temperature profiles and human errors both on the ground and in the air are automatically taken into account by the ZOC software when generating the third line message contents for the next radar sweep.

Clearly, the increase in the amount of information and, the selected presentation will have an impact on the work environment of the controller, and this is discussed below.

2.3. Controller workload and screen clutter

As the radar screen will be the primary man-machine interface for the controller in the foreseeable future, the problem of workload arises immediately. During the large scale simulation of the Zone of Convergence concept at the EUROCONTROL Experimental Centre in Brétigny, France, in 1988, it was proved that it is technically feasible for the ZOC software to achieve the specified accuracy margins, i.e. a delivery accuracy at touchdown of around 10 seconds. However, confirmation emerged of the existence of potential bottlenecks between the information produced by the system and the capabilities of the controllers to scan the radar screen under very high workload conditions when standard vector scanning radar screens were used.

Although the ZOC concept and man-machine interface procedures are completely compatible with this type of screen, it was felt that, under heavy workload, the controller had problems in assimilating all the information presented to him. Several of the problems are directly related to the hardware design of the screens :

a. All information sent to the screen is displayed.

The information is presented in a single plane, and is invariably displayed. Although it is often possible to select the categories of flight to be labelled, the screen can nevertheless become congested. These problems do not originate only in the ZOC system, however, and tools are already available in current ATC systems to improve data presentation, e.g., where two aircraft labels would occupy the same physical screen surface, an automatic label conflict detection function endeavours to resolve the problem through rotation of the labels . This results in a somewhat confusing picture on which the controller sometimes has to search for the information pertaining to a specific flight, whereby his workload is increased.

b. Limited display modes.

In practice, for monochrome displays, four display modes can be distinguished, namely high or low intensity, continuous or blinking ; the "blinking" effect is often not very conspicuous, however owing the screen's phosphor persistence.

Ideally, ATC information from radars and ZOC systems should be presented on the radar screen with encoded priority to ensure that those data which ought to attract the controller's attention do indeed do so, thus easing the controller's radar screen scanning workload. Unfortunately, because of the limited display modes available there is very little potential for organising the flow of information in terms of message priority on standard vector scanning radar screens. Therefore, we believe that the modern high-resolution colour raster scanning display technique constitutes an attractive alternative to these screens.

2. DISPLAY MANAGEMENT SYSTEM.

3.1. Introduction

As discussed above, under the ZOC concept as currently implemented information is converged to the controller via the radar screen, whereby the total amount of data presented is increased. Consequently, a considerable effort has had to be devoted to the display aspects so as to increase the screen's information throughput, basically by means of improved display management using the possibilities offered by raster scanning displays.

The display management software module is referred to as MUPPEDS (Multi User Priority Processed Experimental Display System). Here, all data elements, e.g. aircraft position indicator, individual label lines, airway boundaries, etc., are considered to be users of an information system of which the radar screen is the common resource, in the same way as in the multi-user, multi-tasking operating systems commonly found in computer systems.

For ease of understanding some vocabulary is defined below :

Display resource : The screen is regarded as the common resource to be shared among all users with information to present.

Display user : Any type of information for display at a given moment. This information may be :

- o Geographical data = beacons, markers, sector or TMA boundaries.
- o MET data = wind information, bad-weather areas.
- o A/C position markers and labels.
- o A/C ZOC related data : predicted trajectories, for example.
- o Management data = landing sequence and separation.
- o Information coming from a conflict detection (and resolution) algorithm.

3.2. Display System Concepts

The modern raster scanning display drivers allow the definition of several "display planes" which can be considered as individual screens with visibility priority, so the picture on the highest priority plane is always visible. The images constructed on the lower priority planes will be visible only if the specific area on the screens is not occupied by a picture on a higher priority plane.

On a given display plane, the sequence in which the data are written on it determines whether the data are displayed or immediately lost when overwritten by subsequent data.

It is the function of the MUPPEDS display management module to determine on which display plane a given data element is written and with what priority. The priority approach offers great flexibility and can encompass a wide range of factors, e.g. :

- frequency of change in information content of a display user data element.
- user consulted by the controller, e.g. an a/c label can be selected by the controller to ask for more information.

3.3. Display Data Analysis

Three basic categories of displayable data may be distinguished :

a. Dynamic data :

These are data which are cyclicly updated, e.g., at each radar sweep. The major display elements in this category are the aircraft position markers and the associated label lines.

b. Static data :

This category of data covers static information such as airways, TMA boundaries, beacons, etc. and data with a relatively low update rate such as bad-weather areas.

c. Data presented at controller's request :

This data can be of type a. or b., or be presented only for the time the controller wishes it.

3.4. Display Plane Selection

In general, the static data will be presented on the lower priority planes and the aircraft position marker and the flight identification in the first line of the radar label will be displayed on the top plane.

The selection of the plane for other data, e.g. altitude, ZOC directives, etc., can be modified by the controller for all aircraft displayed or selectively per aircraft. The target plane may also be influenced automatically by the contents of the information to be displayed, in particular in the case of ZOC directives designed to alert the controller.

A high priority plane is also needed for the display users selected by the controller for an input or output operation.

3.5. Display Plane Priority

The sequence in which the data are written on a specific display plane directly defines the "overwrite priority" : what is written last will be displayed. Consequently, information with the lowest presentation priority will be written first. Moreover, for certain priority classes, it may be specified that, if a physical plane area is already in use by another element of the same priority class, a display conflict is flagged which will trigger a conflict resolution module analogous to the label conflict resolution techniques available in present vector scanning displays.

It is obvious that such conditions may also have impact on other planes and, therefore, the plane which can be effected by such actions should be computed first.

3.6. Use of Colour

The question which colour to select for a certain category of display information does not fall within the framework of this paper. Many studies have been and are being carried out elsewhere on the subject and the findings can be directly accommodated in the software developed. However, it is felt that the use of colour is ergonomically of paramount importance in the design of the overall system as colour offers the possibility of modulating the contrast of the different data fields according to the importance of their contents, while also making for greater visual comfort.

4. CONCLUSION

The increasing volume of air traffic calls for a proportional increase in air traffic control capacity. It is believed that air traffic management systems such as the Zone of Convergence (ZOC) concept are a way to achieve this in that they provide the controller with automatic tools to optimise the traffic flow and suggest ATC directives to maintain the plan safely and at minimum flight cost.

If it is to be efficient in high-density environments, the radar screen, being the primary machine-man interface, will need upgrading to avoid controller overload. To this end, a display management program has been developed to optimise the flow of information using modern high-resolution raster scanning displays. This MUPPEDS system (Multi User Priority Processed Experimental Display System) provides a stable display with a minimal radar label rotation requirement and uses automatic colour modulation to attract the controller's attention.

5 ANNEX

Raster scanning displays in the ATC environment.

For some years now SONY has been building a raster scanning display which, in view of its characteristics, is suitable for ATC purposes.

The screen has a display size of approximately 550 mm x 550 mm and the resolution is of the order of 90 dots/inch, which is that of the best computers screens available nowadays.

The screen itself is very flat and the high-resolution/size combination gives a display capacity in terms of information presented simultaneously comparable to that of modern radar vector scanning displays.

Some ATC authorities (such as the FAA in the U.S.) are considering the possibility of introducing such screens for radar display at their ATC centres in the future.

REFERENCES

1. Benoît, A. "Air Traffic Control in a Zone of Convergence. Assessment within
Swierstra, S. Belgian Airspace."
Congress of the International Council of the Aeronautical
Sciences, Toulouse, France, September 9-14, 1984.
Also EUROCONTROL Report 842009, April 1984.
2. Attwool, V.W. "A study of Conflicts within a Zone of Convergence."
Rickmann D. Paper presented at the EUROCONTROL SPACDAR/GERDAC-11,
25-27, September 1984.
EUROCONTROL Doc. 842013(R), October 1984.
3. Benoît, A. "Real-time simulation of an operational procedure suitable for
Garcia, C. the accurate 4-D control of aircraft trajectories".
Swierstra, S. EUROCONTROL Report 862018, in preparation.

PART V

**Guidance of Aircraft in a Time-Based
Constrained Environment**

4-D CONTROL OF CURRENT AIR CARRIERS IN THE PRESENT ENVIRONMENT

Objectives - Status - Plans

by

André Benoît

Engineering Directorate
European Organisation for the Safety of Air Navigation
EUROCONTROL
72, rue de la Loi, B-1040 Bruxelles (Belgium)

SUMMARY

The accurate control of the time of arrival of aircraft will play an essential role in the efficient conduct of air traffic in terms of both economy and capacity. A technique has been developed to select efficiently and control accurately each aircraft trajectory inbound to medium to high density traffic airports.

The selection is made in terms of the overall traffic on the basis of the airline or pilot-preferred criterion, either cost, consumption or time, and the subsequent control is made in a ground/air co-operative manner, using whenever applicable "speed" and/or "track" corrections. This paper concentrates on the 4-dimensional control of individual trajectories as applicable to current air carriers in the present environment, and directly adaptable to future automated air/ground digital communications.

The overall control loop has been simulated in an environment representing in particular the Belgian airspace configuration, using various flight simulators in conjunction with airline pilots and air traffic controllers. The results obtained to date make it possible to envisage on-line tests in the near future, aiming at a 10-second accuracy at the runway threshold for current commercial aircraft.

THE NEED FOR CONTROL INTEGRATION OVER EXTENDED AREAS

Inadequate projection along flight paths leads to congestion

In June 1972, when welcoming the participants to the AGARD "Air Traffic Control Systems" Conference held in Edinburgh, Scotland, Mr N. COLES, Deputy Director of Establishments and Research, concluded with the following observation "...we in the United Kingdom have yet perhaps to experience some of the most acute congestion in the Air Traffic Control field which is arising on the American continent. Nevertheless, on occasions, we experience stacking times equal to or greater than the associated flight times !" (Ref. 1).

Economy and energy conservation demand attention

The expedition of traffic and adequate use of available capacity were the factors considered in seeking to improve such a situation. Shortly afterwards (1973-1974), the sudden and tremendous increase in the cost of fuel added new dimensions to the problem - the conservation of natural resources and the need for economy. The situation was further aggravated by the second oil crisis (1979-1980). The airlines made every possible effort to reduce fuel consumption, but it soon became apparent that appreciably greater savings, in terms both of consumption and cost, could be achieved by appropriate measures which fell within the jurisdiction of Air Traffic Services (see for example Ref. 2 and enclosed bibliography).

Integration of air traffic management and control over Western Europe is desirable and technically feasible

An appreciable volume of the air traffic within Western Europe is composed of flights whose duration is less than one hour. This elicits two remarks. Firstly, a delay which might appear small in absolute terms, say 3 to 6 minutes, may in fact represent a substantial proportion of the flight, say 5 to 20%. Secondly, given the geographical and time scales involved, it should be possible to organise flights in Europe, including the departure and arrival sequences, in such a way that any aircraft cleared to depart would land at its destination after a flight conducted in accordance with airline policy, without alterations resulting from short-term planning and subsequent directives that are disruptive to the air traffic. In practical terms, this would require integrated management over the area concerned, calling for (a) on-line centralisation of detailed traffic information, the generation of departure and arrival time sequences, simultaneous definition of all relevant individual trajectories and (b) subsequent 4-D control to ensure correctness and stability. Studies directed towards these objectives have been initiated (Ref. 3) and it is hoped that the related benefits will become available at a later stage in European development.

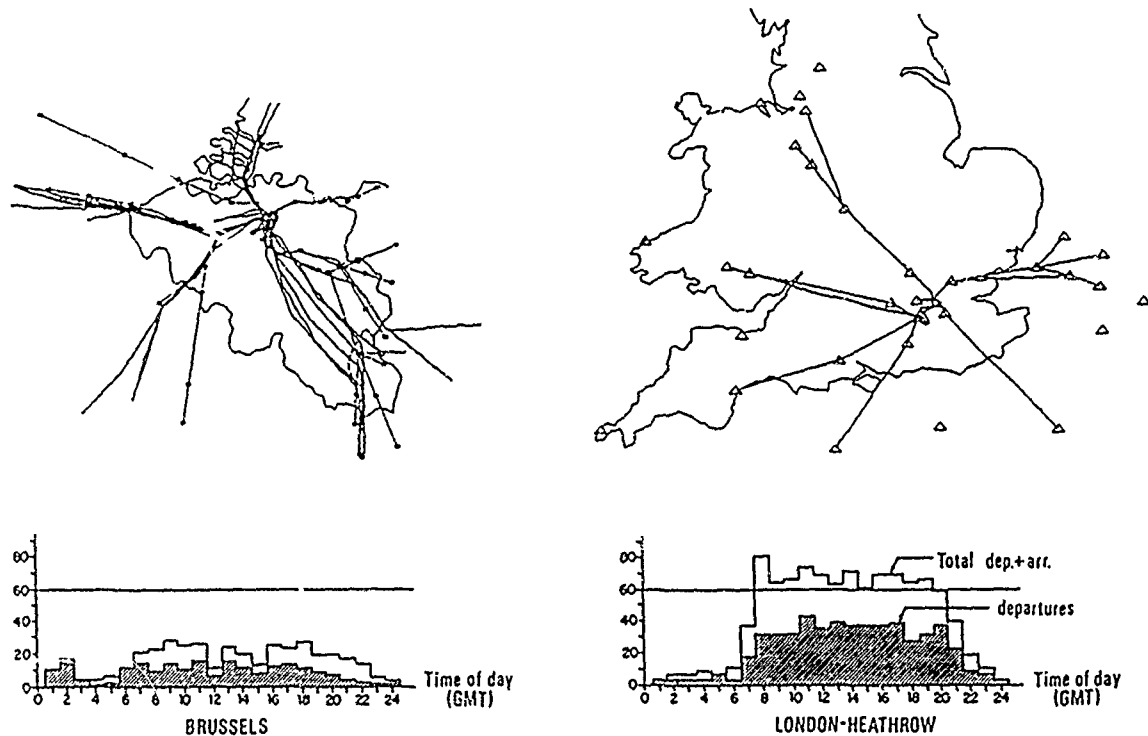
Integration of cruise and descent control phases over an extended area will enhance safety and appreciably reduce delays at destination

In the meantime, it is appropriate to consider the notion of integrated control over the cruise (also possibly the climb phases or appropriate parts thereof) and descent phases, including final approach, in extended terminals and to optimise sets of inbound trajectories so as to minimise the total deviation between trajectories proposed (by ATC) and preferred (by operators). Such an extended terminal (with a radius of from 100 to 200 nm) is referred to as a "Zone of Convergence". It includes and surrounds a main terminal and possibly also a series of secondary airports.

Illustrations of such zones are given in Figure 1 for two typical European medium and high-density traffic terminals, namely Brussels (Belgium) and London (South-East England). Upper and lower parts present the geographical and traffic density characteristics respectively (for London, traffic density is shown for Heathrow airport; in both cases, the observations were made on 8 September, 1985).

For each aircraft entering the Zone of Convergence, the ZOC management algorithm issues a landing time together with the definition of the corresponding trajectory. It has been found that, for both the Brussels (Ref. 4) and London (Ref. 5) configurations, the use of ZOC control techniques and procedures yields an appreciable reduction in overall fuel consumption (some 5 to 6 tons per hour in the London area) and an increase in safety characterised by a 60% reduction in the amount of residual potential conflicts.

As indicated, the ZOC management function generates the definition of a realistic optimum time-of-arrival-constrained trajectory for each aircraft entering the area. The next step consists in directing the aircraft accordingly, with both confidence and accuracy. After a short review of the overall objectives, the technique and procedure proposed will be outlined in the following paragraphs. The results obtained to date will be summarised and for the sake of completeness indications of the plans envisaged for further assessment in the European context will be given.



Examples of zones of convergence

- (a) Brussels, Belgium
- (b) London, South-East England

Figure 1

NEXT GENERATION OF GROUND/AIR PROCEDURES

Aircraft will land at their destination within seconds with respect to the schedule established immediately after entry into the Zone of Convergence airspace

Any ATC system aiming at minimising the cost of transit for overall traffic (from entry into the zone to touch-down) while constrained by limited runway capacity will have to cope with sets of time-of-arrival constrained trajectories. Such systems will become operational and perform efficiently only if each individual flight path can be controlled very accurately as to position and time. Some aircraft are equipped with highly accurate 4-D navigation facilities, others with Flight Management Computer Systems duly configured for 4-D navigation. Such aircraft could determine their own trajectories so as to pass at specific 3-D positions, touch-down point included, at precise moments. These aircraft still constitute a very small fraction of the present fleet. It is unlikely that all the elements of the air traffic will be so equipped in the foreseeable future. Since "ATC must cater for the least as well as the most advanced aircraft in the system" (Ref. 7), a technically and operationally realistic procedure should be available on the ground for the accurate determination of 4-D trajectories and the guidance of all aircraft accordingly.

The definition, development, assessment and validation of such a procedure for the prediction, guidance and control of accurate 4-D trajectories constitute the objective of the work summarised in this presentation.

The leading factors taken into consideration for the definition and design of a practical solution will now be mentioned briefly.

WHAT ATC REQUIRES TO GUIDE AIRCRAFT ACCURATELY

Precision control of an aircraft trajectory implies adequate automated assistance and close cooperation between the ground controller and the pilot

The efficient control of air traffic, in terms of safety, proper utilisation of capacity and economy, by means of a zone-of-convergence type of control system, requires a prediction/guidance/control module capable of conducting each trajectory with a high degree of accuracy in the space-time continuum. The essential prerequisites include :

- (a) ground-based control having a good knowledge of aircraft flight characteristics (aircraft models and performance data banks used in conjunction with available surveillance and meteorological information);
- (b) appropriate selection of navigation aids allowing precise definition of ground-generated directives currently suitable for subsequent pilot action;
- (c) translation of clearance and guidance directives into clear, concise and comprehensive messages not only suitable for use in present voice communications but also tailored to the future automated air/ground/air digital communications environment.

In accordance with these main guidelines, a control procedure has been conceived, developed and assessed in real-time operation.

This is incorporated into a control unit; the accuracy relies on the availability of suitably-located DME stations. The clearance and guidance messages comply with present R/T communications, but are directly adaptable to data link operation (See Ref. 8.).

The essential feature of the control unit is a computer program which can provide :

- a realistic prediction of the flight throughout the area (from entry into the zone of convergence to touch-down;
- accurate guidance of the aircraft from entry to touch-down, in all phases of flight;

and which incorporates:

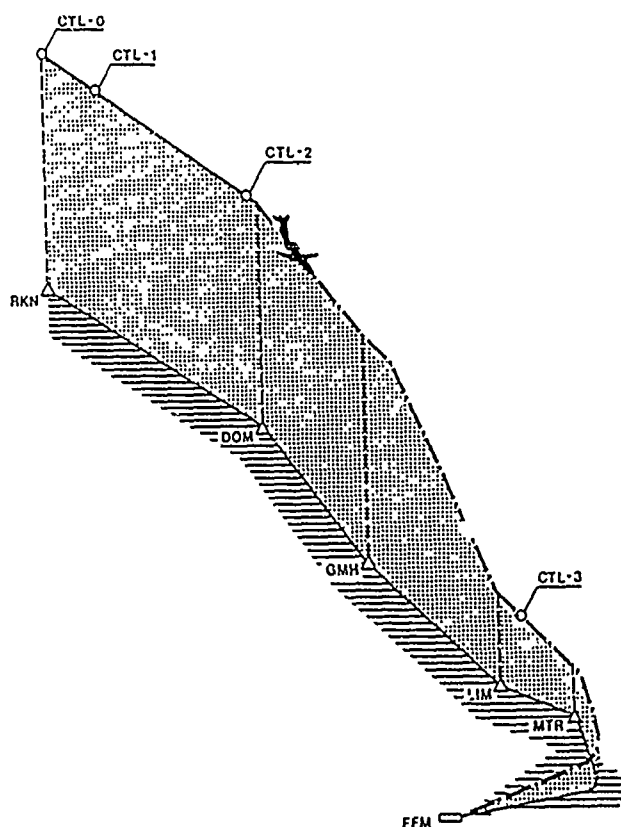
- a correction processor able to compensate for all possible sources of error (such as disturbances resulting from discrepancies in aircraft characteristics, meteorological uncertainties, human errors in communication, navigation, piloting, etc.) and maintain or amend, as appropriate, the trajectory initially selected;
- a specific function to ensure accurate control and guidance for time-of-arrival-constrained trajectories with possible jumps in the landing time sequence, this function being fully integrated into the correction processor.

4-D PREDICTION, GUIDANCE AND CONTROL OF AIRCRAFT IN A ZONE OF CONVERGENCE

An aircraft trajectory for a flight extending over some 160 nm is illustrated in Figure 2 (from Ref. 6). The aircraft coming from Pampus enters an integrated control zone over Rekken (RKN) heading towards Frankfurt (FFR). The characteristic way-points include Dortmund (DOM), Germichhausen (GMH), Limburg (LIM) and Metro (MTR).

The ZOC control messages aim at defining the remaining part of the trajectory while freezing only the coming phase extending to the next ZOC control point. The relevant ZOC control message cover :

- (a) upon entry: the definition of the cruise-descent profile followed by a standard approach to the runway actually in use at the destination (CTL-O/CTL-1);
- (b) before top of descent: confirmation or otherwise of en-route descent profile (CTL-2);
- (c) somewhere between 5,000 and 15,000 ft: definition and/or confirmation of final path in terms of geography and speed (CTL-3);



Schematic presentation of a flight inbound to Frankfurt

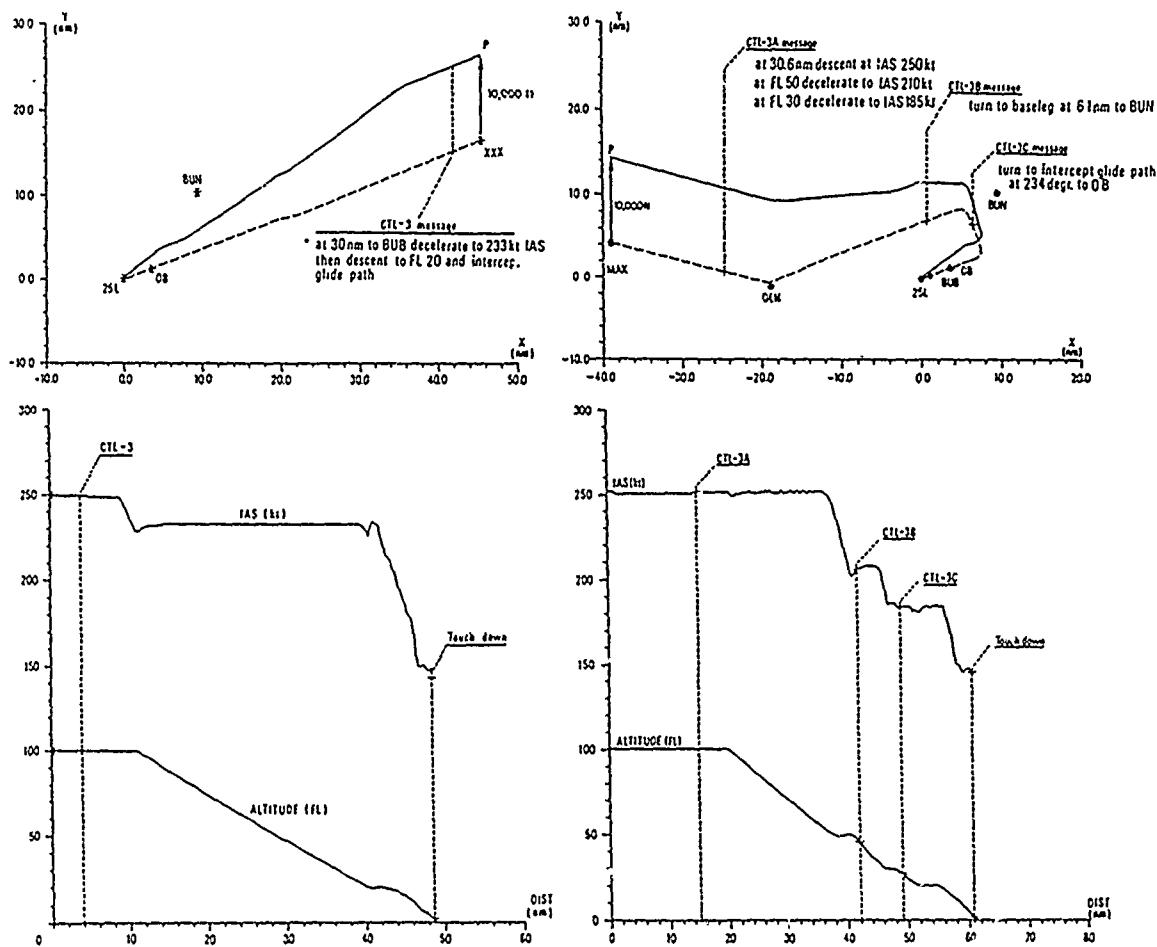
Figure 2

- (d) subsequently, directives for approach, possibly including turn to final base-leg, interception of glide path and speed adjustment (CTL-4 a to c, not shown in the diagram).

During the en-route phase, cruise/descent speed adjustment is the predominant and frequently the only source of control in the aircraft position versus time relationship. In the approach and landing phases, on the other hand, the impact of speed control is rather limited and it is the geography of the aircraft path which offers the widest control range.

Obviously, this varies with the local route system configuration. For a direct approach, speed adjustment offers the only possibility of controlling the arrival time while the geographical control contribution is normally at a maximum in the U-shape approach (twice as much whenever an S-shape approach is used).

Figures 3 (a) and (b) illustrate geographical configurations of direct and U-shape approaches to Brussels.



Configurations of direct and U-shape approaches to Brussels

Figure 3

REAL-TIME ASSESSMENT IN A REALISTIC OPERATIONAL ENVIRONMENT

A simulation facility-coupling aircraft simulator and ATC unit- has been set up to provide a realistic operational testing environment.

The coordinated ATC-AIRCRAFT procedure developed for the prediction, guidance and control of trajectories is being assessed in real-time operation. To conduct such tests in a realistic environment, a simulated ATC unit composed essentially of the main program for the prediction, guidance and control of trajectory, the displays and communications facilities, is coupled with a flight simulator. The simulator. The simulation of the acquisition of the surveillance information is made by connecting the flight simulator to the ATC unit via a micro-processor.

A description of the ATC-AIRCRAFT simulation facility is given in Ref. 9.

During real-time tests, the ATC unit was manned by professional approach controllers and the aircraft operated by professional crews. Ground controllers needed appropriate training before the exercise; pilots usually received a 5 to 10-minute briefing, basically outlining the context and purpose of the operation.

Tests were conducted on several airline simulators, including Deutsche LUFTHANSA Boeing B-737, Airbus A-300 and Boeing B-747, SABENA, Belgian World Airlines, Boeing B-737 and McDonnell Douglas DC-10, NLM City Hopper Fokker F-27 and F-28, and the research flight simulator of the National Aerospace Laboratory, NLR, Amsterdam, reproducing the Fokker F-28 and Boeing B-747.

In the tests conducted to date, most of the usual operational procedures recommended by airlines have been covered. In terms of geography, the tests mainly concentrated on approaches to Brussels, although approaches to Amsterdam were also conducted, as well as approaches to Frankfurt, particularly for the assessment of the enroute phase.

Attention is focused on the stability of the ground guidance and control process under conditions of disturbance, and on the dialogue between the controller and his automated assistant.

The ATC guidance and control program generates the ZOC directives and displays their content on the screen using a maximum of 3 lines, each of 8-character length. Use is made of three presentation types (normal, reverse, reverse and flashing) to characterise the situation and possible action required in terms of urgency.

At the appropriate moment, the controller relays the directive to the pilot using the R/T communication link. The definition and assessment of the messages generated by the computer and transmitted by the controller are carried out in close cooperation with representatives of the Belgian Air Traffic Control Authorities (Régie des Voies Aériennes - Regie der Luchtweegen). A detailed description of the messages, (content, structure and presentation for the computer-generated messages, and phraseology for their transmission by the controller is given in Ref. 10.

The directives generated by the computer, displayed on the ATC screen and transmitted by the controller to the pilot, and the return messages -acknowledgement or otherwise- appear to be adequate for the conduct of the flight and satisfactory in terms of human attention and action.

Although this control technique had been tested in only a limited number of geographical configurations, it has been applied satisfactorily to a range of geometries extending from direct approach to U-shape approaches.

During the tests conducted to date, a number of sources of disturbance were introduced to enable the control range and stability of the overall system to be assessed. Over a series of some 40 flights conducted on 5 different flight simulators with 12 different crews, disturbances including

- turbulence
- wind error: up to 30 kt
- thunderstorms, implying rerouting
- aircraft mass variations: up to 20%
- selected airspeed error: up to 20 kt (IAS)
- various acceleration or deceleration procedures
- de-icing or not

were injected, and a maximum touch-down error of 13 seconds was observed over a series of flights.

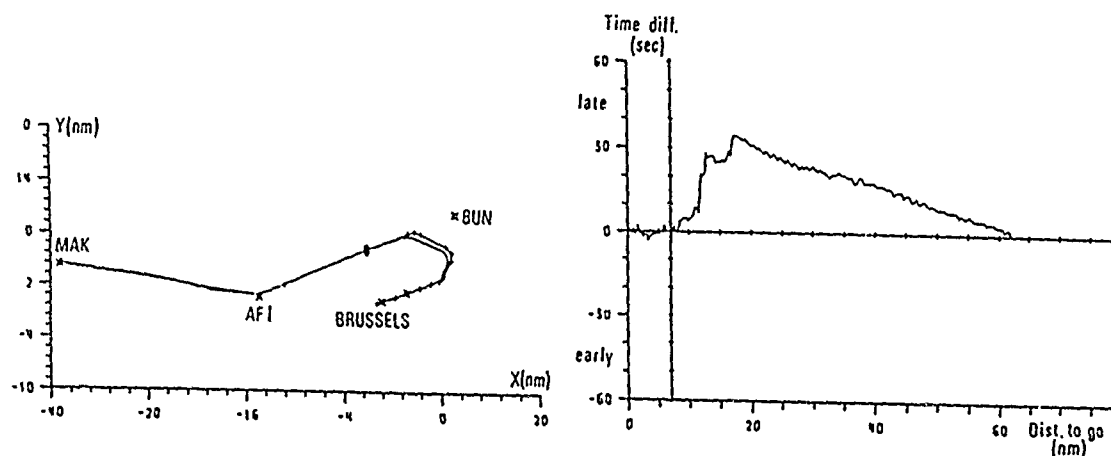


Illustration of time-of-arrival control for an approach to Brussels

Figure 4

Figure 4 illustrates a trajectory correction. From Mackel to the position marked C in the diagram, the error increases because of a 20-kt (IAS) error in the selection of the en-route descent speed. At point C, the ground prediction, guidance and control unit issues the directive to correct the trajectory initially predicted and maintained the arrival time. The message includes the position at which the turn is to be initiated (expressed in DME distance from Bruno) and the heading of the next segment. The following directive defines the intercept segment (initiation of the turn and intercept heading). As may be seen on the diagram, these actions enabled the aircraft to land within seconds of the expected schedule.

CONCLUDING REMARKS

From the series of flights conducted to date, it is expected that the control tool not present under development will provide ATC with the means to control aircraft time-of-arrival to within some 10 seconds of the schedule established at entry into the zone.

The data set required to constitute the aircraft model has been reduced to a minimum; the guidance accuracy relies on the availability of suitably located DME stations; the transmission of information between the controller and the pilot is compatible with both present R/T communications and future automated digital links.

The relations between the human controller and the computerised assistance is characterised by a friendly dialogue and a high level of flexibility. Guidance directive messages appear compatible with present-day practice in terms of both ATC and aircraft operation.

In view of the results obtained, and on the basis of experience gained to date, it is planned to assess the techniques and procedures developed for the control of flights in an advanced TMA in actual operational conditions; the organisation of the validation program is under preparation.

ACKNOWLEDGEMENT

We wish to express our appreciation to all those who have contributed to the work summarised in this presentation, in particular, the Member States of the European Organisation for the Safety of Air Navigation, through their representatives on the Specialist Panel on Automatic Conflict Detection and Resolution (SPACDAR).

Our particular thanks are due to the Belgian Air Traffic Control Authorities (Régie des Voies Aériennes/Regie der Luchtwegen) for their active participation in the definition of the operational aspects and in the conduct of the real-time exercises.

Further, we should mention the participation of several European airlines, including SABENA (Belgian World Airlines), Brussels, Deutsche LUFTHANSA, Frankfurt, NLM City Hopper, Amsterdam, and the Dutch National Aerospace Laboratory, NLR, who provided and operated flight simulation facilities under contract to EUROCONTROL.

REFERENCES

4. "Air Traffic Control Systems", Symposium of the Guidance and Control Panel, Edinburgh, Scotland, June 1972 (AGARD CP-105).
5. "Air Traffic Control in Face of Users' Demand and Economy Constraints", Special Session of the Guidance and Control Panel, Lisbon, Portugal, October 1982 (AGARD CP-340).
6. "Gestion automatisée du trafic aérien sur un ensemble d'aéroports", by S. Khan Mohammadi, Ecole Nationale Supérieure de l'Aéronautique et de l'Espace, Toulouse, France, octobre 1983.
7. "Air Traffic Control in a Zone of Convergence. Assessment within Belgian Airspace", by André Benoît and Sip Swierstra. Congress of the International Council of Aeronautical Sciences, Toulouse, France, September 9-14, 1984. Also EUROCONTROL Report 842009, April 1984.
8. "A Study of conflicts within a Zone of Convergence", by W.V. Attwooll and D. Rickman. Proceedings of the EUROCONTROL SPACDAR 11th Meeting, Brussels, September 25-27, 1984.
9. "A cost-efficient control procedure for the benefit of all airspace users", by A. Benoît and S. Swierstra. AGARD-GCP Conference, Cesme, Izmir, Turkey, 16-19 October 1984. (AGARD CP-360). Also EUROCONTROL Report 842011, August 1984.
10. "Fuel Economies Effected by the Use of FMS in an Advanced TMA", V. Attwooll and A. Benoît. The Journal of Navigation, Vol. 38, n° 1, January 1985. Also EUROCONTROL Report 842003, February 1984.
11. "Possible contributions from SSR Mode S datalink to the conduct of efficient aircraft operations" by M.E.C. Cox, AGARD Symposium, Brussels, 10-13 June 1986.
12. "A simulation facility for assessing the next generation of 4-D Air Traffic Control procedures" by André Benoît and Sip Swierstra. 15th ICAS Congress, London, U.K., September 7-12, 1986.
13. "The next generation of control techniques in advanced TMA" by André Benoît, Sip Swierstra and René De Wispelaere, AGARD GCP Symposium, Brussels, June 10-13, 1986.

CONTROLE DE LA CIRCULATION AERIENNE ET GUIDAGE DES AVIONS

REGULATION 4-D DANS L'INFRASTRUCTURE ACTUELLE

Point de la situation et objectifs à atteindre

par

André Benoît *

Direction Technique
Organisation Européenne pour la Sécurité de la Navigation Aérienne
EUROCONTROL
72, rue de la Loi, B - 1040 Bruxelles

SOMMAIRE

Le contrôle précis de l'heure d'arrivée des vols sera un élément essentiel de la régulation efficace du trafic aérien au double plan de l'économie du transport et de l'utilisation optimale de la capacité de prise en charge disponible. Une technique a été mise au point pour déterminer efficacement et contrôler avec précision les trajectoires d'arrivée aux aéroports de moyenne à forte activité.

Les trajectoires sont définies en fonction des critères que retiennent les compagnies ou les pilotes, à savoir coût, consommation de carburant ou temps de vol ; le contrôle intervient ensuite en donnant les corrections de vitesse et/ou de route requises à partir des éléments "sol" et "air" opérant en synthèse. Ce système de contrôle 4-D est applicable aux trajectoires des avions de transport actuels utilisant l'infrastructure existante, et directement adaptable aux communications air-sol numérisées de demain.

L'ensemble de la boucle de contrôle a fait l'objet de simulations dans un environnement représentant en particulier la configuration de l'espace aérien belge. L'utilisation de simulateurs de vol et la participation de pilotes de ligne et de contrôleurs de la circulation aérienne a permis de prendre en compte les aspects humains d'une manière très réaliste. Sur la base des résultats enregistrés à ce jour, on peut envisager une mise en oeuvre en milieu opérationnel dans un proche avenir avec comme objectif une précision de 10 secondes au seuil de piste pour l'ensemble des avions commerciaux actuels et a fortiori futurs.

INTRODUCTION : GESTION DU TRAFIC - CONTROLE DES VOLS - GUIDAGE DES AVIONS

L'encombrement de l'espace aérien est devenu une pénible réalité. Le reflet de cette situation apparaît désormais pratiquement chaque jour dans la presse à grand tirage.

Au delà des causes habituellement mentionnées et certes très réelles, à savoir l'augmentation constante du trafic et l'indisponibilité fréquente des moyens de gestion et de contrôle suite à des actions de mécontentement de corporations diverses, il en est d'autres peut-être plus profondes.

Dans une approche fondamentale, le contrôle en temps réel du trafic aérien apparaît comme un grand système qu'il s'agira de gérer sur la base de deux composantes essentielles étroitement couplées, à savoir :

- a) la gestion optimisée de l'ensemble des vols selon des critères mixtes combinant sécurité, capacité, économie et confort ;
- b) le guidage de chaque avion conformément aux orientations et/ou décisions résultant de la gestion du trafic.

L'horizon-temps auquel la gestion en temps réel doit-être réalisée dépendra principalement de l'étendue de la zone géographique couverte par le centre de gestion, accessoirement des conditions météorologiques et bien entendu de la vitesse des avions. A titre d'exemple, pour une zone couvrant l'ensemble de la Belgique, l'horizon-temps peut être de l'ordre de l'heure. D'où l'importance d'un système de guidage précis et stable face aux perturbations multiples et variées affectant le déroulement d'un vol d'une telle durée.

NECESSITE D'UNE INTEGRATION DU CONTROLE POUR LES REGIONS ETENDUES

L'insuffisance des projections faites pour les trajectoires de vol aboutit à des encombrements.

Lors de son allocution de bienvenue aux participants de la Conférence AGARD tenue en juin 1972 à Edinbourg (Ecosse) sur le contrôle de la circulation aérienne (désigné habituellement par l'acronyme ATC, Air Traffic Control), M. N. Coles, Directeur adjoint, "Establishments and Research" faisait la déclaration suivante : "... Au Royaume-Uni, il se pourrait que nous ayons un jour à faire face à certains des plus sérieux encombrements que connaît le continent américain. Toujours est-il que nous enregistrons parfois des temps de 'stacking' égaux ou supérieurs aux temps de vol correspondants !" (Bibliographie, Réf. 1)

* Docteur en Sciences Appliquées

Membre de l'Académie Nationale de l'Air et de l'Espace, Toulouse, France
Chargé de Cours, Faculté des Sciences Appliquées, Louvain-La-Neuve.

Contraintes : économie, conservation de l'énergie et utilisation maximum de la capacité disponible.

L'écoulement des vols et la bonne utilisation de la capacité disponible furent dûment considérés dans la recherche à une amélioration de la situation. Peu de temps après (1973-1974), l'augmentation inopinée et très considérable du prix du carburant ajouta une contrainte supplémentaire : préservation des ressources naturelles et nécessité absolue de réaliser des économies. La 2ème crise pétrolière (1979-1980) devait aggraver d'autant cette situation. Les compagnies aériennes se sont donc efforcées de réduire la consommation de carburant mais il est bientôt apparu que des économies bien plus importantes, consommation de carburant et coût, pouvaient être obtenues par des mesures appropriées relevant de la compétence des Services de la circulation aérienne. Il est intéressant et important de noter qu'un système de gestion intégrée tel que préconisé par l'auteur (Bibliographie, Réf. 2), optimise à la fois l'utilisation des pistes et, globalement l'économie de l'ensemble des vols concernés.

L'intégration de la gestion et du contrôle de la circulation aérienne est souhaitable et techniquement réalisable en Europe occidentale

Une part appréciable du trafic opérant en Europe occidentale comporte des vols de moins d'une heure. Cette situation appelle deux observations :

- a) un retard peu significatif dans l'absolu (3 à 6 minutes) risque en réalité de représenter une proportion importante du vol (5 à 20% par exemple) ;
- b) à l'échelle considérée (géographie et temps) il doit être possible, d'organiser les mouvements aériens, séquences de départ et d'arrivée comprises, de telle sorte que tout avion autorisé à décoller puisse atterrir à son point de destination après un vol exécuté conformément à la politique des compagnies, sans modification résultant de mesures de planification à court terme et sans directives ultérieures génératrices de perturbations préjudiciables à l'écoulement du trafic.

Dans la pratique, il faudra, pour l'ensemble de la région, une gestion intégrée, exigeant d'une part une centralisation en temps réel des données de trafic, l'établissement de séquences de départ et d'arrivée et la définition de chaque trajectoire individuelle, et d'autre part, un contrôle 4-D, de manière à garantir exactitude et stabilité. Des études ont été entreprises dans ce sens (Bibliographie, Réf. 3), et les avantages qui en découlent se matérialiseront à un stade ultérieur de l'évolution de l'Europe.

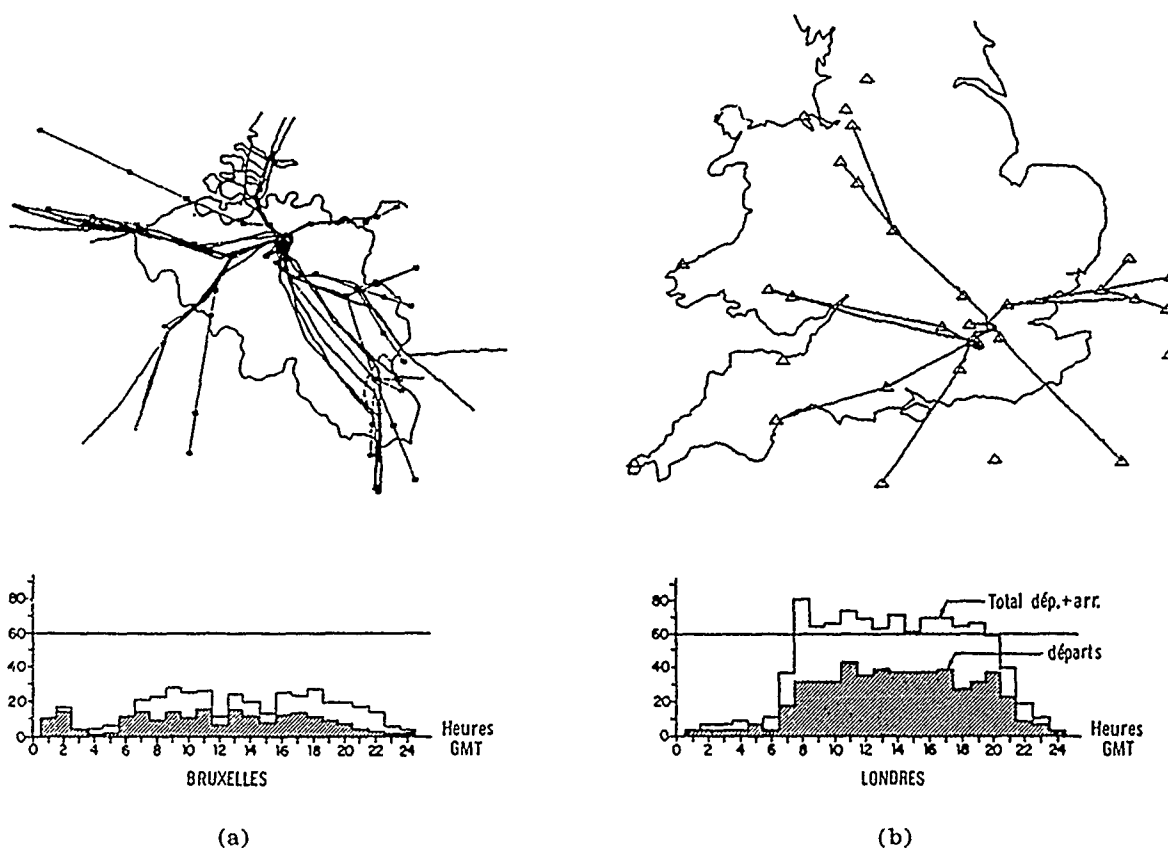
L'intégration des phases de contrôle de croisière et de descente pour une région étendue renforcera la sécurité et réduira sensiblement les retards à l'arrivée.

D'ici là, il est indispensable d'envisager pour les grandes régions terminales :

- a) un contrôle intégré des phases de croisière et de descente (approche finale comprise) voire même partiellement, des phases de montée ;
- b) l'optimisation des ensembles de trajectoires à l'arrivée avec comme critère une différence globale minimum entre la trajectoire proposée par l'ATC et la trajectoire préférentielle des exploitants.

Nous désignons par l'expression "Zone de convergence" (ZOC), ces grandes régions terminales (de 100 à 200 nautiques de rayon) ; elles comprennent une tête de ligne principale et éventuellement plusieurs aéroports d'importance secondaire.

La Figure 1 illustre le principe de la zone de convergence pour 2 têtes de lignes types de moyenne et forte densités de trafic, à savoir Bruxelles (Belgique) et Londres (Sud-Est de l'Angleterre). Les caractéristiques géographiques sont mises en évidence à la partie supérieure de la figure, les densités de trafic indiquées à la partie inférieure.



Exemples de zones de convergence

(a) Bruxelles, Belgique
(b) Londres, Sud-Est de l'Angleterre

Figure 1

Pour chaque avion entrant dans la zone de convergence (ZOC) les algorithmes de gestion établissent un temps d'atterrissage et déterminent la trajectoire correspondante. Autrement dit, pour chaque avion entrant dans la zone, la fonction de gestion "ZOC" définit une trajectoire conforme à une heure d'arrivée optimale : il faut et il suffit ensuite de diriger le vol avec précision de manière à maintenir le système stable face aux multiples perturbations.

Tant pour Bruxelles (Bibliographie, Réf. 4) que pour Londres (Réf. 5), les techniques et procédures "ZOC" conduisent à une diminution sensible de la consommation globale de carburant (quelque 5 à 6 tonnes par heure pour Londres) ainsi qu'à une sécurité accrue (réduction de 60% du nombre des éventuels conflits résiduels).

Dans les paragraphes qui suivent, après un bref examen des objectifs généraux à réaliser, nous proposons une technique et une procédure parfaitement applicables au guidage 4-D des aéronefs à partir du sol. Nous résumons ensuite les résultats obtenus à ce jour. Enfin, nous mentionnons deux applications possibles, l'une belge, l'autre européenne, justifiant l'utilisation de telles techniques et susceptibles d'une mise en oeuvre opérationnelle.

PROCHAINE GENERATION DE PROCEDURES SOL-AIR

L'atterrissage au point de destination s'effectuera à quelques secondes près de l'heure fixée dès l'entrée dans la zone de convergence.

Tout système ATC conçu pour permettre une réduction maximale du coût de la partie des vols comprise entre l'entrée dans la ZOC et l'atterrissage devra, outre les contraintes de capacité inhérentes aux pistes, tenir compte de l'ensemble des trajectoires associées aux séquences optimales des temps d'arrivée. Certains avions sont dotés de moyens de navigation 4-D de haute précision, d'autres d'ordinateurs de gestion de vol dûment adaptés à la navigation 4-D. Il serait donc possible d'établir leurs trajectoires pour qu'ils passent à l'instant "t" à des positions 3-D bien déterminées, point d'atterrissage compris. Mais ces avions ne constituent qu'une infime fraction des flottes actuelles. Dans un avenir prévisible, il est peu probable que tous disposent à bord, des équipements indispensables. De plus, quel que soit le degré de perfectionnement technique de leur équipement de bord, les avions opérant dans l'espace aérien contrôlé sont nécessairement pris en charge par l'ATC (Bibliographie, Réf. 7). Aussi est-il raisonnable de penser que les services au sol doivent disposer des éléments de guidage et contrôle pour la définition et le maintien des trajectoires 4-D précises.

La définition, la mise au point, l'appréciation et la validation de cette procédure pour la prédiction, l'établissement et le contrôle de trajectoires 4-D précises, tel est l'objectif des études dont le présent exposé fait la synthèse.

ELEMENTS DONT DOIT DISPOSER L'ATC POUR ASSURER LE GUIDAGE PRECIS DES VOLS

Le contrôle précis de toute trajectoire implique une assistance automatisée adéquate ainsi qu'une étroite coopération entre contrôleurs et pilotes.

Qu'il s'agisse de sécurité, d'exploitation de la capacité disponible ou d'économie, le contrôle efficace de la circulation aérienne avec recours à un système de type "ZOC" exige un module Prédiction - Guidage - Contrôle qui, dans le continuum espace/temps, permette un suivi très précis de chaque trajectoire. Les conditions préalables comportent en particulier :

- a) un contrôle "sol" possédant une bonne connaissance des caractéristiques de vol des avions (modèles d'avions et banques de données de performances utilisés conjointement avec données disponibles en matière de surveillance et de météorologie) ;
- b) une sélection d'aides à la navigation appropriées qui permettent de définir avec précision toute directive des services au sol se prêtant aux actions des pilotes ;
- c) une transcription des directives concernant les autorisations et le guidage sous forme de messages clairs, concis et complets qui soient non seulement utilisables dans les liaisons vocales actuelles, mais qui se prêtent à la future infrastructure des communications automatiques numérisées air-sol-air.

Conformément à ces grandes orientations, une procédure de contrôle a été conçue, mise au point et évaluée en exploitation temps réel.

L'intégration dans une unité de contrôle est réalisée ; la précision requise est fonction de l'existence de stations de mesure de distance du type DME (Distance Measuring Equipment) judicieusement situées. Conformément aux communications radiotéléphoniques (R/T) actuelles, les messages d'autorisation et de guidage sont directement adaptables aux liaisons de données (Bibliographie, Réf. 8).

L'élément essentiel de l'unité de contrôle est un programme de calcul qui puisse :

- . établir une prévision réaliste des vols pour l'ensemble de la région (de l'entrée dans la zone de convergence jusqu'au point de sortie, en particulier, le point d'atterrissage) ;
- . assurer le guidage précis de chaque avion, quelles que soient les phases de vol.

Entre autres modules, ce programme comporte :

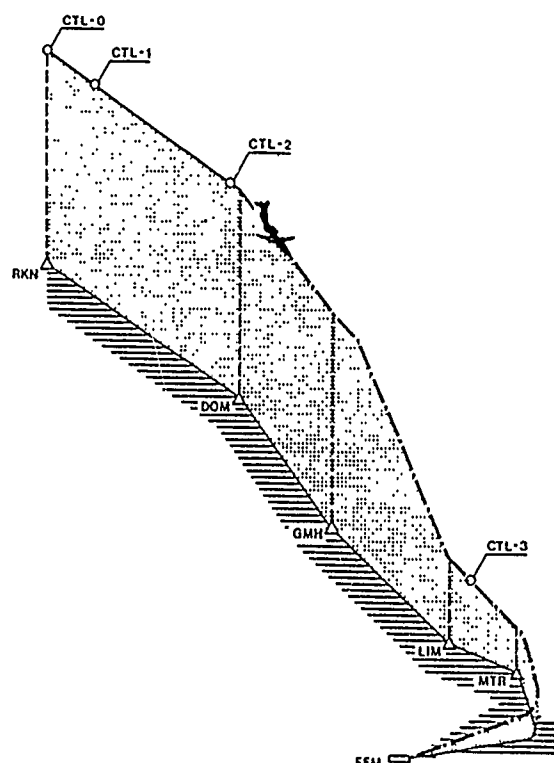
- . un processeur de correction capable de compenser les erreurs inévitables, quelle qu'en soit l'origine (caractéristiques non conformes génératrices de perturbations, conditions météorologiques incertaines, erreurs humaines dans les communications, la navigation, le pilotage etc.), de maintenir et, le cas échéant, modifier la trajectoire initialement retenue ;
- . une fonction spécifique permettant d'assurer le contrôle et le guidage précis des trajectoires en vue de maintenir le temps d'arrivée, avec possibilité de ruptures dans la chronologie des séquences d'atterrissage, cette fonction étant partie intégrante du processeur de correction.

PREDICTION, GUIDAGE ET CONTROLE 4-D DES VOLS DANS UNE ZONE DE CONVERGENCE

La figure 2 schématise la trajectoire d'un vol de quelque 160 nautiques (Bibliographie, Réf. 6). L'avion vient de PAMPUS. Il entre dans une zone de contrôle intégrée à la verticale de REKKEN (RKN). Il se dirige ensuite vers Francfort (FFM). Les points de route caractéristiques sont les suivants : Dortmund (DOM), Germichhauzen (GMH), Limburg (LIM) et Metro (MTR).

Chaque message de contrôle ZOC définit la trajectoire future. Les messages successifs portent sur les points suivants :

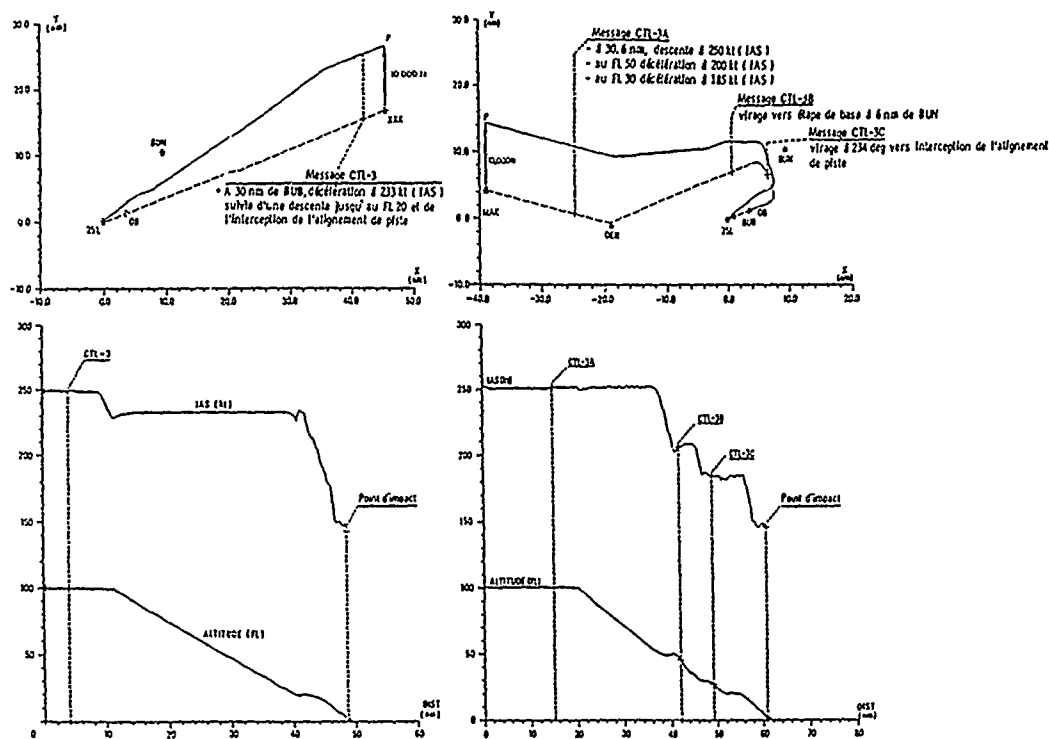
- à l'entrée : définition du profil de croisière/descente suivi d'une approche normalisée en direction de la piste d'atterrissage en service (CTL-O/CTL-1) ;
- avant le début de la descente : confirmation ou modification du profil de descente en-route (CTL-2) ;
- entre 15.000 et 5.000 pieds : définition et/ou confirmation de la trajectoire initiale, (composantes géographiques et vitesses (CTL-3)) ;
- ensuite, directives d'approche, y compris (éventuellement) virage vers l'étape de base, interception de l'alignement de piste et ajustement de la vitesse (Note : les points de contrôle (CTL-4 (a) à (c) n'apparaissent pas à la figure 2).



Représentation schématique d'un vol à l'arrivée de Francfort

Figure 2

Au cours de la phase en route, l'ajustement de la vitesse de croisière/descente est essentiellement et le plus souvent le seul motif d'intervention du contrôle dans la relation position/temps de l'avion, lors des phases d'approche et d'atterrissage, le contrôle de la vitesse n'a guère d'impact, la géographie de la trajectoire offrant alors l'éventail de contrôle le plus large. La configuration du réseau de route influence bien entendu le choix du mode de contrôle : dans les approches directes, l'ajustement de la vitesse est la seule possibilité de contrôle du temps d'arrivée, alors que les approches en "S" offrent une large gamme de contrôle géographique (deux fois autant que les approches en "U"). Les figures 3 a) et b) schématisent des configurations géographiques d'approches (directes et en "U") vers Bruxelles.



Configurations d'approches directes et d'approches en "U" (vers Bruxelles)

Figure 3

EVALUATION TEMPS REEL EN ENVIRONNEMENT OPERATIONNEL REALISTE.

Un dispositif de simulation (couplant jusqu'à deux simulateurs de vol et une unité ATC), a été constitué pour créer un environnement d'essai opérationnel réaliste.

La procédure coordonnée ATC-AVION, mise au point pour la prédiction, la définition et le contrôle des trajectoires, a fait l'objet d'une évaluation en exploitation temps réel. Les essais furent réalisés dans un environnement réaliste, constitué par une unité ATC simulée (comprenant essentiellement le programme principal de prédiction et de contrôle de la trajectoire, les installations d'affichage et de communication) couplée à deux simulateurs de vol utilisés simultanément. Pour la saisie des données de surveillance, les simulateurs sont connectés à l'unité ATC via un microprocesseur. Une description du dispositif ATC-AVION est disponible par ailleurs (Bibliographie, Réf. 9).

Au cours des essais, les positions de l'unité ATC étaient occupées par des contrôleurs d'approche confirmés. Les avions étaient pilotés par des équipages professionnels de Compagnies Aériennes européennes. Les contrôleurs ont dû suivre au préalable une formation appropriée. Par contre, pour les pilotes un briefing de 5 à 10 minutes était amplement suffisant pour leur donner une idée de l'opération et de son objet. En fait, les pilotes peuvent exécuter les directives ZOC sans aucune préparation spécifique préalable.

Plusieurs simulateurs de compagnies aériennes furent utilisés. Entre autres, un Airbus A-300 et des Boeing B-737 et B-747 de la LUFTHANSA (Francfort RFA) ; un Boeing B-737 et un DC-10 de la SABENA (Bruxelles Belgique) ; des Fokker F-28 et F-27 de la NLM City Hopper (Amsterdam, Pays-Bas et Helsinki, Finlande, respectivement) ; des Boeing B-737 et B-757 de la British Airways (Londres, U.K.) ; un Airbus A-310 d'Aéroformation (Toulouse, France) ainsi que le simulateur de vol expérimental du Nationaal Lucht- en Ruimtevaartlaboratorium, NLR (Amsterdam, Pays-Bas).

Les essais menés à ce jour ont porté sur la plupart des procédures opérationnelles courantes recommandées par les compagnies. Le plus souvent, il s'agissait essentiellement d'approches vers Bruxelles mais il y eut également des approches vers Amsterdam et Francfort.

Stabilité du processus de guidage et de contrôle en conditions perturbées.
Dialogue entre le contrôleur et son "assistant" automatisé.

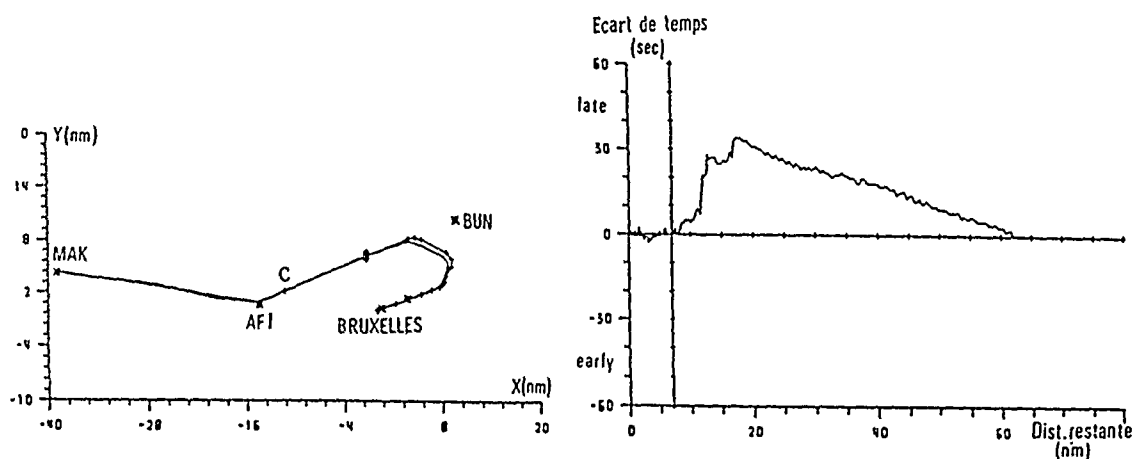
Le programme de guidage et de contrôle 4-D est conçu pour générer les directives ZOC et les visualiser sur l'écran radar du contrôleur. L'étiquette disponible comporte un maximum de 3 lignes, de 8 caractères chacune. Le moment venu, le contrôleur transmet la directive voulue au pilote à l'aide de la liaison R/T. La définition et l'évaluation des messages (générés par ordinateur et transmis par le contrôleur) résultent d'une étroite coopération avec les représentants de la Régie belge des Voies Aériennes. On trouvera ailleurs (Bibliographie, Réf. 10) l'analyse de ces messages (teneur, structure et présentation), ainsi que la terminologie nécessaire à leur transmission.

Les directives émanant de l'ordinateur, visualisées et transmises au pilote par le contrôleur, ainsi que les messages de retour (accusé de réception, etc.) suffisent à la bonne exécution du vol et donnent toute satisfaction sur le plan de la vigilance et des actions humaines nécessaires.

Au cours des essais, de nombreuses perturbations furent introduites pour évaluer la portée et la stabilité de l'ensemble du système. Sur quelque 80 vols réalisés sur 8 simulateurs différents avec une trentaine d'équipages distincts, les perturbations suivantes furent introduites :

- turbulence et modifications de vitesse en résultant,
- erreur de vent (jusqu'à 30 noeuds),
- orages, impliquant réacheminement,
- variations de la masse de l'avion (jusqu'à 20%),
- erreur dans le choix des vitesses (jusqu'à 20 noeuds - IAS),
- diverses procédures d'accélération ou de décélération,
- dégivrage, ou non,

et on observa un écart maximum de 13 secondes au toucher des roues.



Contrôle d'heure d'arrivée - approche sur Bruxelles

Figure 4

Un exemple de correction de trajectoire est schématisé à la Figure 4. De Mackel au point C, l'écart augmente par suite d'une erreur de 20 noeuds (IAS) dans la vitesse de descente. Au point C, l'unité compétente donne l'ordre de corriger la trajectoire initialement prévue et maintient l'heure d'arrivée. Le message indique le point auquel il y a lieu de commencer le virage (distance DME à partir de BRUNO), ainsi que le cap pour le tronçon suivant. La consigne suivante définit la manoeuvre d'interception (début du virage et cap d'interception). Comme le montre la figure, ces actions permettent l'atterrissage à quelques secondes près de l'heure prévue.

APPLICATIONS : MISE EN OEUVRE OPERATIONNELLE

Le système de guidage 4-D préconisé à l'origine pour les vols à l'arrivée (CINTIA : Control of Inbound Trajectories of Individual Aircraft) fut développé et étendu au guidage d'un vol complet, depuis le lâcher des freins jusqu'au toucher des roues. Son domaine d'utilisation est par suite universel. Les deux applications évoquées ci-après, l'une à l'échelon national, l'autre au niveau européen, reflètent bien ce caractère général.

Au préalable, rappelons qu'à l'heure actuelle, l'autorité du contrôleur aérien est absolue ; il est seul à élaborer les ordres de contrôle et à prendre toute décision relative au guidage des aéronefs. Dès lors, il était essentiel d'associer à nos développements des représentants compétents et expérimentés en contrôle en-route et en contrôle d'approche. Cette expertise fut assurée par la Régie des Voies Aériennes. Les interfaces contrôleur/ordinateur furent définies conjointement avec René De Wispelaere * et Félix Degreef ** responsables du contrôle du trafic aérien à Bruxelles-National, (Bibliographie, Réf. 11). Elles furent testées ensuite au Centre Expérimental d'Eurocontrol par un ensemble de contrôleurs européens.

Pour répondre aux exigences résultant, en particulier, d'un trafic constamment croissant (le nombre de mouvements à Bruxelles-National a plus que doublé en quelques années), la Régie des Voies Aériennes a entrepris la réalisation d'un centre de contrôle moderne, connu sous l'acronyme CANAC, Computer Assisted National Air Traffic Control Center (Bibliographie, Réf. 12). La collaboration fructueuse établie au niveau du développement des techniques de guidage permet d'envisager l'intégration de telles techniques dans le nouveau centre national.

Dans un avenir plus ou moins proche, les grandes terminales "voisines" de l'aire géographique du centre de contrôle européen (Maastricht Upper Air Space Centre) auront vraisemblablement leur système propre de gestion, de séquençement et de contrôle des vols à l'arrivée. Leur rayon d'action ira croissant comme le montrent non seulement les études théoriques mais aussi les réalisations proches de la mise en oeuvre opérationnelle (COMPAS à Francfort et sans doute à Dusseldorf, MAESTRO à Paris, TCSDG à Londres, CANAC avec l'introduction possible de fonctions du type ZOC à Bruxelles, etc.).

Aussi, le rôle de la régulation en-route en direct (en-ligne) devient-il essentiel, non seulement sur le plan de la cohérence générale mais également et surtout par l'aide appréciable qu'il peut apporter aux cellules de gestion des terminales. Les techniques de guidage 4-D développées permettront d'assurer une coordination efficace, d'où résultera une amplification appréciable du potentiel de régulation des cellules terminales.

CONCLUSIONS

Il ressort des vols exécutés à ce jour que la procédure actuellement à l'étude donnera à l'ATC les moyens de contrôler l'heure d'arrivée à une dizaine de secondes près de l'horaire fixé dès l'entrée dans la zone de convergence.

Les données constitutives du modèle ont été réduites à un minimum ; la précision du guidage est fonction de l'existence de stations DME judicieusement situées - ce qui ne pose aucun problème en Europe occidentale - ; la transmission d'informations entre le contrôleur et le pilote est possible tant avec les communications R/T actuelles qu'avec les futures liaisons de données automatisées.

Les relations entre le contrôleur et l'assistant automatisé se caractérisent par la facilité du dialogue et une grande souplesse dans les actions de contrôle. Les messages de guidage sont compatibles avec la pratique actuelle aux deux niveaux contrôle et pilotage.

Compte tenu des résultats obtenus et de l'expérience acquise à ce jour, il est prévu d'évaluer, pour une zone de convergence, grande région de contrôle terminale moderne, et en conditions opérationnelles, les techniques et procédures mises au point pour le contrôle des vols; un programme de validation globale et les phases successives, préparatoires à une mise en oeuvre opérationnelle sont en cours de d'élaboration.

* Chef du contrôle d'approche et d'aérodrome (tour) à Bruxelles-National

** Chef du contrôle à Bruxelles-National

REMERCIEMENTS

Nous tenons à remercier tous ceux qui ont contribué aux travaux dont il est rendu compte dans le présent exposé, en particulier, les Etats membres de l'Organisation européenne pour la Sécurité de la Navigation aérienne, par le truchement de leurs représentants au Groupe d'experts en détection automatique et résolution des conflits (SPACDAR/GEDARC).

Nos remerciements s'adressent particulièrement à la Régie belge des Voies Aériennes pour sa participation active à la définition des aspects opérationnels et à l'exécution des exercices temps réel.

Nous mentionnerons en outre la participation de plusieurs compagnies aériennes européennes, dont la British Airways (Londres), la SABENA (Bruxelles), la LUFTHANSA (Francfort), la NLM City Hopper (Amsterdam), ainsi qu'Aéroformation (Toulouse) et le NLR (Laboratoire aérospatial national des Pays-Bas), pour la mise à disposition et l'exploitation des moyens de simulation nécessaires.

REFERENCES

1. "Air Traffic Control Systems"
Symposium de la Commission "Guidage et pilotage" de l'AGARD, Edimbourg, Ecosse, juin 1972 (AGARD CP-105).
2. "Air Traffic Control in Face of Users' Demand and Economy Constraints"
Session spéciale de la Commission "Guidage et pilotage" de l'AGARD
Lisbonne, Portugal, octobre 1982 (AGARD CP-340).
3. "Gestion automatisée du trafic aérien sur un ensemble d'aéroports"
S. Khan Mohammadi
Ecole Nationale Supérieure de l'Aéronautique et de l'Espace
Thèse de Docteur-Ingénieur, Toulouse, France, octobre 1983.
4. "Air Traffic Control in a Zone of Convergence. Assessment within Belgian Airspace"
André Benoît et Sip Swierstra
14e Congrès du Conseil International des Sciences Aéronautiques (ICAS)
Toulouse, France, 9-14 septembre 1984.
Egalement Rapport EUROCONTROL 842009, avril 1984.
5. "A Study of conflicts within a Zone of Convergence"
V.W. Attwooll et D. Rickman
Travaux de la 11e réunion du SPACDAR/GEDARC EUROCONTROL
Bruxelles, 25-27 septembre 1984.
6. "A cost-efficient control procedure for the benefit of all airspace users"
André Benoît et Sip Swierstra
Symposium de la Commission "Guidage et pilotage" de l'AGARD
Cesme, Izmir, Turquie, 16-19 octobre 1984 (AGARD CP-360).
Egalement Rapport EUROCONTROL 842011, août 1984.
7. "Fuel Economies Effected by the Use of FMS in an Advanced TMA"
Victor Attwooll et André Benoît
The Journal of Navigation, Vol. 38, n° 1, janvier 1985.
Egalement Rapport EUROCONTROL 842003, février 1984.
8. "Possible contributions from SSR Mode S datalink to the conduct of efficient aircraft operations"
M.E. Cox
Symposium de la Commission "Guidage et pilotage" de l'AGARD
Bruxelles, 10-13 juin 1986 (AGARD, CP-410).
9. "A simulation facility for assessing the next generation of 4-D Air Traffic Control procedures"
André Benoît et Sip Swierstra
15e Congrès du Conseil International des Sciences Aéronautiques (ICAS)
Londres U.K., 7-12 Septembre 1986.
10. "The next generation of control techniques in advanced TMA"
André Benoît, Sip Swierstra et René De Wispelaere
Symposium de la Commission "Guidage et pilotage" de l'AGARD
Bruxelles, 10-13 juin, 1986 (AGARD CP-410).
11. "The Air Traffic Controller facing automation : Conflict or Co-operation?"
André Benoît, Sip Swierstra et René De Wispelaere
The Royal Institute of Navigation, NAV-87
London, U.K., 29-30 September - 1 October 1987.
Also EUROCONTROL Report 872008, July 1987.
12. "Belgium moves ahead in Air Traffic Control"
Arnold Vandenbroucke, AGARD-GCP Symposium
Brussels, 10-13 June 1986 (AGARD CP-410).

NAVIGATION 4-D EN CIRCULATION AERIEENNE

AIRCRAFT 4-D NAVIGATION

Nicole Imbert & Marc J. Pélegrin

Centre d'Etudes et de Recherches de Toulouse (CERT)
B.P. 4025 - 31055 Toulouse Cédex - France

RESUME

Partant de la constatation que les délais d'attente avant atterrissage sont croissants alors que les cadences maximales possibles ne sont pas atteintes, on a proposé d'introduire une consigne supplémentaire lors de la procédure d'approche consistant en 2 corrections de vitesse et une correction de cap (Nav. 4-D, 3 dimensions espace + temps).

Le premier problème à résoudre fut le choix du modèle mathématique à adopter pour simuler l'avion. La méthode utilisée consistait à partir d'un modèle "le plus complet" (on est parti d'un modèle du 18e ordre) et à le dégrader jusqu'à ce qu'un critère ne soit plus satisfait. Ce critère consistait à mesurer l'erreur entre le modèle complet et le modèle dégradé sur une trajectoire de référence (approche Roissy) longue de 54 km. On admettait que l'erreur apportée par le modèle dégradé ne devait pas atteindre ± 320 m à la balise d'entrée de l'ILS. Un modèle de 6e ordre convenait.

Après un certain nombre de simulations il a été montré que les corrections devaient se placer après l'entrée dans la zone de contrôle (zone de convergence) sur le vol à niveau constant (correction de vitesse), au milieu de la descente effectuée à vitesse indiquée constante (correction de vitesse) et dans la dernière branche avant l'interception de l'ILS (correction de cap).

Par une méthode d'ordonnement on peut déterminer, grâce au modèle utilisé en temps accéléré, un instant de passage optimal à la balise d'entrée de l'ILS, en vérifiant qu'une telle trajectoire peut être obtenue par un "pilotage aisé" (termes qui seront définis dans l'article). Bien entendu, un modèle de l'atmosphère doit être utilisé ; on a vérifié que la sensibilité de la méthode proposée par rapport à ce modèle n'était pas critique. On a également vérifié que l'erreur sur le passage à la balise due à l'incertitude sur la masse de l'avion à sa prise en compte n'était pas critique.

Résultats de simulation et mesures en vol

On a comparé par simulation les dispersions des instants de passage à la balise sans correction et avec corrections. Pour ce faire le pilote était simulé par les erreurs qu'il introduisait dans le pilotage (erreurs définies stochastiquement par rapport à la "procédure compagnie") ; les corrections étaient calculées par l'erreur constatée aux 3 points indiqués précédemment et étaient quantifiées (corrections non inférieures à 3 kts) puis retardées pour tenir compte des délais de transmission.

Sur un lot de 200 simulations on a constaté une division par 3 de l'erreur quadratique moyenne des instants de passage à la balise lorsque les corrections étaient envoyées à l'équipage (9 s au lieu de 27 s), toutes autres conditions étant égales par ailleurs.

Grâce à la collaboration de la compagnie Air-Inter, 4 expérimentations en vols réguliers ont été faites. Les corrections étaient données à bord, grâce à des tables pré-établies et à l'aide du contrôle sol pour les positions exactes de l'avion. Après analyse des résultats et corrections dues au vent, les résultats obtenus par simulation ont été confirmés.

La NASA Langley a, de son côté, repris la même méthode (deux corrections de vitesse et une de cap) et a procédé à des simulations (approche Denver, Colorado ; avion B 737) qui ont confirmé nos premiers résultats (un rapport commun NASA/CERT a été publié).

Perspective pour un ordonnancement temps réel du trafic en zone terminale

Dès leur origine nos études ont été suivies par EUROCONTROL et sur contrats de cet organisme nous avons pu étudier des procédures optimales de descente pour des avions réels (B 727, B 737, DC10, Caravelles 12, A 300) en tenant compte des contraintes réelles d'aéroport (Bruxelles, Londres, Francfort). Les lois de descente devaient minimiser le temps total de circulation des avions et la consommation totale de carburant dans la zone de convergence. La prise en compte d'un nouvel avion dans la zone, oblige à reprendre l'ordonnement et les instants de passage à la balise. Les algorithmes proposés seront décrits.

Avenir

Les études initiales datent de 1975-77 ; elles restent valables aujourd'hui et des expérimentations trafic réel sur des algorithmes mis au point par EUROCONTROL (voisins de ceux proposés) vont avoir lieu prochainement à Bruxelles.

Cependant le développement des FMS conduit à poser le problème en de nouveaux termes : il y a mélange de 2 catégories d'appareil. Le "pilotage aisé" mentionné au § 1 sera confirmé pour les avions non munis de FMS. Par contre ceux munis de FMS pourront recevoir une seule information, celle du passage à l'heure à la balise après calcul par le "contrôle sol" (ATC). Le FMS, possédant un modèle de l'avion, doit

pouvoir retrouver la solution indiquée par le sol. Mais la solution peut ne pas être unique, aussi est-il nécessaire d'assurer la conformité des 2 trajectoires, (celle calculée au sol et celle restituée à bord par le FMS) par l'envoi de paramètres supplémentaires. Une fois la corrélation faite, les données du FMS peuvent être utilisées par le sous-système pilote automatique.

Summary

Bearing in mind that the waiting times before landing are always increasing while the maximum landing rates are not reached, we have suggested to monitor one more parameter during the approach. This is, in fact, two speed corrections and one heading correction (Nav. 4D, 3 space dimension + time).

The first problem to be solved is the choice of the mathematical model to be used to simulate a plane. We proceeded as follows : we started from a model as complete as possible (in fact of the 18th order) and we degraded it until a criterion was no longer satisfied. This criterion was a measurement of the error between the "complete" model and the "degraded" model along a reference trajectory (Roissy approach) of 54 km extension. We assumed that the error due to the use of a simpler model should not reach ± 320 m at the ILS entry beacon. A 6th order model was declared acceptable.

After a number of simulations it has been shown that corrections must arise after the entrance in the "zone of convergence" (ZOC) during the flight at constant level (speed correction) in the middle of the descent flown at constant indicated speed, (speed correction) and during the last leg before the ILS capture (heading correction).

By a management method using a mathematical model on a fast time basis, an optimal time of arrival at the ILS entrance beacon can be determined, corresponding to an "easy to fly" trajectory. A model of the atmosphere must be used and it has been checked that the robustness of the method (3 corrections) with regard to this model is correct. It has also been checked that the time when the final beacon is reached is not sensitive to the mass of the plane at the entrance point.

Simulation results and inflight measurements

Comparison between the times of arrival over the beacon without and with corrections has been performed over 200 runs. To do that, the piloting of the plane was simulated by random errors introduced by the pilot with regard to a nominal flight ; corrections were computed from the errors measured or estimated at the 3 points above mentioned ; (corrections smaller than 5 kts were not transmitted to the plane) ; a random delay was introduced after the computation of the error to take care of the disponibility of the VHF frequency and the time of reaction of the pilot.

Over these 200 simulations, it has been shown that the standard deviation of the times of arrival at the last beacon is divided by 3 when the 3 corrections are sent to the pilot (9 s instead of 27 s), all the other factors always acting according constant statistical parameters.

Thanks to Air-Inter, and to ATC controllers, 4 tests have been made on regular flights ; corrections were given to the pilot, on board, from tables which were pre-calculated, the position of the plane was a fusion of the DME on board indicator and radar position radioed by ATC staff. After careful data analysis and wind corrections, the results obtained by simulation were confirmed.

The same method (2 speed corrections and 1 heading correction) has been implemented in the B 737 NASA/Langley simulator, on the Denver approach routes. Our results were confirmed and a common NASA/CERT technical report has been written.

Real time scheduling of traffic in terminal area

Since the beginning, our studies have been followed by EUROCONTROL ; under contract from this Center, we have studied optimal descents for planes (B 727, B 737, DC 10, Caravelle 12, A 300) with constraints attached to various airports (Brussels, London, Frankfurt). The criterium used for the climbing up was the minimization of the total flying time of the planes in the ZOC and of the total fuel consumption. Each time a new plane enters the ZOC the sequencing and the times of arrival over the last beacon must be re-calculated according to the same criterium. Algorithms used are described in the paper.

Future

Initial studies were performed in 1975-77. They are still valid today and an experimentation with commercial flights, using algorithms developed by EUROCONTROL will be performed in Brussels in the next future.

However the development of FMS gives rise to a new formulation of the problem. There are 2 categories of planes (with and without FMS). The "easy trajectories" will still be offered to planes non-equipped with FMS. As for those equipped with FMS they should receive one single information : the allocated time of arrival over the last beacon, time which is determined by the ATC. The FMS has a model of the plane, thus it can find the 4-D trajectory which will bring it at the prescribed time over the beacon. However the solution may not be unique and it will be necessary to check the identity -within a given tolerance- of the ground and on-board computed trajectories.

Once checked the FMS may transfer its data to the automatic sub-system or may directly monitor it according to the degree of sophistication of the plane. The use of automatic data transmission ground to air and air to ground is a prerequisite.

1. PRINCIPE DE LA NAVIGATION 4-D

1.1. Contrôle du trafic.

Le contrôle d'un avion, en zone terminale qui, en accord avec Eurocontrol sera désormais appelé Zone de Convergence (ZOC) se fait par des autorisations données à l'avion par le Contrôle au Sol (ATC). Ces autorisations données en principe dans un langage préformé indiquent que la prochaine branche du parcours est "claire". Une branche de parcours est toujours identifiée sur les cartes "en route" et sur les "fiches d'approche" (1) ; une indication de niveau ou d'altitude est transmise ou bien une autorisation de descendre ou de monter. Par contre aucune indication de vitesse n'est donnée ; tout au plus le contrôle sol peut-il dire "maintenez la vitesse" ou bien "pouvez-vous réduire de x kts".

Pour atteindre les cadences normales qu'autorise une piste et les aides radio qui lui sont associées, il faut affecter des créneaux temporels de "toucher des roues" et, par conséquent agir sur la vitesse sol de l'avion une fois entré dans la ZOC. Il s'agit donc d'un double problème : à partir d'hypothèses raisonnables sur le pilotage de l'avion

- a) déterminer l'ordonnancement des avions à l'atterrissage afin de tendre vers les cadences maximales,
- b) donner des instructions de vitesse à l'avion afin qu'il respecte "la marche" que le sol lui a assignée dès que l'affectation d'un créneau d'atterrissage a été faite.

Les premières études ont été faites en 1975-78 [1] [2].

Les transmissions entre le sol et l'avion étant effectuées en phonie (VHF ou HF sur les océans ou territoires peu denses) l'encombrement des fréquences est tel qu'il est impossible d'imaginer un suivi en continu d'un avion, même si les moyens informatiques existaient au sol. Nous reviendrons sur ce point dans les conclusions. Nous nous sommes donc orientés vers un contrôle très lâche consistant en des corrections de vitesse -ou de cap- données à 3 instants durant la navigation de l'avion dans la ZOC, d'où le terme de Nav 4-D pour signifier qu'en plus des grandeurs spatiales on agit sur la vitesse, c'est-à-dire que le temps intervient.

L'objectif de ces études était de calculer avec quelle précision on pouvait amener un avion en un point donné de l'espace, en l'occurrence, ici, à la balise d'entrée sur le faisceau ILS (cette balise, souvent matérialisée par un NDB ou un VOR est située à environ 10 à 15 km avant le seuil de piste, dans l'axe). Alors, par un choix optimal des instants de passage à la balise des différents avions en cours d'approche on peut espérer atteindre la cadence maximale d'atterrissage (2).

On admet, en effet, qu'une fois aligné sur l'axe, les dispersions entre les durées passage balise/seuil de piste sont faibles (l'approche se fait pour la plupart des avions à 140 kts ; pour les petits avions les vitesses peuvent s'étendre de 90 à 120 kts ; il faut remarquer que le contrôle tâche de grouper les avions par catégories afin de former des séquences aussi homogènes que possibles).

Les prises en charge des avions dans les ZOC s'effectuent à environ 150 NM de l'aéroport, soit entre 10 et 20 mn avant l'atterrissage suivant la vitesse de l'avion. Les règles actuelles sont du type FCFSSE (first come, first served at system entrance) avec, cependant une certaine souplesse dans l'ordonnancement des avions.

Si l'on admet qu'un certain contrôle de vitesse est envisageable, alors les problèmes à résoudre sont :

- algorithmes d'ordonnancement permettant d'approcher de la cadence maximale,
- nombre et type de corrections à apporter, par rapport aux consignes d'approche, et instants auxquels ces corrections doivent être transmises,
- précision finale résultant de cette procédure compte tenu des erreurs de pilotage et de l'approximation faite sur l'atmosphère.

On voit immédiatement qu'un problème préalable concerne la validité des modèles mathématiques utilisés ; deux sous-problèmes émergent :

- a) quelle complexité adopter ? (chercher le modèle le plus simple)
- b) quelle est la sensibilité de l'algorithme à la masse de l'avion ?

1.2. Modèles mathématiques des avions.

On cherche un modèle rationnel de l'avion. Quel doit être l'ordre de ce modèle ?

(1) sauf en cas de "régulation radar" où le sol guide explicitement l'avion en lui donnant des caps et des altitudes à prendre.

(2) Cette cadence correspond normalement à 150 à 180 secondes entre 2 mouvements lorsque le plafond est de l'ordre de 100 m. Par temps clair et en dehors des jours où le vent est faible et dans l'axe de la piste, ces cadences peuvent être accrues (intervalle entre mouvements 100 à 120 secondes). Par vent de travers (n'excédant pas les normes) ces cadences peuvent encore être accrues (intervalles de 80 à 100 s). C'est en effet les tourbillons d'extrémités d'ailes qui limitent ces cadences. Par vent de travers ces tourbillons s'échappent rapidement de la piste.

Partant d'un modèle aussi complet que possible, on le dégrade progressivement, c'est-à-dire, on réduit son ordre jusqu'à ce qu'un critère ne soit plus satisfait. Le critère que nous avons adopté est le suivant :

Après une trajectoire (correspondant à une route de la TMA d'Orly) longue de 21 km l'erreur entre le modèle complet et le modèle dégradé en cours d'évaluation, par simulation, ne doit pas excéder + 320 m (1).

Le "modèle complet" était du 16e ordre (Falcon 20 équipé d'un PA "Tapir"). Le modèle le plus simple :

$$\dot{\psi} = \frac{g}{V_a} \operatorname{tg} \phi_c$$

(ψ cap, ϕ_c angle de roulis commandé, V_a vitesse aérodynamique)

Après simulations on a été conduit à adopter un modèle du 3e ordre en γ (pente) V_a et Z (altitude) pour le vol longitudinal.

- à cap constant :

$$\frac{1}{2} \rho S V_a^2 C_z = mg \cos \gamma - F \sin(\alpha + \omega) - m V_a \frac{d\gamma}{dt} \quad (\text{portance})$$

$$\frac{1}{2} \rho S V_a^2 C_x = F \cos(\alpha + \omega) + mg \sin \gamma - m \frac{dV_a}{dt} \quad (\text{trainée})$$

- pendant un virage :

$$\frac{1}{2} \rho S V_a^2 C_z = mg \frac{\cos \gamma}{\cos \phi} - F \sin(\alpha + \omega) - m V_a \frac{d\gamma}{dt}$$

$$\frac{1}{2} \rho S V_a^2 C_x = F \cos(\alpha + \omega) + mg \sin \gamma - m \frac{dV_a}{dt}$$

$$\dot{\psi} = \frac{g}{V_a} \operatorname{tg} \phi$$

$$\dot{X} = V_a \cos \psi \cos \gamma + V_{VX}$$

$$\dot{Y} = V_a \cos \psi \sin \gamma + V_{VY}$$

$$\dot{Z} = V_a \sin \psi + V_{VZ}$$

avec

ρ	densité de l'air	C_x	coefficients aérodynamiques
S	surface de référence	C_z	trainée et portance
V_a	vitesse aérodynamique	ω	angle vecteur poussée par rapport à axe référence avion
V_{VX}		γ	pente
V_{VY}	composantes du vent	F	poussée totale
V_{VZ}		m	masse avion
ϕ	angle de roulis	α	incidence
ψ	cap		

1.3. Modèles de l'atmosphère

On part de l'atmosphère standard (2), puis on modélise l'atmosphère réelle supposée au repos à partir des données connues en certains points (pression au seuil de piste, température locale, hygrométrie) ; enfin on modélise les mouvements de l'atmosphère par rapport à un repère fixe au sol (vents et turbulence). Le vent est représenté par un vecteur vent "moyen" auquel on ajoute un vecteur "turbulence". Les 2 composantes de ce vecteur sont supposées gaussiennes avec un σ de 10 kts et un temps de corrélation de 600 s.

Une telle modélisation a été utilisée durant toutes les simulations.

1.4. Routes considérées

Quatre routes ont été considérées ; 2 longues L1 et L3 avec des niveaux d'entrée 190 et 210 et 2 courtes C1 et C3 avec un niveau 70 (Fig. 1).

Par exemple, pour un B727 sur la trajectoire C1 on a adopté les hypothèses suivantes :

- atmosphère standard
- masse avion 65 T
- niveau de vol 70
- vitesse à l'entrée 250 kts

(1) le choix de cette valeur est lié à la partie "linéaire" du champ électrique du "localizer" de l'ILS (± 320 m correspondent à une ouverture de faisceau de $1,8^\circ$ à la balise d'entrée). On rappelle que la "zone de capture" correspond à $\pm 10^\circ$ soit ± 1800 m en latéral à la balise d'entrée après la sortie du circuit d'attente (niveau 70) (Fig. 1). Les altitudes (QNH) ont été fixées à 3000 pieds en C et 4000 pieds en D.

(2) air supposé sec ; pression niveau de la mer 1013,25 hPa ; température 15°C , gradient $-6,5^\circ\text{C}/1000$ m jusqu'à 11000 m, puis température constante au-dessus (-53°C).

la procédure est :

- radiale 360 du VOR "MEL" (from)
- vitesse indiquée constante
- cap 308, en descente à V constante, poussée résiduelle jusqu'à 3000 pieds,
- radiale 76 de OL, palier, décélération jusqu'à 170 kts, (volets 15° à 220 kts), poursuivre jusqu'à l'interception du "glide" à 3000 pieds.

2. RESULTATS DE SIMULATION ET D'ESSAIS EN VOL

2.1. Principe des simulations.

Ayant adopté un modèle de l'avion jugé "suffisamment précis" et un modèle d'atmosphère, on a procédé à 200 simulations numériques sur 4 types d'avions : 100 simulations correspondaient à un pilotage de l'avion suivant les procédures d'approche de chacun des 4 types d'avions considérés et 100 autres correspondaient aux mêmes trajectoires mais avec les 3 corrections calculées suivant un algorithme classique de régulation. Les corrections de vitesse étaient introduites pendant le vol en palier après l'entrée dans la ZOC, avant la descente puis en milieu de descente. La correction de cap était introduite sitôt après le palier à 3000 pieds avant la "capture" du "localizer" de l'ILS (Fig. 2). Pour cette dernière correction, on a tenu compte à la fois de l'erreur longitudinale et de l'erreur latérale. Sur la figure les instants de correction sont en chiffres romains et les points de mesure en chiffres arabes.

Bien entendu afin d'avoir une estimation de l'avantage apporté par les 3 corrections, il a fallu introduire dans ces simulations les erreurs dues au pilotage de l'avion, à la mauvaise connaissance de l'atmosphère et aux erreurs de positions mesurées par le radar.

2.2. Erreurs introduites durant les simulations

On a introduit 7 erreurs : 3 imputables au pilote, 3 dues à la fois au contrôleur sol et au pilote, 1 due aux conditions météorologiques ; toutes ces erreurs sont gaussiennes :

- a) erreur contrôleur/pilote - un écart type σ de 3 kts est pris sur la vitesse assignée.
- b) erreur sur la pente : elle est proportionnelle à la pente écart type $0,125^\circ$ si le vol est à niveau constant et $0,5^\circ$ pour une pente de 5° .
- c) erreur due aux instruments de bord : sur route VOR $\sigma = 1.15^\circ$; pour une branche à cap fixé : 1° pour l'ILS $\sigma = 0,2^\circ$; pour le DME $\sigma = 0,1$ NM.
- d) erreur due à l'instant d'entrée dans la TMA l'erreur est de 10 s à 3 s.
- e) erreur de positionnement de l'avion (radar) : on suppose l'erreur isotrope ; elle est de 0,25 NM à 3 s.
- f) erreur due au temps de réaction du pilote : on a pris un retard constant de 20 s (délai entre l'instant où le contrôleur sol a une instruction précise à transmettre et l'instant où le pilote ayant reçu l'instruction, réagit) auquel on ajoute un délai aléatoire de + 10 s à 3 s.
- g) erreurs dues au vent - on prend deux erreurs, l'une consistant en une erreur de direction aléatoire et de vitesse uniformément distribuée entre - 10 et + 10 kts et une erreur à 2 composantes de valeur moyenne nulle, écart 10 kts à 3σ et temps de corrélation 600 s.

2.3. Procédure

Après discussions avec plusieurs équipages et contrôleurs il a été décidé que 3 corrections interviendraient dans les phases suivantes :

- a) une correction de vitesse -s'il y a lieu- durant la phase de vol à niveau constant après l'entrée dans la TMA.
- b) une correction de vitesse durant la phase de descente qui normalement s'effectue à poussée résiduelle et vitesse indiquée constante.
- c) une correction de cap dans la dernière branche avant la capture de l'ILS, branche qui s'effectue normalement à altitude constante.

Ces corrections sont calculées en fonction de l'erreur entre la position de l'avion réel et celle de l'avion fictif, avion coïncidant avec l'avion réel à l'entrée de la TMA -aux erreurs indiquées ci-dessus, près-, devant passer à l'heure assignée à la "balise d'entrée" et enfin correspondant à un "pilotage aisé" (1). Les calculs font appel au modèle mathématique de l'avion.

Toutes corrections inférieures à 3 kts ne sont pas transmises. Pour la 2e correction il est nécessaire de tenir compte des 2 composantes de l'erreur (longitudinale et transversale). Il en est de même pour le calcul de la correction de cap (3e correction).

(1) par "pilotage aisé", nous entendons : rester dans un sous-domaine intérieur au domaine de vol de l'avion ; éviter les gains d'altitude, éviter les accélérations longitudinales ; minimiser le nombre des manoeuvres.

2.4. Résultat des simulations

Pour chacun des types d'avions étudiés, 200 simulations ont été faites sur 4 trajectoires C1 C3 L1 L3.

Les corrections I, II et III apparaissent sur la Fig. 2 ; l'écart type a été calculé en 5 points notés 1, 2, 3, 4 et 5 sur la figure. Les points 1 à 4 sont fixés par rapport à l'instant origine, le point 5 est un point géographique situé à une hauteur de 3000 pieds sur le "glide" de l'ILS. Le point 1 est à 20 s après l'instant prévu d'entrée dans la TMA, le point 2 se situe après la 1ère correction de vitesse, le point 3 après la 2e correction, le point 4 est un point où les avions sont supposés être soit à 230 kts (réacteurs) ou 150 kts (avions à hélice).

Le tableau I ci-après donne les écarts types pour différentes grandeurs (altitude, vitesse ...) aux 5 points définis ci-dessus pour un B 727 sur la trajectoire C1.

Point	Altitude	Vitesse	B 727 sur C1 Cap	Erreur latérale	Erreur longitudinale
1	0.2 m	2.9 kts	0.6°	21 m	460 m
2	37 m	8.7 kts	0.8°	36 m	365 m
3	36 m	10. kts	6.8°	204 m	528 m
4	9.9 m	5.8 kts	11.3°	368 m	515 m
5	17.6 m	3 kts	9.1°	391 m	251 m

Tableau I

pour le point 5, erreur longitudinale, le temps nominal est de 242,5 s et l'écart type de 9 s et l'équivalent en distance de 810 m.

La Fig. 3 donne la dispersion des instants de passage au point 5 pour ce même cas (B727, trajectoire C1) on note un écart-type de 9,4 s. Pour un jeu de trajectoires sans correction la dispersion eue été de 28 s. On a trouvé des résultats analogues pour les autres avions considérés et les autres trajectoires. On peut conclure que ces simulations indiquent une réduction dans le rapport 3 des dispersions des instants de passage à la balise finale.

2.5. Résultats des essais en vol (1977)

Le 16 mars 1977 on a pu, grâce à la coopération de la Compagnie Air-Inter et des contrôleurs sol, expérimenter en vraie grandeur la procédure préconisée (Caravelle F-BNKG ; trajets Toulouse-Bordeaux ; Bordeaux-Roissy ; Roissy-Bordeaux ; Bordeaux-Toulouse, vols commerciaux).

Les corrections étaient données à bord par l'un des auteurs d'après des tables qui avaient été précalculées et qui se présentaient de la façon suivante :

Vol IT039 Bordeaux-Toulouse 16.03.77 Caravelle FBNKG

a) Conditions météorologiques

CNH 1020 mb - CAVOK
vents à 20000 pieds 180-200° 20 kts
au sol à l'atterrissage 140° 14 kts

b) Piste en service : 15 Rc) Procédure prévue

Toutes les distances sont comptées depuis le DME de Toulouse (117.7 MHz)

- début de descente : niveau 160 - 44.9 NM
150 42 NM
140 39.2 NM
250 kts doit être maintenu.

- point d'entrée dans TMA : t = 0 située à 36.6 NM
alors arrivée prévue à : t = 404 s (6'44") au point Z = 3000' sur le "glide"

- 1ère correction de vitesse à t = 100 s (1'40")
distance nominale : 28.4 NM
la distance réelle est : 29.1 28.6 28.4 27.5 26.4
alors prendre : 270 260 250 240 230

- 2e correction de vitesse à t = 194 s (3'14")
vitesse : 270 kts - distance nominale 21.8 NM

- si distance réelle : 21.8 21.5 21.1 20.9 20.7
alors prendre : 270 260 250 240 230

vitesse 260 kts - distance nominale : 21.4

- si distance réelle :	21.8	21.4	21.1	20.7	20.4
alors prendre :	270	260	250	240	230

vitesse 250 kts - distance nominale : 21

- si distance réelle :	21.8	21.4	21	20.6	20.3
alors prendre :	270	260	250	240	230

vitesse 240 kts - distance nominale 20.6

- si distance réelle :	21.6	21.3	21	20.6	20.1
alors prendre :	270	260	250	240	230

vitesse 230 kts - distance nominale 20.1

- si distance réelle :	21.3	21.1	20.9	20.5	20.1
alors prendre :	270	260	250	240	230

Sans entrer dans le détail d'analyse des vols (corrections de vent) donnons les résultats pour le dernier vol (Bordeaux-Toulouse). Le point d'entrée dans la TMA se situait à 36,6 NM, c'est l'instant de référence : $t = 0$. Le temps estimé d'arrivée sur la "balise d'entrée (3000 pieds sur le glide) était de 404 s par rapport à l'instant de référence. La Caravelle a franchi cette balise après 400 s. Les corrections ont conduit à ajouter 12 s à ce temps, soit un temps "corrigé" de 412 s pour 404 s annoncées. Les 3 autres vols ont donné des résultats similaires.

2.6. Expérimentations menées à la NASA, Langley [3] .

L'algorithme de recalage sur la trajectoire précalculée a été intégré dans une simulation temps réel à la NASA afin d'en évaluer les performances et les contraintes en contexte opérationnel, et de juger la pilotabilité des corrections demandées en vitesse et en cap.

Le simulateur de vol utilisé était le Langley Visual/Motion Simulator (VMS) simulateur à 6 degrés de liberté représentant un B737. Le cockpit est un cockpit conventionnel, mais pendant les tests une représentation sur écran permettait au meneur de test, qui occupait la place du co-pilote, de voir la position relative de l'avion par rapport à sa position nominale.

Les tests ont été menés avec huit scénarios différents afin d'évaluer les effets respectifs de l'erreur sur le temps initial, de la limitation de vitesse à 250 kts, de la modélisation des vents sur les possibilités de réduction de l'erreur finale.

La trajectoire (Fig. 4), d'une longueur de 53 NM permettait, avec deux corrections de vitesse et une de cap, une variation maximale des temps de parcours de - 75.9 à 71.7 sans limitation de vitesse, de 39 secondes avec limitation, comme indiqué tableau II.

Les résultats complets des tests, correspondant aux différentes configurations de simulations sont reportés tableau III.

On peut noter que la difficulté majeure réside dans la connaissance du vent ; d'autre part la réglementation de vitesse limite (250 kts) réduit les possibilités de recalage.

Notons enfin que les pilotes concernés ont considéré que les commandes en vitesse et en cap étaient facilement pilotables et n'engendraient pas de charge supplémentaire.

3. PERSPECTIVES POUR UN ORDONNANCEMENT TEMPS REEL DU TRAFIC EN ZONE TERMINALE [4, 5, 6] .

Dans les conditions actuelles l'écoulement du trafic aérien dans les zones terminales est, globalement parlant, assuré d'une manière essentiellement tactique et c'est en ce sens qu'il serait sans doute plus légitime de parler de "contrôle" que de gestion du trafic. Cette situation est sans doute due à ce que la sécurité du trafic repose essentiellement sur l'opérateur humain - le contrôleur au sol - et qu'il lui est encore difficile :

- de prévoir sur un horizon de temps suffisamment grand et avec la précision requise, l'évolution d'un ensemble d'aéronefs en descente,
- d'analyser une situation complexe,
- de prendre les décisions optimales correspondantes (de fait, il a été montré qu'au delà d'un certain nombre d'avions, le contrôleur ne peut "augmenter" sa capacité qu'en utilisant des processus décisionnels plus "économiques" pour lui - i.e. des actions à court terme sous forme de mises en attente ou de déroutements économiquement très pénalisants.

Ce caractère tactique - lié aussi à l'étroitesse de la zone de contrôle terminale, où les marges de manœuvre sont faibles - contribue à une aggravation du coût d'exploitation du système global : d'une part parce qu'il entraîne des temps d'attente importants, d'autre part parce que l'utilisation de trajectoires non optimales (interruption des descentes, attentes à basse altitude, descentes à vitesse non économique) entraîne un surcroît de consommation non négligeable.

Les résultats obtenus sur les possibilités de guider un avion sur une trajectoire 4D avec une précision suffisante ont permis d'entrevoir les grandes lignes d'une organisation future du trafic. On propose ici une gestion "stratégique" du trafic arrivant sur une zone terminale importante, gestion contrôlant tant le séquençement des avions à l'atterrissage, que les profils de descente. La mise en oeuvre pratique d'une telle politique soulève bien entendu de nombreux problèmes. L'extension de la zone de contrôle -directement liée au caractère stratégique- avec les problèmes humains et politiques qui en résultent, surtout en Europe, n'est sans doute pas le moindre.

3.1. Analyse du problème et critères

Si on examine les objectifs et les contraintes liés à un tel système, on s'aperçoit que le problème de gestion du trafic dans une zone de convergence est particulièrement complexe, à cause de la variété des objectifs à satisfaire, du nombre de contraintes, de la diversité des fonctions à assurer (ordonnancement, séquençement, prévision et résolution des conflits, guidage des avions). Les contraintes sont les contraintes opérationnelles liées à chaque avion, à chaque compagnie, les contraintes liées aux procédures et évidemment les contraintes liées à la sécurité.

La détermination d'un critère économique à utiliser au niveau de l'ordonnancement est chose délicate par suite de la multiplicité des critères à prendre en compte - critères tous plus ou moins connectés mais dont l'importance peut être vue différemment selon le côté où l'on se place : passagers, compagnie, organisme de contrôle.

De fait, la seule chose certaine est que l'organisation actuelle du trafic en zone terminale est dispendieuse, et impose des pénalités significatives au transport aérien. On peut remarquer la variation importante des coûts horaires selon l'avion considéré, le coût pouvant varier dans le rapport de 1 à 8 entre un avion comme le F 28 et le B 747.

La définition généralement admise d'un coût généralisé de trajectoire a l'inconvénient d'agréger deux composantes : le temps à la consommation.

Dans l'optique d'une gestion stratégique du trafic où on se propose -non seulement de résorber au maximum les attentes, mais de plus, dans le cas où elles sont inévitables, de les absorber, au moins en partie, par une modification du profil de vol- il y a intérêt à distinguer ces deux facteurs. Ceci permettra à la fois de mieux chiffrer le critère et de lui donner en même temps plus de souplesse, les considérations économiques, politiques, voire psychologiques ne jouant pas de la même façon sur ces deux composantes.

Dans le cas du contrôle stratégique, comme celui envisagé ici (et portant donc sur une zone beaucoup plus grande que l'actuelle TMA) une économie d'énergie peut être attendue sous deux points de vue, du reste liés :

- réduction des délais d'attente,
- amélioration des profils de descente.

Ces quelques remarques amènent à retenir un critère économique global, représentant le coût total de transit des avions dans la zone, sous la forme d'un coût lié au temps d'utilisation de l'avion et d'un terme représentant le coût du carburant utilisé.

$$C = \sum_i \alpha_i t_i + \beta_i c_i$$

La sommation se faisant sur tous les avions présents dans la zone pendant l'intervalle de temps considéré.

t_i représente le temps de transit de l'avion i dans la zone depuis l'entrée jusqu'au toucher des roues ; il inclut évidemment le temps d'attente éventuel,

α_i est le coût unitaire de transit fonction du type d'avion

c_i représente la consommation totale de l'avion dans la zone

β_i le coût moyen du kilogramme de carburant.

En principe, α_i et β_i représentent des coûts exprimés dans une unité monétaire donnée, toutefois il est possible, par le choix d'autres valeurs de ces paramètres, de pondérer différemment les facteurs temps et combustible, notamment :

- de pénaliser les attentes trop longues en prenant les coefficients croissant en fonction du temps d'attente,
- d'augmenter les coefficients de manière à favoriser le facteur consommation pour tenir compte de soucis politiques de préserver l'énergie.

Si on considère donc les trajectoires de descente d'un avion suivant différents profils de vitesse (Fig. 5), la consommation varie beaucoup du profil le plus rapide au profil le plus lent.

Ainsi donc, pour les six profils de descente considérés, suivant les pondérations apportées aux termes temps et consommation dans le critère, il existe un profil de descente "préférentiel" correspondant au minimum du critère envisagé pour l'avion seul. Si on considère maintenant le critère global tel qu'il a été défini

$$C = \sum_i \alpha_i t_i + \beta_i c_i$$

il est possible de séparer dans le critère la partie liée au transit proprement dit d'un avion depuis le

point d'entrée jusqu'à la piste de la partie associée à l'attente supposée effectuée en holding à l'altitude de croisière.

Si l'avion descend suivant le profil de vitesse k , on peut définir tt_{ik} et c_{ik} comme étant les temps et consommations correspondant au transit proprement dit, tat_i le temps d'attente de l'avion, δ_i la consommation instantanée de l'avion en holding. Le critère peut être réécrit sous la forme :

$$C = \sum_i \alpha_i (tt_{ik} + tat_i) + \beta_i (c_{ik} + \delta_i tat_i) \\ = \sum (\alpha_i tt_{ik} + \beta_i c_{ik}) + \gamma_i tat_i$$

en définissant C_{ik} comme le coût total de transit pour une descente sur le profil k

$$C_{ik} = \alpha_i tt_{ik} + \beta_i c_{ik}$$

et γ_i comme le coût total de la seconde d'attente pour l'avion i , comprenant la consommation ($\gamma_i = \alpha_i + \beta_i \delta_i$), on peut réécrire :

$$C = \sum_i C_{ik} + \gamma_i tat_i$$

Les paramètres intervenant dans le critère sont alors pour chaque type d'avion :

- le coût des différents profils,
- le coût de la minute d'attente.

Il s'agit donc de trouver les profils et les temps d'attentes tat_i , compte tenu des contraintes de séparation, minimisant le critère.

3.2. Ordonnancement dynamique

Le problème de l'ordonnancement dynamique du trafic dans la zone terminale se pose en termes d'optimisation d'un coût global lié au temps d'attente et à la consommation des avions.

Sous le terme d'ordonnancement il faut entendre ici la détermination de l'ordre et de l'instant d'atterrissage des avions ainsi que celle du profil de vitesse adopté en descente par chacun d'entre eux.

Le problème est essentiellement dynamique en ce sens que l'on détermine, à l'instant où un avion pénètre dans le système, l'ordonnancement optimal à ce moment là pour les avions présents dans la zone, ordonnancement qui est remis en question à chaque fois qu'un nouvel avion se présente à une porte de la zone.

Les deux idées de base qui ont conduit à la détermination de la politique d'ordonnancement retenue sont les suivantes :

- d'une part, il est possible "d'améliorer" la séquence d'atterrissage des avions par rapport à ce qui est fait actuellement par le contrôle, de manière à augmenter la capacité de la piste et à réduire les temps d'attente,
- d'autre part, il est possible d'adopter des profils de descente plus ou moins rapides, rapides par exemple pour diminuer l'attente des avions suivants, lents pour absorber une attente éventuelle, l'attente se faisant alors à poussée résiduelle il en résulte une diminution de la consommation.

L'hypothèse retenue est que les attentes sont effectuées à l'altitude de croisière et que l'on ne peut interrompre ou modifier la descente d'un avion. Un avion présent dans la zone ne peut donc être réordonné lors de l'entrée d'un autre avion que s'il ne se trouve pas encore en descente. Le point au-delà duquel il ne peut être réordonné a donc été choisi une minute avant le premier point de mise en descente sur les différents profils possibles, c'est-à-dire le point de descente sur le profil le plus lent. La minute de délai adoptée correspond au temps de calcul, de transmissions, ainsi qu'au temps de réaction du pilote.

Si l'on essaie d'analyser ce qui est fait actuellement par le contrôle, on peut considérer que c'est la politique "first come first served at system entrance" (FCFSSE) qui est actuellement utilisée, mais dans le cadre d'une zone beaucoup plus restreinte que celle qui est envisagée ici, c'est-à-dire que les avions atterrissent dans l'ordre de présentation aux portes de la zone. Une telle politique, appliquée à une zone de 200 NM serait aberrante du fait de la grande dispersion dans les temps de transits pour les différents types d'avions. La politique que l'on peut considérer comme la plus proche de ce qui est actuellement réalisé et qui servira de référence pour l'évaluation des performances de l'ordonnancement proposé est sans doute la politique FCFSRW (first come first served at the runway), c'est-à-dire que l'ordre d'atterrissage est déterminé par l'instant d'arrivée possible à la piste si l'avion descend sur son profil "préférentiel". Cette politique appliquée à une zone de 200 NM équivaut en pratique à une politique FCFSSE appliquée à l'entrée d'une zone réduite. En effet, la dispersion des temps de transit au-dessous de 10000 pieds est faible, si bien que l'ordre d'arrivée à la piste ou l'ordre d'arrivée aux portes d'une zone réduite sont assez équivalents. D'autre part, actuellement le choix du profil de descente ne dépend que de l'avion (compagnie ou constructeur) sans relation avec la densité du trafic ni le contrôle, et on peut penser que le profil "préférentiel" pour une compagnie et un type d'avion correspond à un optimum économique calculé pour un avion seul, c'est-à-dire sans aucune attente.

Cette politique de séquençement FCFSRW traite toutes les classes d'avion de la même façon. Si on envisage par contre une modification de ce séquençement de manière à optimiser le coût global, on risque de défavoriser, par rapport à ce qui est fait actuellement par le contrôle, les classes d'avions dont le coût d'attente est peu élevé.

Si on veut donc que, dans le nouveau séquençement certaines classes d'avions ne se trouvent pas trop défavorisées, même si ceci devrait conduire à une amélioration globale du coût total, il faut d'une manière ou d'une autre limiter les attentes possibles pour ces avions. Plusieurs solutions sont envisageables :

- on peut notamment fixer un temps d'attente maximal, avec l'inconvénient que ce maximum doit certainement être défini en fonction de la densité du trafic et de la classe d'avions considérée,

- il est aussi possible de pénaliser dans le critère les attentes excessives en choisissant pour les coefficients α_i représentant les coûts d'immobilisation des avions des valeurs non constantes, à croissance rapide lorsque le temps d'attente excède un certain seuil.

La solution qui a été retenue est de limiter le nombre de décalages de positions d'un avion par rapport à son ordre d'atterrissage dans le séquençement FCFSRW. Cette politique de maximum position shifting (M.P.S.) permet donc d'éviter que les avions, dont le coût d'attente est faible par rapport à d'autres, soient trop retardés. Un avion ne peut être reculé ou avancé dans la séquence de plus de M positions ; on peut par exemple fixer pour le nombre M les valeurs 1 à 4.

Examinons alors comment se pose le problème lorsqu'un avion se présente à l'entrée de la zone, avec le numéro d'entrée zone IP. On lui affecte tout d'abord un numéro d'atterrissage lié à son temps d'arrivée préférentiel à la piste, c'est-à-dire son numéro FCFSRW, IJ, qui est en général inférieur à IP. Il est alors placé dans la séquence d'atterrissage définie par les ordonnancements précédents en place IJ, les avions séquencés en IJ ou plus se trouvant décalés d'une position. Dans un premier temps, l'ordonnancement est réeffectué avec cet avion comme contrainte terminale, l'avion séquencé en IJ-MPS-2 devient la contrainte initiale. Les avions IJ-MPS-1 à IJ-1 sont réordonnés, c'est-à-dire qu'il s'agit de trouver la permutation de ces MPS + 1 avions et leurs profils, ainsi que le profil de l'avion IJ de manière à optimiser le critère précédemment défini, compte tenu des séparations à la piste à respecter. Une fois la solution optimale trouvée, le processus est répété avec, cette fois, l'avion IJ+1 comme contrainte terminale, l'avion qui se trouve reséquencé en position IJ-MPS-1 comme contrainte initiale ; et ceci doit être réitéré jusqu'au dernier ordonnancement comprenant l'avion IP en contrainte terminale.

Les contraintes à prendre en compte dans ce problème de séquençement sont les séparations en temps qui doivent exister entre deux avions à la piste. Cette séparation temporelle doit assurer une séparation standard en distance tout au long du faisceau ILS et dépend donc des vitesses d'approche et d'atterrissage du couple d'avions considéré ; la matrice des séparations S_{ij} (j suivant i) est calculée en simulation pour les différents types d'avions de l'échantillon.

A la fin de cette phase d'ordonnancement, se pose le problème de la résolution éventuelle des conflits le long de tout le parcours des routes dans la zone.

3.3. Exemple de résultats

Différents échantillons de trafic ont été testés en simulation pour différentes zones terminales étendues, de manière à évaluer les bénéfices que l'on peut attendre de l'algorithme proposé.

Un échantillon de trafic est caractérisé par la distribution entre types d'avions, et par sa densité. Celle-ci est définie par rapport à la capacité de la piste, c'est-à-dire au nombre moyen d'avions pouvant atterrir par heure. Les échantillons testés comportaient 9 types d'avions, variant d'un avion léger aux gros porteurs.

La Fig. 6 montre les résultats obtenus en comparant le coût total de transit dans la zone pour tous les avions pour différentes stratégies de contrôle.

3.4. Perspectives

Les résultats obtenus ont permis de démontrer que la gestion du trafic en temps réel, associée à un suivi 4D des avions en zone terminale permettrait une amélioration des coûts liés aux attentes. Le principe étant qu'un élargissement de la zone permet un contrôle de vitesse des avions en route et en descente amenant la possibilité d'optimiser la séquence d'atterrissage et de réduire les coûts d'attente. Une extension de ce principe serait la coordination entre les aéroports. En effet actuellement l'entrée des avions dans la zone reste quasi aléatoire, mais il serait possible de réguler les départs, c'est-à-dire de faire attendre les avions au sol, plutôt qu'en l'air en zone saturée.

4. AVENIR

Les études initiales datent de 1975-77 ; elles restent valables aujourd'hui : preuve en sont les expérimentations faites par Eurocontrol sur simulateurs (B737, DC10, A300) avec équipages compagnies en utilisant des algorithmes très voisins. Des expérimentations sur le site de Bruxelles avec les avions réguliers vont avoir lieu prochainement.

Nous ne pouvons que regretter ces délais anormalement longs entre l'étude et la mise en service.

Toutefois le développement des FMS (Flight Management Systems systèmes comprenant principalement un calculateur -triplé en général- des capteurs et un clavier pour l'introduction des données) à bord des avions de beaucoup de compagnies conduit à poser le problème en termes nouveaux. Il y a en effet maintenant 2 catégories d'avions à gérer, ceux munis d'un FMS et les autres. Ces derniers peuvent être gérés suivant la procédure indiquée ci-dessus (3 corrections) ; ceux munis d'un FMS peuvent être gérés de façon globale -c'est-à-dire continuellement- avec comme seule instruction l'heure de passage à la balise finale, sous réserve d'une étude sur la capacité du calculateur de bord.

Le problème peut être posé comme suit :

L'avion, muni d'un FMS, entrant dans la TMA est pris en compte par le calculateur d'ordonnement du trafic qui lui assigne un temps de passage à la balise finale de la même façon qu'il le fait pour les avions non munis d'un FMS. Cependant, à cause du pilotage automatique, sous contrôle du FMS, des créneaux qui auraient été éliminés pour un avion non muni de FMS (créneaux qui auraient conduit à sortir du domaine dit de "pilotage aisé") peuvent être retenus pour les avions munis d'un FMS.

Le calculateur de bord résout alors un problème à conditions finales imposées (problème dit du tir au but) en tenant compte des contraintes de navigation (3D) en zone terminale. Les conditions finales sont : l'heure de passage à la balise finale, cap, altitude et vitesse ; les contraintes sont en mémoire dans le calculateur.

Ces calculs nécessitent l'utilisation d'un modèle mathématique de l'avion, modèle tenu à jour notamment en ce qui concerne la masse et éventuellement le centrage de l'avion. On procède normalement par itérations : mais il faut admettre que le problème peut avoir plusieurs solutions : c'est là une première difficulté bien connue dans les problèmes d'automatique ou de recherche opérationnelle. Pour prendre un exemple simple, remarquons qu'on peut atteindre à la même heure la balise finale en commençant la descente en deux points (ou instants) différents, en descendant à vitesse indiquée constante et en passant à une vitesse imposée à la balise finale.

Le nombre des variantes peut se décomposer en continus dénombrables. Dans l'exemple simple ci-dessus, on peut imaginer facilement un "début de descente" à des instants continuellement variables, sachant qu'à chacun des instants correspond une vitesse en palier suivie d'une décélération pour passer à la vitesse imposée à la balise finale. Par contre on peut imaginer un échange entre les consignes de vitesses et de cap sur la dernière branche : ce type de trajectoires constitue un 2e continuum. A l'intérieur d'un continuum il est simple de trouver la solution optimale en introduisant un second critère : le plus utilisé est la consommation minimale. La dernière difficulté réside dans la coïncidence entre la trajectoire trouvée par le sol et celle calculée à bord. Seules des simulations sur un grand nombre de TMA permettront de juger si les dispersions éventuelles entre ces trajectoires peuvent conduire à des écarts inacceptables.

En fait, dans une première étape les avions munis d'un FMS pourront être gérés comme les autres, les corrections de vitesse et de cap étant toujours associées à l'heure de passage à la balise finale mais transmises uniquement si, pour des raisons d'espacement des avions, le sol estimait nécessaire de faire accélérer ou décélérer l'avion. Alors ces données (nouvelles vitesses à prendre ou cap pour rejoindre l'ILS) seraient injectées dans le FMS qui recalculerait la trajectoire optimale à partir de ces nouvelles conditions initiales.

Il est cependant probable que si la procédure nominale reste une descente à poussée résiduelle et vitesse indiquée constante les 2 calculateurs sol et bord trouveront la même trajectoire, donc que les écarts entre l'avion réel et l'avion fictif seront faibles et que ces 2 avions se rejoindront à la balise finale. Il faut en effet limiter au maximum l'introduction de données sur clavier à bord. Ce peut être une opération difficile en cas de turbulence intense, ce peut toujours être une source d'erreur. Dès lors la transmission de l'heure de passage à la balise finale sera la seule transmission indispensable après l'entrée dans la TMA.

Nous concluons en réclamant, une fois de plus, l'instauration d'une liaison automatique sol-air et air-sol. Le radar Mode S devrait techniquement pouvoir assurer cette liaison, mais rien n'est prévu dans un avenir proche. L'arrivée d'avions très "sophistiqués" tels que l'A 320 rend encore plus pressant cette liaison ; les liaisons phoniques actuelles constituent l'un des éléments les moins fiables de la chaîne guidage-pilotage des avions ; la faute humaine -cause principale des accidents- va devenir de moins en moins "catastrophique" dans les avions à commandes électriques où les limitations de sortie du domaine de vol sont automatiques : il est aberrant, alors, d'accepter que la sécurité repose sur les liaisons phoniques. De plus, si une liaison sol-air existe, elle passera nécessairement par un calculateur sol ; alors toute instruction donnée par le contrôleur sol pourra être rapidement corroborée avec la situation réelle présente et, si elle devait provoquer un risque immédiat de collision, elle serait refusée avant transmission et le contrôleur en serait aussitôt averti. De même à bord, l'instruction étant affichée en clair, le pilote devra la collationner en appuyant sur un bouton proche de l'écran.

Le passage à l'heure à la balise et une liaison automatique seraient alors une solution au problème de la saturation des aéroports aux heures de pointes.

REFERENCES

- [1] M.J. Pélegrin
Navigation 4D en zone terminale considérée comme un problème d'automatique.
AGARD, 1975, Conf. n° 188
- [2] M. J. Pélegrin, N. Imbert
Accurate timing in landing through air traffic control
AGARD, 1977, Conference Proceedings 24
- [3] Charles E. Knox, N. Imbert
Ground-based time-guidance algorithm for control of airplanes in a time-metered air traffic control environment
NASA, Technical Paper 2616, November 1986
- [4] N. Imbert
Application de l'algorithme d'ordonnement du trafic aérien à la zone de Londres Heathrow
Rapport CLAT-DERA 1/7240, 1980

- [5] N. Imbert
Algorithme de détection et de résolution de conflits entre trajectoires d'avion
Rapport CERT-DERA 2/7240-02, 1982
- [6] N. Imbert, A.J. Fossard, M. Comes
Gestion à moyen terme du trafic aérien en zone de convergence
Proc. IFAC/IFORS Symp. Comparison of Automatic Control and Operational Research Techniques Applied to
Large Systems Analysis and Control, pp. 155-62, 1979

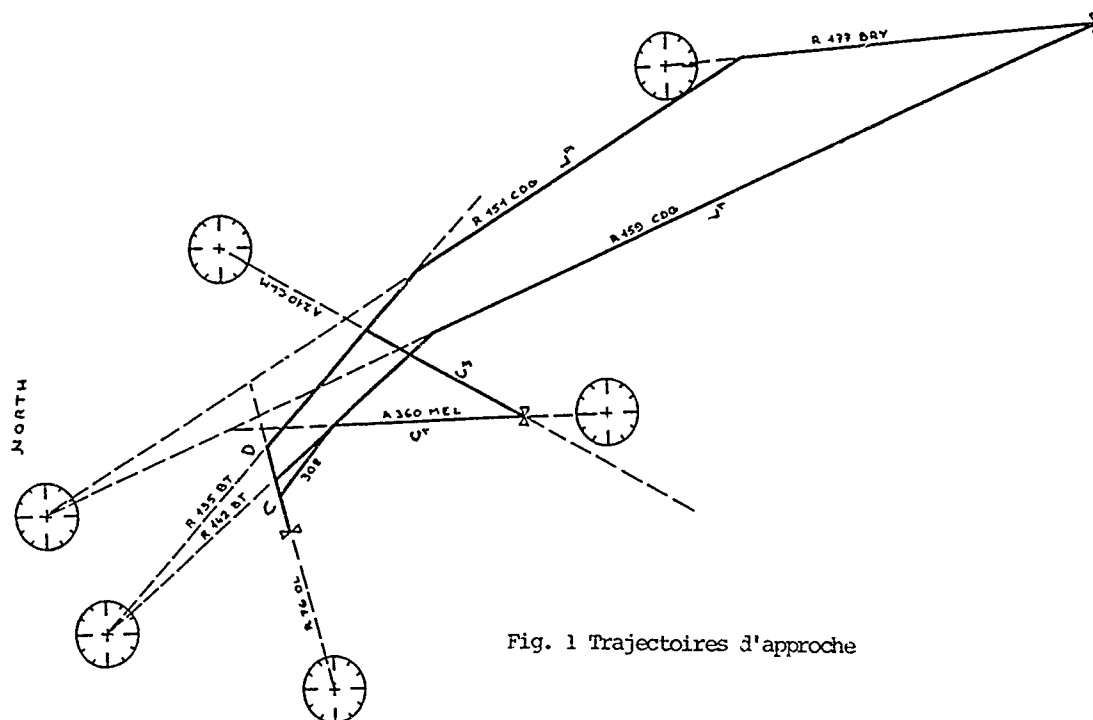


Fig. 1 Trajectoires d'approche

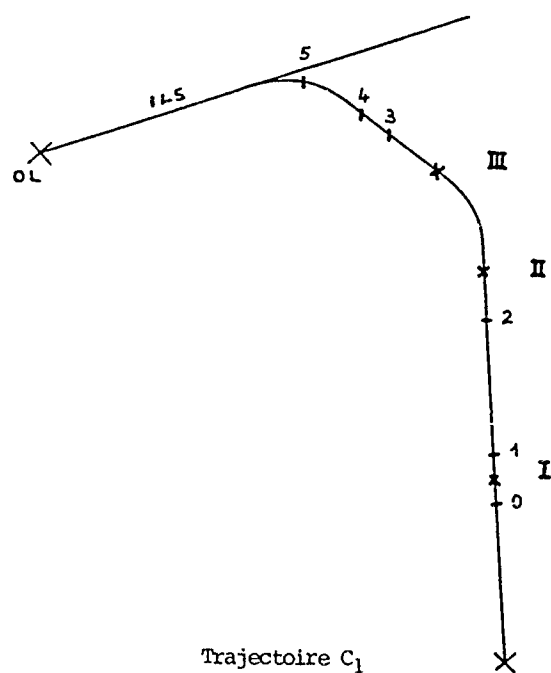
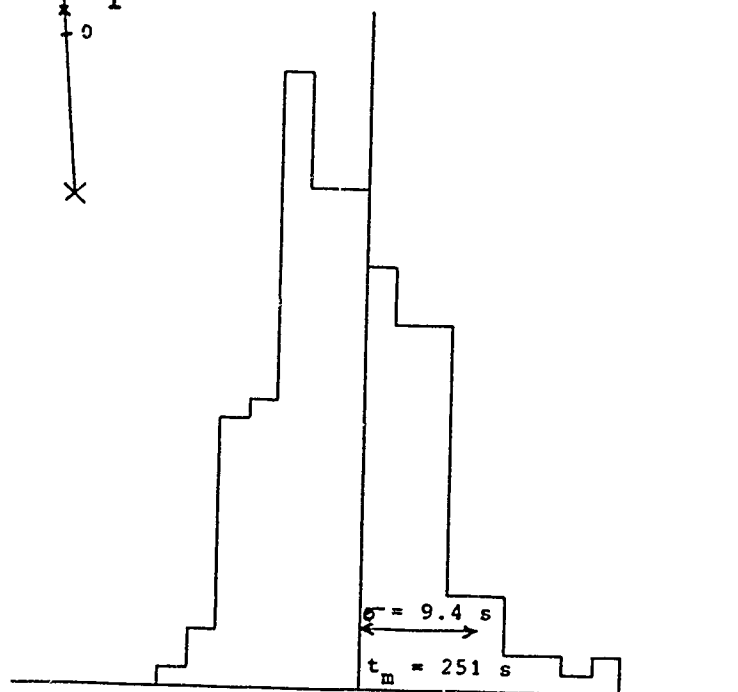


Fig. 2 Points de correction (chiffres romains) et points de mesure (chiffres arabes).

Fig. 3 Dispersion des instants de passage au point 5.



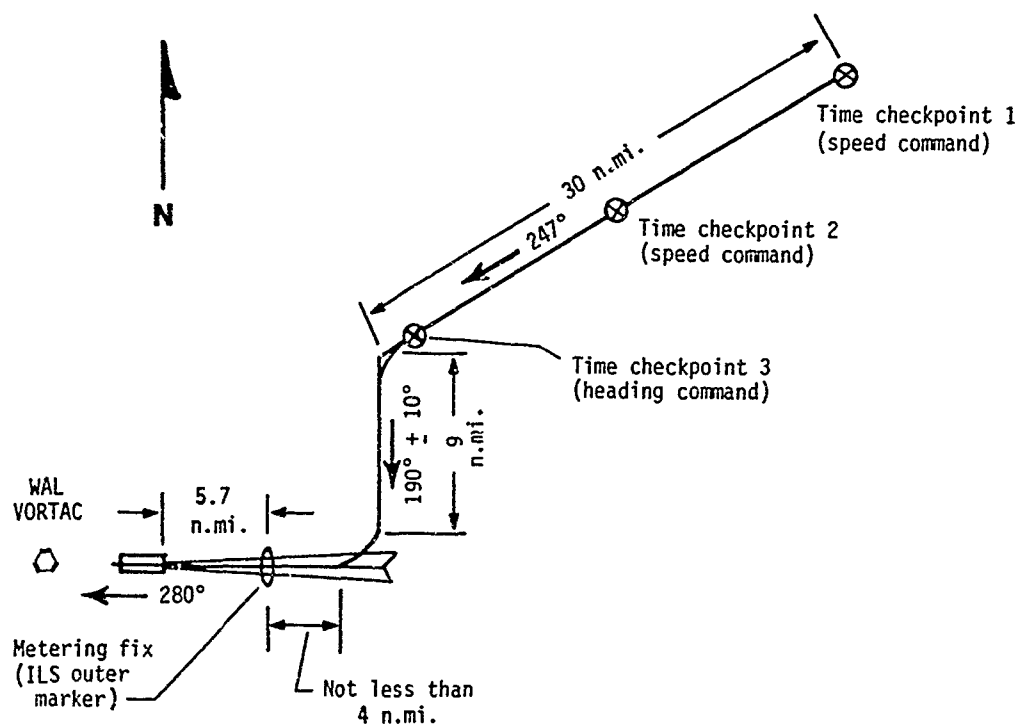


Fig. 4 Nominal test path

Speed command component, sec	Heading command component, sec	Total time controllability, sec	Comments
-34.6	-41.3	-75.9	Early-arrival time error
33.1	38.6	71.7	Late-arrival time error; 250-knot speed limit not applied
0	39.0	39.0	Late-arrival time error; 250-knot speed limit applied

Tableau II - Variation extrêmes du temps de parcours de la trajectoire de test

Test condition	Variable test parameters		
	Was ATC 250-knot airspeed limit applied?	Initial time error, sec (a)	Unplanned wind component
A	Yes	0	0
B	No	0	0
C	Yes	60	0
D	No	60	0
E	Yes	-60	0
F, G	No	0	247°; 10 knots (prevailing head wind)
H	No	0	067°; 10 knots (prevailing tail wind)

^aA positive time error denotes a late arrival requiring greater airspeed commands.

Parameter		Test condition							
		A	B	C	D	E	F	G	H
Metering fix									
Time error at metering fix, sec . . .	Mean	-1.0	-4.0	21.3	2.8	-8.4	28.1	36.0	-32.5
	S.D.	16.7	16.4	13.0	16.5	19.2	16.6	15.9	9.3

Tableau III - Conditions de tests et résultats

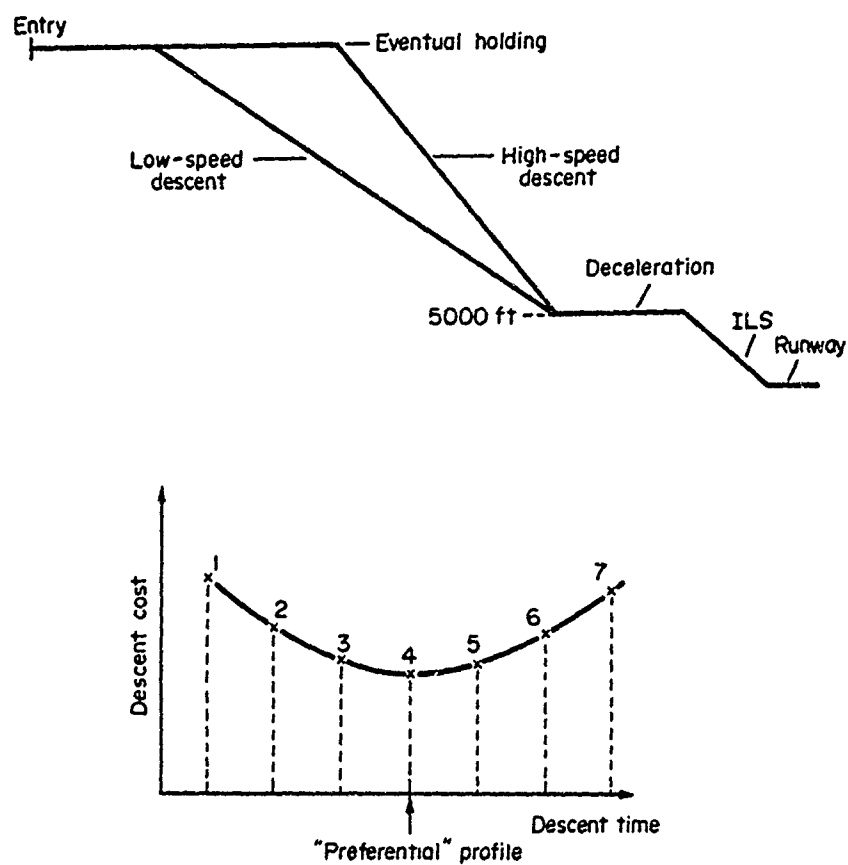


Fig. 5 Définition et coûts des différents profils de vitesse

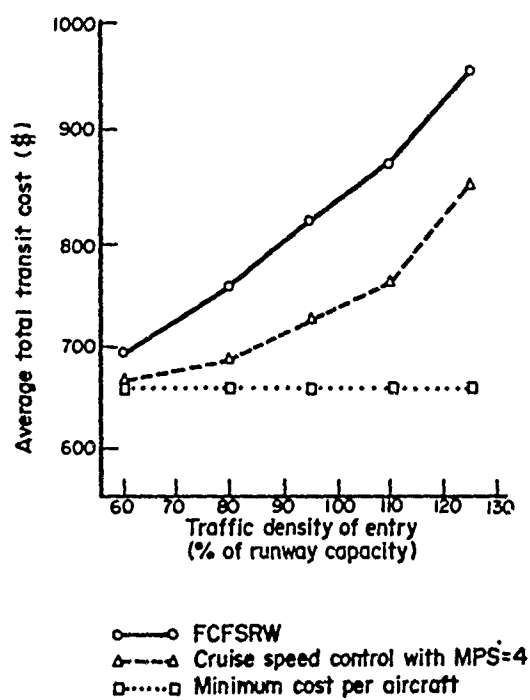


Fig. 6 Comparaison des coûts d'atterrissage pour les différentes stratégies

ON THE AUTOMATION OF FUTURE ATC CENTRES IN THE LIGHT OF THE CONCEPT OF THE "ZONE OF CONVERGENCE"

by

Victor Attwooll

Civil Aviation Authority
National Air Traffic Services
CAA House, Kingsway 45-59
GB - London WC2 BGTE

INTRODUCTION

Describes the Zone of Convergence concept briefly and its potential benefits.

ASPECTS OF SOFTWARE AT ATC CENTRES

Automated assistance will be required by ATC controllers engaged in sequencing arrivals in a Z.O.C. Important sub-routines are the aircraft performance model and the Conflict Detection process.

The Aircraft Performance Model

This is a model to predict the 4D profile of an aircraft for a given pilot (or autopilot) inputs. Once the model is developed, it is a trivial problem to enhance it so as to answer the reverse question : what pilot input is necessary to achieve a desired profile, specifically to achieve a stated gate time. The output from this process forms the basis of the ATC instructions given to the pilot.

Conflict Detection and Resolution

Having estimated the arrival profiles of a number of aircraft which give the correct sequence at the "gate", they should be further checked for infringement of separation standards along their length. Where such conflict exists, the corresponding profile must be modified to remove the conflict and still, hopefully, achieve the correct time at the gate.

INPUTS REQUIRED FOR THE SEQUENCING PROCESS

The basic aerodynamic or performance information on each type of aircraft must be obtained from the manufacturers, hopefully, in a standard format, for insertion into the aircraft performance model. Other, more transient inputs are :

Meteorological

Up-to-date wind, and perhaps temperature information covering the "playing area". Direct measurement from aircraft is preferred - forecasts may not be accurate enough.

Information on the Aircraft's Intentions

Flight Plan information, suitably updated, intended flight levels, speeds, way-points etc.

METHODS OF COMMUNICATION

These include both air to ground and controller to computer (man-machine interface or MMI)

Air to Ground

It is desirable for reduction in both workload and RT loading that, as much as practicable, communication air to ground should be by data-link (Mode S or satellite). The order of implementation of data-link facilities is likely to be: first ground data held in store (VOLMET etc) ground to air, then ambient meteorological data air to ground, then data on the current state of the aircraft (content of Flight Management Systems) air to ground and finally executive ATC instructions ground to air.

MMI

Possible modes of rapid insertion of updated information to the computer include Direct Voice Input as well as more conventional means.

SUMMARY AND CONCLUSIONS

This would include comments on the potential benefits and likely time-scales of the projects considered. Attention would be drawn to the need for developments to proceed in step with each other and to the need for proper validation before operational service.

THE CONTROL OF INBOUND FLIGHTS

Basic principles

by

André Benoît and Sip Swierstra

EUROCONTROL

European Organisation for the Safety of Air Navigation
Engineering Directorate
72, Rue de la Loi, B-1040 Brussels

SUMMARY

This paper describes the basic principles of the method developed to guide aircraft accurately down to the runway in a time-of-arrival constrained environment. The method is designed to be used in a Zone of Convergence context or in any similar advanced Air Traffic Control (ATC) system characterised by the integration of control phases over an extended area on the one hand and true "computer assistance" to the air traffic controller on the other, i.e. assistance provided at the decision-making level through the automatic generation of guidance advisories.

The method includes two closely coupled basic components, namely, a "predictor", which computes a trajectory once initial conditions and plans are known, and a "profile manager", which adapts the plans to meet the time constraint and generates the guidance directives on the basis of present position, actual surveillance information, aircraft operation and route constraints.

1. INTRODUCTION

The next evolutionary step in air traffic control (ATC) will be the introduction of knowledge-based control systems which will actually assist the air traffic controller in the decision-making process. Such systems will affect nearly all ATC fields, from overall air traffic management at the planning level to the selection of resolution strategies for potential conflicts at the executive level. One state-of-the-art approach is the Zone of Convergence (ZOC)* concept developed in the Engineering Directorate of the EUROCONTROL Agency in Brussels, Belgium (See Papers 22 and 29). This tackles the problem of efficient on-line management of a stream of aircraft inbound to one or more major airports by advising the controllers in en-route sectors and terminal manoeuvring areas (TMAs) on how to optimise the traffic stream in terms of safety and cost efficiency while at the same time ensuring maximum throughput by making the best use of available capacity. The ZOC concept covers all phases of flight from brake-release until touchdown and, from a traffic flow point of view, efficiently integrates all ATC sectors in a given area of jurisdiction.

Several research institutions worldwide have reported on their activities in this field (Refs. 2 to 5). Although the projects are often adapted to specific local situations, the approaches followed are generally similar and consist of three main modules :

- 1) The **sequencer/scheduler**, which establishes a target landing sequence and associated landing times on the basis of one or more optimisation criteria ;
- 2) The **guidance and control** module, which generates the control advisories to achieve the planned sequence based on observed radar tracks, and
- 3) A **man/machine interface** compatible with the existing controller work position and/or the general ATC data processing system, designed to facilitate an ergonomic controller/system dialogue.

This paper describes the general data flow through the ZOC system and subsequently discusses in more detail the guidance and control logic applied to generate the advisories.

* Note : . The term **Zone of Convergence** or the acronym **ZOC** refers to an extended area including and surrounding a main terminal and possibly secondary airports, the phases of control being integrated over a sufficiently long distance (R. Erwin, 1975), from 150 up to 300 nm from the main set of runways. The term was introduced (A. Benoît and A. Fossard, 1977) to avoid any ambiguity with the current Terminal Manoeuvring Area.

Nevertheless, in this particular paper the term ZOC is used to refer to the specific techniques developed in the Engineering Directorate of the EUROCONTROL Agency in order to handle on-line (management of traffic and guidance of individual flights) the inbound traffic in an extended zone of convergence.

2. THE PROCESSING STEPS IN THE ZOC SYSTEM

On-line management of air traffic relies heavily on the predicted flight profiles of the individual aircraft concerned. Although the route to be followed and aircraft operating procedures may be agreed upon between the aircraft operator and ATC in advance of the flight, the validity of the predicted profile is nevertheless strongly affected by numerous random perturbations, which include:

- uncertain meteorological conditions;
- conflict resolution actions (initiated either in the air or on the ground), which force the aircraft to leave the planned route and/or the planned vertical profile;
- errors resulting from ground/air communications difficulties;
- human error both in the air and on the ground.

Designed for operation in a real environment and because of that subject to such a variety of perturbations, the ZOC concept incorporates, for the sake of efficiency, a dynamic sequencing and scheduling mechanism whereby the landing sequence maintained by the ZOC system is constantly checked against actual traffic evolution. On the one hand, this approach offers total freedom of decision to the controller but, on the other, it complicates enormously the task of providing reliable and useful computer-based assistance. In particular, the traffic situation tends to be most complex under heavy workload conditions and, for obvious reasons, man/machine interaction has to be minimised at such times. It is on this aspect that most of the work on the ZOC system has concentrated.

ZOC PROCESSING STEPS

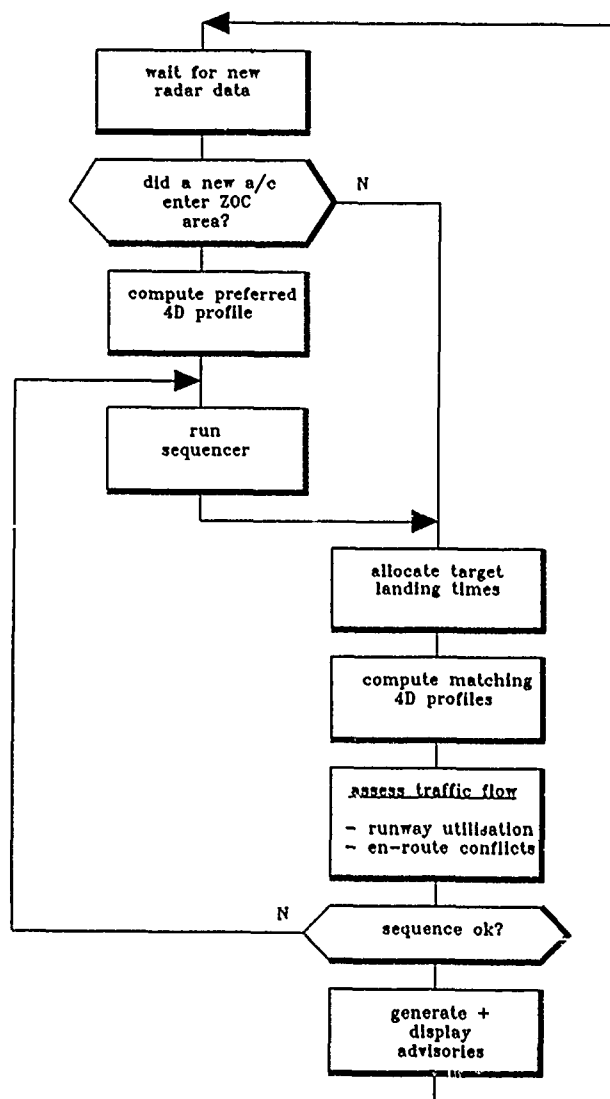


Figure 1 ZOC processing steps

The main processing steps involved are shown in Figure 1. The system is triggered every time new radar data are generated. If data for a newly entering aircraft are available, an estimate of its **preferred flight profile** is made (i.e. the profile the aircraft would follow if it was the only one in the sky). On the basis of the preferred flight profiles of all aircraft and a specific set of criteria, a **landing sequence** is proposed. Subsequently, a **landing time** is assigned to each flight based on its position in the landing sequence, the estimated landing time of the first aircraft in the sequence and the minimum separation requirements on the localizer.

The 4-D start and end positions are then defined for each individual flight, after which an attempt can be made to find a matching flight profile from present position till touch-down, within the limitations of the aircraft performance and possible ATC constraints.

On completion of this initial step, estimates of the future flight paths are available and subsequently runway utilisation and potential en-route conflicts can be assessed.

If the result of this evaluation is acceptable, the ATC advisories are generated and displayed to the controller(s), or else the landing sequence will be updated in accordance with the findings.

In this sequence of steps, three main modules may be identified. The central module is the **sequencer/scheduler**. In the discussion of the ZOC implementation, this module is referred to as ROSAS (Regional Organisation of Sequencing and Scheduling), which proposes a landing sequence taking into consideration :

- automatic, dynamic delay minimisation according to traffic demand;
- equal priority treatment for aircraft on short or long routes in the control zone;
- minimisation of potential conflicts in en-route sectors;
- automatic adaptation of the sequence to the actual traffic situation as it develops;
- controller override of certain automatic sequencing algorithms to accommodate runway changes, special flights, conflict resolution, etc.;
- flow control limitations for specific arrival routes.

The last module comprises the **man/machine interface**, which generates and arranges for the display of the ATC advisories. The approach chosen in the ZOC concept does not require any additional hardware displays at the controller working position. The advisories are formulated so as to be directly compatible with the typical instructions in use today and, accordingly, may be displayed in an additional line in the aircraft identification label on the controller's radar screen without causing any inconvenience. This avoids additional workload for the controller which would otherwise arise from a need for multiscreen scanning. It should also be noted that the structure of the advisories is such that they are directly compatible with automatic digital ground/air/ground data communications, as planned, for instance, within the future Mode S/Data Link environment.

This paper concentrates on the third module, which includes the **profile calculation and guidance and control functions**. This module is generally referred to as CINTIA (Control of Inbound Trajectories for Individual Aircraft).

3. THE CINTIA MODULE

In the ZOC concept, the CINTIA module has a support function, to compute the "preferred" and "actual" 4-D flight profiles, whereby it endeavours to match the constraints defined by the sequencer/scheduler at minimum cost for the individual aircraft. In addition, it provides the sequencer with data on control range boundaries such as "earliest possible landing time", etc. The CINTIA module has two main functions, as shown in Figure 2.

The **predictor** constitutes the core of CINTIA. It computes the 4-D flight profile on the basis of :

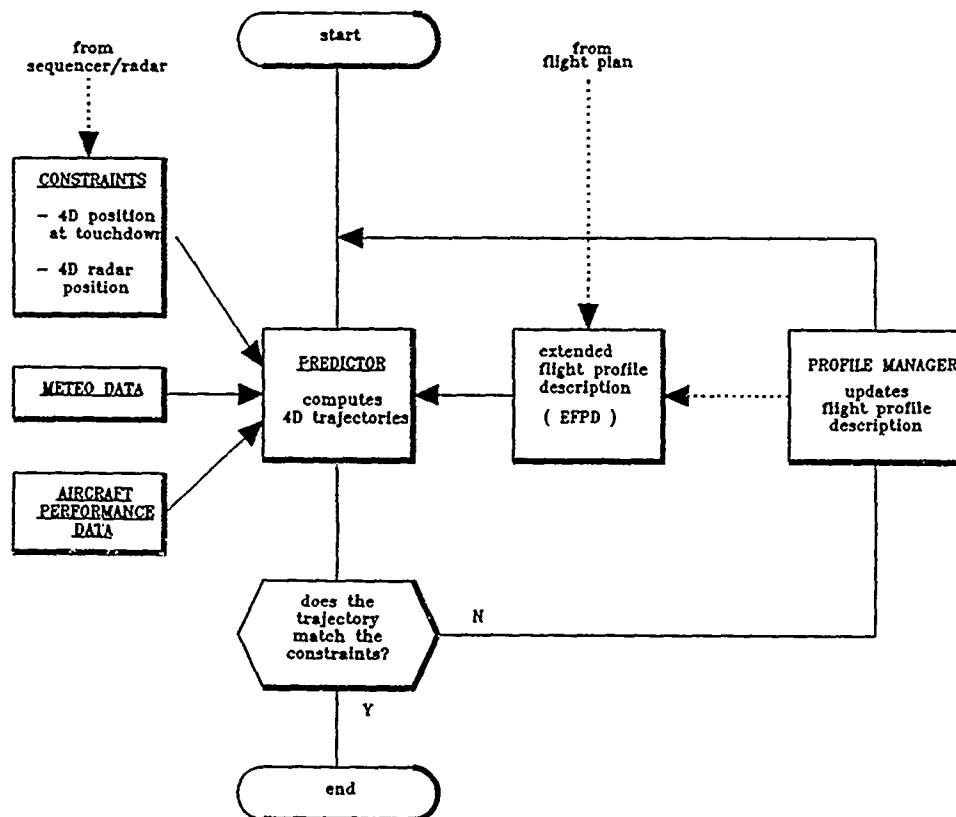
- the extended flight profile description (EFPD);
- constraints from the sequencer/scheduler, if available;
- meteorological data;
- aircraft performance data.

The **predictor** starts a typical trajectory computation at the "end" constraint, i.e. the 4-D position at touchdown, and computes backwards to the current (x, y, z) positions as observed by radar. Where the sequencer/scheduler has constrained the transit time, steps must be taken to establish whether the time at the "start" constraint is met. Otherwise, the second CINTIA function is activated, namely the **profile manager**. The latter updates the extended profile description (EFPD) in the light of the observed discrepancies between constraints, computed trajectory and flight phase. Subsequently, in the next try, a further check is made to establish whether the new flight profile is acceptable.

Effectively, the **predictor** and **profile manager** are independent functions which interface through the extended flight profile description. The EFPD comprises a composite set of information consisting of an exact description of every phase of the flight profile and the associated supporting data. Its basis is the standard ICAO flight plan defining, for example, call sign, planned route, cruise conditions and aircraft type. The EFPD is compiled from various databases such as : preferred company operating procedures ; standard instrument departure and arrival procedures (SIDs and STARs) ; current ATC constraints, e.g. runway in use ; meteorological conditions, e.g. visibility limitations ; aircraft performance data.

The resulting sequence of flight phases is coded in a special "language" which can be directly interpreted by the predictor. A more extensive description of the predictor algorithms is presented in Paper 17.

Let us discuss the mechanics of CINTIA's "constraint matching" by reference to an example.



Figures 2 CINTIA functions

4. CONTROL VARIABLES

In order to retain sufficient capability to accommodate perturbations during the flight, a careful balance is required between the maximum range of possible arrival times available at entry to the ZOC and the retention of sufficient flexibility in the later phases of flight. Obviously, the choice of control variables usable by CINTIA's profile manager at any given time during the flight is limited in the first place by the flight phase itself.

To illustrate this, a typical example of a flight from Dover (DVR) inbound to Brussels (EBBR) is shown in Figure 3. It shows a specification for the "preferred" flight profile in terms of route, altitude and speed definition for flight XYZ 384. On entering the ZOC area around Dover, the aircraft is cruising at FL 230, 300 kt IAS. The planned descent speed is 310 kt IAS leading to an approach to runway 25L at Brussels National airport.

An expanded view of the "preferred" approach path of the flight is presented in Figure 4. The length of the U-shaped path is determined by the preferred distance flown on the localizer (in the example, 8 nm). The flight path from the en-route airway to the localizer is defined by two ATC specified radar vectors, the first turning the aircraft onto a base leg (heading 120 degrees) and the second involving a right turn to the intercept leg (heading 210 degrees) associated with a clearance to intercept the localizer.

In Figure 4 it is suggested that control of the speed of the aircraft be divided into two ranges. Before the clearance to intercept the localizer has been issued, the pilot should maintain as closely as possible the speeds advised by ATC. After having received the "intercept" clearance, the pilot should reduce his speed in accordance with a schedule previously agreed by the aircraft operator and ATC. Thus, ATC will only exceptionally have to adjust the speed of the aircraft in the final approach phases.

The control variables accessible to the profile manager in the various flight phases are shown in Figure 5. In the en-route flight phases the main control variables are the en-route speeds. If, however, the imposed transit time from the aircraft's current position to its planned landing time is such that it cannot be achieved through en-route speed control, other delaying techniques must be applied. It is first necessary to check whether an additional delay can be obtained by extending the localizer to the maximum distance allowed in the given geography. If this is the case, the aircraft will be advised to proceed at the minimum acceptable operational speed and the precise definition of the radar vectors will be handled subsequently when CINTIA processes the approach phases.

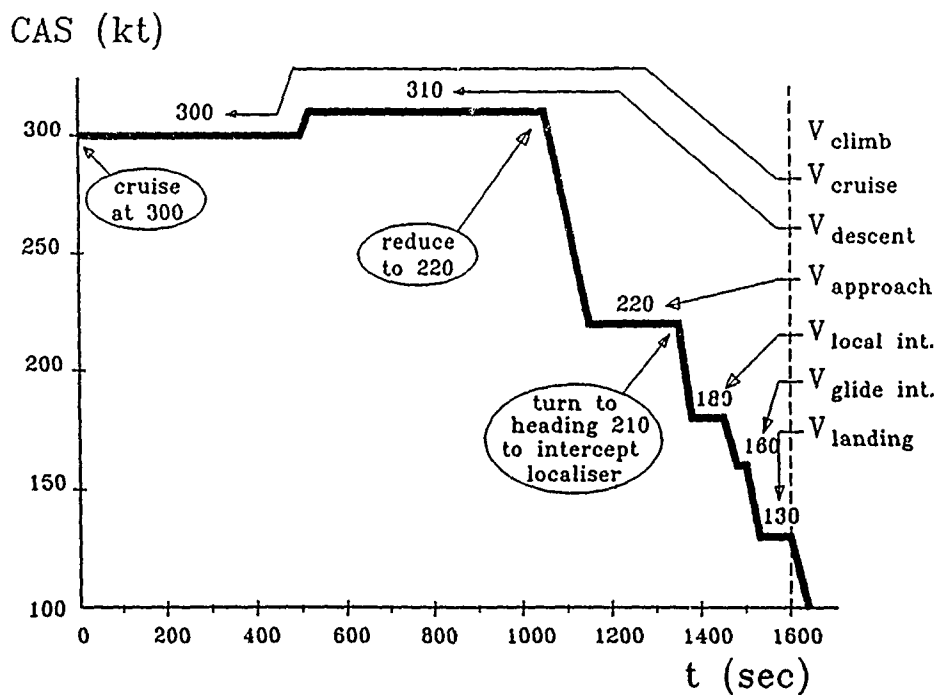
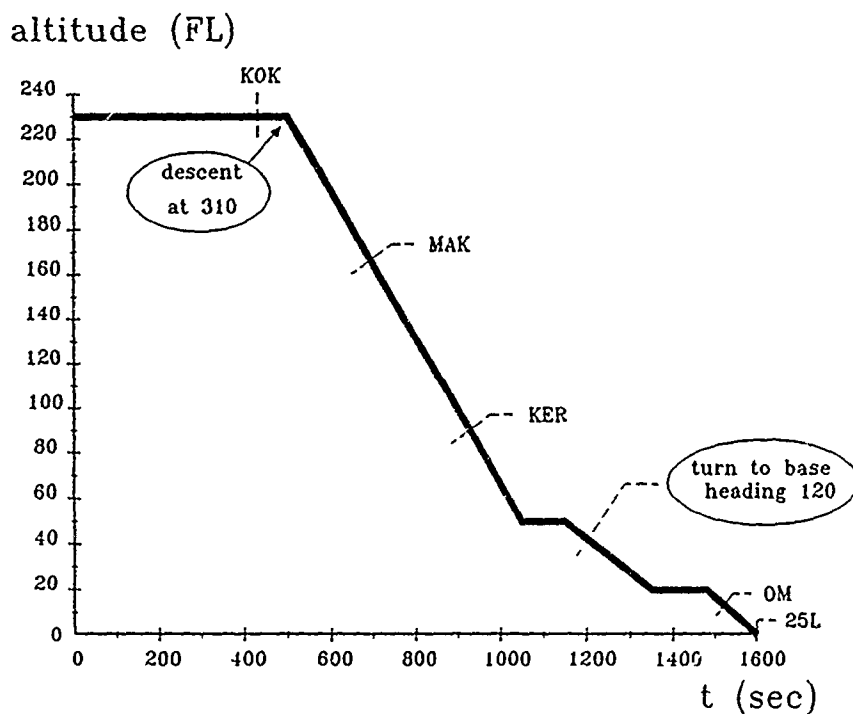
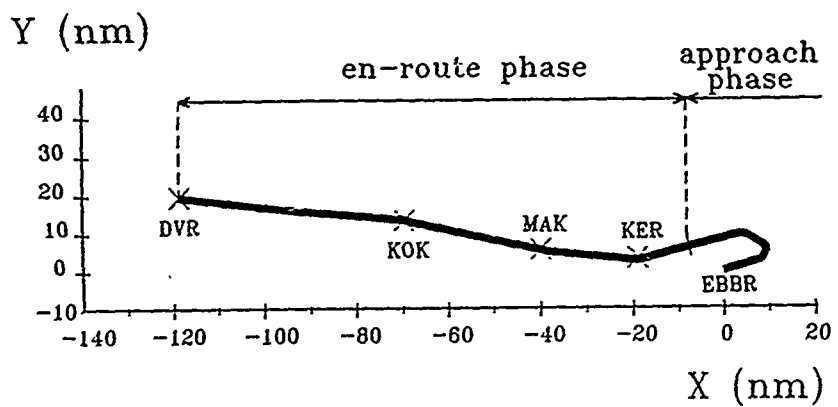


Figure 3 Preferred route, altitude and speed profiles of XYZ384

However, if the transit time obtained on the maximum localizer distance is still shorter than that requested, the controller will be informed of the additional delay which should, if possible, be absorbed in the en-route sectors, or otherwise by low-altitude holding at a later stage. If the requested transit time is shorter than the minimum duration possible, the sequencer/scheduler module will be informed accordingly and will decide on appropriate action. If the discrepancy is only a few seconds, the sequencer may accept the resulting minor reduction in landing capacity, but where the time differences are greater, resequencing might, provide a better overall situation.

In the approach phases of flight, the controller has to issue radar vectors to guide the aircraft from the airway to the localizer and CINTIA will provide appropriate assistance. The definition of the heading advisories specifying the base leg and intercept leg constitute the main control variables in these phases of flight. The limits imposed on CINTIA are shown in Figure 4. The shortest flight path is defined by the minimum distance on the localizer acceptable to the aircraft operator under the given conditions. The longest path is defined by the geographical TMA limit which, in the case of the example, corresponds to a maximum localizer distance of 12.5 nm. Finally, after alignment on the localizer, only very limited possibilities for speed control remain, since they have a considerable impact on the safe operation of the aircraft.

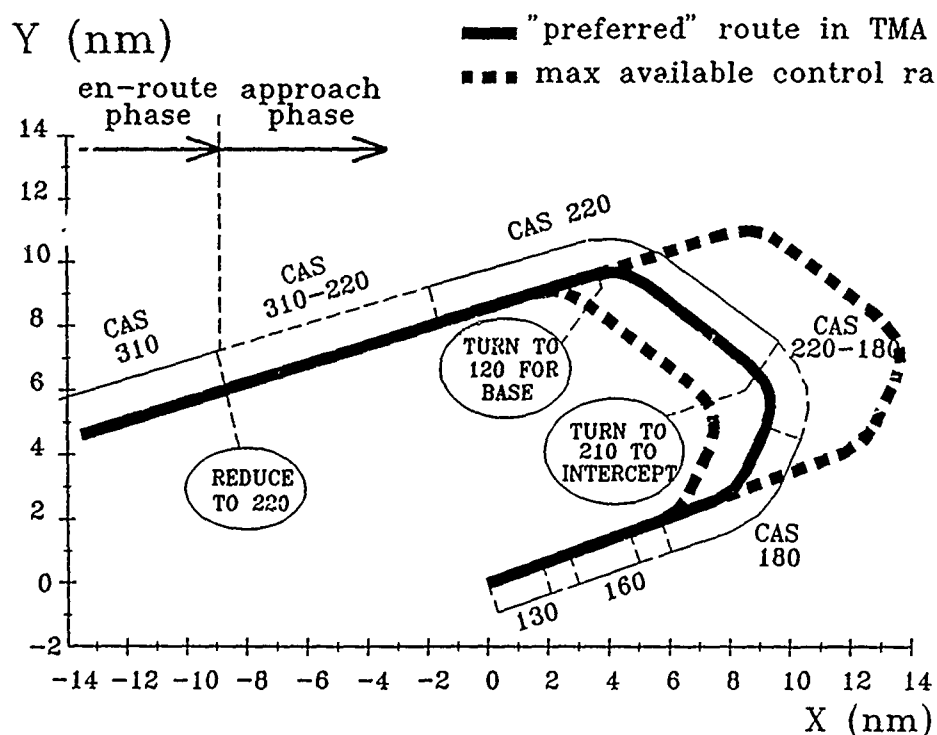


Figure 4 Preferred approach profile XYZ384

5. CINTIA's TIME-OF-ARRIVAL CONTROL POTENTIAL

It is of interest to see how CINTIA's ability to control of the time of arrival varies during progress through the Zone of Convergence. Figure 6 shows the available arrival time control range as a function of the distance to touchdown in relation to the "preferred" flight profile.

When the aircraft enters the ZOC at Dover, CINTIA can find matching flight profiles for requested transit times which are from 11 min. longer to 1.5 min. shorter than that corresponding to the preferred profile. The maximum delay is obtained by reducing the aircraft speed in the en-route part to "minimum clean speed" and extending the distance flown on the localizer to the maximum allowable. At the end of the en-route phase, approximately 25 nm from touchdown, CINTIA can accommodate a delay of up to 2.5 min. or an advance of up to 1.25 min., again in relation to the preferred profile. This range is determined virtually completely by the definition of the radar vectors in the TMA. After the aircraft has been vectored to the base leg, potential control of arrival time becomes extremely limited. In the example, at 8 nm from touchdown, it is still possible to gain 8 sec. in relation to the preferred profile or to lose a maximum of 30 seconds by reducing to landing speed and configuration. It should be noted that, as long as the aircraft is in the en-route flight phases, optimum efficiency is ensured by defining minimum cost solutions to match the sequencer constraints. Subsequently, in the approach phases, the full potential operating range of the aircraft is harnessed to provide optimum flexibility in order to achieve maximum system throughput.

CINTIA		PHASES OF FLIGHT						remarks
control variables		climb	cruise	descent	approach			
					approach leg	base leg	int. leg / localiser	
ATC defined speeds	speed profile definition							
	climb	*						
	cruise	*	*					
	descent	*	*					
A/C operation defined speeds	approach						*	
	localiser int.						*	
	glide int. landing							
route definition								
	distance on localiser	(*)	(*)	(*)	*	*		
	baseleg heading				(*)			
	other techniques at controllers's discretion	*	*	*	*	*		e.g. holding

Figure 5 CINTIA'S control variables

6. CINTIA - CONTROLLER INTERFACE

So far it has been explained how CINTIA's **profile manager** updates the **extended flight profile** description to allow the **predictor** to generate a trajectory which matches as closely as possible the constraints defined by the **sequencer/scheduler**.

In order to have the plan thus modified implemented, CINTIA generates control advisories on two application levels. The **Executive Control Advisories** pertain to the current suggested clearance. They may include the current valid speed advice or the specification of a radar vector. Advisories of this level will be displayed in an additional line of the standard radar label for each inbound flight. The advisories are formulated so as to be compatible with the standard phraseology in use today.

In addition, CINTIA also provides **Advance Warning Advisories** which show the "executive control advisory" for the next control action. For example, when the executive control advisory suggests a cruise speed, the advance warning advisory displays the remaining flight time to the top of descent and the expected descent speed. Obviously, as the latter messages have a lower priority, they are usually collated in a table and displayed on an otherwise unused part of the radar screen.

There are two display modes for the **executive control advisories**, namely **warning** and **alert**. The specific techniques used to attract the controller's attention when an advisory is displayed in alert mode depend on the display hardware used. On a monochrome random scan display, flashing or other intensity modulation techniques may be used. On a colour raster scan display, a change of colour may be considered in addition. In general, speed advisories are displayed in **warning mode** only, since they are not very time-critical. However, the controller will be alerted if the speed measured from the radar track deviates by more than a certain amount from the suggested speed. Control advisories which may be displayed in **alert mode** include the **top-of-descent** advisory and the definition of imminent radar vectors such as **turn-to-base-leg** and **localiser-intercept** clearances.

Figure 7 (a) shows a typical radar label layout as used during the large-scale real-time simulation of the ZOC concept at the EUROCONTROL Experimental Centre, Brétigny sur Orge, France.

The first line shows the flight call sign (XYZ384), the weight category (Medium) and the planned number in the landing sequence (8). The second line displays the current flight level as extracted from SSR Mode C data (230) and the ground speed measured from the radar track (420 kt). The third line contains the executive control advisory for flight XYZ384 during the cruise phase. It suggests that the landing time constraint can be met by cruising at an indicated air speed of 300 kt.

The information for flight XYZ384 displayed at the same time in the **Advance Warning Table** might be as shown in Figure 7 (b). The message indicates that the top of descent is expected in 5 minutes and that a descent is planned at 310 kt IAS. For a more extensive discussion of the proposed man/machine interface, see Reference 6.

CINTIA's arrival time control range

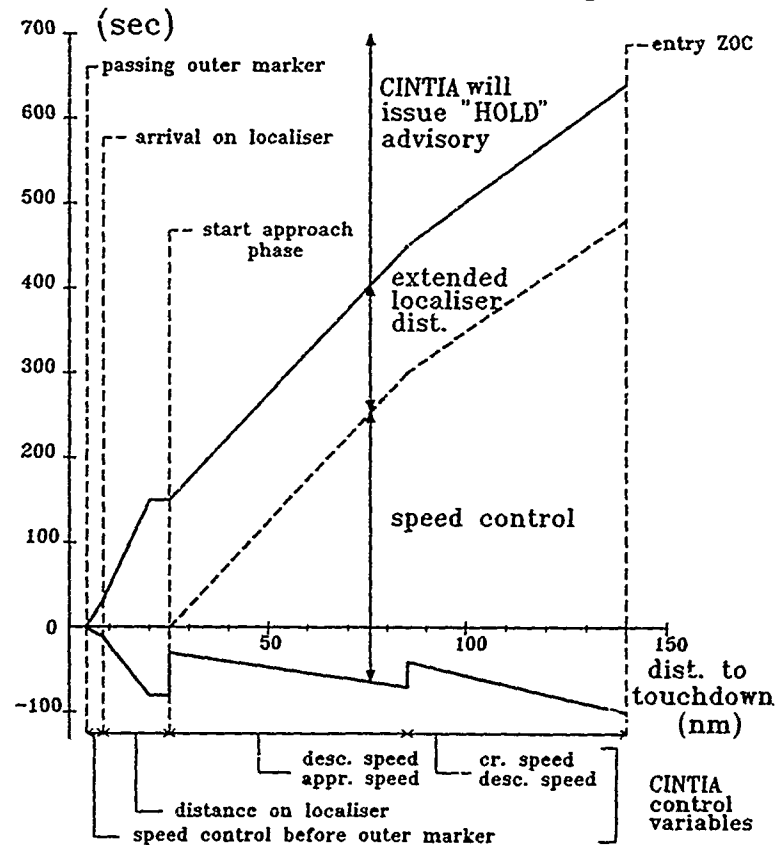


Figure 6. Illustration of CINTIA's arrival time control range

XYZ 384 M 8 230 42 /30	ABC 123 15 D 84/34 DEF 456 5D /30 XYZ 384 5D /31
(a) Example of Executive Control Advisory in radar label.	(b) Example of Advance Warning Advisory in table.

Figure 7. CINTIA advisory messages

7. OTHER ARRIVAL PROCEDURES

So far, all discussions have concentrated on the U-shaped arrival procedure shown in Figure 3. Clearly, in the case of a "straight in" procedure, where almost the entire flight path would be approximately in the direction of the runway, it is not attractive to include TMA path stretching among the control variables in the default procedure. Accordingly, when the required transit time precludes the straight-in procedure, the controller may update the basic flight plan to specify, for example, an alternative S-shaped procedure which would offer sufficient control range using the standard techniques discussed above. The same applies for flights arriving from the north or south in the case of an east-west runway orientation.

8. RESULTS

To validate the CINTIA algorithms, test flights were organised using full-scale airline flight simulators such as the DC 10 and B737 at Sabena, the B757 and B737 at British Airways, the F27 and F28 at Nederlandse Luchtvaart Maatschappij and the A310 at Aeroformation, all manned by complete crews. Numerous tests have been conducted under sometimes extreme meteorological conditions and simulated traffic situations. From these it was concluded that it is quite feasible to specify "preferred" company procedures for given operational conditions and that the advisories generated by CINTIA are totally compatible with present cockpit operating procedures.

In addition the CINTIA advisories allowed the controller to maintain a predefined landing time with an accuracy of within 10 seconds despite many deliberate or accidental perturbations (Reference 7).

CINTIA's man-machine interface was evaluated during large-scale real-time ATC simulations at the EUROCONTROL Experimental Centre in Brétigny, France. These proved that the chosen concept is compatible with ATC operation under high workload pressure with the present infrastructure in both en-route and TMA sectors.

9. CONCLUSIONS

In the Zone of Convergence concept the control of inbound flights is effected by the CINTIA module. This paper describes in general the specific role of CINTIA and its interaction with the other major ZOC module - the sequencer/scheduler (ROSAS).

CINTIA has two main modules, namely the **profile manager**, which applies predefined ATC strategies depending on the actual evolution of the traffic, and the **predictor**, which handles the trajectory calculation task. An illustration has been given of how the profile manager dynamically applies the guidance strategy to control the arrival time.

For a concept like the ZOC to be effective, arrival times should be predicted and maintained with a high degree of accuracy through a man-machine interface which is acceptable to the controller under heavy workload conditions. CINTIA has been evaluated extensively using various full-scale airline flight simulators manned by professional crews. The landing time of an aircraft over a flight length of 80 mn is controlled with an accuracy of within 10 seconds.

The proposed man-machine interface was intensively assessed during a large-scale real-time simulation of the ZOC concept at the EUROCONTROL Experimental Centre in Brétigny, France, during June 1989. It has proved to be compatible with real-time operation under heavy workload conditions in both ACC and TMA sectors.

It appears to be the right path to go down to meet future requirements.

10. REFERENCES

1. Benoît A., Swierstra S., "Air traffic control in a Zone of Convergence - Assessment within Belgian Airspace"
ICAS Symposium, Paper 4.10.1, Toulouse, France, 1984.
2. Voelkers U., "Computer assisted arrival sequencing and scheduling with the COMPAS system"
AGARD GCP Symposium, Brussels, June 1986 ; AGARD CP-410, December 1986.
3. Garcia J., "Amelioration of arrival traffic flow management at Paris-Orly"
Proceedings of the Specialist Panel on Automatic Conflict Detection and Resolution (SPACDAR)
EUROCONTROL, September 1987.
4. Magill S., Tyler A., Williamson E., Fich W., "Computer-based tools for assisting air traffic controllers with arrivals flow management"
RSRE Report N° 88001, 1988.
5. Erzberger H., Nedell W., "Design of automated system for management of arrival traffic"
NASA Technical Memorandum 102201, June 1989.
6. Benoît A., Swierstra S., De Wispelaere R., "Next generation of control techniques in advanced TMA - Automatic assistance for the controller/pilot dialogue"
AGARD GCP Symposium, Brussels, June 1986 ; AGARD CP-410, December 1986.
7. Benoît A., Swierstra S., "Ground-based 4-D guidance of flights in strong wind
- Experiments conducted with British Airways B-737 and B-757 flight simulators"
EUROCONTROL Doc. 872010, August 1987.
8. Benoît A., Evers E., "Aircraft trajectory prediction data for ATC purposes"
AGARDograph AG-209, July 1975.
9. Benoît A., Swierstra S., "Aircraft performance data for the control of inbound traffic"
EUROCONTROL Doc. 812032, December 1981.
10. Benoît A., Swierstra S., "Generation of aircraft trajectories for airline operation -
Methods - Techniques - Tools".
AGARDograph AG-301, Paper 17. To be published.
Also EUROCONTROL Report 892008-E, December 1989.

LE GUIDAGE DES VOLS JUSQU'AU SEUIL DE PISTE

Principes généraux

par

André Benoît et Sip Swierstra

EUROCONTROL

Organisation européenne pour la sécurité de la navigation aérienne

Direction technique

72, rue de la Loi, B - 1040 Bruxelles (Belgique)

RESUME

Le présent document décrit les principes fondamentaux de la méthode mise au point pour assurer le guidage précis des aéronefs jusqu'à la piste dans un environnement conditionné par l'heure d'arrivée. La dite méthode trouve son champ d'application dans le cadre d'une zone de convergence ou de tout autre système comparable de contrôle évolué de la circulation aérienne, caractérisé par l'intégration des diverses phases du contrôle dans une zone étendue, allant de pair avec la possibilité, pour le contrôleur, de disposer d'un véritable outil informatique, c'est-à-dire d'être "assisté par ordinateur" dans la prise de décisions grâce à la production automatique d'émissions consultatives en matière de guidage.

La méthode comprend deux éléments essentiels et étroitement associés ; le "predictor" (l'élément de prévision), qui effectue le calcul d'une trajectoire dès que lui ont été communiqués les conditions et plans initiaux, et le "profile manager" (élément de gestion des profils), qui adapte les plans en fonction des contraintes horaires et produit des directives de guidage fondées sur la position actuelle, les données effectives de surveillance, la conduite de l'aéronef et les servitudes de route.

1. INTRODUCTION

La prochaine évolution en matière de contrôle de la circulation aérienne (ATC) consistera en l'avènement de systèmes étayés par des ordinateurs "intelligents", qui apporteront au contrôleur une aide effective dans la prise de décision. Ces systèmes interviendront pratiquement dans tous les domaines de l'ATC, de la gestion globale du trafic au niveau de la planification jusqu'au choix des stratégies de résolution des conflits potentiels, à l'échelon tactique. L'état des connaissances en la matière peut être illustré par le concept de zone de convergence élaboré par la Direction technique de l'Agence EUROCONTROL établie à Bruxelles, en Belgique. Il s'agit ici, eu égard au problème de la gestion efficace, en direct, d'un courant d'aéronefs se dirigeant vers un ou plusieurs grands aéroports, de conseiller les contrôleurs des secteurs de route et des régions de contrôle terminales (TMA) quant à la manière d'optimiser les courants de trafic sur le plan de la sécurité et de l'efficacité des coûts, tout en garantissant un débit maximum par l'exploitation optimale de la capacité disponible. A cet effet, le concept de ZOC englobe toutes les phases de vol, du lâcher des freins au toucher des roues, et, sur le plan de l'acheminement des vols, intègre efficacement tous les secteurs ATC au sein d'une zone de compétence donnée.

Plusieurs instituts de recherche ont, de par le monde, réalisé des travaux dans ce domaine (Réfs. 2-5). Quoique les projets soient souvent adaptés en fonction de situations locales spécifiques, on observe généralement une grande similitude dans la manière d'aborder ce problème, qui se fonde sur trois éléments principaux :

- 1) L'élément d'ordonnancement et de régulation (séquenceur-régulateur) qui, partant d'un ou plusieurs critères d'optimisation, définit une séquence d'atterrissage correspondante ;
- 2) Le module de guidage et de contrôle, qui produit les émissions consultatives de contrôle propre à la réalisation de la séquence projetée et fondée sur l'examen des pistes radar ;
- 3) Une interface homme-machine compatible avec le poste de travail de contrôleur existant et/ou l'ensemble du système de traitement des données ATC, et conçu pour promouvoir un dialogue ergonomique entre le contrôleur et le système.

Le présent document offre une description globale de la manière dont circulent les données dans le contexte de la ZOC et propose ensuite une explication plus précise de la logique de guidage et de contrôle appliquée pour la production des émissions consultatives.

2. LES PALIERS DE TRAITEMENT DANS LE SYSTEME ZOC

La gestion directe de la circulation aérienne se fonde dans une large mesure sur les profils de vols prévus pour chacun des aéronefs intéressés. Si la route à suivre et les consignes d'utilisation de l'aéronef peuvent être convenues avant le vol entre l'exploitant et le centre de contrôle, il n'en reste pas moins que la validité du profil prévu est largement compromise par de nombreuses perturbations aléatoires telles que :

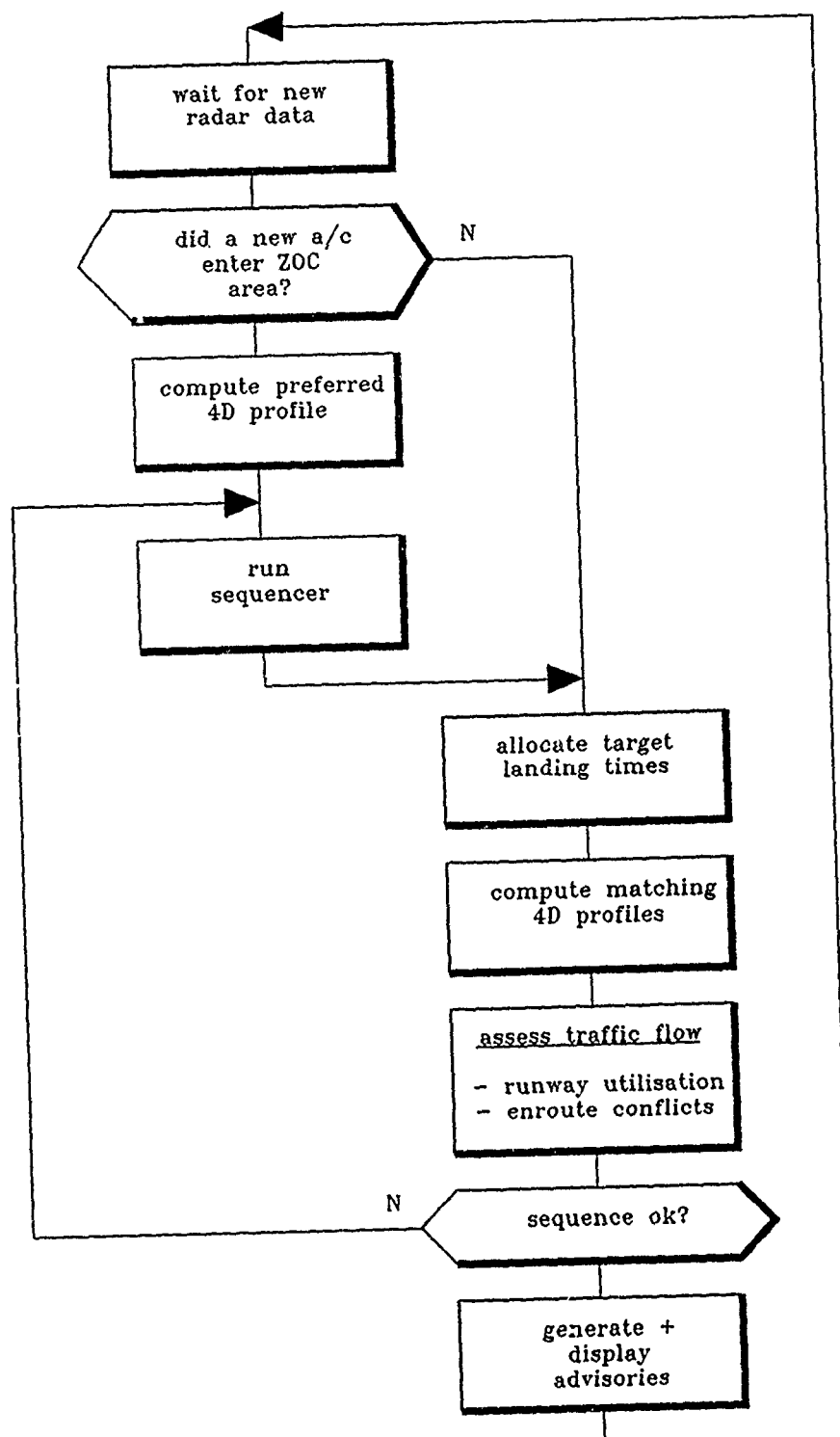


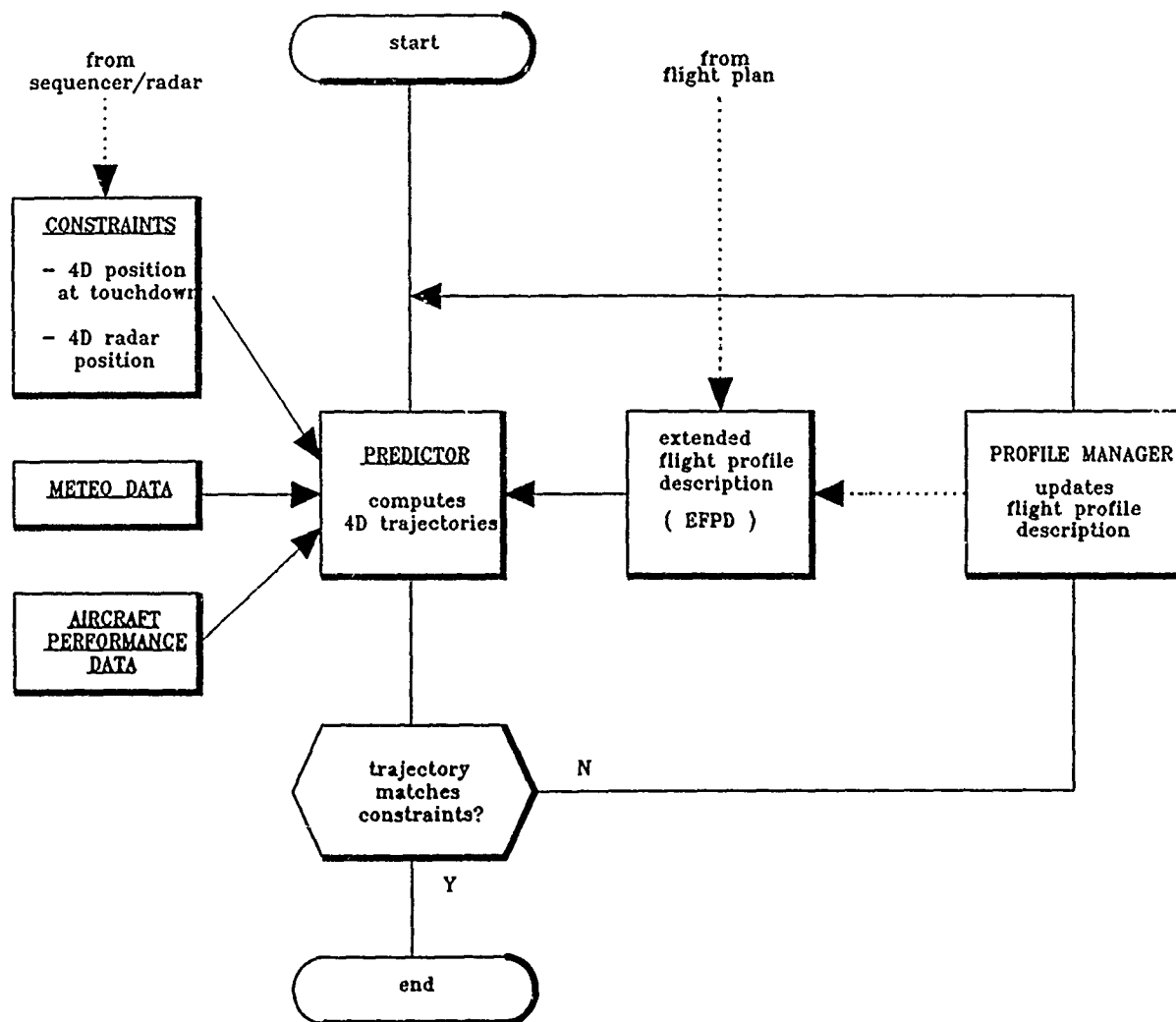
Schéma des principaux paliers de traitement
(CINTIA/ROSAS/ZOC)

Figure 1

- le caractère incertain des conditions météorologiques,
- les manoeuvres de résolution de conflits, engagées au sol ou en vol, et qui contraignent l'aéronef à s'écarter de la route et ou du profil vertical prévus,
- les erreurs résultant de difficultés survenues dans les communications sol-air,
- les erreurs humaines, tant à bord qu'au sol.

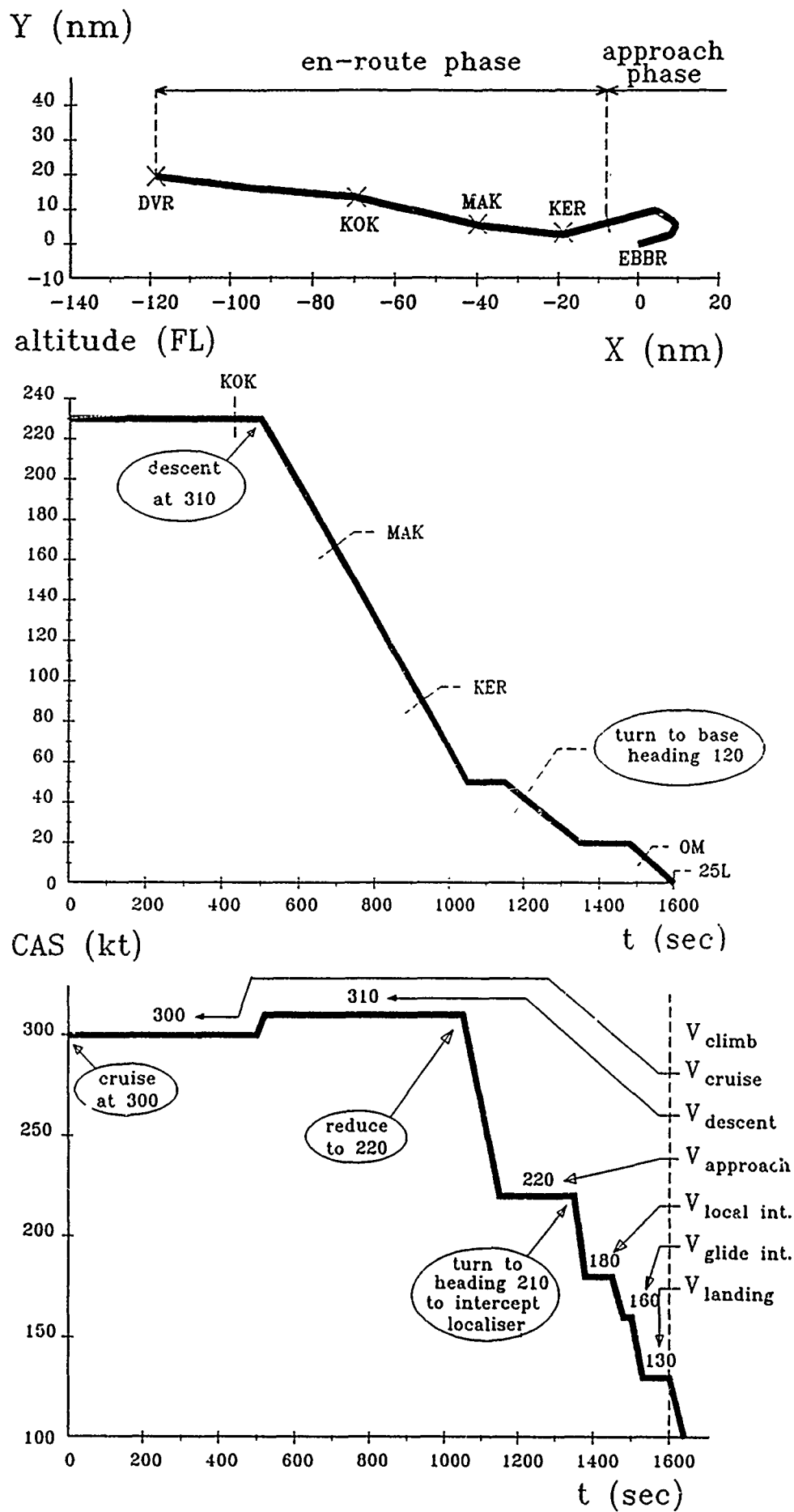
Compte tenu de cet environnement instable, le concept ZOC a été doté, à des fins d'efficacité, d'un mécanisme dynamique d'ordonnement-régulation grâce auquel la séquence d'atterrissage maintenue par le système est reconsidérée en permanence eu égard à l'évolution effective du trafic. Si cette approche laisse au contrôleur la faculté de décider en toute indépendance, elle complique en revanche dans une très large mesure la tâche consistant à fournir une aide sûre et efficace. Ainsi, lorsque la charge de travail est élevée et que la situation du trafic devient de plus en plus complexe, est-il nécessaire, pour des raisons évidentes, de limiter l'interaction homme-machine. C'est sur ce point qu'ont porté l'essentiel des travaux relatifs au système ZOC.

La figure 1 présente un schéma des différents paliers de traitement. Le système est enclenché à chaque production de nouvelles données radar. Lorsque sont connues les données relatives à un nouveau venu dans la zone, il est procédé à une estimation du profil de vol idéal de ce dernier (c'est-à-dire du profil que l'appareil serait amené à suivre s'il était seul dans le ciel). Une séquence d'atterrissage est alors proposée en fonction d'une série de critères et du profil de vol idéal de tous les aéronefs en vol. Un instant d'atterrissage est ensuite attribué à chaque vol, compte tenu de sa place dans la séquence d'atterrissage, de l'instant d'atterrissage prévu pour le premier aéronef de la séquence et des exigences minimales d'espacement au radiophare d'alignement de piste.



Fonctions principales de CINTIA

Figure 2



Profil préférentiel : route - altitude - vitesse

Figure 3

Les positions initiale et finale sont maintenant définies pour chaque vol dans les quatre dimensions, et le système peut alors s'efforcer de trouver un profil de vol adapté, compte tenu des limites de performance des aéronefs et des servitudes du contrôle, telles que les limites de secteur.

Cette phase étant terminée, le système, qui dispose des estimations des futures trajectoires de vol, peut ensuite procéder à une évaluation de l'utilisation des pistes et des conflits de route potentiels.

Si cette évaluation donne des résultats acceptables, le contrôle produit alors des émissions consultatives aussitôt affichées à l'intention des contrôleurs ; dans le cas inverse, la séquence d'atterrissage est corrigée en fonction de ces résultats.

Cette succession d'actions fait intervenir trois éléments principaux. Le module central est ici le **séquenceur-régulateur**. Dans la mise en oeuvre du système ZOC objet de notre étude, ce module est désigné par le sigle ROSAS ("Regional Organisation of the Sequencing and Scheduling of Aircraft System", soit : Système régional d'ordonnancement-régulation des vols) et propose une séquence d'atterrissage où sont pris en considération les principes suivants :

- limitation automatique et dynamique des attentes en fonction de la demande de trafic ;
- égalité de traitement prioritaire pour les aéronefs dans la zone de contrôle, quelle que soit la longueur de la route suivie ;
- réduction maximale des conflits potentiels dans les secteurs de route ;
- adaptation automatique de la séquence à l'évolution effective de la situation de trafic ;
- annulation par le contrôleur de certains algorithmes d'ordonnancement automatique, afin de permettre des changements de pistes, des vols spéciaux, l'évitement de zones orageuses, la résolution de conflits, etc. ;
- limitations de la régulation du débit pour certaines routes d'arrivée.

Le dernier module est constitué par l'**interface homme-machine**, qui produit les émissions consultatives ATC et en organise l'affichage. L'approche choisie pour le concept ZOC ne nécessite aucun affichage machine complémentaire au poste de travail du contrôleur. Les émissions consultatives sont formulées de manière à être directement compatibles avec les instructions types utilisées actuellement et, de ce fait, peuvent être affichées sur une ligne supplémentaire de l'étiquette d'identification de l'aéronef apparaissant sur l'écran radar du contrôleur sans qu'il en résulte d'inconvénient. Cette formule épargne au contrôleur le surcroît de travail associé à la lecture multi-écran. On notera également que la structure de ces avis les rend directement compatibles avec les formats de liaisons de données numériques sol-air tels qu'on les prévoit pour l'environnement futur du mode S.

Le présent document est essentiellement consacré au troisième élément, à savoir la commande du **calcul des profils et la fonction de guidage et de contrôle**. Les spécialistes désignent ce module par le sigle CINTIA ("Control of Inbound Trajectories for Individual Aircraft", soit : Régulation individuelle des trajectoires d'arrivée).

3. LE MODULE CINTIA

Le module CINTIA intégré dans le concept ZOC remplit une fonction d'appui, notamment pour le calcul des profils de vol "idéaux" et "effectifs" dans les quatre dimensions, où il s'efforce de tenir compte des contraintes définies par le séquenceur-régulateur à moindre frais pour chaque aéronef. Il fournit en outre au séquenceur les données relatives aux limites de portée du contrôle, telles que l'heure d'atterrissage la plus rapprochée, etc.

Le CINTIA s'articule en deux fonctions principales, illustrées à la figure 2.

Le "predictor", qui constitue le noyau du CINTIA, calcule le profil de vol quadridimensionnel en fonction de :

- la description du profil de vol élargi (EFDP) ;
- les servitudes définies par le séquenceur-régulateur, si elles existent ;
- les informations météorologiques ;
- les données relatives aux performances des aéronefs.

Le "predictor" entreprend le calcul d'une trajectoire type à la servitude "finale", soit la position quadridimensionnelle au toucher des roues, et poursuit ce calcul en amont aux positions x, y et z observée par le radar. Si le séquenceur-régulateur a limité la durée du transit, il convient de vérifier que l'heure de la servitude au "départ" a été respectée ; dans la négative, la seconde fonction du CINTIA - le **gestionnaire de profil** - est mise en service. Elle actualise la description du profil élargi (EFDP) eu égard aux discordances observées entre les servitudes, la trajectoire calculée et la phase du vol. Un nouvel essai permet ensuite de vérifier si le nouveau profil de vol est acceptable. Le "predictor" et le **gestionnaire de profil** sont en fait des fonctions indépendantes, couplées par la description du profil de vol élargi. L'EFDP comprend un ensemble d'informations composé de la description précise de chaque phase du vol et des données complémentaires correspondantes. Elle complète le plan de vol normalisé de l'OACI, dans lequel sont définis, par exemple l'indicatif d'appel, la route prévue, les conditions de croisière et le type d'aéronef.

L'EFDP est établie au départ de plusieurs bases de données, telles que :

- les consignes d'utilisation préférées par les compagnies ;
- les procédures de départ et d'arrivée normalisées aux instruments (SID et STAR) ;
- les servitudes de contrôle en vigueur, p. ex. les pistes en service ;
- les conditions météorologiques telles que les limitations de la visibilité ;
- les données relatives aux performances des aéronefs.

La séquence de phases de vol qui en résulte est codée en un "langage" spécifique, que le "predictor" est en mesure d'interpréter directement. Voyons maintenant, à l'aide d'un exemple, comment fonctionne le mécanisme d'adaptation aux contraintes du CINTIA.

4. LES VARIABLES DE CONTROLE

Il est nécessaire, afin de conserver une capacité suffisante d'adaptation aux perturbations affectant le vol, d'établir un subtil équilibre entre la plus vaste fourchette possible d'heures d'arrivée disponible à l'entrée dans le ZOC et la sauvegarde d'une souplesse suffisante pour les phases ultérieures du vol. Il est manifeste que le choix des variables de contrôle exploitables par le gestionnaire de profil du CINTIA à un instant du vol est d'abord limité par la phase de vol elle-même.

La figure 3 illustre ce qui précède par un exemple type de vol à destination de Bruxelles (EBBR) au départ de Douvres (DVR). Il présente les caractéristiques du profil de vol "idéal" du vol XYZ 384 quant à la définition de ses routes, altitude et vitesse. A son entrée dans la ZOC à proximité de Douvres, l'aéronef évolue en croisière à 300 noeuds VI, à une altitude de 23.000 ft. La vitesse de descente prévue est de 310 kt VI jusqu'à l'approche de la piste 25L de l'aéroport de Bruxelles-National.

La figure 4 présente un schéma agrandi de la trajectoire d'approche "idéale". La longueur du profil en U est déterminée par la distance idéale à parcourir sur le radiophare d'alignement de piste (8 NM sans l'exemple choisi). La trajectoire de vol allant de la voie aérienne de croisière au radiophare d'alignement de piste est définie en fonction de deux guidages radar spécifiés par le contrôle, dont le premier concerne le virage d'amorce du parcours de base (cap 120°), et le second un virage à droite pour l'interception du faisceau ILS (cap 210°), assorti d'une marge d'interception suffisante. La figure 4 fait apparaître deux portées différentes du contrôle de vitesse de l'aéronef. Avant de recevoir l'autorisation d'intercepter le radiophare d'alignement de piste, le pilote devrait respecter autant que possible les vitesses conseillées par le contrôle de la circulation aérienne. Il devrait ensuite, après avoir reçu l'autorisation d'interception, réduire sa vitesse conformément à un plan déjà convenu entre l'exploitant de l'aéronef et l'ATC. C'est donc à titre exceptionnel que ce dernier sera appelé à intervenir pour modifier la vitesse de l'aéronef durant les phases d'approche finale.

La figure 5 présente les variables de contrôle accessibles au gestionnaire de profil pendant les diverses phases du vol. Les principales variables de contrôle relatives aux phases de croisière sont les vitesses de croisière. Si, toutefois, la durée d'acheminement imposée entre la position actuelle de l'aéronef et l'heure d'atterrissage prévue est telle qu'il est impossible de la respecter par la régulation de la vitesse de croisière et/ou de descente et/ou d'approche, il convient d'appliquer d'autres techniques de retardement. On vérifie si le fait d'augmenter la portée du radiophare d'alignement de piste à la plus grande distance autorisée dans l'environnement donné permet de ménager ce délai supplémentaire. Dans l'affirmative, il sera conseillé à l'aéronef de poursuivre sa trajectoire au minimum de la vitesse acceptable de fonctionnement, et la définition précise des vecteurs radar sera transmise ultérieurement, lorsque l'élément CINTIA traitera les phases d'approche.

Si la durée d'acheminement obtenue sur la distance maximale du radiophare d'alignement de piste reste malgré tout inférieure à celle qui avait été demandée, le contrôleur est informé de la longueur du délai supplémentaire qu'il faudrait si possible ménager dans les secteurs de route ou, à défaut, par le maintien ultérieur à une altitude inférieure.

En revanche, si la durée d'acheminement demandée est plus courte que le délai minimum possible, le séquenceur-régulateur sera informé en conséquence et décidera alors de la manœuvre appropriée. Si l'écart n'est que de quelques secondes, il se peut que le séquenceur accepte la légère réduction de capacité d'atterrissage qui en résulte ; mais dans le cas de différences plus importantes, il conviendra d'établir si une nouvelle mise en séquence ne permettrait pas d'aboutir à une meilleure situation globale.

Le contrôleur doit, au cours des phases d'approche du vol, délimiter des vecteurs radar destinés à guider l'aéronef de la route aérienne au radiophare ; il est secondé, pour ce faire, par le CINTIA. La définition des avis concernant le cap et spécifiant le parcours de base et l'étape d'interception constituent les principales variables de contrôle relatives à ces phases de vol. Les limites imposées au CINTIA apparaissent à la figure 4. La trajectoire de vol la plus courte est définie par la distance minimale indiquée au radiophare d'alignement de piste et jugée acceptable pour l'exploitant de l'aéronef dans les conditions données. La trajectoire la plus longue est définie par les limites géographiques de la TMA ; elle équivaut dans l'exemple choisi, à une distance minimale de 12,5 NM au radiophare. En définitive, les moyens propres à réduire la vitesse restent très limités dès qu'il y a alignement sur le radiophare, car leur incidence sur le bon déroulement de la manœuvre présente des aspects de sécurité évidents.

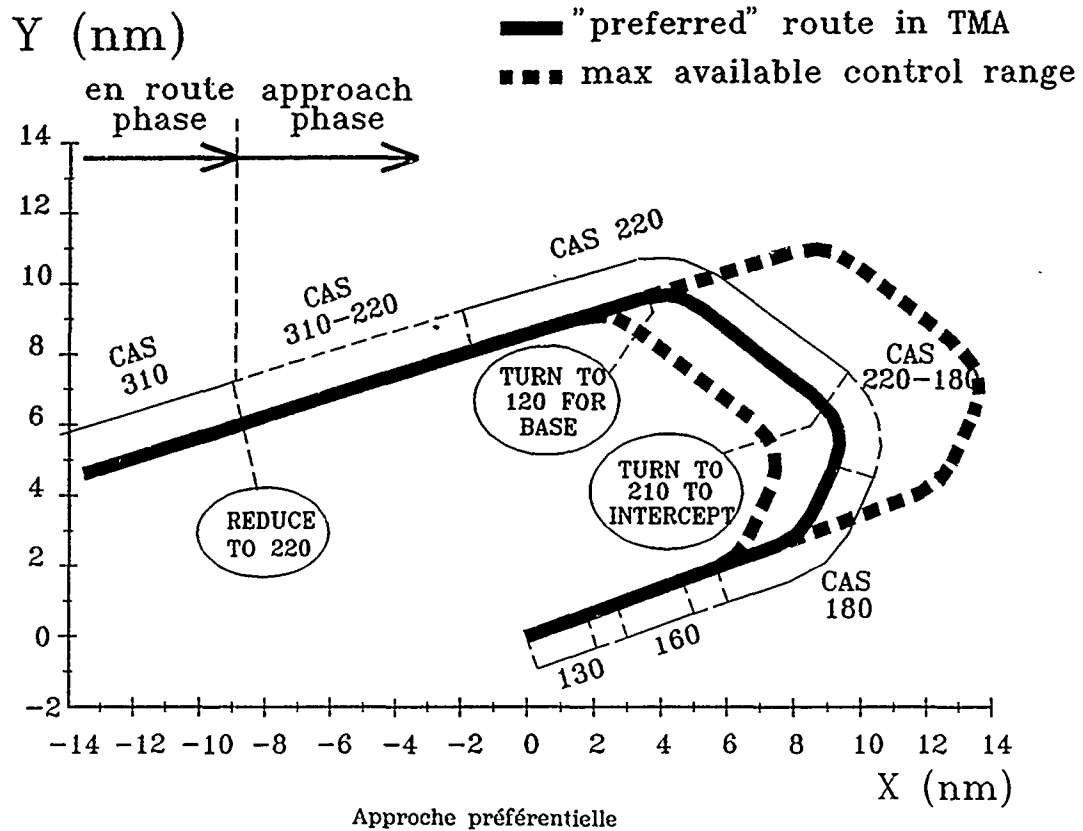


Figure 4

5. CAPACITE DE REGULATION DE L'INSTANT D'ARRIVEE PAR LE CINTIA

Il est intéressant d'observer les variations de la capacité de régulation de l'instant d'arrivée par le CINTIA au cours de l'évolution dans la zone de convergence. La figure 6 montre la capacité disponible de contrôle de l'heure d'arrivée en fonction de la distance à parcourir jusqu'au toucher des roues pour ce qui est du profil de vol "idéal".

A l'entrée dans la ZOC (Douvres), le CINTIA est en mesure de définir un profil de vol correspondant aux durées d'acheminement demandées, qui oscillent entre 11 minutes de plus et 1,5 minute de moins que les temps du profil idéal. Le retard maximum est obtenu en réduisant à la "vitesse nette minimale" la vitesse de l'aéronef dans les phases de croisière, de descente et d'approche tout en allongeant au maximum admissible la distance parcourue au radiophare d'alignement de piste.

A la fin de la phase de croisière, soit à quelque 25 NM du toucher des roues, le CINTIA peut ménager des écarts allant de 2,5 minutes de retard à 1,25 minute d'avance par rapport au profil idéal. Cette fourchette résulte presque entièrement de la définition des vecteurs radar dans la TMA.

Après le guidage de l'aéronef sur vecteur jusqu'au parcours de base, la capacité de régulation de l'heure d'arrivée devient extrêmement restreinte. Dans l'exemple choisi, il est encore possible, à 8 NM du toucher des roues, de gagner 8 secondes par rapport au profil idéal ou de perdre au maximum 30 secondes en passant aux vitesses et configuration d'atterrissage. On notera que, tant que l'aéronef évolue dans les phases de croisière, l'efficacité optimale est assurée par le choix de solutions à coût minimal correspondant aux servitudes énoncées par le séquenceur. Au cours des phases d'approche qui suivent, c'est l'ensemble de la capacité potentielle d'utilisation de l'aéronef qui est bridée afin de ménager un maximum de souplesse et de grandir ainsi le rendement maximum du système.

6. L'INTERFACE CINTIA-CONTROLEUR

Nous avons expliqué plus haut de quelle manière le gestionnaire de profil du CINTIA actualise la description du profil de vol élargi afin de permettre au "predictor" d'élaborer une trajectoire qui corresponde le plus étroitement possible aux servitudes définies par le séquenceur-régulateur.

C'est pour assurer la mise en oeuvre du plan ainsi modifié que le CINTIA produit, à deux niveaux d'application, des émissions consultatives relatives au contrôle. Les émissions consultatives de contrôle tactique concernent l'autorisation en vigueur proposée. Elles peuvent comporter l'avis relatif à la vitesse valable en vigueur ou la spécification d'un vecteur radar. Ce type d'émissions consultatives est affiché sur une ligne supplémentaire de l'étiquette radar accompagnant normalement chaque vol à l'arrivée. Ces émissions consultatives sont formulées de manière à correspondre aux expressions conventionnelles en usage aujourd'hui.

Le CINTIA émet en outre des avertissements anticipés, qui font apparaître l'émission consultative de contrôle tactique relative à la manoeuvre de contrôle suivante. Ainsi, lorsque ladite émission de contrôle tactique propose une vitesse de croisière, l'émission d'avertissement anticipé affiche-t-elle le temps de vol restant jusqu'à l'amorce de la descente et la vitesse de descente prévue. Ces derniers messages revêtant bien sûr un moindre degré de priorité, ils sont normalement rassemblés sur une plateau et affichés sur une plage inutilisée de l'écran radar.

Les émissions consultatives de contrôle tactique peuvent être affichées selon deux modes distincts : avertissement et alerte. Les techniques particulières servant à attirer l'attention du contrôleur sur l'affichage d'un avis en mode d'alerte varient suivant le type d'équipement utilisé. Sur un visualisateur monochrome à balayage cavalier, on aura recours au clignotement ou à d'autres techniques de modulation d'intensité. Dans le cas d'un balayage couleur type TV, on envisagera éventuellement un affichage dans une autre couleur. D'une manière générale, les émissions consultatives relatives à la vitesse ne sont affichées qu'en mode avertissement, le facteur temps ne revêtant pas une importance très critique. Toutefois, l'attention du contrôleur sera sollicitée s'il existe, entre la vitesse mesurée sur la base de la piste radar et la vitesse proposée, une différence supérieure à un écart donné. Les émissions de contrôle destinées à l'affichage en mode alerte comportent l'avis relatif à l'amorce de descente et la définition de vecteurs radar imminents (autorisation de virage d'amorce du parcours de base et d'interception du radiophare d'alignement de piste, par exemple).

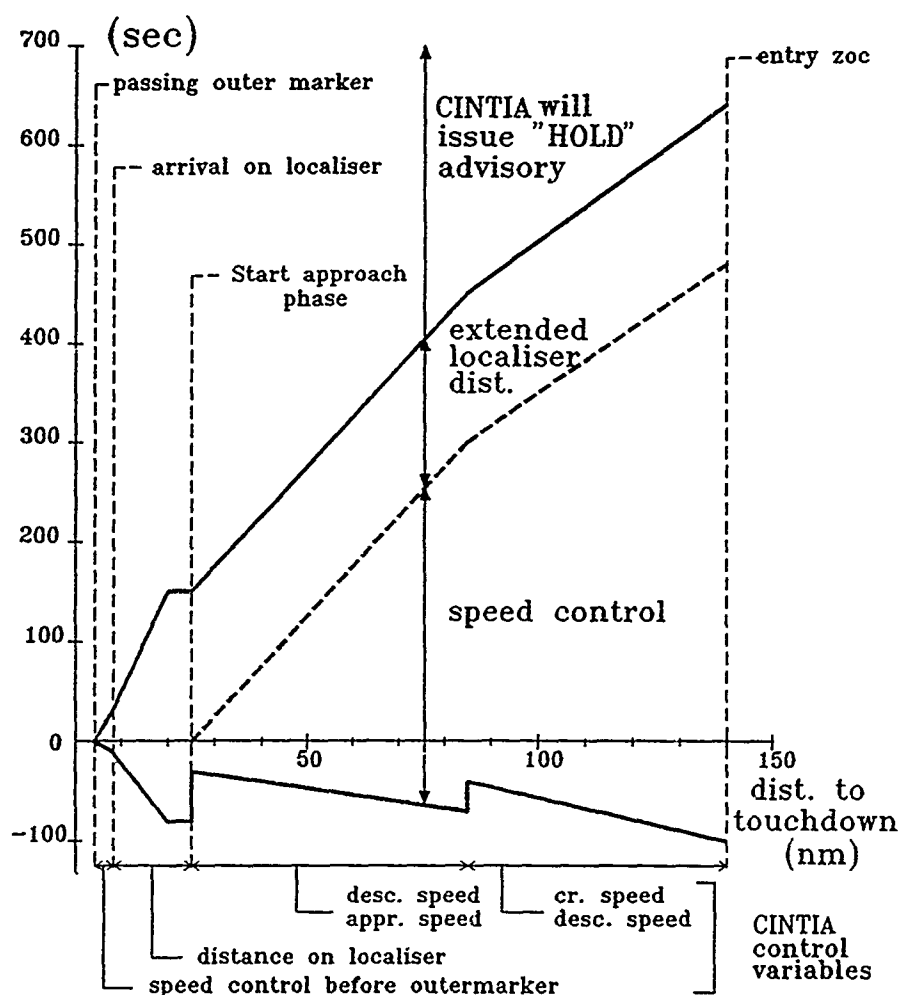
La figure 7 (a) présente la structure de l'étiquette radar utilisée lors des simulations du concept ZOC réalisées en temps réel et à grande échelle au Centre expérimental EUROCONTROL de Brétigny-sur-Orge, en France.

La première ligne affiche l'indicatif d'appel (XYZ384) du vol, la catégorie de tonnage de l'aéronef (Medium) et le numéro d'ordre dans la séquence d'atterrissage (8). La deuxième ligne indique le niveau de vol actuel, extrait à partir des données du Mode C du SSR (230) ainsi que la vitesse-sol calculée sur la base de la piste radar (420 kt). La troisième ligne est réservée aux avis de contrôle tactique relatifs au vol XYZ 384 pendant la phase de croisière. Elle fournit une estimation selon laquelle le créneau d'atterrissage peut être respecté en volant à la vitesse propre indiquée de 300 kt VI.

CINTIA		PHASES OF FLIGHT					
control variables		climb	cruise	descent	approach		
					approach leg	base leg	int. leg / localiser
ATC defined speeds	speed profile definition						
	climb	*					
	cruise	*	*				
	descent	*	*				
A/C operation defined speeds	approach						*
	localiser int.						*
	glide int. landing						
route definition							
distance on localiser		(*)	(*)	(*)	*	*	
base leg heading					(*)		
other techniques at controllers's discretion		*	*	*	*	*	c.g. holding

Variables de contrôle disponibles dans CINTIA

Figure 5



Capacité de contrôle de l'instant d'arrivée

Figure 6

Les informations relatives au vol XYZ384 affichées simultanément au tableau d'avertissements anticipés pourraient être structurées comme l'indique la figure 7 (b). Le message signale que l'amorce de descente devrait avoir lieu 5 minutes plus tard et qu'une descente est prévue à 300 kt VI. On trouvera à la référence 5 une analyse plus détaillée de l'interface homme-machine proposée.

XYZ 384 M 8
230 42
/30

ABC 123 15 D 84/34
DEF 456 5D /30
XYZ 384 5D /31

(a) Exemple d'émission consultative
de contrôle tactique sur étiquette radar

(b) Exemple d'émission consultative
d'avertissement anticipé apparaissant
au tableau

Figure 7. Emissions consultatives produites par le CINTIA

7. AUTRES PROCEDURES D'ARRIVEE

Les études ont été centrées, jusqu'à présent, sur la procédure d'arrivée en U illustrée à la figure 3. De toute évidence, le fait d'inclure l'allongement de trajectoire TMA comme variable de contrôle dans la procédure par défaut n'offre aucun intérêt particulier dans le cas de procédure d'approche rectiligne, où la quasi-totalité de la trajectoire de vol correspond à peu près à l'orientation de la piste. En conséquence, lorsque la durée de transit requise est telle qu'il est absolument impossible d'inscrire l'aéronef dans la procédure d'approche rectiligne, le contrôleur peut être amené à actualiser le plan de vol d'origine et à définir par exemple une procédure de remplacement dans laquelle une approche en S offrirait une portée de contrôle suffisante à l'aide des techniques normalisées étudiées plus haut.

Il en va de même des vols en provenance du nord ou du sud dans le cas de pistes orientées d'est en ouest.

8. RESULTATS

C'est à l'effet de valider les algorithmes du module CINTIA que des vols d'essai ont été effectués à l'aide de simulateurs de vol grandeur nature appartenant à des compagnies aériennes - tels que les DC10 et B737 de la Sabena, les B757 et B737 des British Airways, les F27 et F28 de la Nederlandse Luchtvaart Maatschappij et l'A310 d'Aéroformation - tous servis par des équipages professionnels complets. De nombreux essais ont été réalisés dans des conditions météorologiques parfois extrêmes et à partir de situations difficiles de trafic simulé. Ces tests ont permis d'établir qu'il était tout à fait possible de définir pour chaque compagnie des procédures "idéales" dans des conditions d'exploitation données, et que les émissions consultatives produites par le CINTIA étaient totalement compatibles avec les procédures d'habillage actuelles.

Les émissions consultatives du CINTIA permettaient en outre au contrôleur de respecter une heure d'atterrissage fixée au préalable avec une précision de l'ordre de 10 secondes, malgré l'incidence de nombreuses perturbations accidentelles ou provoquées (référence 6).

Le Centre Expérimental EUROCONTROL situé à Brétigny, France, a procédé à l'évaluation de l'interface homme-machine du CINTIA dans le cadre de simulations ATC en temps réel et à grande échelle. Il a ainsi été démontré que le concept retenu était compatible avec la bonne marche du contrôle de la circulation aérienne lorsque la charge de travail est élevée dans les secteurs de route et TMA, compte tenu de l'infrastructure actuelle.

9. CONCLUSIONS

Le concept de Zone de convergence (ZOC) prévoit que la régulation des vols d'arrivée sera assurée par le module CINTIA. Le présent document propose une description globale du rôle spécifique du CINTIA et de son interaction avec l'autre module principal de la ZOC : le séquenceur-régulateur (ROSAS).

Le module CINTIA s'articule en deux éléments essentiels : le gestionnaire de profil, qui applique des stratégies ATC définies au préalable en fonction de l'évolution réelle de la circulation, et le "predictor", dont la tâche est de calculer les trajectoires. Nous avons vu de quelle manière le gestionnaire de profil procède à l'actualisation dynamique de la stratégie de guidage et de la fourchette de régulation de l'heure d'arrivée qui en résulte.

Un concept tel que celui de la ZOC ne sera efficace que si les heures d'arrivée sont prévues et respectées avec la plus grande précision grâce à une interface homme-machine que le contrôleur puisse accepter lorsque sa charge de travail est élevée. Le CINTIA a été soumis à des essais approfondis, réalisés à l'aide de simulateurs de vol grandeur nature, appartenant à diverses compagnies aériennes ZOC européennes et servis par des équipages professionnels. L'heure d'atterrissage d'un aéronef sur une distance de vol de 80 MN peut être contrôlée avec une marge d'erreur inférieure à 10 secondes.

L'interface homme-machine proposée a fait l'objet d'une évaluation approfondie dans le cadre d'une simulation du concept ZOC, réalisée en temps réel et à grande échelle au Centre expérimental EUROCONTROL de Brétigny-sur-Orge, France, en juin 1989. Elle s'est révélée compatible avec les opérations de contrôle en temps réel effectuées par charge de travail élevée, dans les secteurs ACC et TMA.

10. REFERENCES

1. Benoît A., Swierstra S., "Air traffic control in a Zone of Convergence - Assessment within Belgian Airspace"
ICAS Symposium, Paper 4.10.1, Toulouse, France, 1984.
2. Voelkers U., "Computer assisted arrival sequencing and scheduling with the COMPAS system"
AGARD GCP Symposium, Brussels, June 1986 ; AGARD CP-410, December 1986.
3. Garcia J., "Amelioration of arrival traffic flow management at Paris-Orly"
Proceedings of the Specialist Panel on Automatic Conflict Detection and Resolution (SPACDAR)
EUROCONTROL, September 1987.
4. Magill S., Tyler A., Williamson E., Fich W., "Computer-based tools for assisting air traffic controllers with arrivals flow management"
RSRE Report N° 88001, 1988.
5. Erzberger H., Nedell W., "Design of automated system for management of arrival traffic"
NASA Technical Memorandum 102201, June 1989.
6. Benoît A., Swierstra S., De Wispelaere R., "Next generation of control techniques in advanced TMA - Automatic assistance for the controller/pilot dialogue"
AGARD GCP Symposium, Brussels, June 1986 ; AGARD CP-410, December 1986.
7. Benoît A., Swierstra S., "Ground-based 4-D guidance of flights in strong wind
- Experiments conducted with British Airways B-737 and B-757 flight simulators"
EUROCONTROL Doc. 872010, August 1987.
8. Benoît A., Evers E., "Aircraft trajectory prediction data for ATC purposes"
AGARDograph AG-209, July 1975.
9. Benoît A., Swierstra S., "Aircraft performance data for the control of inbound traffic"
EUROCONTROL Doc. 812032, December 1981.
10. Benoît A., Swierstra S., "Generation of aircraft trajectories for airline operation
- Methods, techniques, tools". This AGARDograph, Paper 17.

GUIDANCE CONCEPTS FOR TIME-BASED FLIGHT OPERATIONS

by
 Dan D. Vicroy
 NASA Langley Research Center
 Hampton, Virginia 23665-5225
 United States

SUMMARY

Airport congestion and the associated delays are severe in today's airspace system and are expected to increase. The National Aeronautics and Space Administration in conjunction with the Federal Aviation Administration, is investigating various methods of alleviating this problem through new technology and operational procedures. One concept for improving airspace productivity is time-based control of aircraft. Research to date has focused primarily on the development of time-based flight management systems and Air Traffic Control operational procedures. Flight operations may, however, require special onboard guidance in order to satisfy the Air Traffic Control imposed time constraints. This paper presents the results of a simulation study aimed at evaluating several time-based guidance concepts in terms of tracking performance, pilot workload, and subjective preference. The guidance concepts tested varied in complexity from simple digital time-error feedback to an advanced time-referenced-energy guidance scheme.

SYMBOLS

Symbol	Definition	Units
d	distance to metering fix	feet
ΔE_{3D}	3D energy error	feet
ΔE_{4D}	4D energy error	feet
g	acceleration due to gravity (32.2)	ft/sec ²
h	airplane altitude	feet
h_{ref}	reference profile altitude	feet
t	current time	sec
t_{MF}	desired metering fix arrival time	sec
t_{ref}	reference profile time	sec
v_g	airplane ground speed	ft/sec
v_{gref}	reference ground speed	ft/sec

1. INTRODUCTION

Airport congestion and the associated delays are severe in today's system and are expected to increase. The National Aeronautics and Space Administration (NASA), in conjunction with the Federal Aviation Administration (FAA), is investigating various methods of alleviating this problem through new technology and operational procedures. One concept for improving airspace productivity is time-based (4D) control of aircraft. Under this concept, inbound aircraft would be assigned arrival times at "feeder fix" or "metering fix" waypoints. These times would be assigned so as to optimally sequence and space the inbound traffic.

In addition to improving airspace productivity, time based control and navigation may also have some military application. Tanker rendezvous and multidirectional coordinated strikes are two such examples.

Research to date has focused primarily on the development of time-based flight management systems (4D FMS) and Air Traffic Control (ATC) operational procedures. NASA conducted a series of flight tests of such a 4D FMS onboard the Transport Systems Research Vehicle (TSRV) B-737 airplane in the Denver en route metering system (Knox, Cannon, 1980). These tests were the first to combine a 4D FMS equipped airplane and a time-based ATC environment. Similar tests were conducted by the Lockheed Corporation of a 4D FMS onboard a L-1011 airplane in the Atlanta, Dallas-Fort Worth, and Denver Terminal Areas (Moor, 1984). Both tests demonstrated the ability of the respective flight management systems to deliver the airplane to a metering fix point at a time specified by ATC.

In order for time-based control to be a feasible operational procedure, aircraft must be provided adequate guidance to meet the imposed time constraints. Both NASA and Lockheed tests provided a form of time guidance to the pilot; however, no effort has been made to compare various time guidance schemes to determine their relative merit. The purpose of this study was to evaluate a series of time guidance schemes in terms of tracking performance, pilot workload, and subjective preference. The guidance concepts tested varied in complexity from simple digital time-error feedback to an advanced time-referenced-energy guidance scheme.

2. SIMULATION TEST DESCRIPTION

2.1 The Simulator

The guidance study was conducted in a fixed-base simulator configured as the aft research cockpit of the TSRV airplane (figure 1). The simulation includes a six-degree-of-freedom digital model of the airplane dynamics incorporating the nonlinear aerodynamic and engine characteristics.

The velocity-vector control-wheel steering semiautomatic control mode was used throughout the study. The pilot interface to the control system was provided through a two-axis sidestick controller rather than the panel-mounted controllers generally associated with this simulator. The throttles were manually operated throughout the study. Descriptions of the systems operations can be found in Gandelman, Holden, 1980 and Steinmetz, 1980.

The display system is made up of a primary flight display, a navigation display, an engine display, and a vertical situation display. The layout of the various displays in the cockpit is shown in figure 1. The baseline primary flight display format for this study is shown in figure 2. In addition to the conventional attitude, pitch and roll information, this display also has many additional features such as moving tape altitude and airspeed scales, velocity vector information, reference profile guidance and altitude, and airspeed trend information. A detailed description of this display is provided in Steinmetz, 1986 and Abbott, Steinmetz, 1987.

The baseline navigation display is shown in figure 3. This display provides the pilot with a plan view of the desired route and optionally displayed features such as radio fixes, navigation aids, and airports. A curved trend vector is displayed in front of the triangular airplane symbol to aid the pilot with route capture and tracking. The trend vector is composed of three consecutive lines which represent the airplane's predicted position in the next 30, 60, and 90 seconds based on the current ground speed and bank angle. A more detailed description of this display is provided in Gandelman, Holden, 1980. The baseline vertical situation display is shown in figure 4. This display format shows a side view of the desired flight path and a time line which displays the minimum arrival time, the minimum fuel arrival time, and the estimated and planned arrival times for a designated metering fix. A curved trend vector similar to that of the navigation display is also available on this display. The vertical trend vector is a single curved line, the end of which represents the predicted position in the next 15 seconds based on the current ground speed and vertical acceleration. The triangular airplane symbol position is fixed on the display and rotates according to flight path angle. A digital display of the altitude error and an altitude error bar are located on the left side of the display. The desired speed schedule is also presented at the top of the display.

2.2 Test Scenario

Six subject pilots were used to test five different time guidance display formats. The path over which the display formats were tested was a 100 nm. cruise-descent from 29,000 to 10,000 feet along the route shown in figure 5. Each of the display formats were flown twice by each subject pilot; once with accurately modeled winds and once under mismodeled wind conditions. The magnitude of the wind error for the mismodeled conditions was plus or minus 10 knots, in the direction of the cruise segment. In an effort to diminish the monotony of the task, two different descent speed schedules were used randomly throughout the test. The sequence of the test runs were also varied between pilots. Each test run began at waypoint START at the correct cruise conditions. It was assumed at this point that ATC had assigned an arrival time, altitude, and airspeed for crossing waypoint MF and that the flight management system had computed a reference profile to meet those constraints based on forecasted wind. The pilot's task was to manually fly the reference profile with the guidance provided so as to arrive at the metering fix at the desired time, altitude and if possible the proper airspeed. The test run would end approximately 15 minutes later when the airplane crossed waypoint MF.

2.3 4D Guidance Concepts

Four different time guidance concepts were used in the five test display formats. The simplest of these was a digital presentation of the current time error relative to the reference profile. This type of guidance is analogous to what was presented in the Lockheed tests. It should be noted here that the Lockheed tests were autopilot/autothrottle operations. The digital time error as well as other relevant time information were provided as situational information to aid the pilot in monitoring the system. It was not intended to be used as guidance to manually fly a 4D profile. In this study, the usefulness of this information as guidance will be evaluated. The sign convention for the digital time error was negative for late, positive for early.

The second guidance concept was one used in the NASA 4D-FMS flight tests at Denver. The time guidance was provided through a box symbol on the navigation display which moved along the desired route. The time box, shown in figure 6, represents the position along the route where the airplane should be based on the reference profile. The time error is nulled by maneuvering the airplane so that the airplane symbol is contained

within the time box. Three smaller boxes are located in front of the time box which represent the time box position in the next 30, 60, and 90 seconds.

The next two guidance concepts are energy error guidance concepts. The first of these will be referred to as the "3D" energy error. The 3D energy error combines speed and altitude error information in terms of total energy error (potential + kinetic) and energy error rate.

$$\Delta E_{3D} = h - h_{ref} + \frac{1}{2g} (v_g^2 - v_{g_{ref}}^2)$$

This information can be used to determine throttle of speed brake requirements to track the reference profile. The energy error is represented by the deviation of the energy error bug from the zero reference line as shown in figure 7. If the bug is above the reference line then the airplane has an excess of energy, and correspondingly if the bug is below the line then the airplane is low on energy. The error rate is represented in the form of an arrow emitting from the energy error bug. The length of the arrow is a function of the magnitude of error rate. The direction of the arrow is a function of the sign of the energy error. If the energy error rate is positive the arrow will be drawn as shown in the figure. If the energy error is negative the arrow will be drawn from the bottom of the error bug pointing down. In this way the error rate arrow always points in the direction in which the energy error bug is moving. The length of the arrow is an indication of how fast the error bug is moving. By centering the error bug about the reference line and nulling the error rate the pilot will match the energy required to fly the reference profile. The pilot can null a time error by adding or subtracting energy from the reference.

The other energy concept and the last of the time guidance concepts is the "4D" energy error. The 4D energy error is the same as the 3D with the exception that the time error is also related to an increment of energy error.

$$\Delta E_{4D} = \Delta E_{3D} + \frac{d^2}{2g} \left[\frac{1}{(t_{MF} - t_{ref})^2} - \frac{1}{(t_{MF} - t)^2} \right]$$

The 4D energy error and energy error rate were presented in the same manner as the 3D with the exception that the energy bug had a "4" drawn in the middle to distinguish between the two. The 4D energy error bug represented the amount of energy required to arrive at the metering fix at the proper time, altitude and ground speed. By centering the energy bug, nulling the energy error rate, and flying the reference altitude profile the pilot could be assured of arriving at the metering fix at these required conditions.

2.4 Time Guidance Display Formats

Five different time-guidance formats were used throughout the study involving changes to the baseline formats of the primary flight display, navigation display and the vertical situation display. These display configurations are shown in figures 8 through 12 and are described as follows:

- Format (a) - The time guidance is provided by the digital time error displayed in the upper right corner of the primary flight display. The vertical situation display is not provided. This represents the simplest of the five test formats.
- Format (b) - The time guidance is provided by the digital time error on the primary flight display and the time box on the navigation display. The vertical situation display is also provided.
- Format (c) - This display format is the same as (b) with the addition of the 3D energy bug located on the primary flight display.
- Format (d) - This display format is the same as (c) with the exception of the 3D energy bug being replaced by the 4D energy bug on the primary flight display.
- Format (e) - This display format is the same as (d) with the exception of the 4D energy bug being moved from the primary flight display to the vertical situation display.

2.5 Data

Quantitative performance data in terms of profile tracking, and metering fix crossing accuracy were collected for each test run. Occulometer data, to monitor the pilots scan of the various guidance options, were also collected. Subjective evaluations of the guidance concepts were conducted through a questionnaire which was completed by each test pilot at the conclusion of the test series. Frequency and amplitude of control inputs were collected for each test run to measure the pilot physical workload. The pilots also evaluated the workload associated with each test run through the NASA Task Load Index. This is a subjective workload rating procedure that is based on the

weighted average of six workload categories: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration. Details of the NASA Task Load Index are provided in Hart; Staveland, 1987.

3. Test Results

3.1 Tracking Performance

The pilot's primary task objective for this test was to cross the metering fix at the proper time, altitude and airspeed. The accuracy with which this objective was met, using the five test display formats, is illustrated in figures 13 through 15. The mean and standard deviation of the indicated airspeed error at the metering fix for each display format is shown in figure 13. The mean errors were all within 5 knots of the desired crossing speed with no appreciable performance difference between the display formats. As was expected, the standard deviations for the wind error cases were higher than those with the accurately modeled winds. This is due to the fact that the 4D reference profile dictates a required groundspeed schedule; under mismodeled wind conditions the pilot must deviate from the reference airspeed to maintain the required groundspeed schedule.

The mean and standard deviation of the altitude error at the metering fix are shown in figure 14. Again there was no significant performance difference between the display formats. The mean errors were all well within 50 feet of the desired crossing altitude. The standard deviations were again greater for the mismodeled wind cases.

Of the three metering fix crossing conditions, the time objective was given the highest priority. Figure 15 shows the mean and standard deviation of the time error at the metering fix. The mean errors were all within 1.5 seconds of the desired crossing time. The standard deviations of formats (a) and (b) were slightly higher than the other three. The best accuracy was obtained with format (e).

3.2 Workload Analysis

The frequency and amplitude of the throttle inputs associated with each display format are shown in figures 16 and 17 respectively, as a measure of the pilot's physical workload. There was no significant difference in the frequency of throttle inputs between display formats. With the exception of format (a), the frequency of throttle inputs were all higher for the wind error cases. With format (a) the frequency was lower but the amplitude was higher for the mismodeled case. The lowest amplitude of throttle inputs were associated with format (d).

The total workload of each test run was evaluated by the test pilots through the NASA Task Load Index. The mean and standard deviation of these ratings for each display format is shown in figure 18. The workload ratings followed the same trend as the throttle amplitude data. The lowest perceived workload was associated with format (d). The mismodeled wind cases were all perceived to be a higher workload with the exception of format (d).

3.3 Subjective Evaluation

The results of the questionnaire completed by the pilots at the conclusion of the test series are shown in figures 19 and 20. Figure 19 shows the averaged response of the pilots when asked to rate the display formats from most to least preferred. Format (d) was clearly the most preferred as five of the six pilots gave it the highest rating. The dissenting pilot preferred format (e) the most. Figure 20 shows the averaged response when the pilots were asked to rate each of the four individual guidance elements on a scale from 0 to 4; 4 being good, 0 being poor. The 4D energy bug was rated a 4 (good) by five of the six pilots; the other pilot rated it a 3. The time box received the lowest rating of the four guidance elements. This was primarily due to the lack of trend information provided by this concept. The pilots were also asked which of the five display formats would be the minimum guidance required for a 4D FMS. Once again five of the six pilots were in agreement, selecting format (a) as the minimum required. The other pilot selected format (d) as the minimum.

3.4 Oculometer Results

Oculometer data was collected to monitor the pilots scan of the various guidance options. The cockpit displays were divided into fourteen zones, as shown in figure 21. The average dwell time in each of the zones was computed for each test run. The average percent of the dwell time spent in each zone was then computed for the five display formats. Those zones which had a significant change in the average percent dwell time for the different display formats are presented in figure 22. There was a considerable increase in the percent of dwell time in zone 1 for display format (d) and a corresponding decrease in zones 4 and 5. Zone 11 also had an increase in the percent of dwell time with display format (e). These findings indicate that the energy guidance was useful and supports the pilot's subjective preference for the 4D energy bug concept. The results of zone 12 indicate that the vertical situation display was used when made available. Zone 13 shows an increase in the percent of dwell time with

display format (b) indicating an increased use of the navigation display when the time box and digital time error are the only forms of time guidance.

4. Conclusions

The results of this study indicate that any of the five display formats tested could be used to accurately deliver the airplane to the metering fix at the required time, altitude, and airspeed. However, from the workload analysis and subjective evaluation, the 4D energy bug was clearly the preferred form of guidance.

The test pilots provided many comments and suggestions, throughout the testing, about the various guidance schemes. Several pilots commented that the time box would be more helpful and the digital time error much less helpful in the situation of large time errors which required vectoring or holding. They also felt that trend information on the time box symbology would greatly enhance it's utility. The placement of the 4D energy bug was also commented on. Some felt that the primary flight display was cluttered with the addition of the energy bug, but liked having it in the primary scan. One pilot preferred the energy bug on the vertical situation display where it was close to throttle and speedbrake controls.

"Guidance Concepts for Time-Based Flight Operations"

Vicroy, D.

References

1980

Gandelman J., Holden R.

"A Pilot Training Manual for the Terminal Configured Vehicle Electronic Attitude Director Indicator." NASA CR-159195, 1980.

Knox C.E., Cannon D.G.

"Development and Test Results of a Flight Management Algorithm for Fuel-Conservative Descents in a Time-Based Metered Traffic Environment." NASA TP-1717, 1980.

Steinmetz G.G.

"Simulation Development and Evaluation of an Improved Longitudinal Velocity-Vector Control-Wheel Steering Mode and Electronic Display Format." NASA TP-1664, 1980.

1984

Moor D.A.

"Time Flies - An In-Service Evaluation of a 4-D Flight Management System." AIAA Digital Avionics Systems Conference, 1984.

1986

Steinmetz G.G.

"Development and Evaluation of an Airplane Electronic Display Format Aligned With the Inertial Velocity Vector." NASA TP-2648, 1986.

1987

Abbott T.S., Steinmetz G.G.

"Integration of Altitude and Airspeed Information Into a Primary Flight Display Via Moving-Tape Formats." NASA TM-89064, 1987.

Hart S.G., Staveland L.E.

"Development of a NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research." In P. A. Hancock and N. Meshkati (Eds.), Human mental workload. Amsterdam: Elsevier, 1987.

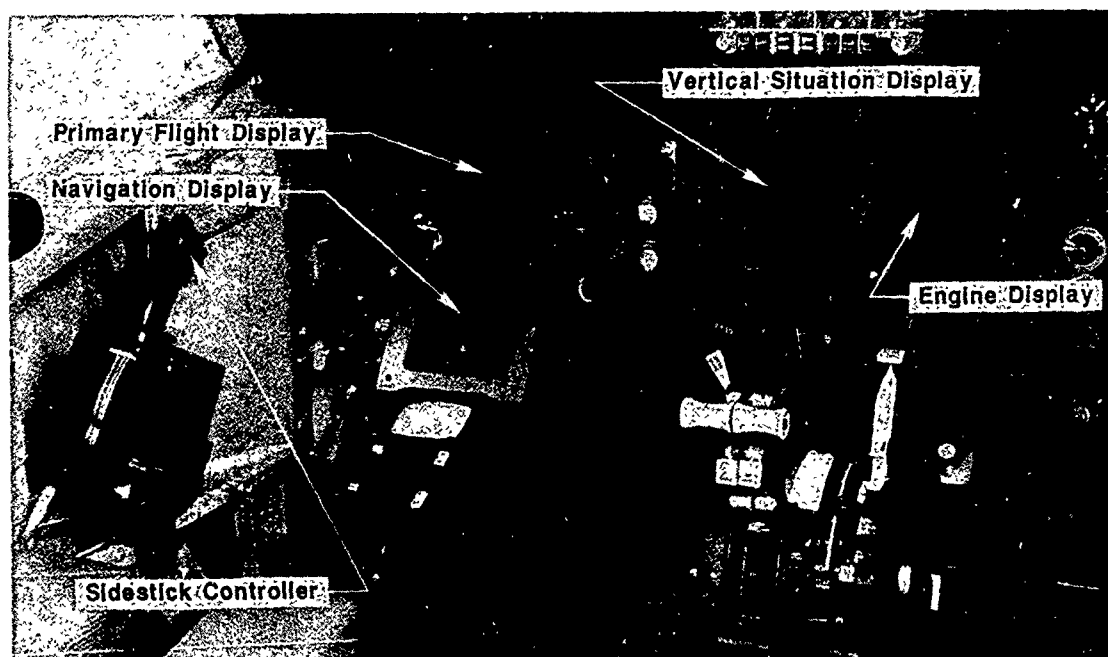


Figure 1: Transport Systems Research Vehicle fixed-based simulator.

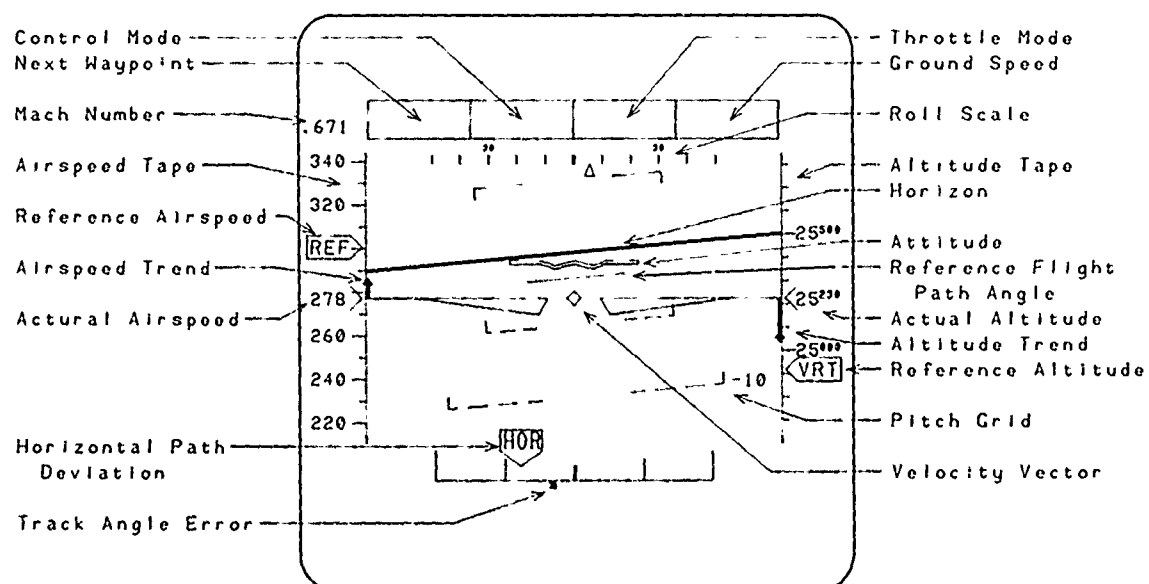


Figure 2: The baseline primary flight display format.

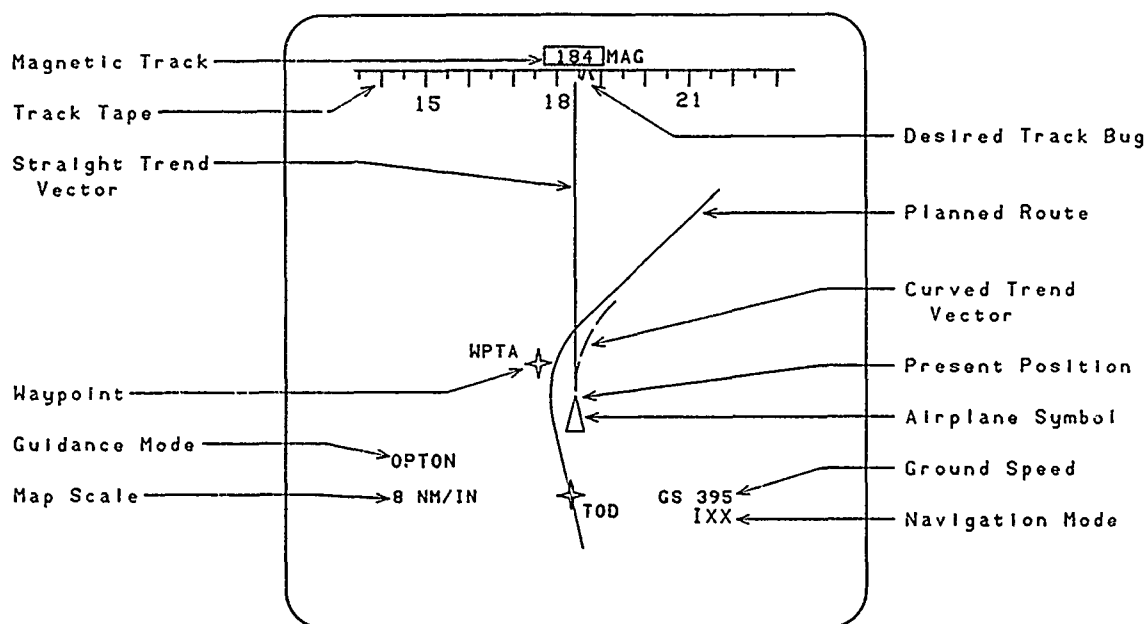


Figure 3: The baseline navigation display format.

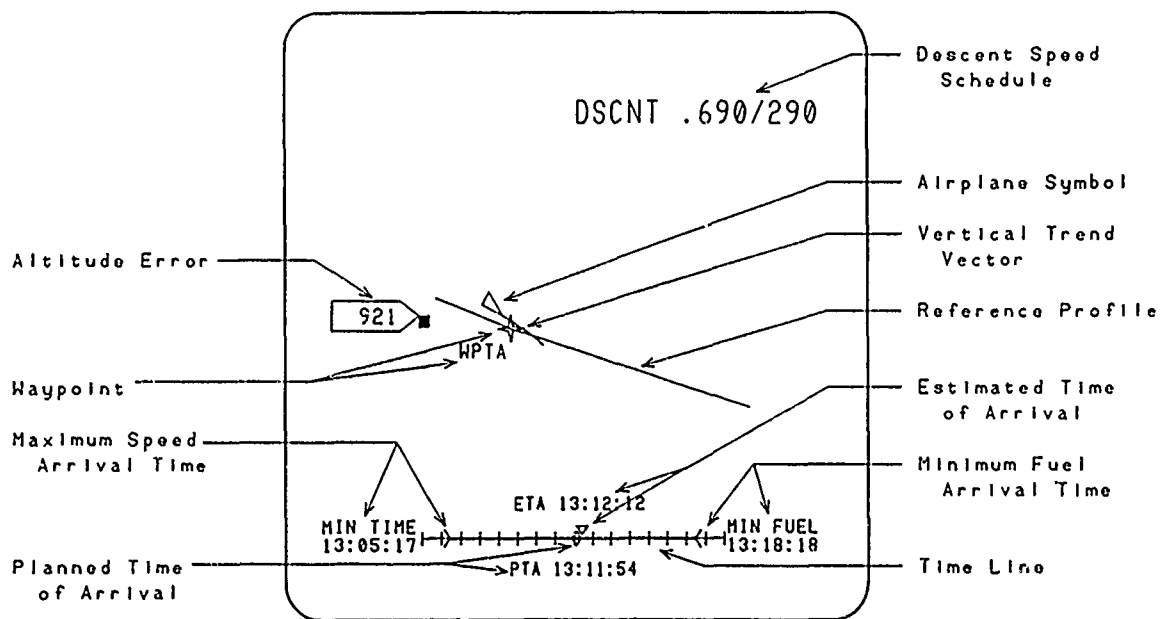


Figure 4: The baseline vertical situation display format.

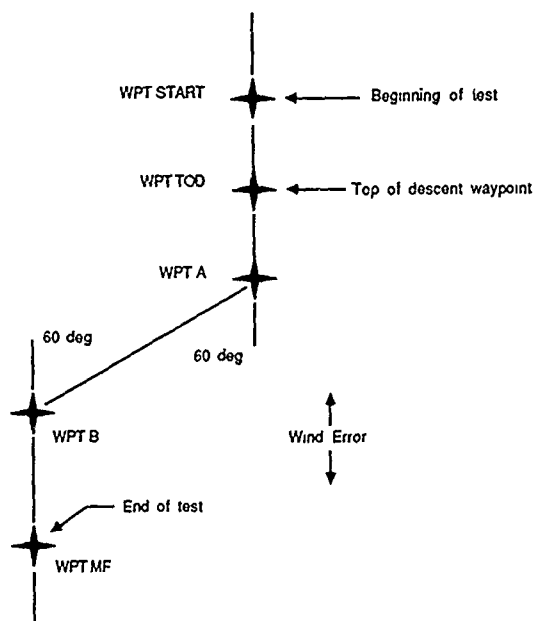


Figure 5: Cruise/descent test route.

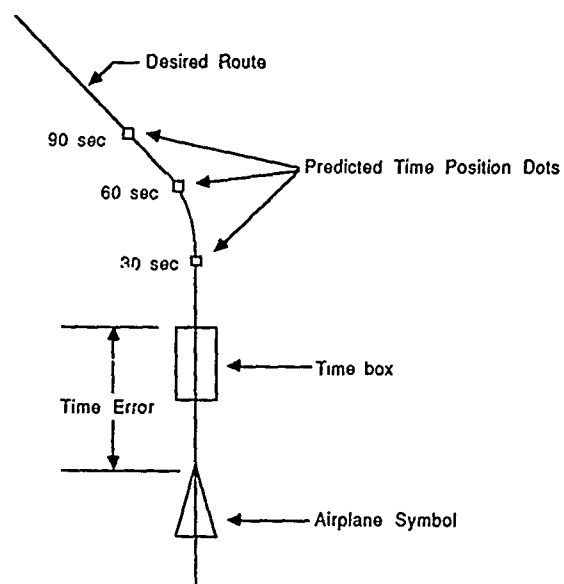


Figure 6: Time box guidance concept.

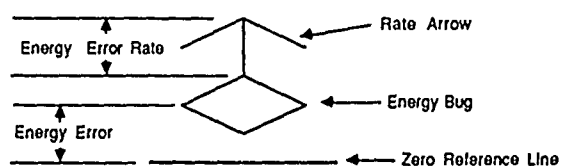


Figure 7: Energy bug guidance concept.

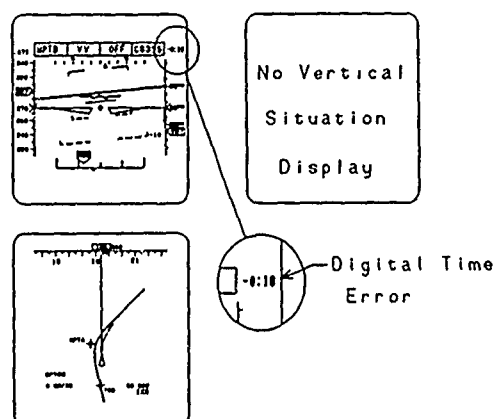


Figure 8: Test display format (a).

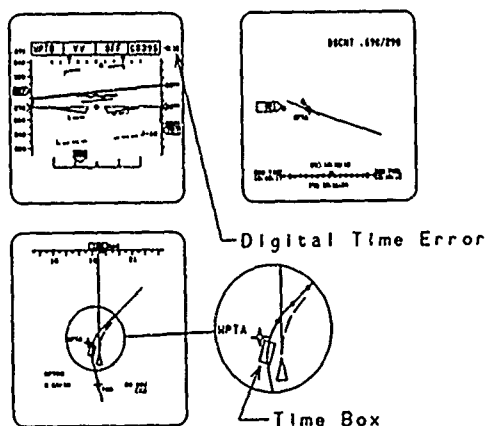


Figure 9: Test display format (b).

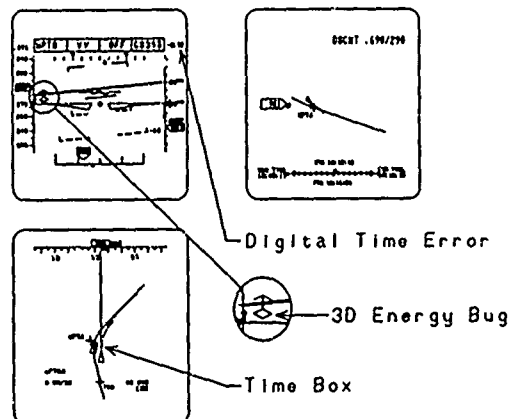


Figure 10: Test display format (c).

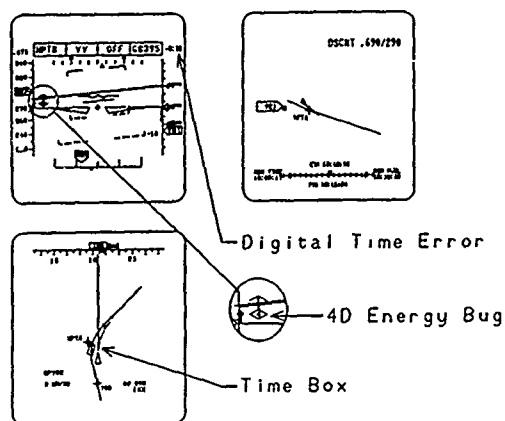


Figure 11: Test display format (d).

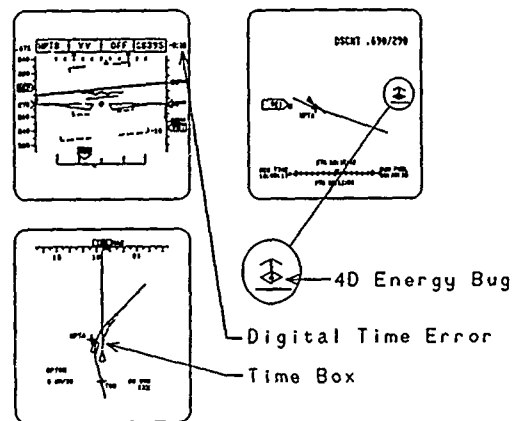


Figure 12: Test display format (e).

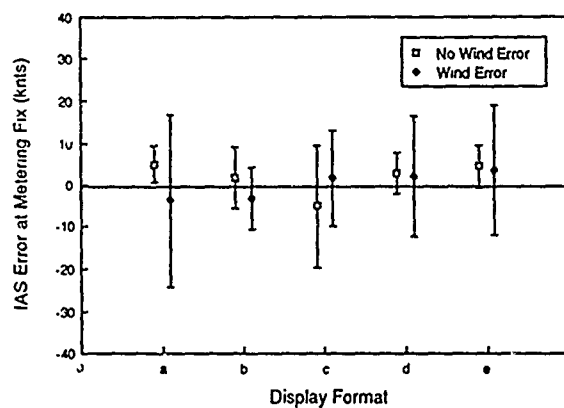


Figure 13: Mean and standard deviation of the indicated airspeed error at the metering fix.

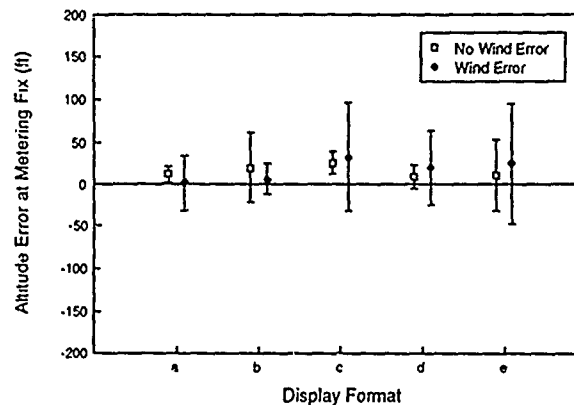


Figure 14: Mean and standard deviation of the altitude error at the metering fix.

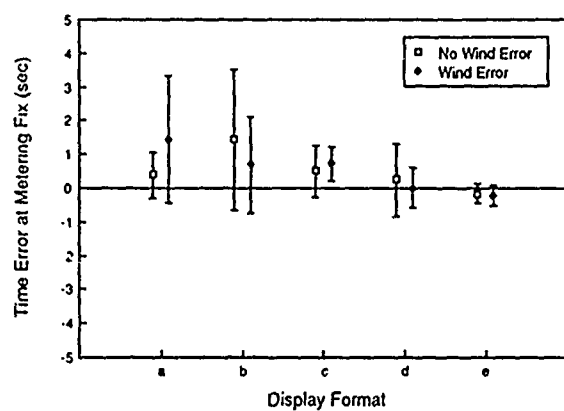


Figure 15: Mean and standard deviation of the time error at the metering fix.

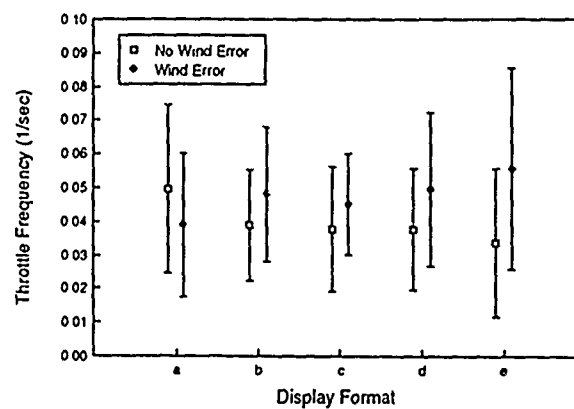


Figure 16: Mean and standard deviation of the frequency of throttle inputs.

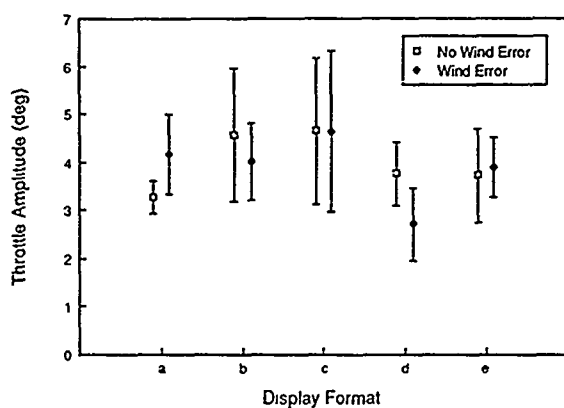


Figure 17: Mean and standard deviation of the amplitude of throttle inputs.

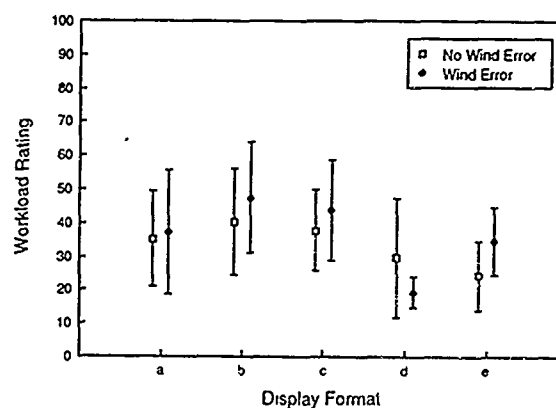


Figure 18: Mean and standard deviation of the NASA Task Load Index ratings.

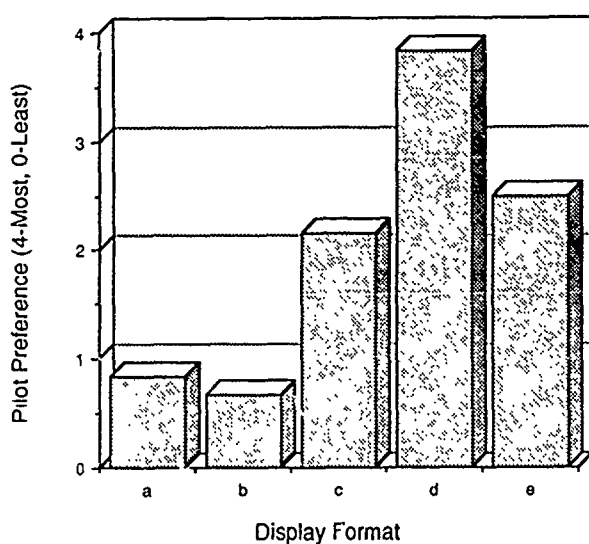


Figure 19: Averaged pilot preference of test display formats.

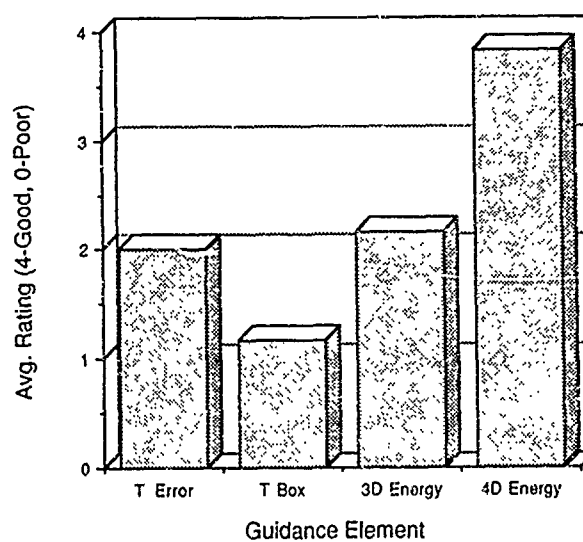


Figure 20: Averaged pilot preference of time guidance elements.

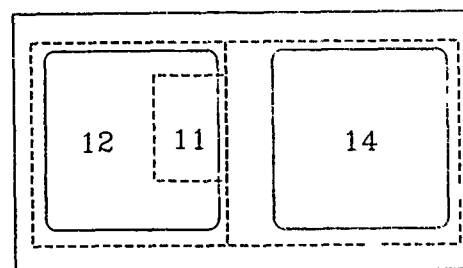
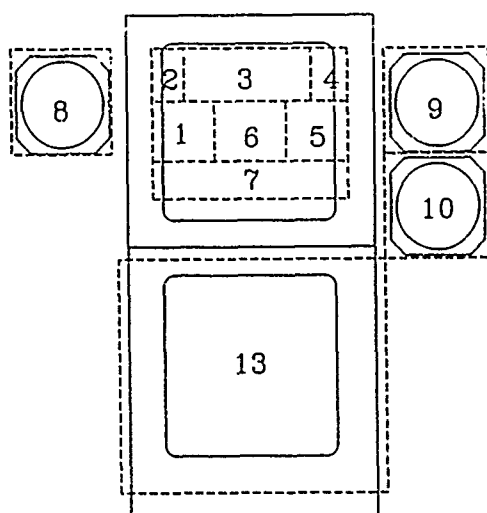


Figure 21: Occulometer zones.

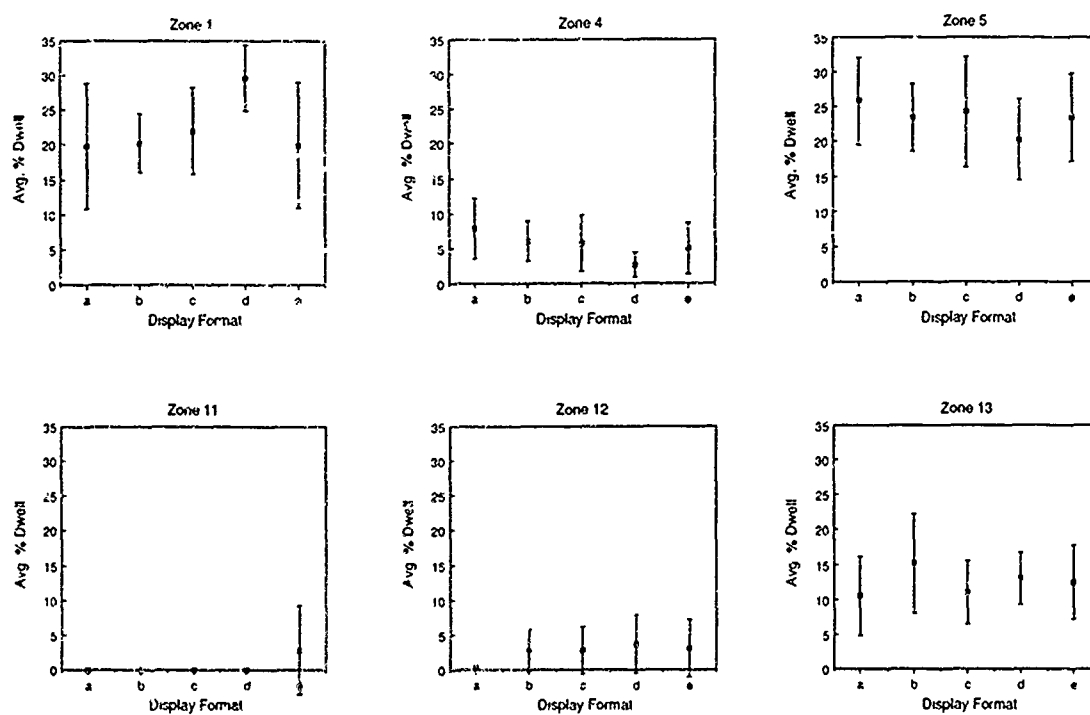


Figure 22: Mean and standard deviation of the average percent of dwell time in selected oculometer zones.

4D DESCENT TRAJECTORY GENERATION TECHNIQUES UNDER REALISTIC OPERATING CONDITIONS

by

David H. Williams and Charles E. Knox
 NASA Langley Research Center
 Hampton, Virginia 23665
 United States

SUMMARY

The NASA Langley Research Center has been conducting and sponsoring research in airborne energy management for a number of years. During the course of this research, two fundamental techniques for the generation of 4D (fixed time) descent trajectories have emerged as viable candidates for advanced flight management systems. The first technique utilizes speed schedules of constant Mach number transitioning to constant calibrated airspeed chosen empirically to produce minimum fuel usage. The second technique computes cost optimized speed schedules of variable airspeed developed through application of optimal control theory. Both techniques have been found to produce reasonable and flyable descent trajectories. This paper evaluates the formulation of the algorithms for each technique and discusses their suitability for operations in realistic conditions. Operational factors considered include: airplane speed, thrust, and altitude rate constraints; wind, temperature, and pressure variations; Air Traffic Control altitude, speed, and time constraints; and pilot interface and guidance considerations. Time flexibility, fuel usage, and airborne computational requirements were the primary performance measures.

SYMBOLS

a_{sos}	speed of sound
ATC	air traffic control
CAS	calibrated airspeed
D	drag
DOC	direct operating cost
E	specific energy
EPR	engine pressure ratio
f	engine fuel flow
g	gravity acceleration
H	Hamiltonian function
h	true altitude
h_p	pressure altitude
LFM/PD	local flow management/profile descent
M_c	cruise Mach number
M_d	descent Mach number
P	atmospheric pressure
P_0	sea level standard atmospheric pressure
PMS	performance management system
T	thrust
t	time
T_k	atmospheric temperature, Kelvin
$T_{k,std}$	standard atmospheric temperature, Kelvin
T_{T2}	total air temperature
TSRV	transport systems research vehicle
V_a	true airspeed
$V_{a,Mach}$	true airspeed at descent Mach number
$V_{a,CAS}$	true airspeed at descent calibrated airspeed
V_c	calibrated airspeed
V_g	groundspeed
V_w	wind speed
W	weight
x	range
γ	flight path angle relative to airmass
λ_E	energy adjoint
λ_x	range adjoint

1. INTRODUCTION

Rising fuel costs and other economic factors during the 1970's have prompted considerable interest in fuel efficient flight trajectories. Airplane Performance Management Systems (PMS) with varying degrees of sophistication were developed in response to this interest and resulted in improved efficiency of individual aircraft flight profiles. In the 1980's, increased traffic density, coupled with other ATC factors, have resulted in increased flight delays and airport capacity constraints at the major terminal areas. ATC procedures developed to cope with these delay and capacity problems have limited the use of the fuel efficient flight trajectories generated by onboard computer systems resulting in additional operating costs. However, advanced ATC systems are being designed to incorporate both the efficient handling of air traffic from a global standpoint as well as from an individual airplane standpoint. One such ATC concept promises to provide both an increase in airport capacity as well as to provide the opportunity for improved fuel efficiency through the time-based sequencing of aircraft to the airport, coupled with advanced airborne flight management systems capable of efficient 4D flight operations.

The NASA Langley Research Center has been conducting and sponsoring research in flight operations of advanced transport airplanes for a number of years. During the course of this research, operational issues have been a primary concern. One of the areas of this research has been the practical implementation of flight management concepts to permit fuel efficient operations in a time-based ATC environment. Several descent trajectory generation techniques, designed to achieve prespecified arrival times at a terminal area metering fix, have been investigated.

Two significantly different techniques for the generation of 4D descent trajectories are considered in this paper. The first involves descent trajectories with speed schedules of constant Mach number transitioning to constant calibrated airspeed (constant Mach/CAS) chosen empirically to produce minimal fuel usage. These trajectories are similar to those being flown during routine airline operations and are readily flyable with conventional flight guidance. The second technique utilizes optimal control theory to compute a vertical trajectory in which Mach number and airspeeds are variable during descent. Although these trajectories require special flight guidance, piloted simulation tests have shown that they are easily flown (Vicroy, 1985).

The purpose of this paper is to summarize a comparison of descent trajectories computed with both the constant Mach/CAS and the optimal control techniques. A background section on the development of the two trajectory generation techniques is presented. Next, the equations of motion are developed, followed by a description of the operational factors which affect trajectory generation. Finally, numerical results are presented which detail the time flexibility, fuel efficiency, and computational requirements of the two techniques when constrained by selected operational factors involving airplane performance and atmospheric modeling uncertainties.

2. HISTORICAL DEVELOPMENT

2.1 Operational Objectives

Economic and operational pressures have resulted in industry requirements for more efficient air traffic control and aircraft operations. In response to this need, the Federal Aviation Administration (FAA) developed an automated form of air traffic control for arrivals into the airport terminal area. This concept, called Local Flow Management/Profile Descent (LFM/PD), provides for increased airport capacity and fuel savings by combining time-based metering with profile descent procedures. Advanced ATC concepts are also being developed which incorporate time-based metering and profile descent (Credeur, 1986). Time-based metering procedures provide for the sequencing of arrivals to the airport through time control of airplanes at metering fixes located 30 to 40 flying miles from the airport. Time metering of airplanes at these fixes reduces the low-altitude vectoring (and associated fuel consumption) required to position the airplanes into a final queue for landing. In addition, delays due to terminal area sequencing may be absorbed at higher altitudes which further minimizes fuel usage (Stein, 1979 and Cunningham, 1977).

Profile descent procedures permit the initiation of the airplane descent at the pilot's discretion so that the airplane passes the metering fix at a specified altitude and airspeed. This procedure allows the pilot to plan for a fuel-conservative descent while accounting for the performance characteristics of his particular airplane.

The flight crews are responsible for meeting both airspeed and altitude constraints specified on special "Profile Descent Charts" published for each procedure. Crew workload is high since little or no computed guidance is available to aid them with the descent. Flight crews, thus, are forced to use past experience and various rules-of-thumb to plan the trajectory and determine when to begin the descent. Each rule-of-thumb requires the pilot to compute the horizontal flying distance necessary to descend from one altitude to another. Depending upon the degree of sophistication of the rule-of-thumb, the pilot can also account for other factors such as wind and temperature. However, without electronically computed guidance, the full potential of fuel savings from a planned descent is not consistently obtained.

The ATC controller has the responsibility of delivering the airplane to the metering fix at a preassigned time. The controller accomplishes this task with path-stretching radar vectors and/or airspeed control commands. Obviously, if the pilot is forced to deviate from his planned descent profile for time control purposes, more fuel will be used.

2.2 Constant Mach/CAS Schedule Technique

The NASA Langley Research Center has both conducted and sponsored research and flight tests aimed at reducing flight crew and ATC controller workload and for increasing fuel conservation during the LFM/PD process. The thrust of this research included development of airborne flight management system algorithms that computed fuel conservative descents which would satisfy time, airspeed, and altitude constraints and result in greater fuel savings. Workload was decreased by providing the pilot with computed guidance that would allow him to fly the descent profile.

The first airborne flight management descent algorithm developed at Langley Research Center was implemented in the NASA Transport Systems Research Vehicle (TSRV, formerly known as the Terminal Configured Vehicle) and flight tested in the Federal Aviation Administration's LFM/PD environment at Denver, Colorado. This airborne flight management descent algorithm computed the parameters required to describe a five-segment cruise and descent profile between an arbitrarily located entry fix to an ATC specified metering fix. These parameters were then used in the navigation and display systems to present guidance to the pilot and/or autopilot. The descent profile was based on empirically derived linear approximations of airplane performance for an idle-thrust, clean-configured (landing gear up and flaps zero) descent. Airplane gross weight, wind, and nonstandard temperature and pressure effects were also considered in these calculations. Details of these computations may be found in Knox, 1980.

This flight management descent algorithm was designed to be used in either of two modes. The primary mode was designed to be used for time-metered operations. In this mode, pilot inputs included the estimated or actual time of arrival at the entry fix and the ATC specified arrival time at the metering fix. The descent profile was then computed through an iterative process to determine a constant Mach/CAS descent speed schedule that would closely satisfy the crossing times for both of these fixes. The iterative process (usually less than three computation cycles) was completed when the computed time error at the metering fix was less than five seconds.

In the second mode, the pilot could input the Mach/CAS descent schedule to be flown, and the descent profile was calculated in a single computational iteration and was independent of an assigned metering fix time. However, if a metering fix time was subsequently assigned, some time error, which would have to be nulled by the pilot, would result since an arbitrarily specified descent speed schedule would generally not satisfy both the entry fix and the metering fix time constraints.

The results of the flight tests conducted at Denver demonstrated that the concept of time guidance and control in the cockpit was acceptable to both the pilots and the ATC controllers. The procedures for these tests required the pilots to leave the engines at flight idle and not to use the speed brakes once the descent was begun so that airplane performance modeling could be evaluated. Although this procedure precluded the pilot from nulling the time error during the descent, airplane arrival at the metering fix resulted in standard deviations in airspeed error of 6.5 knots and in arrival time accuracy of 12 seconds. These accuracies indicated a good representation of airplane performance and wind modeling. Pilot workload was reduced by eliminating the need for rules of thumb and/or extensive experience to achieve a solution to a complex 4D navigation problem and by providing steering guidance for 4D path following. ATC controller workload was reduced through a reduction of required ground-to-air communications and through the transfer of time navigation responsibilities to the cockpit (Knox, 1980 and Knox, 1985).

The NASA also sponsored 4D research and flight tests with the Lockheed-California Company for demonstration of 4D flight with an L-1011 airplane (Lee, 1984). This research illustrated how time navigation could be added to an existing 3D (lateral and vertical navigation) flight management system.

The design approach for this 4D implementation was somewhat different than the approach taken for the NASA flight tests at Denver. The flight management descent algorithm in the L-1011 airplane would compute metering fix arrival times for up to five constant Mach/CAS descent profiles using five standard descent airspeed schedules. The descent profile that had the metering fix arrival time that most closely matched the arrival time assigned by ATC would be used by the flight guidance/autopilot systems. The flight guidance/autopilot systems would then null the time error through airspeed control.

Flight tests were conducted in California to verify design and software implementation and at the Dallas-Ft. Worth (Texas) Airport in the FAA's LFM/PD ATC environment. During these flight tests, a standard deviation of 9.5 seconds was achieved for the airplane crossing the metering fix. Subsequent 4D flight tests were conducted by Lockheed and Delta Airlines, under a limited certification from the FAA, on routine airline flights into airports located at Dallas-Ft. Worth, Texas; Denver,

Colorado; and Atlanta, Georgia. These tests resulted in similar time errors and favorable comments from both ATC controllers and pilots.

The Lockheed and NASA flight management descent algorithms both utilized empirical models of the airplane performance to compute the descent trajectories. These techniques were utilized in order to save computation time and reduce computer memory requirements for the airborne implementation of the algorithms. For the analytical studies presented in this paper, a more general treatment of the Mach/CAS schedule technique was utilized. Airplane performance was computed through use of airplane drag polars and engine thrust and fuel flow models. The trajectories were then computed through integration of the point mass equations of motion.

2.3 Optimal Control Technique

Calculation of optimal flight trajectories has been the subject of numerous investigations. These studies have explored applications using the energy state formulation of aircraft performance using a variety of techniques. Rutowski considered the minimum-time-to-climb and minimum-fuel-to-climb problem from a graphical viewpoint (Rutowski, 1954). Schultz and Zagalsky applied the calculus of variations to fixed end point flight-path optimization problems using several aircraft mathematical models (Schultz, 1972). That study revealed that the form of the equations was important in determining whether optimization techniques would produce optimum performance.

Erzberger and Lee (Erzberger, 1978 and Lee, 1979) applied the principals of optimal control theory (Bryson, 1969) to obtain an efficient algorithm for computing optimum vertical profiles. In this formulation, the state variable was range-to-go and the independent variable was energy. The trajectory was assumed to be composed of three segments; namely, a climb with monotonically increasing energy, a cruise at constant energy, and a descent with monotonically decreasing energy. This analysis provided an algorithm capable of determining optimum speed and throttle settings which minimized Direct Operating Cost (DOC) for typical airline missions. It further highlighted the importance of engine performance characteristics. In particular, the non-linear dependence of fuel consumption on thrust in determining the characteristics of the optimum trajectory and the need for throttle-setting optimization. It was found, for example, that the engine characteristics of a typical jet transport (Erzberger, 1978) were such that fixed throttle climb and descent produced no more than a one percent penalty in fuel consumption compared to the optimized free-throttle settings.

Sorenson, et al expanded on the Erzberger algorithm to produce a computer program for NASA Langley flight management research (Sorenson, 1981 and Sorenson, 1983). Important results in their analyses included the need for smooth, continuous mathematical functions of airplane drag, thrust, and fuel flow to provide satisfactory performance of the optimization algorithm. This was especially true when iterating to obtain a 4D solution. Operational problems, such as descent rate limits and engine bleed losses, were also addressed in the development of the optimization program.

Calise applied singular perturbation theory to solve problems in flight performance optimization (Calise, 1977). This technique reduced the high-order two-point boundary-value problem associated with trajectory optimization to a series of lower order problems. Chakravarty utilized this technique to develop an algorithm for computing optimal trajectories of jet transport aircraft (Chakravarty, 1985). Comparisons of the Erzberger and Chakravarty algorithms have shown them to be functionally equivalent. The cost functions which are minimized in cruise, climb, and descent are identical for both algorithms. Differences in the computed trajectories are due solely to different numerical techniques and airplane performance models contained in the algorithms. Enhancements made to the Chakravarty algorithm (Buckham, 1986) have made it the preferred algorithm for the analyses of this paper.

Descent trajectories computed by the optimal control algorithms are characterized by variable airspeeds and Mach numbers throughout the descent. Piloted simulation tests were conducted at NASA Langley to investigate the basic guidance requirements for flying these variable speed trajectories (Vicroy, 1985). Results of these tests showed that special 4D, speed command guidance and altitude error and flight path angle situation information, coupled with an augmented control wheel steering flight control system, allowed the pilot to easily follow the optimized trajectories.

3. TRAJECTORY GENERATION

To provide a meaningful comparison between the constant Mach/CAS and optimal control descent strategies, the algorithms must be formulated and the trajectories computed based on common equations of motion. This section details the equations and algorithm formulations used for this study. The optimal control formulation was based on the methods described in Chakravarty, 1985.

3.1 Equations of Motion

The point mass equations of motion in a vertical plane, assuming small angles and equilibrium of vertical forces, can be written as follows:

$$\dot{V}_a = g(T-D)/W - g\gamma - \dot{V}_w \quad (1)$$

$$\dot{h} = V_a \gamma \quad (2)$$

$$\dot{x} = V_a + V_w = V_g \quad (3)$$

The time rate of change of wind speed, \dot{V}_w , can be represented as a vertical wind shear

$$\dot{V}_w = (dV_w/dh)h = (dV_w/dh)V_a \gamma \quad (4)$$

Equation (1) then becomes

$$\dot{V}_a = g(T-D)/W - g\gamma - (dV_w/dh)V_a \gamma \quad (5)$$

The equations of motion are further simplified by combining altitude and airspeed into a single state variable, specific energy:

$$E = h + V_a^2/2g \quad (6)$$

Differentiating equation (6) yields

$$\dot{E} = \dot{h} + V_a \dot{V}_a/g \quad (7)$$

Substituting equations (2) and (5) into (7)

$$\dot{E} = V_a (T-D)/W - \gamma (V_a^2/g) (dV_w/dh) \quad (8)$$

The control variables in equation (8) are airspeed V_a and thrust T . This is the energy state approximation model which is widely used in trajectory optimization problems.

3.2 Optimal control formulation

The optimization problem is to steer the system described by equations (3) and (8) from an initial state (x_1, E_1) at t_1 to a final state (x_f, E_f) at fixed final time t_f so that the fuel used is minimized. Equivalently, the expression

$$J = \int_{t_i}^{t_f} C_f dt \quad (9)$$

is minimized in which C_f is the cost of fuel.

The Hamiltonian for equations (3), (8), and (9) is

$$H_1 = C_f + \lambda_x (V_a + V_w) + \lambda_E \dot{E} \quad (10)$$

in which λ_x and λ_E are the range and energy adjoint variables. Pontryagin's minimum principle (Bryson, 1969) states that the Hamiltonian is minimum along an optimal trajectory. Furthermore, since the final time is fixed, and H_1 is not an explicit function of time, H_1 is constant along the optimal trajectory and given by

$$\min_{T, V_a} \{H_1\} = K \quad (11)$$

K has the units of cost per unit time, and if $C_t = -K$ is selected, equation (11) may be rewritten

$$\min_{T, V_a} [C_t + C_f + \lambda_x (V_a + V_w) + \lambda_E \dot{E}] = 0 \quad (12)$$

along the optimal trajectory. It therefore reduces to a direct operating cost (DOC) optimization with free terminal time and cost parameters C_f and C_t . The 4D optimization

problem is solved by fixing C_f and appropriately selecting C_t through an iterative process until the desired flight time is computed.

The outer solution, according to singular perturbation theory (Chakravarty, 1985), is reduced to

$$\min_{h, V_a} [C_t + C_f + \lambda_x (V_a + V_w)] = 0. \quad (13)$$

(T=D)

Using Pontryagin's minimum principle, we get

$$-\lambda_x = \min_{h, V_a} \left[\frac{C_t + C_f}{(V_a + V_w)} \right]_{T=D}. \quad (14)$$

The ratio to be minimized in (14) is referred to as the cruise cost function.

During climb/descent, Equation (12) is transformed into

$$\min_{T, V_a} [C_t + C_f + \lambda_{xc} (V_a + V_w) + \lambda_E \dot{E}] = 0 \quad (15)$$

in which λ_{xc} corresponds to the value of (14) during the cruise segment. To minimize equation (15), the energy adjoint equals

$$\lambda_E = - \min_{V_a, D < T \leq T_{max}} \left[\frac{C_t + C_f + \lambda_{xc} (V_a + V_w)}{\max_{V_a, T_{min} \leq T < D} \left[\frac{V_a (T-D)/W - \gamma (V_a^2/g) (dV_w/dh)}{V_a} \right]} \right]_E. \quad (16)$$

The minimization is done to get the climb solution, and the maximization to get the descent solution. The ratio in equation (16) to be optimized at current energy E , is called the climb/descent cost function.

3.3 Constant Mach/CAS schedule

The constant Mach/CAS descent strategy provides a much simpler control formulation. As discussed previously, an empirical model of calibrated airspeed as a function of descent Mach, with the descent Mach equal to the cruise Mach, provides a fuel efficient descent speed schedule with near optimal performance. Cruise Mach may be empirically modeled as a function of time and fuel costs, or computed from optimal control formulation with nearly equivalent results. For this paper, equation (14) was used to determine cruise speed for the constant Mach/CAS schedule technique. The true airspeed descent schedule could then be computed at each altitude during the descent using the following airspeed relations:

$$M_d = M_c \quad (17)$$

$$V_{a, Mach} = a_{sos} M_d \quad (18)$$

$$V_{a, CAS} = a_{sos} \{ 5 [(P_o/P \{ [1 + .2(V_c/661.5)^2]^{3.5} - 1 \} + 1) \cdot 286 - 1] \}^{.5} \quad (19)$$

The descent true airspeed is then chosen to be the lesser of $V_{a, Mach}$ and $V_{a, CAS}$.

3.4 Trajectory integration

Trajectory integration is accomplished in the same manner for both the optimal control and the constant Mach/CAS schedule techniques. Steps in pressure altitude and true airspeed are converted to energy steps using

$$\Delta E = \Delta h_p (T_k/T_{k, std}) + \Delta(V_a^2/2g) \quad (20)$$

in which, the temperature ratio $(T_k/T_{k, std})$ is used to correct the pressure altitude difference to a true altitude difference for nonstandard atmospheric temperature conditions (Russel, 1951).

Time and range during descent are then computed as

$$\Delta t = \Delta E / \dot{E} \quad (21)$$

$$\Delta x = V_g \Delta t \quad (22)$$

4.0 OPERATIONAL FACTORS

This section describes the various operational factors which affect the calculation of airplane flight trajectories. A discussion of the effects of a subset of these operational factors on the performance of the constant Mach/CAS and optimal control techniques is contained in the Analytical Results section of the paper.

4.1 Airplane Characteristics

4.1.1 Speed limitations

All airplanes have speed restrictions based on controllability, structural, and performance limitations. Additionally, operational limitations may be imposed by the aircraft operators or ATC. Typically, the operational limitations will further restrict the speed envelope of the airplane. Figure 1 illustrates the airframe and operational speed envelope as a function of altitude for the NASA TSRV B-737-100 airplane for the cruise configuration.

The low speed airframe limit, typically referred to as minimum maneuvering speed, is a function of stall speed. In operation, this low speed limit is simplified to be a single indicated airspeed of 210 knots, which is a conservative value for typical airplane weights. Some operators provide the pilots with speed cards showing minimum speeds as a function of airplane weight to expand the operational speed envelope. High speed airframe limits are based on an equivalent airspeed at low altitudes and based on a Mach number at high altitudes.

Operational limitations include a 250 knot indicated airspeed limit below 10 000 feet altitude imposed by ATC in the United States for safety considerations. In addition, constant CAS descent schedules restrict the maximum indicated airspeed to 350 knots. This is necessary since airframe speed limits would be violated if the maximum indicated airspeed at 350 knots equivalent airspeed at higher altitudes was maintained during the descent.

Additional operational limitations may be imposed by specific airlines or airplane operators. The performance algorithms used in the calculations of flight trajectories must include the actual operational limitations rather than the airframe limits if the computed flight trajectories are to conform to FAA and company procedures.

4.1.2 Thrust limitations

Engine thrust on jet transport airplanes is constrained on the high end by maximum takeoff, climb, and cruise power settings. Company policy may also require derated thrust to be used during takeoff and climb for extending engine life and noise abatement. Thrust at the low end is constrained by the idle performance of the engine and for pressurization and anti-icing requirements. For the JT8D-7 engines on the NASA TSRV B-737-100 airplane, maximum power settings are well-defined schedules of Engine Pressure Ratio (EPR) versus total air temperature. Idle performance, however, occurs at a physical throttle position and cannot be represented by easily defined power settings. Since descent trajectories are flown at or near idle thrust, the determination of idle performance is a necessity.

The exact relationship for idle power setting is determined by the fuel controller of the particular engine. Minimum fuel flow limits are imposed to provide satisfactory engine performance at idle. In addition, anti-surge bleed valves are employed to relieve pressures in the engine to prevent surging and stalling of the engine, thus further complicating determination of idle thrust. The resulting mathematical model for idle thrust to be utilized by a trajectory generation algorithm can be quite complex and contain several discontinuities. A more complete description of the idle performance model used for the NASA TSRV airplane engines can be found in Williams, 1986.

4.1.3 Altitude rate restrictions

Descent at idle thrust for high airspeeds can result in very high descent rates (4 000 to 6 000 ft/min, or greater) in jet transport airplanes. Altitude rate restrictions are often placed on aircraft by airframe manufactures, operators, and through cabin pressurization constraints. In addition, pilots will often limit descent rates during prolonged descents based on their own experience and when approaching level flight segments during a climb or descent. The inclusion of descent rate limitations in the trajectory calculation must be handled consistent with operational practices.

4.2 Atmospheric Conditions

4.2.1 Wind

Variations in wind speed and direction have a primary effect on the flight time of an airplane over a given range. As such, wind can be the most predominant atmospheric condition affecting 4D trajectory calculations. Known winds affect the speed schedule and descent path the airplane flies to achieve a desired time. Unknown winds force the airplane to fly non-optimal speed schedules and descent paths to achieve the same arrival time, thus, resulting in a higher cost of operation.

4.2.2 Temperature

Variations in air temperature affect the true airspeed of an airplane for a given Mach number (equation 18) as well as the actual true altitude rate during descent (equation 20). As with wind, known temperature deviations affect the speed schedule and descent path calculated to achieve a pre-specified time.

4.3 Air Traffic Control

The 4D trajectory generation algorithm must produce flight profiles which are compatible with Air Traffic Control procedures and restrictions. These include the navigation route to be followed, altitude assignments and crossing constraints, speed restrictions, and time assignments at specific navigation way points. Furthermore, the trajectory generation program must provide information in a timely manner to facilitate pilot interaction with ATC controllers.

4.3.1 Altitude restrictions

Aircraft are required to fly at specific altitudes assigned by ATC. Typically, cruise altitudes are requested by the airplane operator in the flight plan submitted prior to the flight. Individual controllers will assign specific altitudes as necessary to insure separation of all air traffic. Altitude changes are expected to be made in a timely manner.

Descents into the terminal area are typically made with altitude restrictions resulting in intermediate level flight path segments or the requirement to use speed brakes or some thrust during the descent. In some cases, ATC may issue a clearance for the pilot to begin the descent at his discretion, thus allowing the pilot the opportunity to fly an efficient trajectory. Altitude restrictions during a descent will almost always result in more fuel being used than during an unconstrained descent regardless of the method of descent planning or trajectory generation technique. Thus, for fuel efficient operations, ATC imposed altitude constraints must be continuously reviewed and the unnecessary ones eliminated. On the other hand, the flight management and guidance systems must also be designed to efficiently and economically accommodate multiple altitude constraints during a single descent.

4.3.2 Speed restrictions

The airspeed an airplane can fly is often dictated by ATC. Below 10 000 feet altitude, all aircraft in the United States are required to fly no faster than 250 knots indicated airspeed. In addition, controllers often request aircraft to fly specific Mach numbers or indicated airspeeds to provide and maintain separation from other aircraft. Certain navigation fixes, such as entry points to busy terminal areas, have crossing speeds associated with them to ease the workload of controllers in busy sectors. These speed restrictions, if known in advance, must be included in the calculation of the flight trajectory to attain maximum efficiency.

4.3.3 Time assignment

The essence of time-based ATC is the regulation of the flow of aircraft to an airport by assigning a unique time for each aircraft to cross a navigation fix. This time assignment adds an additional constraint to the trajectory computations. Time assignments to a navigation fix change the cost optimization trajectory computations into ones for minimum fuel trajectories with speed schedules that satisfy the time constraints.

4.3.4 Pilot interface

The pilot must approve and execute the instructions received from ATC. As such, the necessary information from the trajectory generation program is required to acknowledge an ATC request which affects or constrains the flight profile. While the details of the pilot interface requirements are independent of trajectory generation technique, the availability of the information in a timely manner is very much dependent on the computational requirements of the trajectory algorithm.

5. ANALYSIS TECHNIQUE

An analytical comparison of the constant Mach/CAS and the optimal control trajectory generation techniques, with certain operational constraints, was conducted. Numerical data and results from several NASA Langley research efforts were used in this comparison. Where necessary, a common baseline scenario and trajectory tracking computer program were utilized to provide a direct comparison of the primary performance parameters.

5.1 Baseline Scenario

A 150 nautical mile final cruise and descent flight segment was used as the basic scenario for the analysis. This flight phase was consistent with the region of active arrival time selection found in advanced time-based air traffic control system concepts being developed. Initial conditions for the baseline scenario for the NASA TRSV B-737-100 were chosen to be Mach .72 at 33 000 feet altitude with a gross weight of 85 000 pounds. Final conditions were 10 000 feet altitude with an indicated airspeed of 210 knots. Other scenarios and conditions taken from previous studies are described in the Analytical Results section.

5.2 Trajectory Tracking

A vertical profile tracking program was used to provide actual fuel and time required to fly along the reference profile for both trajectory generation techniques analyzed in this paper. The tracking program utilized the same airplane performance models and equations of motion used in the trajectory generation computations. Speed brake limits were also modeled to limit airplane tracking of profiles to the actual capabilities of the airplane.

The vertical tracking program attempted to force the airplane to maintain the inertial flight path angle and ground speeds computed for the reference trajectory. With all atmospheric conditions and airplane performance parameters modeled exactly, the thrust required to maintain the flight path angle and ground speeds would match that of the reference profile computations. This would result in the airplane crossing the metering fix at the assigned time and using the predicted amount of fuel. For mismodeled conditions, however, the tracking program would adjust the true airspeed of the airplane by changing thrust or adding drag through speed brakes, so that the ground speed of the airplane matched that of the reference trajectory. If airplane speed, thrust, or speed brake limits were encountered, the limiting value would be maintained and a time error would accumulate. If the time error exceeded two seconds, groundspeed of the simulated airplane would be appropriately adjusted in increments to null the time error. Total groundspeed adjustment was limited to 10 knots faster or slower than that specified in the reference trajectory.

6. ANALYTICAL RESULTS

6.1 Time Flexibility

An important measure of a trajectory generation algorithm's compatibility and utility in a time-based air traffic control system is the flexibility it affords in achieving prespecified arrival times. This time flexibility can be represented as a time window defined by the maximum and minimum times available to fly a given range as calculated by the trajectory generation program.

6.1.1 Speed limitations

The maximum and minimum times an airplane can achieve correspond to flying the minimum and maximum speed schedules, respectively, of the airplane. The time window, assuming no path stretching maneuvers, is primarily a function of the speed limits imposed on the trajectory generation algorithm. As discussed in the Operational Factors section, the speed limitations observed in actual operations are generally somewhat conservative compared to absolute airframe limitations. These limitations must be observed within the trajectory generation computations if the airplane is to successfully fly the trajectory. This requirement tends to eliminate any differences in time window capability between the Mach/CAS and optimal control techniques under normal conditions. However, the potential exists to expand the time window for either trajectory generation technique by using the actual airframe limits. Further gains are possible using the optimal control technique by varying the desired descent speed schedule as a function of altitude. The time windows available for the baseline scenario with both the constant Mach/CAS and optimal control techniques for both operational and airframe speed limits are shown in the following table.

Time Window (minutes)

Control technique	Operational speed limits	Airframe speed limits
Mach/CAS	8.12	8.94
Optimal	8.12	9.36

Both control techniques had the same time window when operational speed limits were imposed. When airframe speed limits were used, the time windows were expanded. The difference between Mach/CAS and optimal time windows when airframe speed limits were applied was due entirely to restricting the CAS portion of the Mach/CAS descent to be a constant value throughout the descent. Thus, the minimum speed CAS profile would use the minimum airframe CAS at cruise altitude for all altitudes during descent even though minimum airframe CAS actually decreases with decreasing altitude. Similarly, the maximum CAS for the constant Mach/CAS technique must be selected such that the limiting value at the lowest altitude of the descent was not exceeded. The major factor lowering the operational time window for both control techniques was the imposition of the 210 knot indicated airspeed lower speed limit. This accounts for nearly one minute off the optimal airframe-limited time window. Limiting maximum Mach number to maximum cruise Mach accounts for approximately an additional 15 seconds loss in time flexibility.

6.1.2 Wind

The impact of wind on the time flexibility of 4D descent trajectories was investigated in a previous NASA study (Williams, 1987). As described in that report, known winds have the affect of shifting in time the time cost versus flight time relationship for a given fixed range situation. This is illustrated in figure 2 for the 200 nautical mile scenario of that paper. As a result, a fixed flight time occurs at different time costs for different wind conditions. Further, the time window available for the given range is seen to shift with the different winds. Mismodeling the winds results in a loss of time flexibility since these shifts in time window are not considered. Further, the airplane will not be able to achieve flight times associated with reference profiles commanding speeds and/or descent flight path angles beyond the capabilities of the airplane. This results in additional loss of time flexibility under mismodeled wind conditions. The summary plot of lost time flexibility versus wind error is presented in figure 3 (Williams, 1987).

6.2 Fuel Usage

Minimizing fuel usage is a primary concern for airplane operators. Time-based air traffic control promises reduced flight delays which should provide major fleet-wide fuel reductions. Individual aircraft profiles, however, will be penalized to some degree by requiring 4D trajectory control compared to 3D control. Trajectory generation programs must therefore provide fuel efficient operation in order to realize the maximum benefits from time-based air traffic control. The formulation of the trajectory generation algorithm, as well as operational constraints, will affect the actual fuel economy.

6.2.1 Algorithm formulation

The optimal control strategy provides the best fuel economy for a given range and flight time. The advantage of optimal control speed schedules over constant Mach/CAS schedules, however, is found to be small. Figure 4 presents the fuel versus time performance spectrum for both optimal and constant Mach/CAS techniques for the baseline scenario. As seen in the figure, optimal performance is only slightly better at the mid-time region, tapering to no advantage at the extremes of the time window.

Further illustration of the relative insensitivity of fuel usage to speed schedule variations is shown in figure 5. This figure presents descent calibrated airspeed versus cruise/descent Mach number contours of constant time for the baseline scenario. Superimposed on the time contours are speed schedules corresponding to minimum fuel and speed boundaries of one percent increase in fuel over the minimum fuel schedule. For a given flight time, therefore, a fairly broad selection of cruise/descent Mach and descent calibrated airspeed are available which result in fuel usage within one percent of the minimum. For example, a flight time of 23 minutes could be achieved using speed schedules ranging from approximately .69 cruise/descent Mach and 290 knots descent calibrated airspeed to .74 cruise/descent Mach and 260 knots descent calibrated airspeed with essentially the same (within 1 percent) fuel usage.

6.2.2 Idle Thrust

The effect of variations in idle thrust on calculation of descent trajectories was studied in Williams, 1986. Essentially, idle thrust errors result in reference descent flight paths requiring throttle or speed brake compensation. A summary plot of fuel penalty per unit power setting (.01 EPR) error versus flight time (from Williams, 1986) is presented in figure 6. An example of the level of idle thrust mismodeling which can occur is illustrated in figure 7. Flight data showing idle EPR versus altitude during a constant calibrated airspeed descent of the NASA B-737-100 TSRV airplane is compared to modeled EPR based on handbook performance. Significant errors, on the order of .06 EPR, are evident between the model and the actual engine performance. Further the left and right engines are seen to exhibit asymmetric performance at idle. Referring to figure 6, a .06 EPR error at idle would result in a fuel penalty of approximately 25 to 50 pounds, depending on flight time. This equates to a penalty of between 2 and 5 percent of the total fuel for the 150 nautical mile baseline scenario. This penalty is the same regardless of trajectory generation technique.

6.2.3 Wind

Atmospheric wind variations have a significant affect on fuel usage over a fixed range. Figure 8 illustrates the fuel versus time performance for the baseline scenario, computed using the optimal control technique, with several levels of constant wind. As seen in the figure, wind has the effect of shifting the fuel versus time curve both in fuel used as well as in time required. For a fixed flight time, therefore, a headwind results in an increase in fuel and a tailwind requires less fuel.

A comparison of the performance achieved using the constant Mach/CAS versus optimal techniques is presented in figure 9. This figure shows the fuel penalty above optimal incurred by using the Mach/CAS technique for several constant wind conditions. Wind is seen to have little affect on the magnitude of the fuel penalty, with average values of less than one percent for most flight times and wind conditions. The largest penalties are seen to occur at the high tailwind conditions, with approximately 1.5 percent fuel penalty. It should be noted that the constant Mach/CAS technique used the same descent speed schedule for all wind conditions. Some small improvement would be possible by adjusting the speed schedule for wind.

Wind errors result in fuel penalties regardless of the trajectory generation technique. These penalties arise principally from the improper descent range being computed, requiring throttle or speed brake compensation to maintain reference flight path (Williams, 1987). Figure 10 illustrates the average fuel penalties (relative to optimal performance in known winds) for a 200 nautical mile cruise/descent scenario incurred while correcting for mismodeled winds. In general, a mismodeled tailwind will penalize the airplane to a greater extent than a headwind. The reference descent range in a mismodeled tailwind is less than it would be if the wind had been modeled correctly. This results in more time spent at cruise altitude, speed brake required in descent, and correspondingly higher average throttle settings. In mismodeled headwinds, the airplane will descend early with only small increments in thrust above idle needed to maintain the reference flight path. At higher speeds, however, the drag increase associated with increasing Mach number (compressibility drag) demands considerable thrust requirements in mismodeled headwinds. This in turn results in higher fuel penalties at high Mach and large headwind errors. This situation is illustrated in figure 11 for two airplane configurations flying in two levels of mismodeled headwind. For the lower headwind error (25 knots), the fuel penalties are seen to be approximately the same at all flight times for both airplanes. With a 50 knot headwind error, however, a steep increase in fuel penalty is evident at the minimum time end of the time window, corresponding to the highest airspeeds. The two airplanes have significantly different fuel penalties under these conditions as a result of their high speed drag characteristics. The tri-jet configuration was designed for higher speeds and is therefore more tolerant of headwind errors than the twin-jet configuration. This situation highlights the configuration dependence of fuel penalties in mismodeled wind conditions.

6.2.4 Temperature

Figure 12 illustrates the affect of variations in atmospheric temperature on the fuel versus time performance of the airplane. Colder than standard temperatures result in slower true airspeeds for a given Mach number. As a result, higher Mach numbers and greater fuel usage are required for the same flight time. Further, the airplane is cruising at a lower geopotential altitude on a cold day for the same indicated pressure altitude. Less distance is therefore required for descent. The opposite situation is true for hotter than standard temperatures. Lower Mach numbers, less fuel required, and longer descent distances for the same time and distance are experienced on hot days.

Errors in the atmospheric temperature profile during calculation of a reference trajectory using either the optimal or constant Mach/CAS techniques will result in fuel penalties. Figure 13 shows the fuel penalties versus flight time computed for the baseline scenario with temperature errors of plus and minus 20 degrees Centigrade. Actual temperatures 20 degrees hotter than predicted are seen to result in approximately a 6 percent fuel penalty, while temperatures 20 degrees colder produce about a 2 percent penalty. Since required descent range increases in hotter temperatures, unexpected warm

temperatures require additional drag or speed brake in order to fly the miscalculated shorter reference descent path. This situation is similar to an unexpected tailwind where significant fuel penalties are incurred by remaining at cruise altitudes and throttle settings beyond the ideal top of descent point. Conversely, unexpected cold temperatures result in an early descent requiring small thrust increments to fly the longer reference descent path. As with mis modeled headwinds, the fuel penalties are less than would be incurred by descending late. The level of fuel penalties for mis modeled temperatures was found to be the same for the optimal control trajectory generation technique.

6.3 Computational Requirements

The optimal control and constant Mach/CAS techniques described in this paper are both computationally intensive algorithms which would have been impractical to implement on airborne computers just a few years ago. Rapid advancements in both memory and speed of micro computers is now making it feasible to incorporate these algorithms in future flight management computers. It is, however, important to minimize the size and maximize the execution speed of any software competing for the computing resources onboard the aircraft. Furthermore, time-critical functions, such as coordinating clearances with ATC, may dictate speed requirements which the complex algorithms are unable to accommodate. With these issues in mind, the computational performance of the optimal control and Mach/CAS algorithms were compared.

Both algorithms were contained in the same computer program for the analytical studies presented in this paper. Common atmospheric and airplane performance routines were utilized as well as a common routine for integrating the equations of motion. Differences in execution time were then solely due to the different methods used for speed selection during descent. The computer used for the analysis was a desktop micro computer utilizing a 12 MHz Intel 80286 microprocessor with an 80287 math coprocessor.

The Mach/CAS algorithm was found to execute approximately three times faster than the optimal control technique for the same conditions. Execution time for a typical 3D Mach/CAS profile was 6 seconds, with an average of 4 iterations required for a 4D trajectory. This compared to over 17 seconds per iteration required for the optimal control algorithm. While absolute execution times could be reduced by more efficient software coding, the relative difference between the Mach/CAS and optimal techniques would probably remain the same.

Experience with flight tests and piloted simulations of descent guidance algorithms indicates that computation times of less than 10 seconds would be desirable, if not required, to provide timely information to the pilot. This requirement is principally driven by the need to respond to ATC when given a time clearance. The pilot needs to be sure he can comfortably achieve a specified arrival time prior to accepting the clearance. Actual implementation of the algorithm may require a separate or simplified method for determining maximum and minimum time capabilities in order to satisfy the time critical task of communicating with ATC. Once the arrival time window has been established, calculation of the actual profile can proceed at a slower pace.

7. CONCLUDING REMARKS

Two techniques for the generation of 4D descent trajectories have been evaluated. Constant Mach/CAS speed schedules chosen to produce minimal fuel usage have been compared with optimal control speed schedules for typical cruise/descent flight segments. Operational factors consisting of airplane performance characteristics, atmospheric variations, and ATC requirements have been considered in the analysis.

The advantage of using optimal control was found to be less than one percent savings in fuel under most situations. In fact, a fairly broad spectrum of cruise/descent speed schedules were found to produce nearly the same fuel usage for a given flight time over a fixed range. The optimal technique, however, provided nearly a 5 percent increase in time flexibility for the test scenario by permitting operation of the airplane at airframe speed boundaries at all altitudes during descent. This greater time flexibility was found to be eliminated when typical operational speed limits were imposed on the airplane.

Atmospheric variations and mis modeling of winds and temperatures were found to affect both the constant Mach/CAS and optimal techniques in the same manner. Wind has the effect of shifting the fuel versus time performance in both fuel used as well as time required. For a fixed time, a headwind results in an increase in fuel and a tailwind requires less fuel. Wind errors result in an improper descent range requiring throttle or speed brake to maintain reference flight path and speed. A wind error of 25 knots was found to reduce time flexibility by 30 to 40 percent and produce fuel penalties of from 2 to 6 percent. Unexpected tailwinds produced the largest penalties. Temperature variations produced similar results, with warm temperatures reducing fuel requirements and cold temperatures increasing fuel for the same flight time. An unexpected temperature deviation of 20 degrees Centigrade resulted in fuel penalties of 2 to 6 percent, with warmer than expected temperatures producing the highest penalties.

Computationally, the constant Mach/CAS technique is a minimum of three times more efficient than the optimal control technique. Further improvement on the constant

Mach/CAS technique would be possible by empirically modeling the performance of the airplane and simplifying the integration of the equations. The optimal control technique, however, will remain computationally intensive due to the need for minimization of the cost function at each altitude step in order to determine the optimal speed schedule.

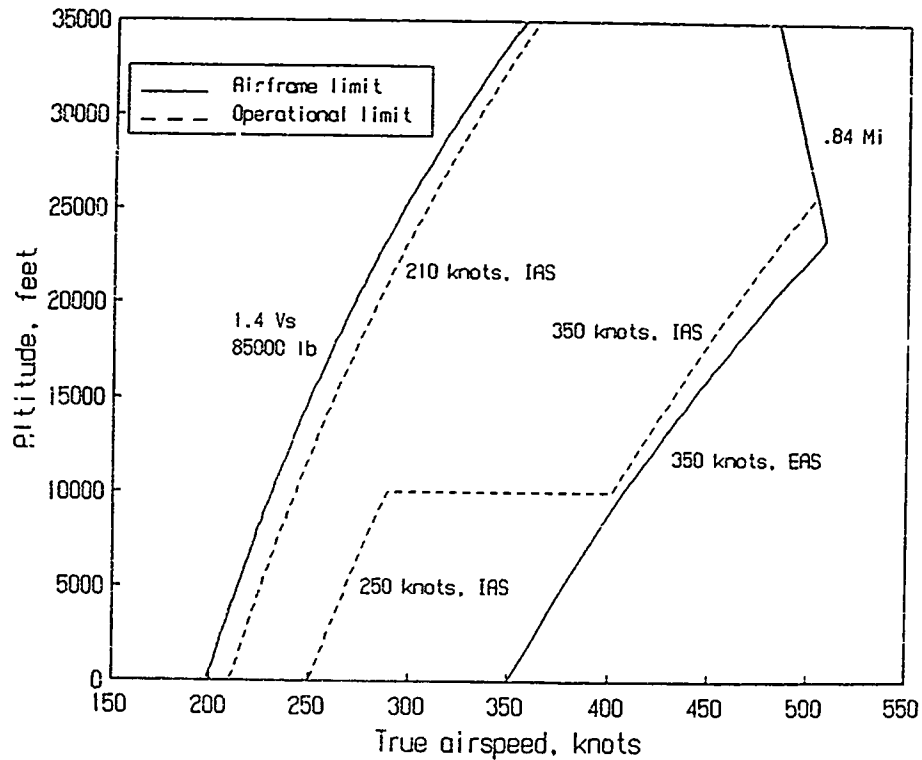


Figure 1: Speed envelope for the NASA TSRV B-737-100 airplane, cruise configuration (flaps and landing gear retracted).

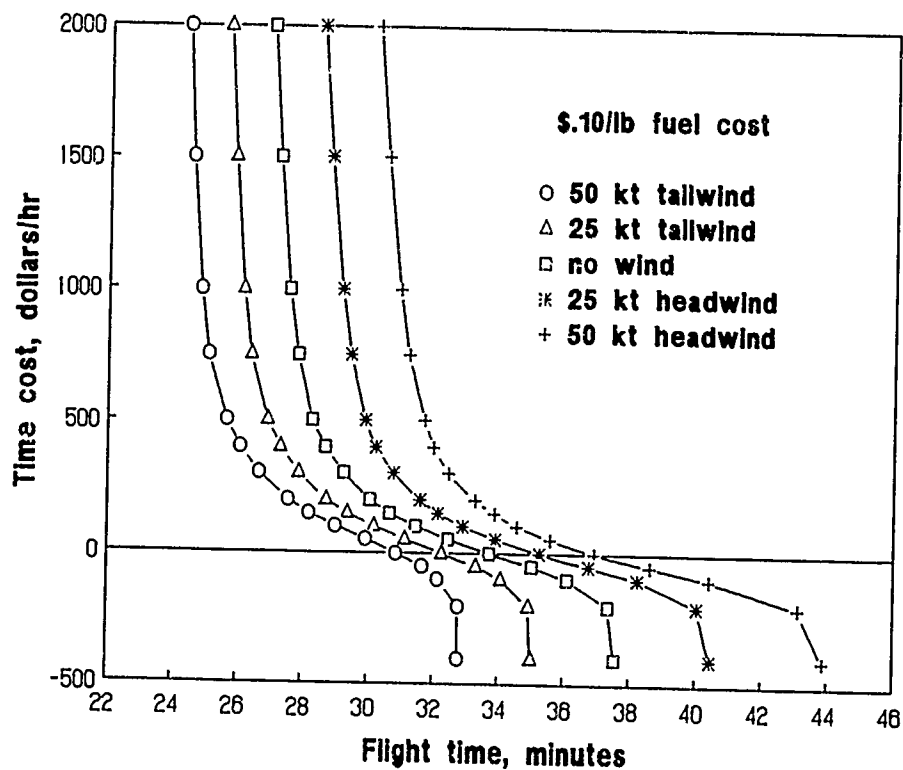


Figure 2: Time cost versus flight time for constant winds, 200 nautical mile cruise/descent, NASA TSRV airplane.

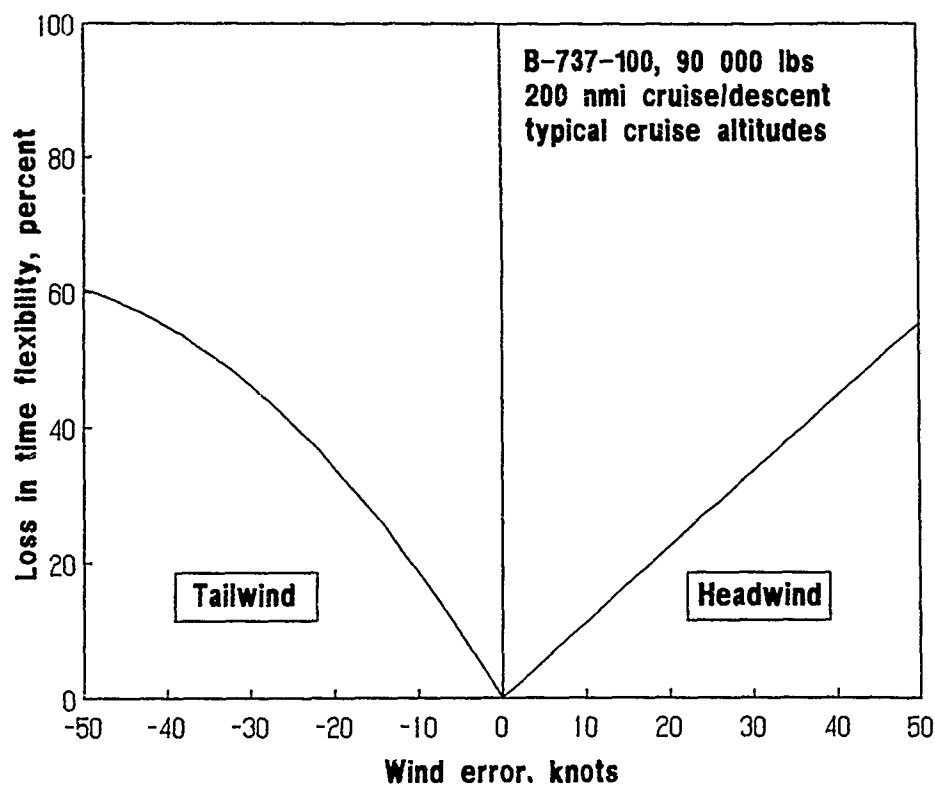


Figure 3: Loss in time flexibility versus wind error, 200 nautical mile cruise/descent, NASA TSRV airplane.

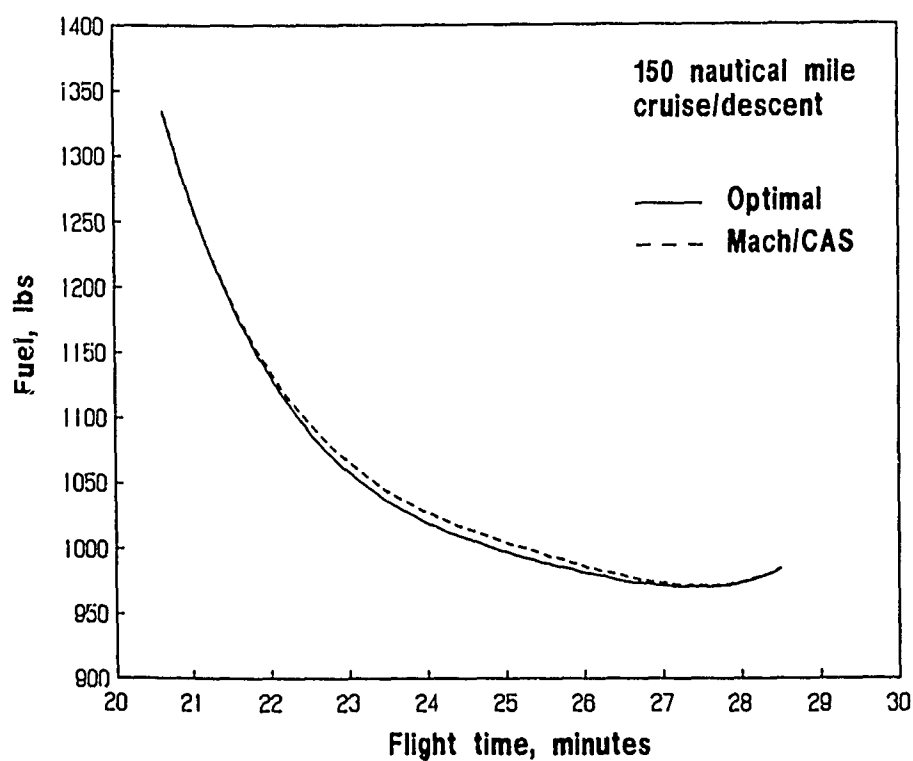


Figure 4: Fuel versus time comparison for optimal control and constant Mach/CAS descent strategies.

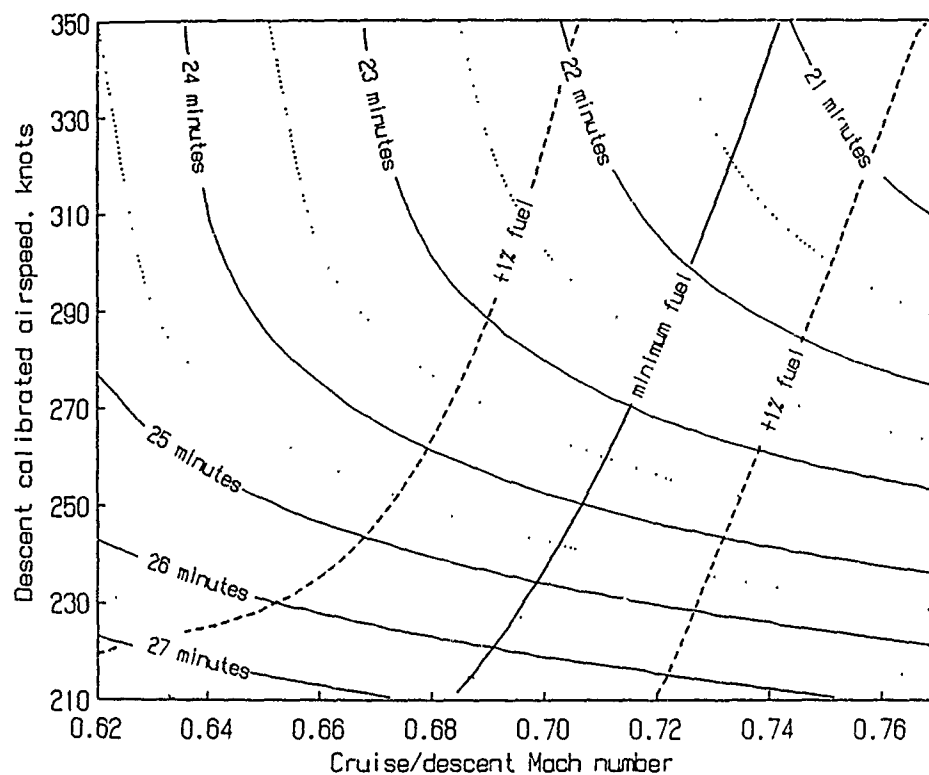


Figure 5: Mach/CAS descent speed schedule contours of constant time for 150 nautical mile range, FL330 cruise, descent to 10 000 feet, NASA TSRV airplane.

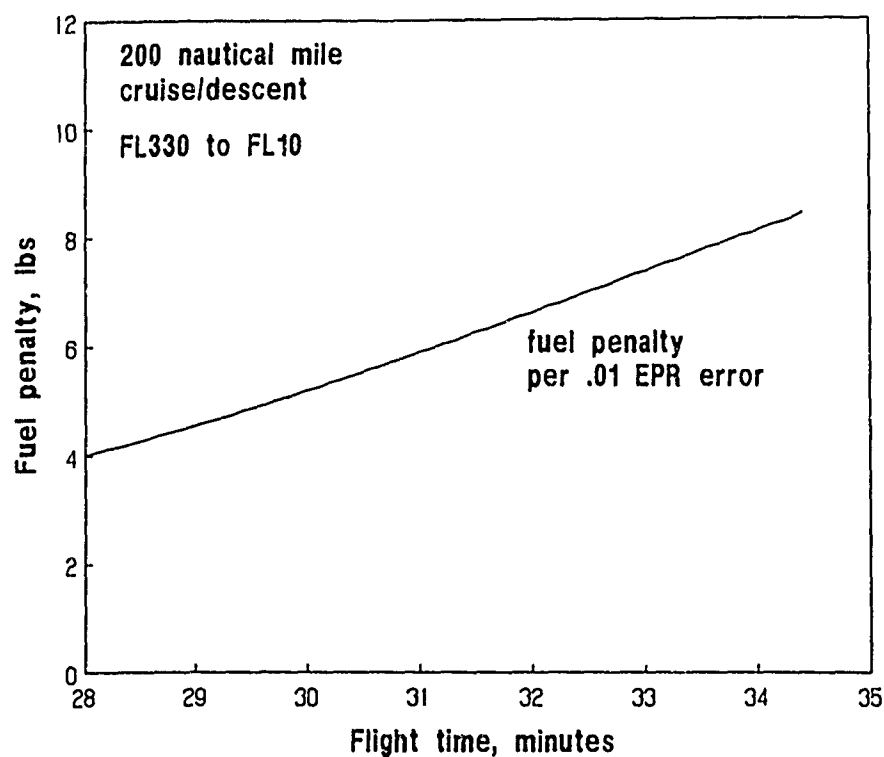


Figure 6: Fuel penalty for mis modeled Engine Pressure Ratio (EPR) at idle for the NASA TSRV airplane.

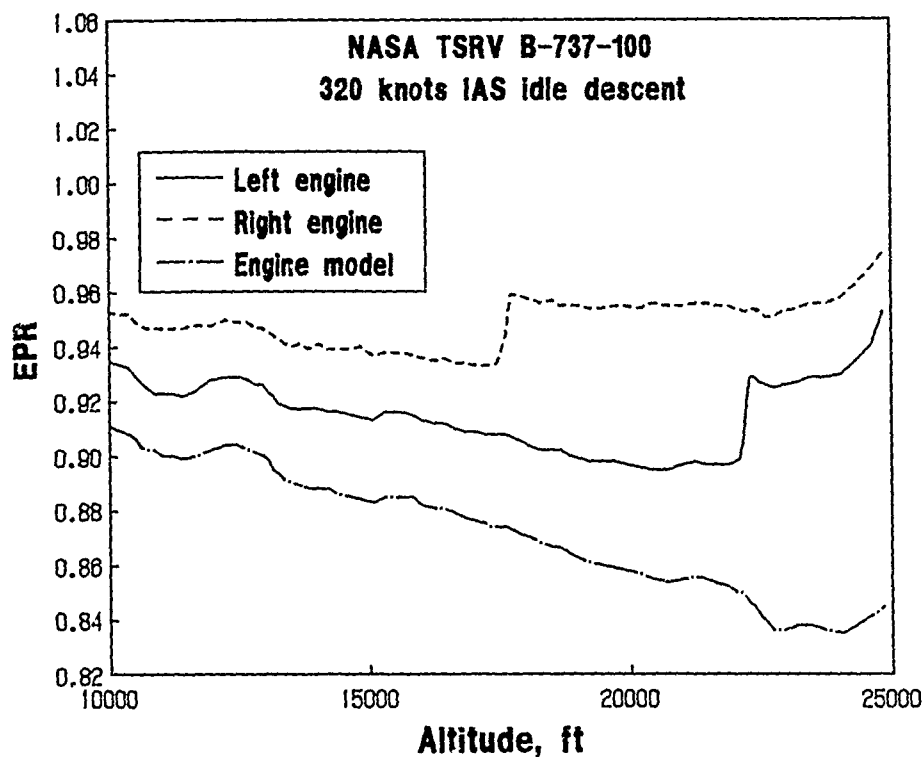


Figure 7: Comparison of actual idle EPR with handbook engine model during constant CAS descent for the NASA TSRV airplane.

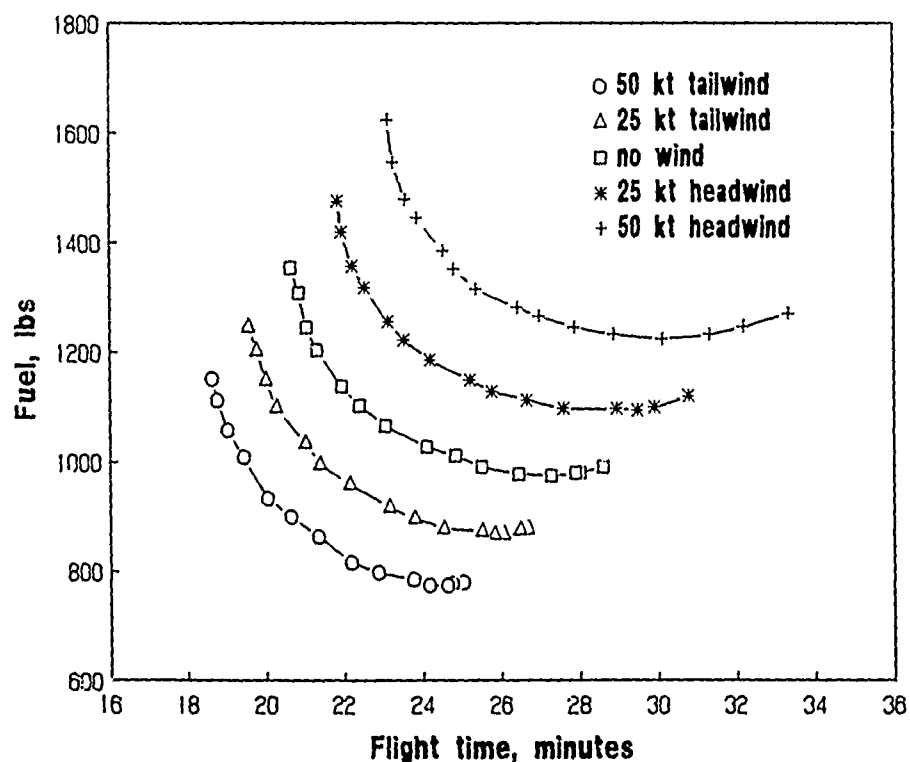


Figure 8: Fuel versus flight time for constant wind, 150 nautical mile cruise/descent, NASA TSRV airplane.

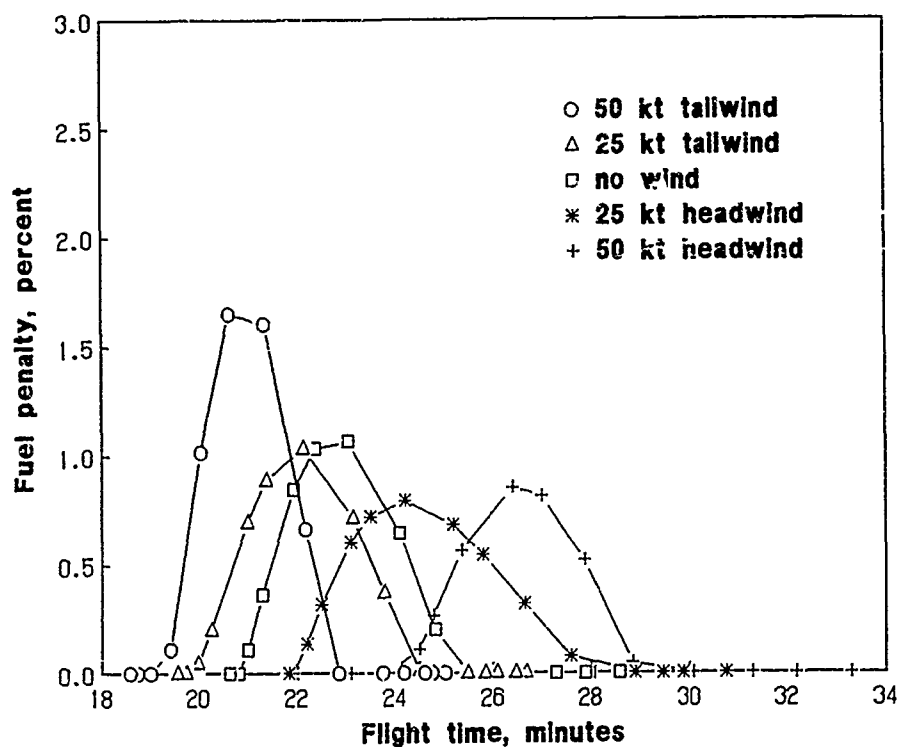


Figure 9: Fuel penalty for constant Mach/CAS compared to optimal descent strategy in the presence of known winds, 150 nautical mile cruise/descent, NASA TSRV airplane.

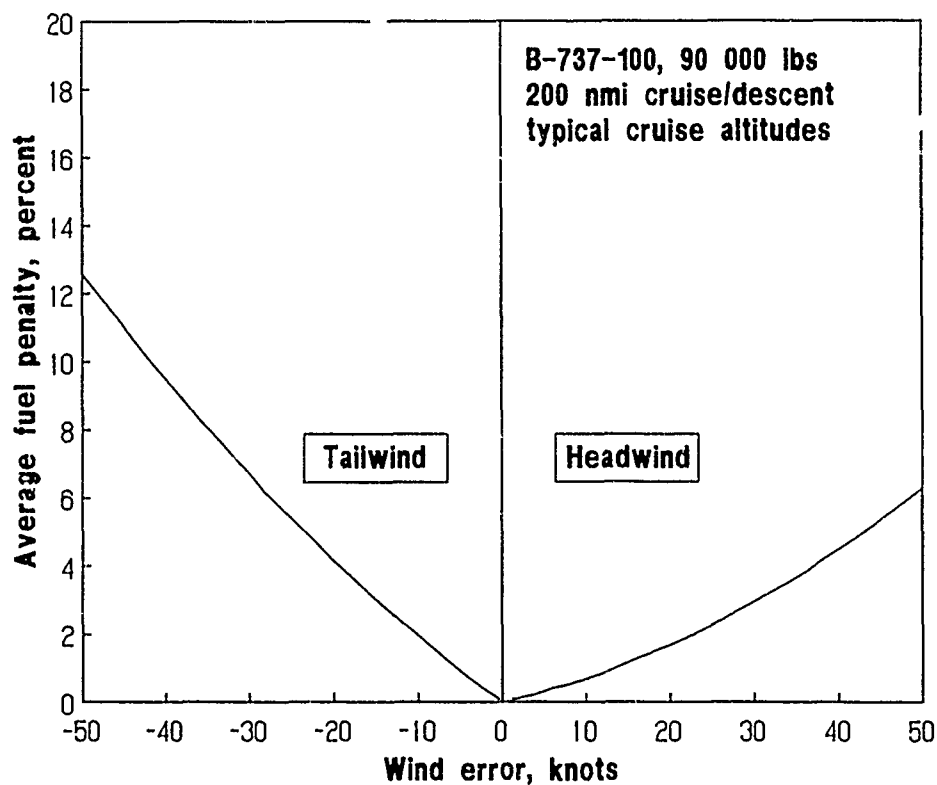


Figure 10: Average fuel penalty versus wind error for 200 nautical mile cruise/descent, NASA TSRV airplane.

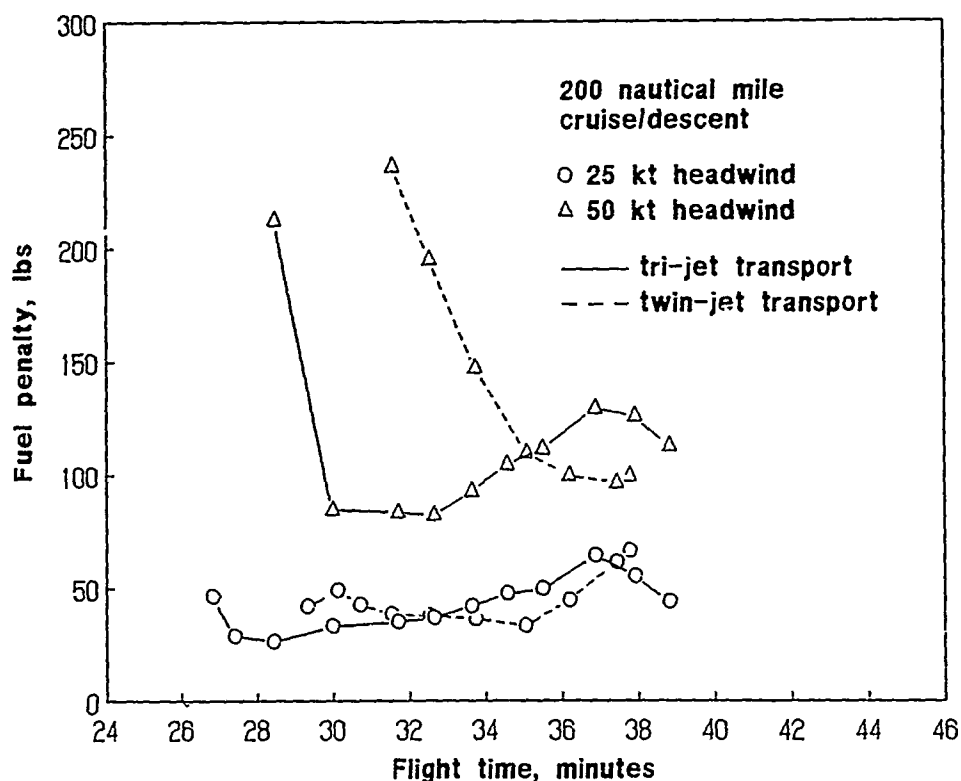


Figure 11: Comparison of fuel penalty versus flight time in mismodeled headwinds for two jet transport airplane configurations.

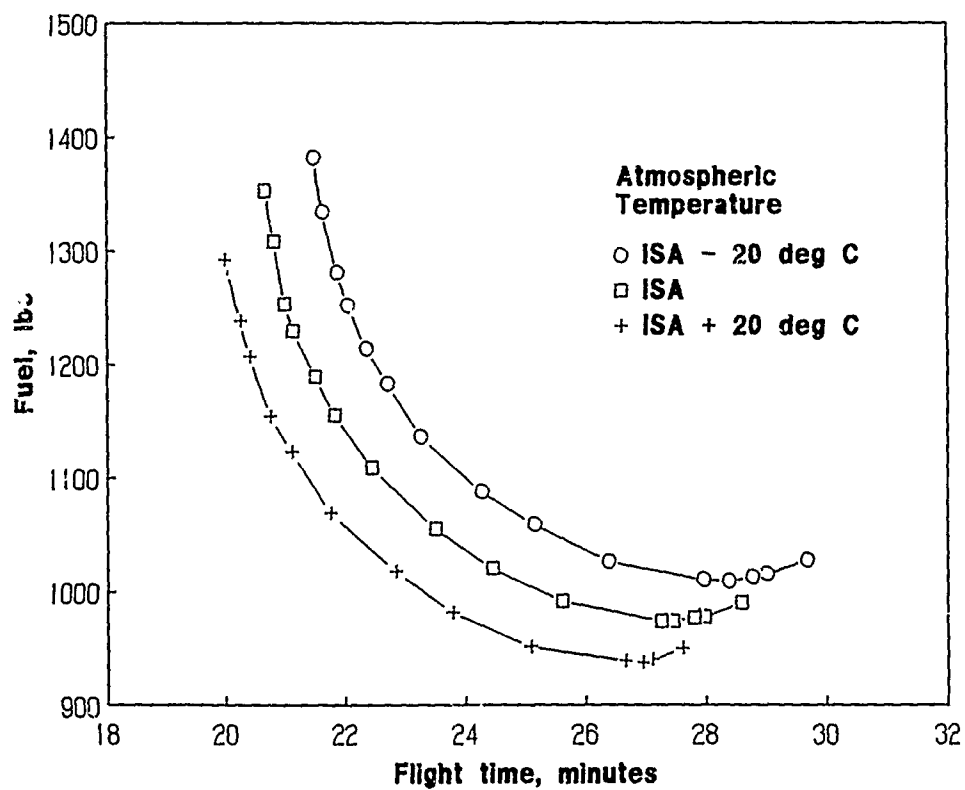


Figure 12: Fuel versus flight time for constant atmospheric temperature deviations, 150 nautical mile cruise/descent, NASA TSRV airplane.

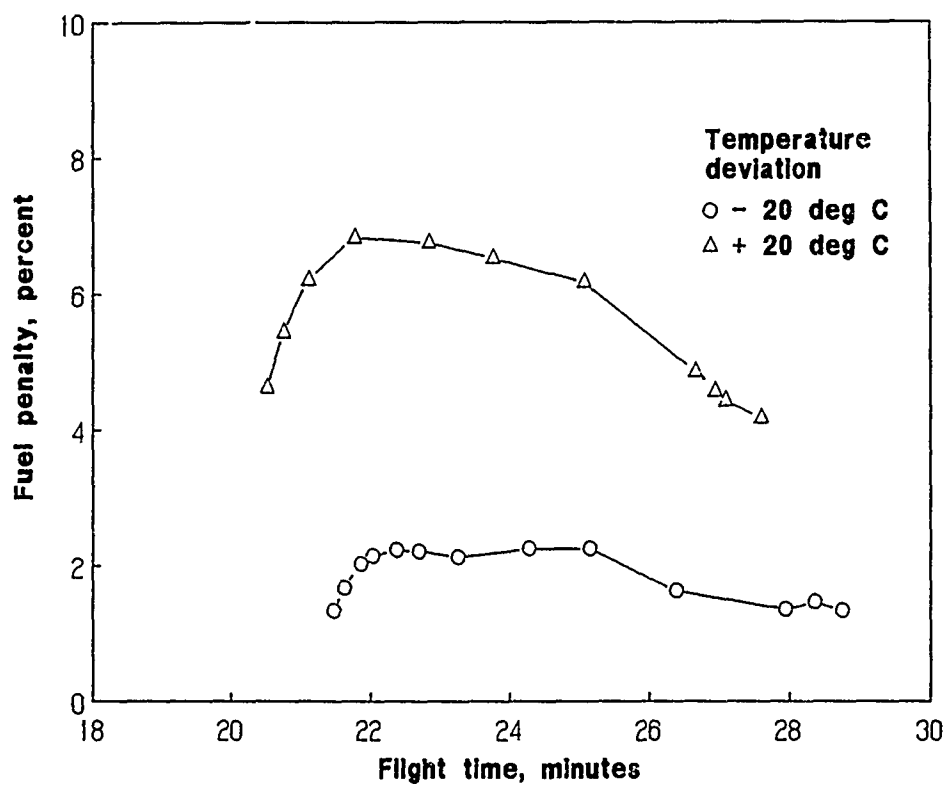


Figure 13: Fuel Penalty versus flight time for mismodeled atmospheric temperature, 150 nautical mile cruise/descent, NASA TSRV airplane.

"4D Descent Trajectory Generation Techniques Under Realistic
Operating Conditions"

Williams, D. - Knox, C.

References

1951

Russel M.H. et al "Flight Test Engineering Handbook," AFTR No. 6273, May 1951.

1954

Rutowski E.S. "Energy Approach to the General Aircraft Performance Problem," Journal of Aeronautical Sciences, Vol. 21, pp. 187-195, March 1954.

1969

Bryson A.E., Ho Y.C. "Applied Optimal Control," Chap. 2, Blaisdell, Waltham, MA, 1969.

1972

Schultz R.F., Zagalsky N.R. "Aircraft Performance Optimization," Journal of Aircraft, Vol. 9, No. 2, pp. 108-114, February 1972.

1977

Calise A.J. "Extended Energy Management Methods for Flight Performance Optimization," AIAA Journal, Vol. 15, No. 3, pp. 314-321, March 1977.

Cunningham F.L. "The Profile Descent," AIAA Paper 77-1251, August 1977.

1978

Erzberger H., Lee H. "Characteristics of Constrained Optimum Trajectories With Specified Range," NASA TM-78519, September 1978.

1979

Lee H., Erzberger H. "Algorithm for Fixed Range Optimal Trajectories," NASA TP-1565, 1979.

Stein K.J. "New Procedures Key to Fuel Savings," Aviation Week and Space Technology, Vol. 111, No. 9, pp. 105-111, August 27, 1979.

"Advanced Systems Aid Profile Descents," Aviation Week and Space Technology, Vol. 111, No. 8, pp. 57-62, August 20, 1979.

1980

Knox C.E., Cannon D.G. "Development and Test Results of a Flight Management Algorithm for Fuel-Conservative Descents in a Time-Based Metered Traffic Environment," NASA TP-1717, October 1980.

1981

Sorenson J.A., Waters M.H. "Generation of Optimum Vertical Profiles for an Advanced Flight Management System," NASA CR-165674, March 1981.

1983

Sorenson J.A., Waters M.H.,
Patmore L.C.

"Computer Programs for Generation and Evaluation Near-Optimum Vertical Flight Profiles," NASA CR-3688, May 1983.

1984

Lee H.P., Leffler M.F.

"Development of the L-1011 Four-Dimensional Flight Management System," NASA CR-3700, February 1984.

1985

Chakravarty A.

"Four-Dimensional Fuel-Optimal Guidance in the Presence of Winds," Journal of Guidance, Control, and Dynamics, Vol.8, No. 1, January-February 1985.

Knox C.E., Vicroy D.D.,
Simmons D.A.

"Planning Fuel-Conservative Descents in an Airline Environment Using a Small Programmable Calculator," NASA TP-2393, May 1985.

Vicroy D.D.

"A Preliminary Study of the Basic Display/Guidance Requirements for Flying Near-Optimal Trajectories," 1985 American Control Conference, Boston, MA, June 19-21, 1985.

1986

Buckham C.A.

"Computational Enhancements to a 4D Algorithm," 1986 American Control Conference, Seattle, WA, June 18-20, 1986.

Credeur L., Williams D.H.,
Howell W.E., Spitzer C.R.

"Advanced ATC: An Aircraft Perspective," AGARD 42nd Symposium of the Guidance and Control Panel, June 10-13, 1986.

Williams D.H.

"Impact of Mismodeled Idle Engine Performance on Calculation and Tracking of Optimal 4D Descent Trajectories," 1986 American Control Conference, Seattle, WA, June 18-20, 1986.

1987

Williams D.H.

"Fuel Penalties and Time Flexibility of 4D Flight Profiles Under Mismodeled Wind Conditions," NASA TM-89128, March 1987.

EXPERT SYSTEMS FOR THE GENERATION OF TERMINAL AREA ARRIVAL PATHS FOR CIVIL TRANSPORT

Robert W. Simpson

Director, Flight Transportation Laboratory

Room 33-412, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology
Cambridge, Massachusetts 02139 U.S.A.SUMMARY

Efficiencies can be gained from dynamic scheduling of the takeoff and landing operations for the system of runways at a major civil airport. It is then necessary to be able to generate a conflict-free set of flight paths which implements this schedule, and which can be easily changed. For landing arrival aircraft, these flight paths start at a known time, point and speed in the descent towards the airport, and end at a reduced speed and time at the outer marker of the final approach to the assigned runway where desired in-trail separations must be achieved.

To generate sets of conflict-free arrival paths, an "expert systems" computer program finds and selects a path feasible within the performance limits of each aircraft from a set of "patterns" which are easily understandable by the human controller. This technique is easily adaptable to the geometric characteristics of different terminal areas and runway configurations, and easily accepts rules and procedural limitations which can be specified and implemented by ATC controllers themselves, as desired.

INTRODUCTION

Advances in the technologies of surveillance, digital communications, aircraft automatic flight control systems, and computer displays, networks, and software now provide the possibility of introducing real-time interactive automated decision support systems for ATC controllers. These support systems have the potential to increase the capacity and efficiency of terminal area ATC procedures, thus lowering time and fuel costs for aircraft operators, decreasing the workload of pilots and increasing the productivity of ATC controllers.

The integration of these technologies will require significant long-term research over the next several years to provide the information necessary to plan a phased implementation of the new ATC software, hardware, and terminal area procedures acceptable to the international aviation community. The efficiencies are associated with creating a pre-planned, time-based ATC process which coordinates the team of enroute arrival, final spacing, runway, and departure controllers. This creates new interactive, real-time automation functions known as Runway Scheduling, Path Generation, Path Conformance Monitoring, Automated Final Spacing, etc. which are designed to assist the controller in his responsibilities for handling air traffic.

This paper describes a preliminary investigation (Reference 1) of the application of Expert Systems software technologies to the problem of Path Generation for aircraft arriving for landing. This approach seems promising compared to previous methods considered for Path Generation (see Reference 2) since it provides a generic method of generating 4-D paths for aircraft, capable of being used in many ATC environments, and capable of easily accepting a wide variety of constraints, rules, procedures, etc.

1. DESCRIPTION OF AIRCRAFT OPERATIONS IN TERMINAL AREA AIRSPACE1.1 General

There are two distinct classes of traffic flows in terminal area operations: a convergent, inbound flow of aircraft intending to land; and a divergent, outbound flow of aircraft after takeoff. The landing flows enter from several directions at various cruise altitudes. Their entry points may be taken as the Top of Descent (TOD) which may be as much as 150 n. miles and 30 minutes away from landing. The airborne paths followed by landing traffic flows are generally monotonically decreasing in altitude and speed. The takeoff traffic flows enter about 5 minutes away from takeoff as aircraft depart from the gate (or ramp) and taxi to the runway along ground paths. The airborne paths followed by takeoff traffic flows are monotonically increasing in speed and altitude.

There is generally a diversity of types of aircraft (such as jets, turboprops, pistons, helicopters) in the traffic flows, causing varying performance limitations in terms of airspeeds, climbs and descent rates, cruise altitudes, desired speeds on final approach, runway length required, etc. There is also diversity in performance of aircraft guidance-and-control systems due to piloting (or levels of automation in onboard flight control systems), which creates significant differences in the expected conformance of aircraft to paths commanded by ATC.

A typical geometrical configuration for terminal area operations at a busy airport is shown in Figure 1. The airport has three runways (two parallel, one crossing) simultaneously in operation with some assignment of landings and takeoffs by type or class of aircraft to each runway. Figure 1 shows four entry fixes at 30-40 n. miles from the airport, where there are holding stacks established at the ends of arrival airways. It shows two departure corridors and a departure zone for initial climb after takeoff. This departure zone has an upper altitude limit imposed to provide

separation from landing aircraft until departure aircraft can laterally clear the landing traffic flows. Then the departure aircraft are allowed to continue their climb so as to pass above various landing zones (which then places an altitude limit on landing traffic). Crossing paths in the horizontal are an inescapable part of terminal area operations. For each runway, there is a final spacing-and-merge zone where aircraft are fed into the common approach path to the runway. Currently, the length of the common approach path, is of the order of 5 n. miles downwind of the runway for Instrument Landing System (ILS) operations. The merge zones extend another 10-15 n. miles.

Figure 1 provides only a meager indication of the complexity of terminal area flight paths at a busy airport since only the nominal, no-traffic paths are shown. We will expand the path description later, but it is important to note that there will be other arrival and departure paths for helicopters, turboprops, and piston engine aircraft. Also, for any given airport there will be several configurations like that shown in Figure 1 as runway directions are changed due to wind, visibility, noise, etc. Indeed, there are hundreds of variations on these several basic operating configurations if we include runway assignment of aircraft landings and takeoffs by type or class of aircraft. In major centers, there may be more than one airport in the terminal area, and there may be a number of low-level, Visual Flight Rules (VFR) corridors for general aviation and helicopter overflying traffic. The real traffic flows within a busy terminal area are much more complex than that shown in Figure 1 and require automation techniques which can completely master this complexity if they are to be operationally acceptable.

1.2 Capacity Limits on Traffic Flow Rates: Delays

ATC separation criteria applied at both the merge area where final approach spacing is established, and at the runway between landing and takeoff operations causes an upper limit or "capacity" to be placed upon average traffic flow rates. There is a landing flow capacity, a takeoff flow capacity, and a mixed runway operations flow capacity.

These capacities are expressed in average operations per hour, and will vary up and down in any given hour due to the actual separations which must be applied to the actual mix and sequence of types of aircraft in that particular hour's traffic flow. There are capacity benefits to be gained in optimally assigning aircraft to runways, in setting sequences of aircraft operations which avoid larger separations, and in adjusting landing arrival intervals to accommodate takeoff operations (Reference 3). This automation function is known as "Runway Scheduling".

As traffic flow rates increase towards capacity flow rates, there will be an increasing percentage of delayed aircraft, and an increase in average delay per aircraft. Approximately, the percentage of aircraft which are delayed equals the percentage of capacity being used. As traffic flow rates peak and temporarily exceed capacity flow rates, 100% of arriving aircraft are delayed in that "busy period". At lower traffic rates, the probability of an arrival finding the runways idle (and therefore experiencing no delay) increases.

To accommodate arrival delays, all paths must be extended in time either by "path stretching" or "speed reduction". For the landing flows, there is a limit on the amount of delay which can be accommodated on airborne paths. As delays get longer, it becomes necessary to initiate path modifications earlier and to use holding patterns. The possibility of unexpected cessation of runway operations due to weather or operational incidents will always require that holding patterns be available in all planned terminal area configurations. For the takeoff flows, lengthy delays can be taken easily in the queue at the takeoff runway, but the physical length of that queue may necessitate holding aircraft on the ramp.

To prevent congestion in the terminal area airspace, the landing flows may be "metered" to control the number of aircraft which are simultaneously present in any sector of the terminal airspace. This is a smoothing process which tries to eliminate short-term peaking in arrival rates by causing early delays to certain aircraft in the landing stream. In a similar vein, arrivals at the runway for takeoff are metered by gate-hold processes which take the delay on the ramp. Delays due to runway capacity are experienced away from the runway when metering functions are in effect.

Irrespective of where or how the delay is applied, once a landing or takeoff arrival has entered the terminal area ATC system, the amount of delay due to runway capacity which it must incur is precisely determined, and the time costs associated with delay are fixed. By taking delays at higher altitudes, or at the ramp with engines off, the fuel costs associated with delay can be reduced.

However, there is a danger of these metering processes causing unnecessary additional delay when taking these delays further away from the runway, due to errors which cause "starvation" of the traffic flows reaching the runway. If the runways go idle due to lack of traffic reaching them during what should be a busy period, then considerable extra time and fuel costs are incurred by all subsequent aircraft of that busy period. Therefore, metering processes have the strategy of controlling the size of airborne and ground queues near the runway to values which are small, but which are always positive, i.e. not all of the estimated delay should be removed early in traffic flow paths if an efficient, minimum-cost terminal area is to be operated.

1.3 Current Control Processes in Terminal Area ATC

Today, terminal area ATC systems operate in a loosely coordinated, unplanned, tactical manner. Enroute Controllers, who are controlling descending arrivals for landing, may receive some metering advisories from a centralized automated process (which now exists at a few airports), but they are

usually simply told by terminal area controllers either that holding will be necessary or that a minimum in-trail spacing should be applied to arrivals at the terminal area. The terminal area Arrival and Final Spacing Controllers accept the resulting traffic flows from the entry points, and execute the merge and final spacing processes with little or no recognition of current takeoff operations on the runway system. (Runway Controllers may ask them for extended spacings for certain peak departure periods when it is desired to insert more takeoffs in the landing traffic flow, but otherwise the landing traffic flow is established independently by the Final Spacing controllers.) In turn, Runway Controllers insert takeoffs into the landing flows in a tactical, ad hoc fashion and are often not sensitive to any requirements from departure traffic flows. Departure Controllers usually accept the departures as arranged by the Runway Controllers.

All of these terminal area controllers are not aware of each others' activities -- they are attempting to work independently of each other. To maintain independence, inefficient procedures are adopted. The existence of excellent computer LANs (Local Area Networks) now allows us to tie this group of terminal area controllers together with instantaneous real-time communication displays.

The common mode of exercising control over arrival and departure paths is called "radar vectoring". While there is a general pattern to the paths being used, there is no precise, predetermined 4-D trajectory or path for each aircraft. At appropriate intervals, the ATC controller specifies a change in heading, airspeed, or altitude by issuing a "vector" command by voice radio communication. Path errors arise from pilot response to these commands, from pilot conformance to the commanded values, and from windspeed variations in location, altitude, and time. The actual 4-D track executed by the aircraft may not conform exactly to the ATC controller's vague intentions, but an adjustment can always be made in issuing the next vector. This non-precision control mode is based upon a 2-D pictorial display driven by radar and beacon surveillance data which provides position and altitude information at 4-5 second intervals. ATC controllers monitor successive intervals to guess at the current direction and groundspeed of aircraft. Current "radar trackers" are straight-line, steady-state systems incapable of providing accurate and reliable groundspeed and direction, or altitude rate for roughly one minute after any commanded change in these quantities, and hinder the application of their output to terminal area automation. Thus, the future 4-D paths of aircraft are only known in a vague, general manner, and actual paths are determined in a real-time, piece-meal fashion as unplanned, tactical situations occur.

1.4 Future Control Processes in Terminal Area ATC

It is clear that there would be efficiencies in transitioning from the tactical, unplanned control processes of current terminal area traffic control processes to more strategic, preplanned control processes. Precise pre-planning of both landing and takeoff operations on a multiple runway system is the core element in moving towards "time-based" ATC system processes. This "Runway Scheduling" function involves the optimal assignment and sequencing of takeoff and landing operations on the multiple runway system (so as to minimize delay, fuel, or finish time). It produces a dynamically changing schedule as new entrants for landing and takeoff arrive, and as operational deviations occur. To perform runway scheduling, the desired final approach airspeeds must be declared early to the ground controllers and considered by pilots as a commitment to be actually flown.

But if a schedule is created, it must be possible to control aircraft so as to execute the schedule with some degree of accuracy and reliability. This means that 4-D paths must be flown by arriving and departing aircraft, i.e. there must be more rigor in the "Path Generation" function which creates feasible 4-D paths to be flown, and increased discipline in the "Path Conformance Monitoring" function whereby aircraft adherence to their pre-planned, assigned paths is monitored.

"Path Generation" involves determining a complete 4-D arrival path which is feasible in terms of airspeed, climb/descent speed, etc, and which is free of conflicts from all other existing planned terminal area flight paths. It cannot be done onboard each aircraft -- because of the need to be conflict-free, it is necessarily a centralized, ground-based process. Since the schedule and the associated set of conflict-free paths are dynamically changing, it will not be efficient to commit to a fixed 4-D path early in the descent phase of aircraft arriving for landing, and landing arrival paths must be generated in a manner to allow flexibility in rescheduling. At some point closer to landing, the schedule and paths may become fixed and at that time a complete 4-D path could be transmitted to the aircraft (if it is capable of executing a 4-D flight path automatically). It is not possible to predetermine a 4-D path for landing arrivals from TOD points because the landing and takeoff schedule cannot be determined at that time. Takeoffs have not yet entered the schedule.

"Path Conformance Monitoring" involves ground monitoring of the capability of an aircraft to follow a 2-D, 3-D, or 4-D path, given its navigation and guidance systems. In the traffic, there will always be a mix of varying levels of conformance capability. Conformance errors are one source of operational deviations. As each deviation occurs, there is a choice between regaining the planned path, or generating a new path from the current position. There are other operational deviations caused by missed runway exits, missed approaches, new takeoff insertions, runway closures and changes, etc. Path Conformance Monitoring is a new automation function to be added to future terminal area processes when paths become explicitly defined.

Finally, if a planned, time-based ATC process is to be introduced to future terminal area ATC processes, it will be necessary to provide improved communication to coordinate the activities of the arrival, final spacing, runway, and departure controllers of the current ATC organizational structure so that they are all aware of the plan and can contribute to it. This is possible with digital communications and computer displays using today's technologies in computer networking. There may be significant organizational restructuring of terminal area sectors and responsibilities as such capabilities are introduced.

Within the framework given above, there are still many issues and alternatives for future terminal area ATC control processes. For example, what degree of control shall the ground air traffic control exert over the aircraft path? Will a complete 4-D path be transmitted to the aircraft as modified from time to time, or only a partial description of the path? Shall paths be defined in 2-D, 3-D, or 4-D, or a mix of different ways depending on the capabilities of the aircraft? Will the air traffic controller and the pilot always be integral elements of the control process? (Note that the MATCALS terminal area ATC system under development by the US Marine Corps (References 4,5) specifies both datalinked cross pointer display information to guide the pilot on a complex path, and also an automatic mode which sends computer-generated ground commands directly to the AFCS (Automatic Flight Control System) of modern navy tactical aircraft. Marine ground controllers will be able to draw desired 2-D terminal area flight paths on their display screen with a light pen, and specify altitudes at way points; the pilot retains control over throttles, airspeed and disengage button!)

Given the presence of multiple ownership of civil aircraft, including international ownership, it will be necessary to reach agreement on an internationally accepted, long-term plan for introducing phased degrees of automated control processes in the terminal areas of busy civilian airports. There is a need for extensive research to support the development of such a plan.

2. PROBLEM STATEMENT — PATH GENERATION FOR LANDING ARRIVAL

The problem of 4-D path generation for landing aircraft may be stated as follows:

Given:

- 1) a schedule of landing and takeoff operations for a multiple runway system
- 2) the performance limitations of aircraft in terms of airspeed, climb/descent rate, runway length, etc.
- 3) the pertinent ATC separation criteria stated in terms of time, distance, and altitude
- 4) the position and airspeed of arriving aircraft as they enter the terminal area ATC system

Find a set of feasible, conflict-free flight paths for landing arrivals which:

- a) meets the schedule
- b) can be easily rescheduled to accommodate missed approaches, changes of runway, etc.
- c) is easily understood by controllers and pilots
- d) uses the 2-D, 3-D, or 4-D guidance capabilities of aircraft in the mix of arriving traffic
- e) can accept interventions by controllers which modify the arrival paths in both short term and longer term
- f) accommodate pilot requests for arrival paths, runways, etc.

In developing such an interactive automation system for ATC, it is now possible to display quickly and briefly for the ATC controller the proposed path for any aircraft, with its encounters (an encounter is another path crossing this path at minimal or specified separation), or to select a small subset of co-existing planned paths for display. The operational automation system must be easily transferable to various airports, and be capable of being quickly and easily modified in the field to accommodate the inevitable changes in operating environments and procedures which occur on a daily and monthly basis at any given airport. It must be generic in nature to avoid writing a software system customized to every configuration and airport, and every change in operating requirements. It is even possible to envision a system which can be tailored to some degree by each individual controller to match his style of controlling traffic.

3. AN EXPERT SYSTEMS APPROACH TO HANDLING PATH GENERATION

The requirements established above suggest an "Expert Systems" approach to constructing an automated path generation system. In this approach, an expert system "shell" or "core" or "software system" is created which provides a generic means of easily creating sets of landing arrival paths called "Patterns". It provides a simple means of selecting a 4-D path from a Pattern, given aircraft performance. It also provides an easy method to impose constraints arising from ATC practice and procedures, ATC separation criteria, controller intervention, etc. on the path selection process. In creating the Expert System, it is accepted that not all possible Patterns are yet known, and that not all future constraints, interventions, etc. have been identified. A "software system" is provided by the designer so that later "knowledge engineers" can use it to tailor its application to the specific requirements of operations of any particular terminal area. An analogy is the provision of a higher order computer language by a computer systems designer for later application codes written by engineers. The computer languages of LISP and PROLOG are used in Reference 1 to begin the initial construction of such a "software system" for ATC Path Generation.

A "Path" can be viewed as a sequence of segments. Each segment is a turn, or a deceleration, or a descent, or a straight and level path, and each has a start and end time. The end time of one segment is the start time of the next segment. Note that each segment corresponds to a "radar vector" where a change in heading, altitude, or speed is commanded so that a Path can be viewed as a sequence of "radar vectors". The origin of a path is the current position and altitude of the aircraft. The destination for a landing path is the runway threshold at the scheduled time. At both the origin and destination, there is an estimated groundspeed and direction. For landing aircraft, there is a declared airspeed on final approach which must be reached before the outer marker of the ILS. Once the outer marker and glide path are reached, there can be no further

changes commanded by ATC since the pilot or autopilot is expected to fly in a stabilized, steady condition on the final path segment. Note that a "Path" is defined in four dimensions: speed and altitude can be varied on the same 2-D path to create a "new" Path.

A "Pattern" consists of a fixed sequence of segments where the timing of the segments, or the heading, speed, and altitude of those segments can be selected to get a particular path belonging to the Pattern. This selection also includes the possible elimination of any segment (eg. a speed or altitude or heading change of zero). These Patterns are similar to the current STARS (Standard Arrival Routes), and can be published to allow pilots and controllers to have a mutual understanding of the arrival paths, at least in general terms.

Figure 2 provides examples of two Patterns for the nominal arrival paths from the northeast and southwest entry points to the runway 01L shown in Figure 1. This expands the nominal paths shown in Figure 1, and actually only a few discrete paths are shown in Figure 2. Other typical Patterns for runway 01R are shown in Figure 3. A set of Patterns is called a "Configuration" since it corresponds to any operating configuration of the terminal area airspace.

The actual number of Paths in a Pattern is infinite since the timing of speed, heading, and altitude changes can be chosen in a continuous domain. To be consistent with current practice, speed changes are quantized to 5 knots, heading changes to 5 degrees, and altitude changes to 500 foot intervals.

There are multiply redundant degrees of freedom in selecting a Path to meet the requirements of any aircraft. For example, consider the "Overhead" Pattern from the northeast entry point of Figure 2. There are seventeen path parameters which determine the actual Path flown within this Pattern:

- 1,2 initial descent time and altitude
- 3,4 initial speed reduction and time
- 5,6 second descent time and altitude
- 7 overhead divergent heading
- 8,9 divergent descent time and altitude
- 10 lateral offset of downwind leg
- 11,12 downwind speed reduction and time
- 13 time of turn to base leg
- 14 time of turn to intercept leg
- 15 time of speed reduction to final approach airspeed
- 16 minimum time deviation for any segment
- 17 minimum length of straight 2-D path segments (to allow radar trackers to establish groundspeed and direction)

For any aircraft and desired origin-time and destination-time, there are many degrees of freedom in finding a path. An ATC controller can easily impose many further constraints in real time; for example, that there should be no initial descent until 5 miles from a point overhead the airport, and/or that overhead passage should be below 5000 feet, and/or that the lateral offset of the downwind leg be 4 nautical miles from the runway centerline. Alternatively, the ATC controller may wish to impose general rules or strategies for path selection, e.g. to declare a nominal offset for the downwind for normal aircraft, reserving an inner downwind offset for slow aircraft (say, less than 125 knots), and an outer downwind offset for faster aircraft (say, the Concorde).

Even with these additional rules and constraints, there are still multiple residual degrees of freedom to define arrival paths which maintain safe separation from all other paths and still arrive at the outer marker at the desired time, speed, and altitude. The computer process of selecting these residual parameters in the Expert System consists of an "ordered search process" which has priorities or preferences for "nominal" certain values of heading, speed, and altitude, and which may depend on other factors such as the sequence of landings and takeoffs on runway 01L, or aircraft entry points. The Path Generation process begins with this "nominal" phase.

As each segment of a potential nominal path is defined, it will have a start and end time. If there is a "time overlap" with certain segments of previously determined arrival paths in certain other patterns, then a "conflict identification" phase of the Path Generation process proceeds to see if it also conflicts in other dimensions of altitude, and/or lateral distances. If segments are found to be in conflict, then a "conflict resolution strategy" phase is entered to specify pertinent path parameters depending on the situation for these conflicting segments. The Path Generation process then returns to continue the ordered search for a conflict-free path. For example, in Figure 4, the overhead divergent segment of a path from the northeast entry point is found to be in conflict with an arrival from the northwest entry point destined for runway 01R. In this case, the "conflict resolution strategy" specifies the maximum altitude of the divergent segment and this necessitates changes of the descent time and altitudes for the second and initial descent segments. Similarly, a conflict with another departure for runway 01R at the northeast entry point delays the initial descent point, thereby causing the initial and second descent segments to join into what appears to be one continuous segment. Later in this arrival path, yet another conflict in the base leg area exists with an arrival from the southwest entry point to runway 01L. In this case the use of altitude separation has been ruled out by the ATC controller and the lateral offset of the downwind leg is increased to allow this prior landing to safely cross in front of the example aircraft (a message is sent to the ATC controller explaining why his desired offset is not being used). Alternatively, a speed reduction might have resolved this base leg conflict. The path adjustments to maintain correct delivery at the outer marker in spite of these three "conflicts" can still be made in selecting the divergent heading, downwind deceleration, turn to base, etc.

There are still an infinite number of conflict-free paths to be found. In this example, there was no initial speed reduction imposed upon leaving the entry fix. A single speed reduction on the first segment might have contributed to eliminating both the overhead and base leg conflicts due to a later arrival in these areas, but would perhaps cause problems in the conflict at the entry point with the arrival for runway 01R. There are many ways to create conflict-free paths, and many useful, generic "rules" to develop in establishing the Expert System. Note that these Paths are selected sequentially — a conflict-free path is found given that all the conflict-free paths previously determined are not to be changed. This avoids a combinatorial explosion in the size of the search process for finding a Path.

In the "Conflict Identification" phase, notice that there are Patterns where no conflict between any segments can ever occur. For example, the Base Fan Patterns for runways 01L and 01R shown in Figures 2 and 3 can never conflict until their arrival on the runway centerlines, and the runway scheduling process will have resolved the conflict at that point. For every segment in any Pattern, the search for conflicts can be pre-determined to be made amongst certain other segments in certain other Patterns of the current Configuration. The first test is whether or not any of these segments co-exist in time with this segment. This reduces the search size for conflict identification.

For cases where there are successive landings on the same runway and the second aircraft is going to fly a slower approach airspeed, paths can be constructed to ensure a merge to the runway centerline as near to the outer marker as possible, perhaps using altitude separation at the merge. In this special "slow merge" case, it is also possible to recommend imposing a higher final approach airspeed for certain slow aircraft when the available runway length is clearly excessive. If the controller gains concurrence from the pilot, a suitable arrival path predicated on the agreed approach speed will be found, and the clearance to fly the approach will contain this speed restriction when it is time to transfer control to the runway controllers. However, when Runway Scheduling is in effect, there are many situations where takeoffs can be inserted in the landing traffic flows so that the inefficient, large gap at the runway ahead of a slower landing aircraft can be efficiently utilized, thus avoiding the necessity of imposing these special "slow merge" procedures which maximize runway capacity.

All of the paths shown in these examples and in Reference 1 have started at the entry points to the terminal area. Obviously, they can start earlier during the descent on airways towards the entry point and can include the possibility of a preplanned number of "racetrack loops" in the holding pattern at a given altitude before continuing into the terminal area airspace. Such an extension would allow a smooth handling of interruptions in runway activities, e.g. closure due to reduction in ceiling and visibility, or change of runway directions. Note that as weather drops through current category I, II, and III limits, some aircraft will be able to continue to land while others must be held awaiting diversion or improvements in the weather. It is necessary for the Path Generation process to be able to go into "holding" in a smooth continuous manner, to be able to minimize the number of holding aircraft, and to work towards eliminating holding aircraft as quickly as capacity and traffic flow rates allow. It is not possible to monitor aircraft conformance within a holding stack, and difficult to control precisely the exit times of holding aircraft.

4. DYNAMIC OPERATION OF MERGE AND FINAL SPACING

The generation of pre-planned 4-D landing paths from some point in descent is an example of a metering process which distributes delays along the arrival path. Since metering will plan to leave some small delay to be taken at a point near the runway, it is not necessary to conform to these paths with a high degree of precision until the final three segments, i.e. turn to base leg, turn to intercept leg, and reduction to final approach speed. Aircraft with 4-D capabilities in their AFCS would be capable of executing these final three segments by themselves. Other aircraft would need assistance from the ground in timing both the turns and airspeed reduction. This requires good Conformance Monitoring from the ground, and timely, efficient, precise communication between the aircraft and ground. If digital communications are available, it would be useful to send current heading (or track direction) and current airspeed (or groundspeed) from the aircraft to the ground to assist in tracking of maneuvering aircraft, and thereby provide "intelligent" surveillance tracking for the Conformance Monitoring function. Digital Communications would also be used to uplink path commands and improve timely response to these last three commands. Improving the precision of control over these final three segments is essential to achieving precision in executing the runway schedule, and thereby operating at full capacity rates. There is no capacity benefit from good conformance to earlier segments, but some lower degree of conformance is still needed to ensure safety.

The creation of an automated ground control process for "Final Spacing" of landing aircraft is not a candidate for an Expert System approach. It can be a distinctly separate deterministic control process associated with the Path Generation function described above. Because of conformance errors and operational deviations, it must be dynamic in nature and capable of making small adjustments in retiming of runway operations as small conformance errors occur.

However, there will also be sudden large adjustments in retiming and rescheduling runway operations for aircraft already in the Merge and Final Spacing Zone. These result from the inevitable occurrence of unexpected operational deviations at the runway. While these may be rare events, any automated system for generating ATC flight paths must be capable of handling them in a smooth, continuous manner before it is operationally acceptable. The Expert System approach can be extended to handle these events.

Examples of these unexpected operational deviation events are: landing aircraft missing their expected exit due to late touchdown, poor braking, poor visibility, etc, thereby spending more time on the runway, and blocking a planned takeoff insertion; a missed approach declared by one, or

several aircraft (if a sudden change in visibility or runway icing conditions occurs); a wind change requiring closure of a runway for landings; an aborted takeoff; an airborne emergency necessitating an immediate landing (and perhaps subsequently a blocked runway).

All of these events require a sudden rescheduling of runway operations, both landings and takeoffs. For a single landing aircraft, a missed-approach path at low altitudes must be found from the current position on approach back to the same runway (or perhaps another runway in visual conditions). This causes a rescheduling of all operations, and a sudden insertion of this aircraft into previously-planned landing sequences. There are many issues -- What are the restrictions defining various missed approach paths by aircraft type or conformance capability? What is the best re-insertion sequence to minimize loss of capacity?

For a takeoff aircraft, a missed insertion requires rescheduling of all takeoff operations and perhaps minor adjustments of landing gaps to accommodate the new takeoff insertion sequence. For a sudden unexpected runway closure, it must be possible to handle several sequential missed approaches. For a planned change of runways, there is the problem of deciding on the best aircraft to be the last landing on the current runway and the best aircraft to be the first operation on the new runway. In between these two aircraft, there may be several landing aircraft which execute missed approaches (or modify their planned paths to go to the new runway) and which must be rescheduled into the new landing traffic flow. As this is executed, there is a similar problem in scheduling takeoff operations on the old and new runways. Holding of aircraft arrivals at the entry points may suddenly be part of the new plan. The possibility of such a sudden event requires an implicit assignment of holding altitudes on all planned landing arrival paths so that holding occurs smoothly. These unexpected deviations have a major influence on the design of Patterns.

Failure to handle these unexpected events automatically means that human controllers will take over and impose some ad hoc plan which is likely to be inefficient, but safe and simple. Given a manual takeover, there is a problem in re-initializing the automated scheduling and path generation functions. Given the short-term dynamics of potential operational deviations, these are not simple automation systems, but handling these events is necessary for operational acceptance. There may be a general requirement to build an interactive automation system in which the controllers can easily intervene at any point to resume manual operation, and can also easily restore at any point various levels of the automation functions of runway scheduling and path generation. Re-establishing automated operations must be easily accomplished and practiced during normal operations.

A hypothetical example of rescheduling for a single missed approach is shown in Figure 5. An aircraft has declared a missed approach on runway 01R during a busy period where there is a continuous stream of planned landings from the northeast and southeast entry points. These streams are not a flow of equally spaced arrivals since there may be several successive arrivals from one entry point and corresponding gaps in the arrival flow from the other entry point. The missed approach may take up to 15 minutes to reach the Merge and Final Spacing Zone (there may be a minimum time desired to allow the pilots time to recover safely and execute the procedures of a Missed Approach). In the interim several aircraft have landed. Because of a gap in the arrival flow from the southeast entry point, the twelfth aircraft behind the missed approach aircraft can be slowed substantially without affecting arrivals behind it. Due to rescheduling, the missed approach is inserted as the tenth landing after its original position, causing the original tenth to be switched to the eleventh position since its downwind leg can be extended without conflict and since there are efficiencies in rescheduling the takeoffs. The "trombone" extension of the downwind leg is quickly brought back to a normal position by the slowdown which was applied to the twelfth landing arrival, as it now arrives later and can use a closer base leg to follow than the new eleventh arrival from the northeast entry point. Similar slowdowns have been applied to three subsequent arrivals to successfully avoid any holding, and there are two takeoffs now being inserted later than originally planned. To impose all these changes in the few minutes after the missed approach is a challenge. There also may be constraints from communications capabilities, which must be considered to ensure that all changes can be transmitted to aircraft in a timely fashion.

5. SUMMARY AND CONCLUSIONS

Terminal area ATC operations around a busy civil airport are complex. Introducing automated decision support to assist ATC Controllers in decision-making will require a significant effort in research to provide results adequate to allow planners to agree upon a phased approach of implementation. The new software technologies seem to provide a basis for developing generic systems capable of handling this complexity over a wide variety of terminal area configurations and procedural practices, and adaptable to long- and short-term operational changes at a given airport.

There are many real-world operational events which need to be considered since they direct the Expert Systems methodology into directions which provide capabilities necessary for operational acceptance. Similarly, since the maximum capacity of any runway system is achieved when interdependent takeoff and landing operations are scheduled, it is necessary to consider both takeoff and landing operations and multiple runway systems as essential parts of the research problem since they will direct the methodologies to be explored.

In this paper, the generation of departure flows has not been addressed, but when introduced this will affect the generation of paths for landing aircraft. While the research activities must consider the full problem at the outset, a phased program implementation and testing must be achievable.

REFERENCES

1. Trivizas, D.A., Parallel Parametric Combinatorial Search - Its Application to Runway Scheduling, MIT, Flight Transportation Laboratory Report R87-4, 1987.
2. Wilz, R.R., Warnock A., MATCALs: Expansion of Capacity for Expeditionary Airfields, Paper at the 20th Guidance and Control Panel Symposium, AGARD Meeting at Cambridge, Ma., May 1975.
3. Development of Scheduling and Flight Path Generation Algorithm for MATCALs, Technical Report to Naval Electronics Systems Command, Washington D.C. by Flight Transportation Associates, March 1983.
4. Sadoune, M., An Expert System for Generating Terminal Area Flight Paths for Arriving Aircraft, MIT, Flight Transportation Laboratory Report R87-10, 1987.
5. Simpson, R.W., Advanced Automated Control of Aircraft in Terminal Airspace, MIT, Flight Transportation Laboratory, First Year Progress Report (unpublished) under NASA Grant NAG-2-190, September 1983.
6. Simpson, R.W., Odoni, A.R., Salas-Roche, F., Potential Impacts of Advanced Technologies on the ATC Capacities of High Density Terminal Areas, NASA Contract Report 4024, October 1986.
7. Erzberger, H., Tobias, L., A Time-Based Concept for Terminal Area Traffic Management, AGARD CP-401, November 1986.
8. Credeur, L., Williams, D.H., Howell, W.E., Spitzer, C.R., Advanced ATC: An Aircraft Perspective, AGARD CP-401, November 1986.
9. Hormann, A., Accuracy Requirements for Terminal Area Navigation, Seminar on "Information in Air Traffic Control", Capri, October 1985.

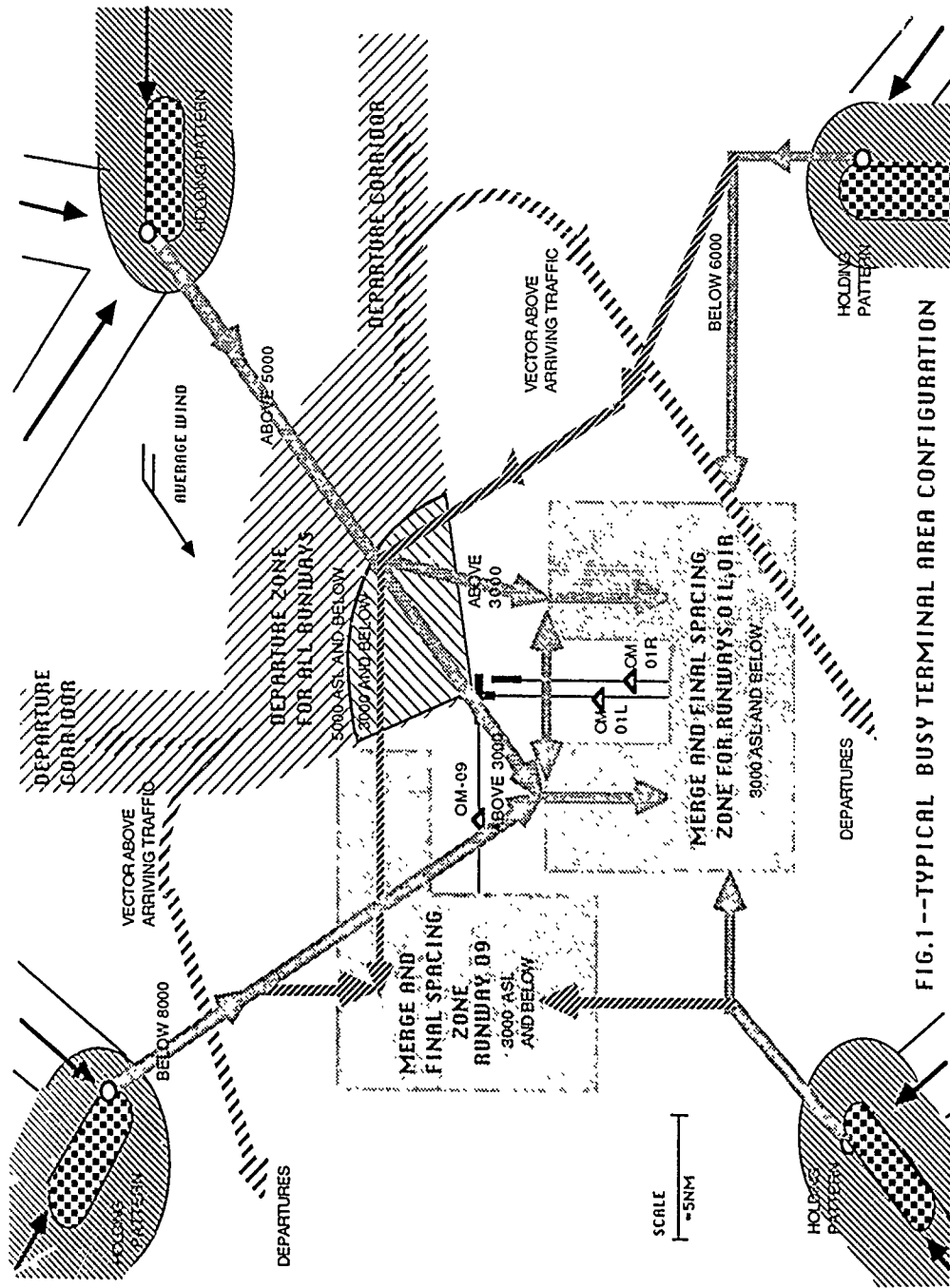
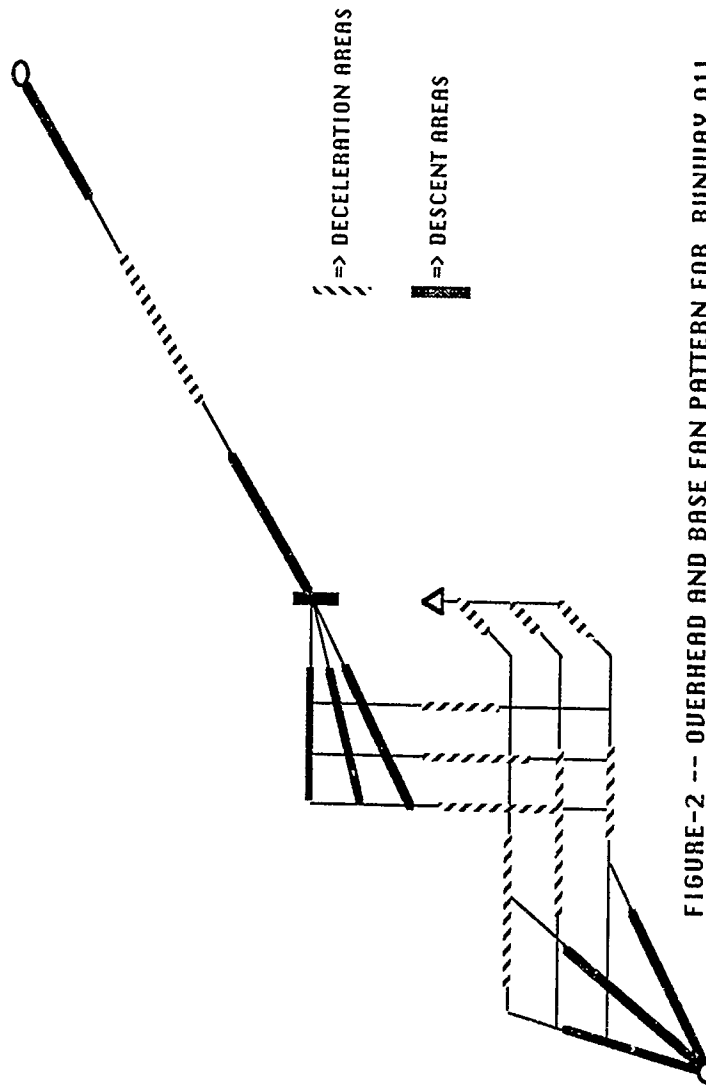
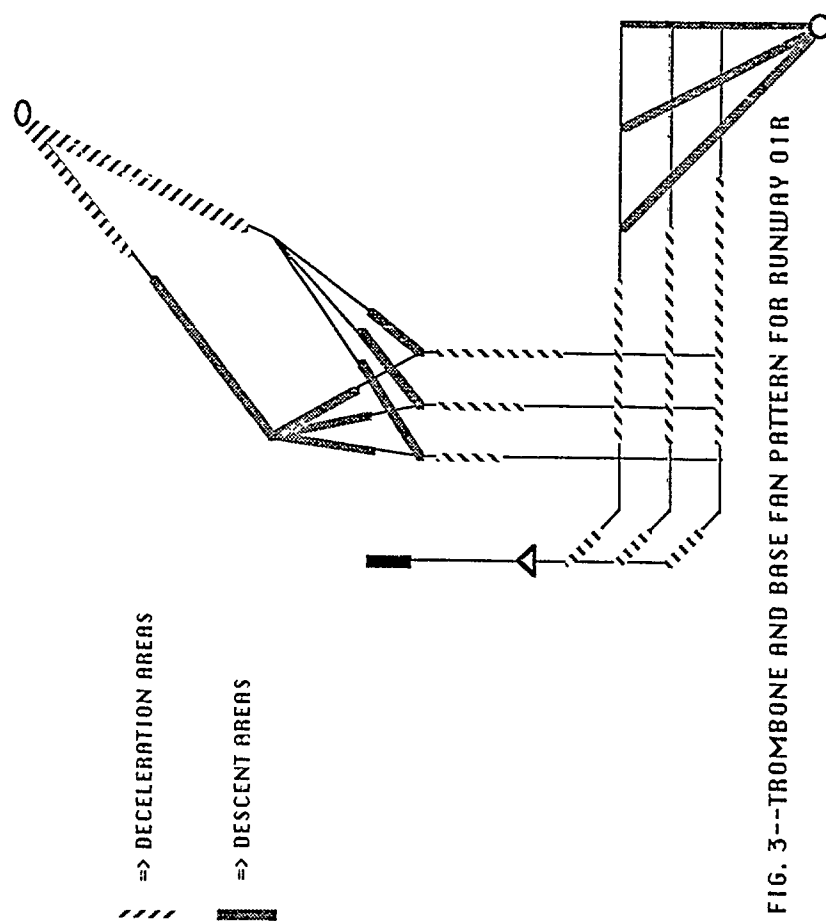


FIG.1--TYPICAL BUSY TERMINAL AREA CONFIGURATION





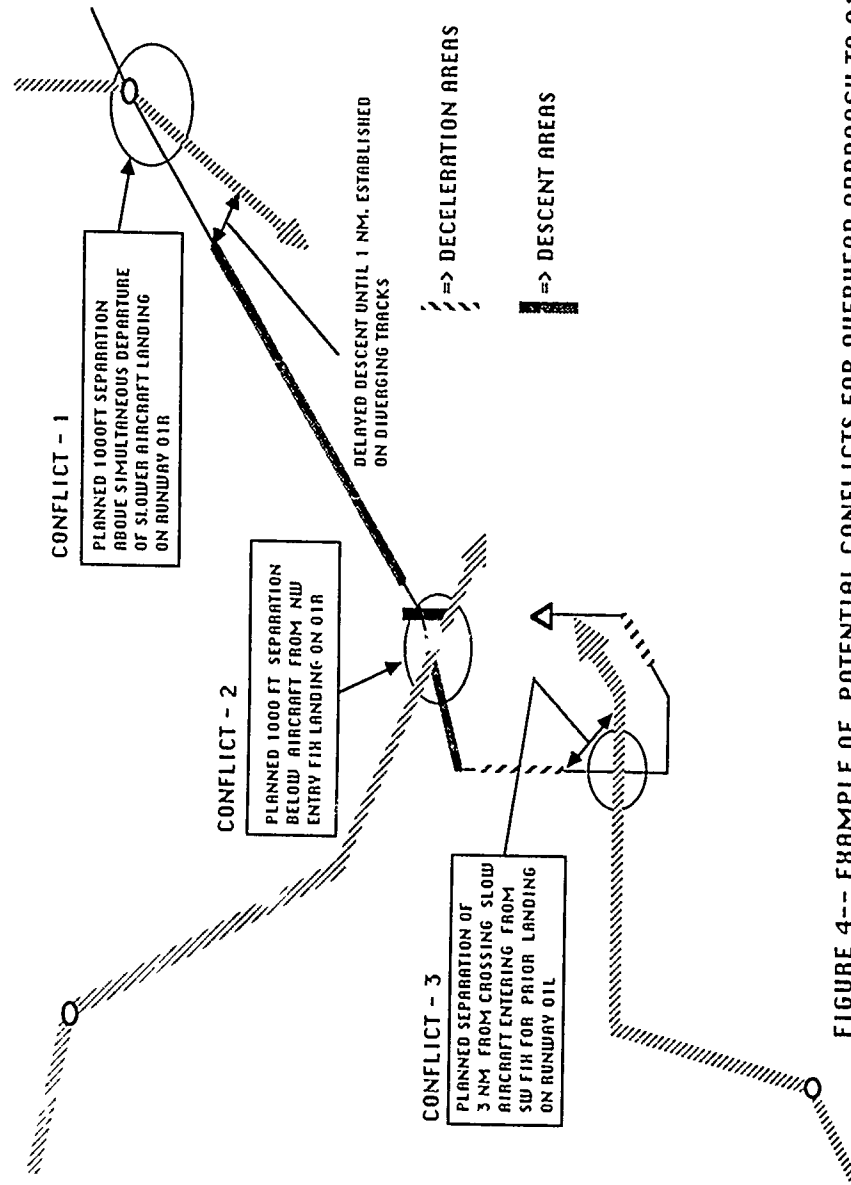


FIGURE 4-- EXAMPLE OF POTENTIAL CONFLICTS FOR OVERHEAD APPROACH TO OIL

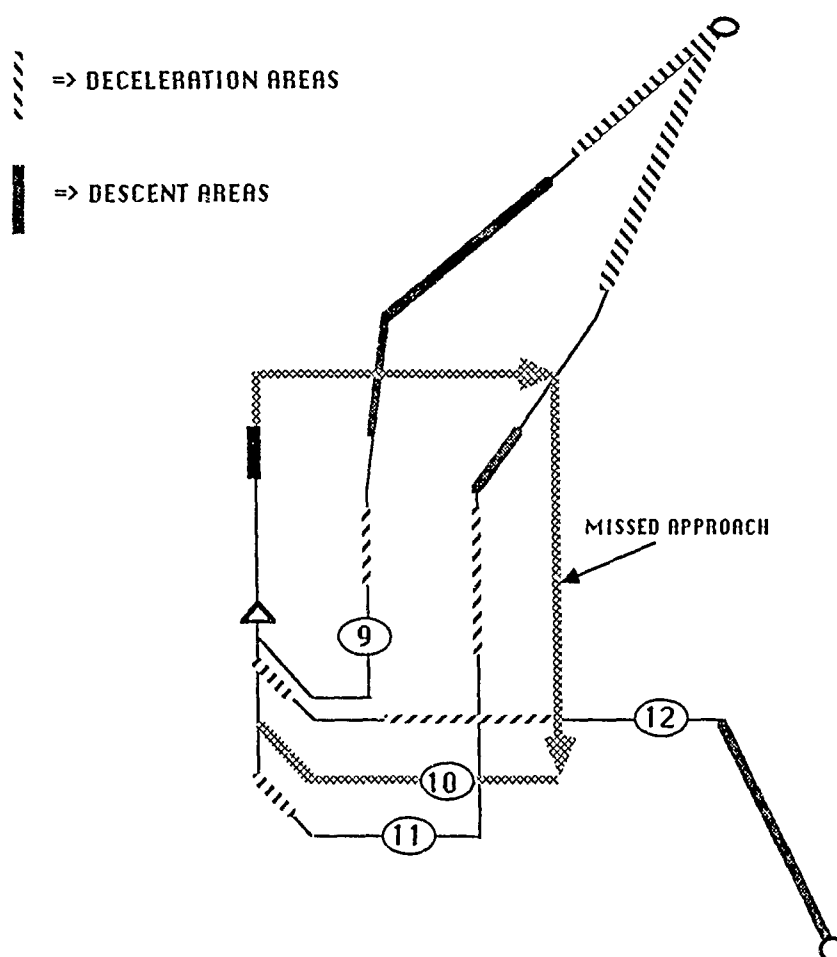


FIG. 5-- SCHEDULING A MISSED APPROACH FOR RUNWAY 01R

LIST OF FIGURES

- Figure 1. Typical Busy Terminal Area Configuration
- Figure 2. Overhead and Base Fan Pattern for Runway 01L
- Figure 3. Trombone and Base Fan Pattern for Runway 01R
- Figure 4. Example of Potential Conflicts for Overhead Approach to 01L
- Figure 5. Scheduling A Missed Approach for Runway 01R

A DESCRIPTION AND EVALUATION OF "TIMER"--A TIME-BASED TERMINAL FLOW-CONTROL CONCEPT

by

Leonard Credeur
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

and

William R. Capron
PRC Kentron
Hampton, Virginia 23666
United States

SUMMARY

A description of a time-based ATC concept called TIMER (Traffic Intelligence for the Management of Efficient Runway-scheduling) and the results of a fast-time and real-time computer evaluation are presented. The concept was designed to improve the efficiency of extended terminal area operations (en route approach, transition, and terminal flight to the runway). TIMER integrates en route metering, fuel-efficient cruise and profile descents, terminal sequencing and spacing together with computer-generated controller aids, in order to fully use runway capacity and improve efficiency of delay absorption. The concept, by using simplified aircraft models, accommodates both 4-D and non 4-D equipped aircraft and is designed for integration into the manual, voice-linked ATC system in an evolutionary manner and still be able to accommodate proposed system upgrade features such as data link and further ground automation.

Fast-time and real-time computer simulation results identify and show the effects and interactions of such key variables as horizon of control, metering fix and final approach delivery time errors, aircraft separation requirements, delay discounting, wind, flight technical error, and knowledge of aircraft final approach speed. The current ATC system has a runway interarrival-error standard deviation of approximately 26 seconds. Simulation results indicate that, with computer aiding, the runway interarrival-error standard deviation for non 4-D equipped traffic can be reduced to the region of 8 to 12 seconds if expected-final-approach speed is known; however, the reduction is only in the region of 16 to 20 seconds if expected-final-approach speed is unknown. Another major finding is that en route metering fix delivery-error standard deviation should be kept to less than a number somewhere between 35 to 45 seconds to achieve full runway capacity. This requirement implies the need for either airborne automation or assistance to the controller since the current manual performance in today's en route metering environment is in the order of 1.5 minutes.

1.0 INTRODUCTION

In the United States, air travel delays have become a major problem because aircraft traffic demands are overtaking the current operational capacity of the nation's major airports (U.S. Department of Transportation, FAA, June 1986). Environmental considerations have restricted both the expansion of existing airports and the building of new terminals. Consequently, several efforts described in the above reference are directed at enhancing the capacity of existing terminals. One of the major challenges facing Air Traffic Control (ATC) system designers is to determine how best to take advantage of advances in airborne capability to improve the overall system (aircraft-ATC) performance. One of the outcomes of advanced avionic research by NASA and others has been the development of aircraft 4-D Flight Management Systems (FMS). These systems not only navigate efficiently to a specified x, y, and z point in the airspace but are capable of arriving at the point at a designated time.

Time control is not new to ATC, in fact it was the basis of separation before radar. The current ATC system has evolved into a separation-based system primarily because relative aircraft distances are displayed to controllers from radar data. However, the two major variables that limit longitudinal separation are time-based. These are, (1) the time required for an aircraft's wake vortex to decay to a safe level, and (2) the aircraft's runway occupancy time. Runway arrival capacity will be used to its fullest potential when these variables can be satisfactorily modeled and manipulated. Therefore, an ideal, automated, time-based ATC system could be postulated which schedules aircraft to the runway as a function of these two variables and within the range of arrival time capability of each aircraft.

Research and development in the areas of runway guidance, high speed turnoffs, accurate weather prediction, and wake vortex modeling should eventually permit the use of variable, reduced time separation as a function of weather conditions. This development together with improved delivery precision form the basis for significant potential increases in runway arrival rates. In such a time-based system aircraft would use their onboard flight management systems to precisely meet their respective scheduled landing times. This is the ultimate goal or ideal system model to improve airport capacity. There are many operational issues that must be resolved before such a system is

implemented, but the concept appears technically feasible. The problem is how to get to that ideal environment from the manual, separation-based ATC of today. This paper describes an extended-terminal flow management concept called TIMER (Traffic Intelligence for the Management of Efficient Runway-scheduling) designed to bridge the gap from the current system. Results of fast-time and real-time simulations of the TIMER concept are also presented.

2.0 CONCEPT DEVELOPMENT

The period of the late 50's, 60's, and early 70's witnessed a substantial amount of effort in the areas of analysis and study of computer-aided spacing systems for terminal ATC. Much of that work was focused on final-approach spacing aids to the controller. (Holland, F. C., March 1975) contains an excellent summary of this activity and has 75 entries in its bibliography. In spite of all this effort there is still no terminal computer-aided spacing in operation. Some of the reasons these earlier efforts did not result in an operational system are:

1. There was a lack of coupling or integration of en route arrival metering with computer-aided terminal sequencing and spacing.
2. The trajectory and time calculations did not use aircraft type or model-specific performance data.
3. The limitations and state of computer, display, data processing, and tracking technology at the time were a handicap.
4. Computer derived separation criteria and operational procedures that handle the loads and throughput of VFR conditions were not developed.
5. There was insufficient controller involvement early in the design phase and a lack of organized controller/machine interface activity.
6. There was inadequate flexibility and consideration to real-world requirements like pop-ups, active runway changes, and weather disturbances.

The TIMER concept together with advanced technology addressed the first three shortcomings. In addition, TIMER introduces a needed perspective and consideration of aircraft and avionics capability and development. The resolution of the fourth item depends more on criteria definition and procedural factors than on technical limitations. Further research and development will be required before the important concerns of items five and six are satisfied.

Because the present ATC is a tactical system that handles delays through a series of local separation actions, the opportunity to realize arrival efficiency is restricted during periods of heavy traffic. The current U.S. En Route Metering (ERM-1) is characterized by relatively coarse planning and by a lack of interactive coupling between terminal and en route control (Grobe, R. L., May 1986). ERM-1 uses interarrival time spacings based only on an average arrival rate without aircraft performance modeling or controller aids to deliver aircraft at the desired times. The terminal control facility uses the output of the ERM-1 process without knowing its intended landing sequence or target times. The present terminal control process is characterized by two or more controllers solving a series of localized merge and separation problems (tactical rather than strategic control).

The mutual objectives of pair separation and aircraft fuel efficiency are not contradictory but require a more sophisticated ground/airborne interactive process, which must be strategic in nature, in order to control the en route/terminal transition region. Earlier activities oriented toward that approach are documented in (Erwin, R. L., February 1976) and (Benoit, A., October 1982). What is needed is an approach that is broad enough to simultaneously address several issues. How can aircraft operations during peak demand periods be improved? How can ATC not only accommodate aircraft with advanced avionics but go further and take advantage of this capability, while still handling conventionally equipped traffic? What can be done to improve delivery precision and reduce interarrival separation so as to increase capacity? Answering these questions requires a multi-disciplinary, systems approach such as shown in figure 1. The answers lie not in the specific fields of Communication, Navigation, or Surveillance (CNS) so much as in the areas of ATC/aircraft interaction, flexible fuel-efficient 4-D flight management systems, and automated controller aids.

An ATC/aircraft system oriented approach is being taken by the NASA Langley Research Center Advanced Transport Operating Systems Program Office (ATOPS). One of the principal thrusts of the ATOPS program is to define and evaluate evolutionary ATC concepts which improve the capacity, reliability, and economy of extended terminal flow operations (en route approach, transition, and terminal flight to the runway) when used with projected ground and avionics hardware. The TIMER concept is an output of that activity. It was designed to perform the task of assisting the air traffic controller with traffic management in the extended terminal area. TIMER is a step in the direction of using computers for control assistance, not just data formatting and transfer. It is evolutionary in nature, accommodating today's aircraft as well as 4-D equipped advanced technology aircraft. The algorithm, employing simplified aircraft performance models, is designed for integration into the manual, voice-linked ATC system and later

accommodates proposed National Airspace System (NAS) features such as data link and further ground automation (U.S. Dept. of Transportation, FAA, June 1986). TIMER was also designed to bridge the gap between today's en route/terminal process for handling arrival traffic at major terminals and the future situation where presumably most of the aircraft will have advanced 4-D flight management systems capable of data exchange with ground automation. A block diagram of how information might flow in such an advanced future system is shown in figure 2.

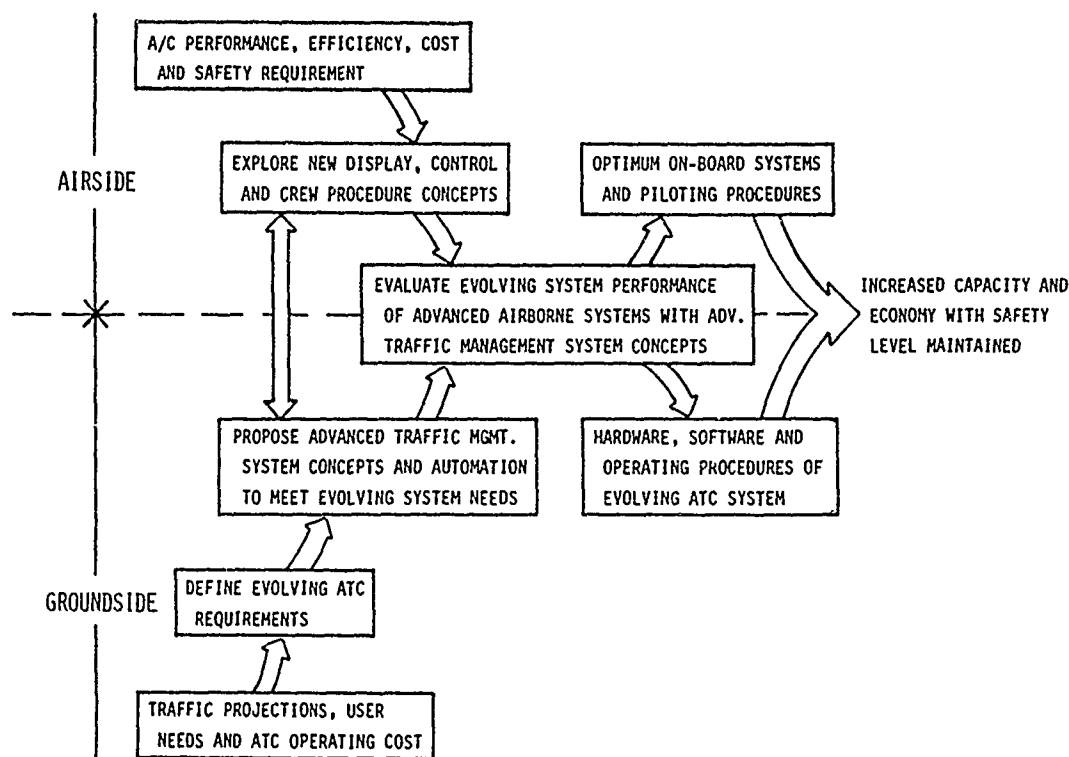


Figure 1: Integrated and interactive airborne/ground research and development approach to improve the National Airspace System performance.

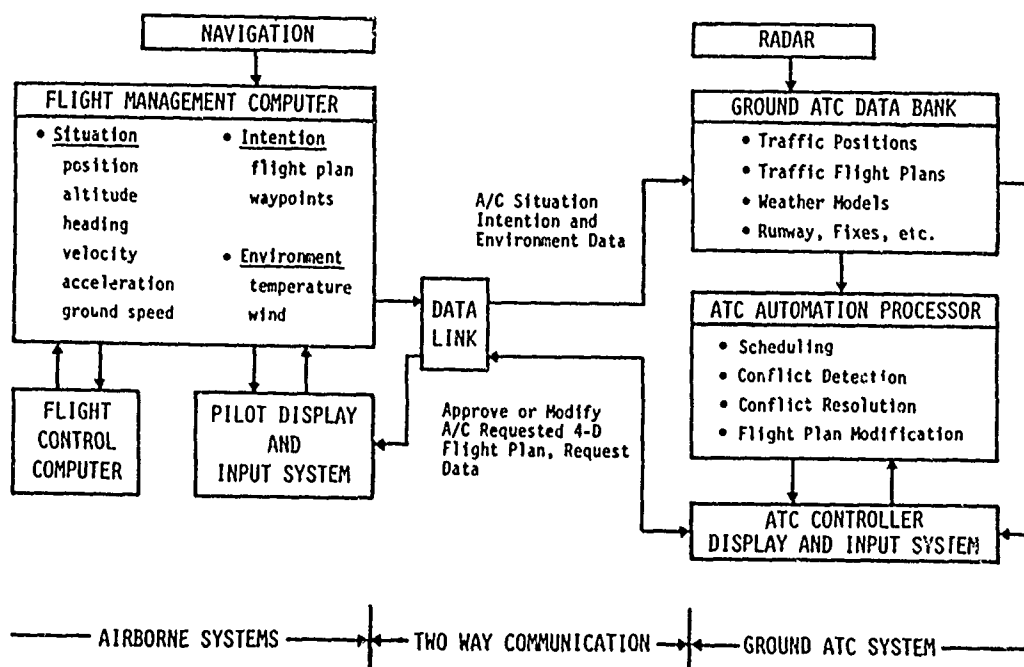


Figure 2: Possible integration of airborne capability in an advanced ground based automated ATC system.

3.0 CONCEPT OVERVIEW

In essence, TIMER integrates en route metering, fuel-efficient profile descents and terminal sequencing and spacing, together with computer-generated controller aids, in order to fully use runway capacity and improve fleet fuel efficiency. The principal features and areas of operation of the TIMER concept are shown in figure 3. The major steps in the system's operation are as follows:

1. Derandomize the arrival traffic stream into the extended terminal area at the horizon of control, by establishing a proposed aircraft landing sequence and building a list of aircraft target landing times based on safe separation. The desired metering fix time as a result of the assigned landing time is also determined.
2. Nominal estimated times of arrival used in step one are based on fairly simple yet representative aircraft performance models. Using these models and predicted winds, a ground computed trajectory is determined to meet the aircraft's assigned target landing time.
3. Computer generated assistance is given to the controller to help him meet aircraft target times based on the trajectory calculations.
4. Adjustments to the target landing times and even changes in the landing sequence will be necessary to accommodate errors and anomalies.
5. The aircraft trajectory will be fine-tuned in the final approach region in order to meet the aircraft's final target landing time with limited uncertainty.

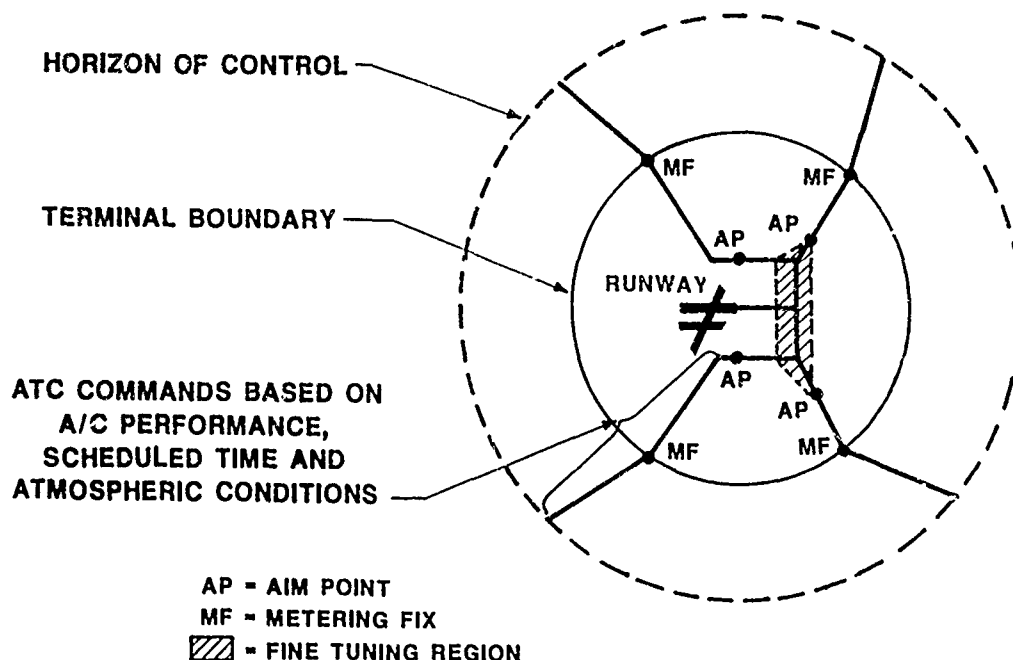


Figure 3: Principal features and areas of operation of the TIMER concept.

4.0 DESCRIPTION OF ARRIVAL TRAFFIC DYNAMIC CONTROL PROCESS

A more detailed explanation of the TIMER flow control system is perhaps best done by unfolding the sequence of events for the upper northwest route, depicted in figure 4, as an aircraft flies from the horizon of control to the runway. At the horizon of control, the ground system begins the process of determining the landing sequence. Nominal arrival speeds, route segment distances to the runway, and predicted winds are used to determine aircraft's undelayed Estimated Time of Arrivals (ETA). Currently the sequencing criteria used is a projected first-to-reach-runway ordering. More advanced versions would employ sequencing algorithms which take advantage of the variable spacing between classes of aircraft to slightly increase the runway throughput rate.

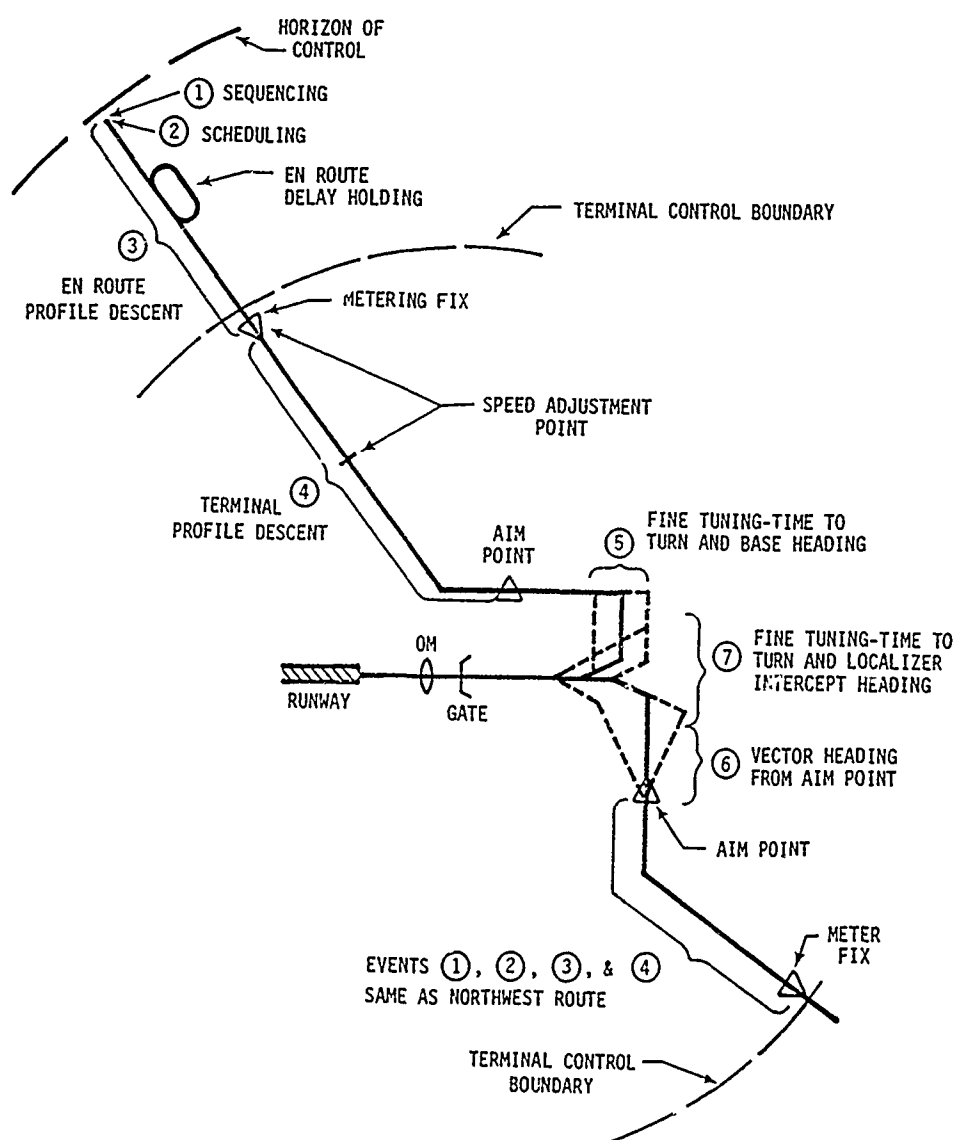


Figure 4: Sequence of events an arrival aircraft would experience in the TIMER concept.

Starting at the horizon of control, there is a range of earliest and latest landing times that the aircraft can achieve by varying its speed between nominal approach values and slowest possible speeds imposed by performance considerations. If the landing time assigned exceeds the latest attainable speed-control time, then the additional delay must be absorbed by path stretching or holding. For the sake of discussion, it will be assumed that the scheduling process has assigned a landing time within the range attainable by speed control. The time and distance associated with all descent and deceleration segments are calculated from aircraft-type-specific point-mass equations of motion for a clean configuration with flight-idle thrust and predicted winds. The details of the trajectory calculation are presented in (DeJernett, F. R., February 1984). As shown in figure 5, the flight path is divided into a cruise segment and several descent and level deceleration segments. An iterative process is used to determine the required metering fix altitude and the resultant time using as input the scheduled runway time, the aim point (location where clean idle descent normally ends), the wind, and the nominal speeds for the segments inside the terminal from the metering fix. Another iterative process calculates the cruise Mach, the Mach/CAS descent speeds to the metering fix, and time to begin the descent so that the aircraft arrives at the metering fix at the prescribed time, altitude, and speed.

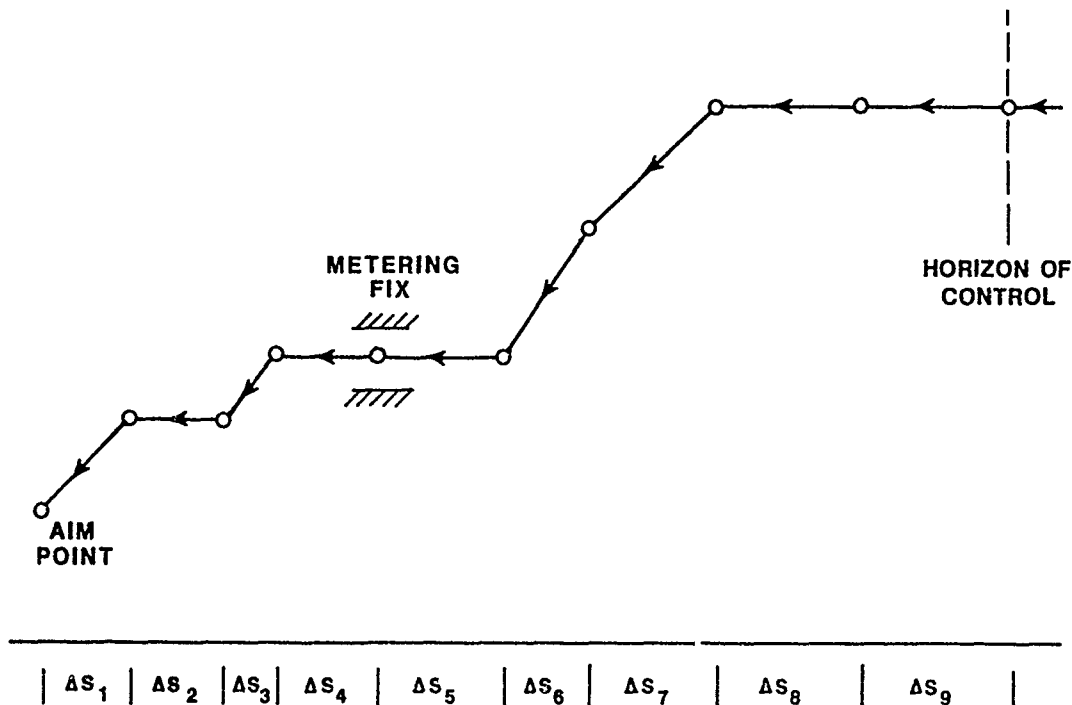


Figure 5: The trajectory calculation divides the arrival flight path into a cruise segment and several descent and level deceleration segments using a MACH/CAS flight-idle thrust, profile descent approach.

The initial Scheduled Landing Time (SLT) for the example aircraft is determined by taking the larger of the following: (the aircraft's undelayed, estimated landing time) or (the landing time of the previously scheduled aircraft + separation criteria + T_B). T_B is a buffer time to account for system delivery uncertainty. From the trajectory calculations briefly described earlier, a non 4-D aircraft's desired metering fix time, the cruise Mach, and the time to begin as well as the Mach/CAS speed to perform the descent would be displayed to the controller. Using this information the controller can assist the non 4-D aircraft to meet its schedule in a fuel-efficient manner. The 4-D equipped aircraft could be given either its metering fix or aim point time. Figure 6 presents examples of the types of controller messages envisioned for both 4-D and non 4-D traffic. There are many 4-D path solutions possible. Thus, proper coordination and interfacing between ground system designers and airborne flight management system designers are essential if there is to be compatibility between the paths flown by 4-D and non 4-D aircraft. Ideally, the only difference would be the greater time precision expected from the 4-D aircraft.

The aircraft's SLT may be changed when it arrives at the metering fix either because of the action of preceding traffic or because of the aircraft's own metering fix time error. The TIMER system is flexible enough to accommodate aircraft time errors. This is particularly important in the initial implementation when, presumably, a large percentage of unequipped aircraft would be present. Depending on circumstances, the aircraft's SLT may be slipped forward or backward, or its landing sequence may even be altered if the schedule slippage warrants such action. Using the aircraft's updated landing time based on its actual metering fix arrival, the trajectory calculation determines the terminal profile descent speeds needed to meet the target landing time. Those speeds are given to the unequipped aircraft, whereas the aim point (end of terminal profile descent) time is given to the 4-D aircraft. Example controller messages inside the metering fix are also shown in figure 6.

In the final approach region there are two computer-aided fine-tuning maneuvers which attempt to reduce delivery error. In keeping with the evolutionary mode, the initial design was configured to be similar to the conventional approach performed today. The pilot would not be able to distinguish between a TIMER-assisted final approach and a conventional manual control approach. The process currently under study is based on a regularly updated ETA calculation which displays how early the aircraft would be if its turn instructions were issued immediately. This gives more information than a straight clock countdown. With expected communication and response times factored in, the display indicates when and to what heading the controller should vector the aircraft for the base and localizer intercept segments. The fine-tuning region must accommodate minor schedule changes due to other aircraft errors, wind estimate errors, or own aircraft flight errors which have accumulated since the last speed control point. Future efforts with both 4-D equipped and unequipped simulated aircraft will explore the advantages of alternative fine-tuning schemes.

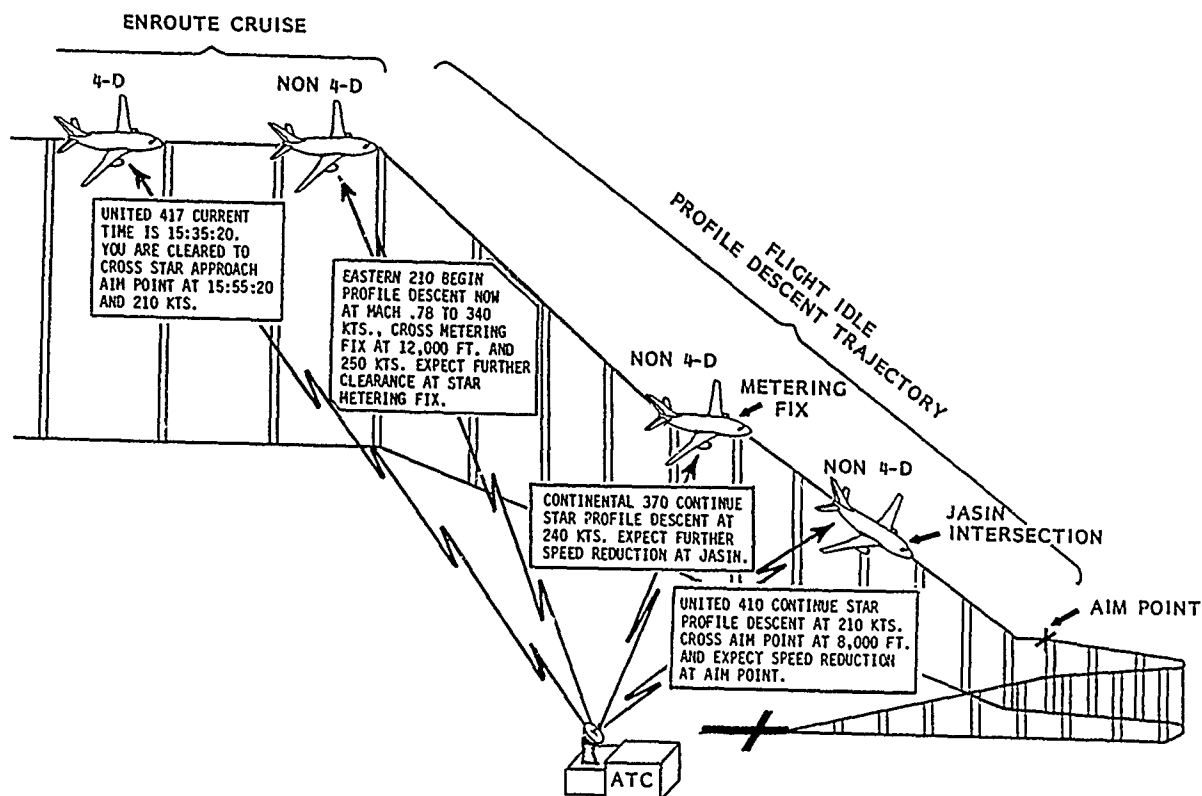


Figure 6: Example TIMER control instructions for 4-D and non 4-D equipped aircraft doing flight-idle thrust, profile descent approaches.

The TIMER concept described has several potential benefits. The initial metering, sequencing, and scheduling of aircraft to the terminal takes place early enough in the en route airspace where most of any required delay can be taken in a more fuel-efficient manner. The en route and terminal control processes are integrated and coupled so that the strategic fuel-efficient descent is continued into the terminal area down to the aim point near the final approach region. 4-D equipped aircraft will be allowed to use and benefit from their capability. TIMER services both today's and 4-D equipped aircraft by making use of ground-aided profile descent instructions for unequipped aircraft and target time objectives for 4-D equipped traffic. The Mach/CAS type of descent profiles calculated can be flown with today's conventionally instrumented cockpits. The final-approach controller spacing aid is based on the customary turn instructions normally issued to landing aircraft. Its use would be transparent to the pilot.

5.8 DESCRIPTION OF PARAMETRIC SENSITIVITY ANALYSIS

The TIMER concept described earlier was incorporated into the TAATM (Terminal Area Air Traffic Model) simulation (Credeur, L., August 1981) so the effect of significant parameters could be studied. The TAATM is a flexible dynamic model of the airborne, navaid, ground control, and communication aspects of the terminal area environment which can run in either fast-time (batch mode) or in real-time (with controller/pilot interaction). Pertinent en route times, delays, and errors are stochastically modeled in the TAATM. A fast-time parametric sensitivity evaluation of the basic TIMER concept was performed.

Data collected from fast-time (batch) data runs of the TAATM simulation were used as a basis for evaluation. Each of the parametric data points is a statistical combination of at least two independent runs for the conditions studied. Each of the individual runs contains two hours of steady-state landing data. If the output performance measure of each run in a set did not closely agree, an additional two run set was performed and the total results were combined in a pooled estimate of the variable of interest.

The Denver Stapleton approach routes operating in a runway 26L landing configuration (figure 7) were used with IFR commercial arrival traffic. The metering fixes are KEANN, KIOWA, BYSON, and DRAKO. The Official Airline Guide was used to determine the aircraft type distributions. The traffic consisted of a set of large and heavy transport type aircraft with 8.6 percent of the traffic in the heavy category. None of the simulated traffic were equipped with 4-D flight management systems. The minimum wake turbulence separation requirements were defined in terms of nautical miles distance. Using aircraft velocities and simulated winds, the separation distances are converted to separation times. The distance separation criteria (nmi) used in terms of the lead and trail aircraft of a pair are:

3/4/5 criteria

	trail	
lead	large	heavy
large	3	3
heavy	5	4

2.5/3.5/4.5 criteria

	trail	
lead	large	heavy
large	2.5	2.5
heavy	4.5	3.5

2/3/4 criteria

	trail	
lead	large	heavy
large	2	2
heavy	4	3

The simulation arrival traffic was distributed to the four metering fixes or corner posts in the following manner:

Metering fix	Percentage of total traffic
KEANN	26
KIOWA	32
BYSON	26
DRAKO	16

6.0 SIMULATION RESULTS AND DISCUSSION

6.1 Horizon of Control

A major goal of the TIMER concept is to meter, sequence, and initially schedule arrival aircraft early enough in the approach so that any delays needed to derandomize the traffic can be taken in a fuel efficient manner. The trade-off is to determine how early or at what expected flight time to the metering fix should the horizon of control be located without extending too far back in time from the airport to cause coordination and territorial problems. Figure 8 shows measured en route delay means and their pooled standard deviation for the two types of approach routes for various horizons of control (flight time between initial scheduling and metering fix). The western routes (DRAKO and BYSON) are the long routes whereas the eastern routes (KEANN and KIOWA) are identified as the short routes relative to their flight times from the metering fix to the runway. The data were obtained from simulation runs with a traffic arrival rate equal to the runway acceptance rate (35 aircraft per hour) for a traffic sample of large and heavy aircraft using IFR 3/4/5 nautical miles separations and a metering fix error standard deviation (σ) of 30 seconds. The sequencing scheme (projected first-to-reach-runway ordering) in some delay situations imposes longer en route delays to aircraft on the shorter routes. The result is longer overall average delays for the shorter routes when operating at or near the system acceptance rate. Therefore, for the conditions simulated, the short route delay is the more demanding case which will be used to define the desirable horizon of control.

Also shown in figure 8 are the contours of delay possible by speed reduction to Mach 0.63 from a range of initial cruise speeds. The profile descent delay capabilities were determined using the procedure in (DeJernett, F. R., February 1984). The nominal cruise speeds of commercial aircraft vary with aircraft type as well as individual airlines policy. Using the Mach 0.78 data as a representative cruise speed, a horizon of control of 27.5 minutes from the metering fix is enough so that speed control will absorb all the en route delays that are less than the mean delay plus 1σ (approximately 84 percent of delay cases). If the criteria is the ability to handle all delays less than the mean delay plus 1.28σ (90 percent of delay cases), the horizon of control would be 30.2 minutes. The 1.65σ (95 percent of delay cases) criteria would place the horizon of control at 32.7 minutes.

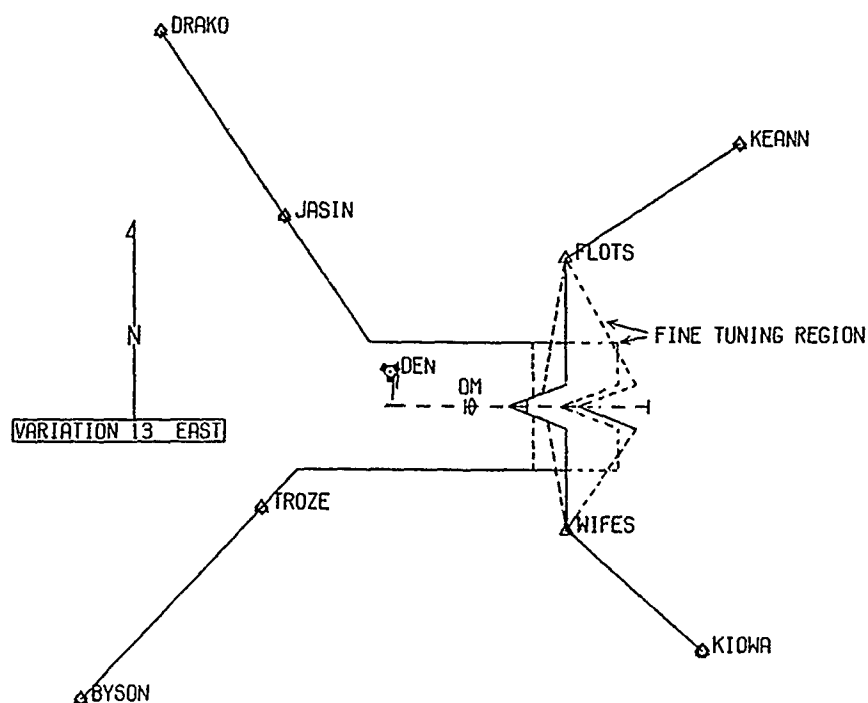


Figure 7: Terminal geometry simulated for approaches to Denver runway 26L.

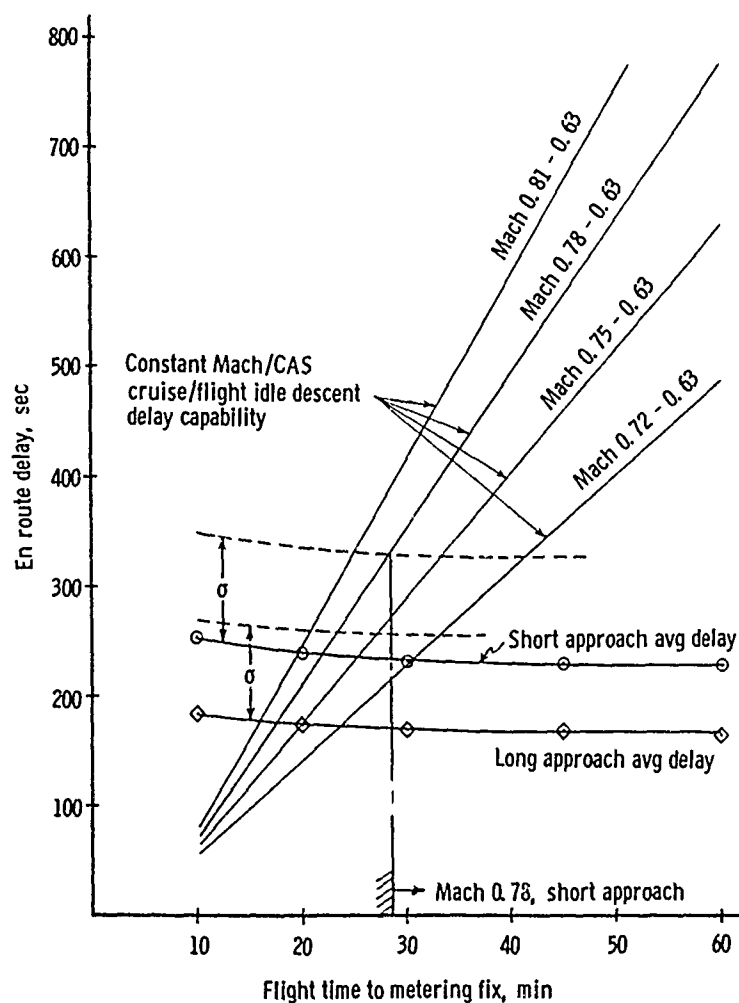


Figure 8: Horizon of control needed to efficiently absorb delay for range of cruise speeds (3/4/5 nautical miles separation).

Figure 8 shows the slight en route delay effect which results from changing the horizon of control. There is also a terminal area delay effect which must be considered. From the moment an aircraft is scheduled at the horizon of control and begins its flight toward the metering fix, there are schedule changes that occur as a result of both the preceding traffic's metering fix time errors and flight technical errors inside the terminal. The dynamic Scheduled Landing Time (SLT) slippages, caused by preceding traffic's terminal area technical errors, are not always accounted for while the aircraft is still in the en route region. Consequently, when an aircraft arrives at the metering fix, its SLT could have been shifted from the earlier assigned landing time which originally established the metering fix target time. The longer the flight time to the metering fix the more the SLT is likely to have shifted. Figure 9 shows this effect. The results differ slightly from that shown in (Credeur, L., June 1986). In those earlier simulation runs of TIMER, the effect of preceding aircraft's terminal dynamic slippage were never added to an aircraft's metering fix target time. In the data of this report, the accumulated dynamic slippages since originally scheduled are sometimes added to an aircraft's metering fix target time. Specifically, this occurred only when an aircraft's metering fix target time is pushed back (delayed) as a result of a preceding aircraft's metering fix error.

In figure 9, the measured mean terminal area delays, plus their pooled σ about their fitted curve, are shown as a function of horizon of control for the same traffic and error conditions as in figure 8. Also shown are the speed control delay capability boundaries of the nominal routes and the combined speed and path delay capability using the maximum delay routes of the final approach region shown by the dashed line longer path in figure 7. A system goal is to use fuel-efficient speed control as much as possible inside the terminal as well as en route. A horizon of control is needed that is large enough to absorb most of the expected en route delays and yet does not impose terminal delays that exceed the terminal speed control capability. For the simulation conditions studied and using the current schedule adjustment algorithm, no upper boundary was imposed on the horizon of control by the terminal area's SLT dynamic shifts.

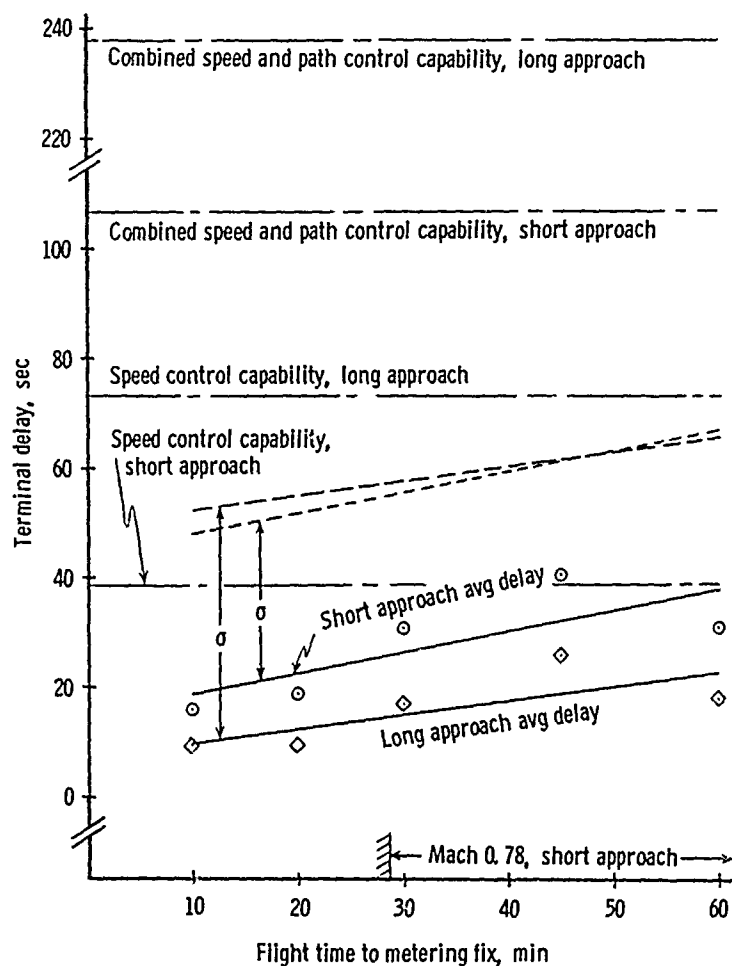


Figure 9: Horizon of control region needed to stay within the terminal area nominal delay capability (3/4/5 nautical miles separation).

Figure 10 shows the same information as figure 8, but for a traffic arrival rate equal to the runway acceptance for a 2/3/4 nautical miles separation criteria. The two cases shown in figures 8 and 10 span the range of separations likely to be used in the foreseeable future. For the conditions of figure 10, the horizon of control boundaries are less than for the larger separation criteria of figure 8. The horizons of control needed with the 2/3/4 nautical miles separation are 24.5 minutes for mean delay plus 1σ (84 percent of delay cases), 26.2 minutes for 1.28σ (90 percent of delay cases), and 28.5 minutes for 1.65σ (95 percent of delay cases). Figure 11 verifies the situation observed in figure 9. There is no upper horizon of control boundary imposed by the terminal area within the range of conditions simulated.

Figures 8 and 10, reveal several factors an ATC system designer must consider in selecting the design value for horizon of control. A weighted, expected nominal cruise Mach should be determined from expected airline company policies and projected aircraft types. The separation standard to be used must also be considered. Slower airline cruise speeds, to conserve fuel, require a larger horizon of control whereas reduced separations tend to reduce the necessary horizon of control time. Without the benefit of detailed traffic or policy projections, a working number of 30 minutes is reasonable. This translates to about 220 nautical miles for an aircraft flying at Mach 0.78, 35,000 feet and no wind.

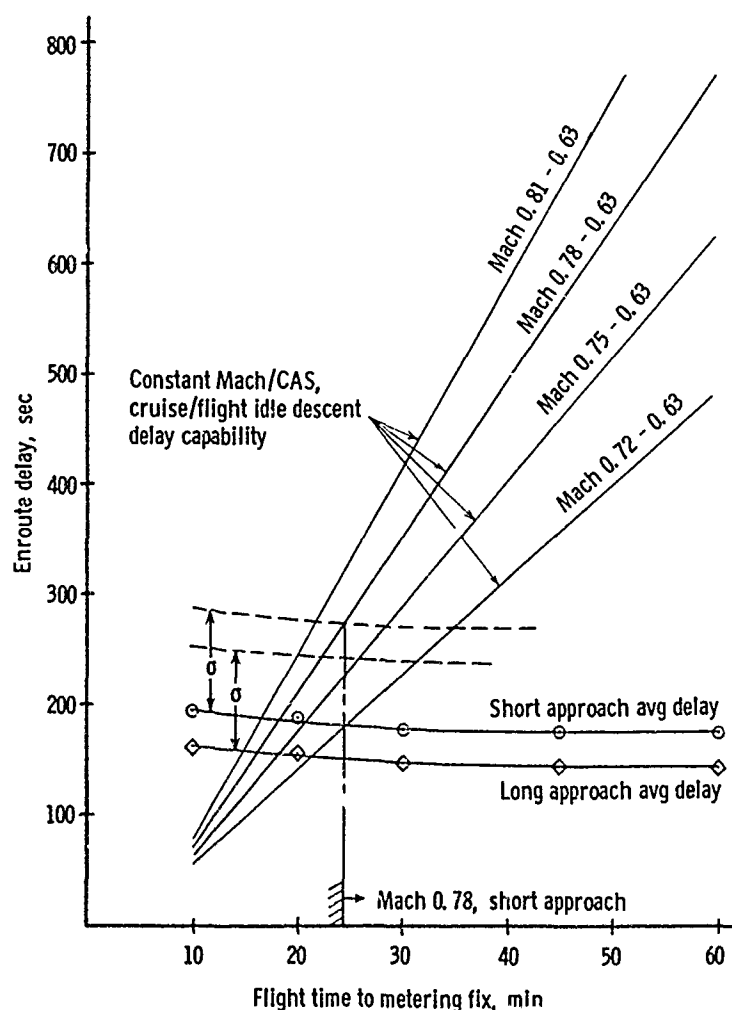


Figure 10: Horizon of control needed to efficiently absorb delay for range of cruise speeds (2/3/4 nautical miles separation).

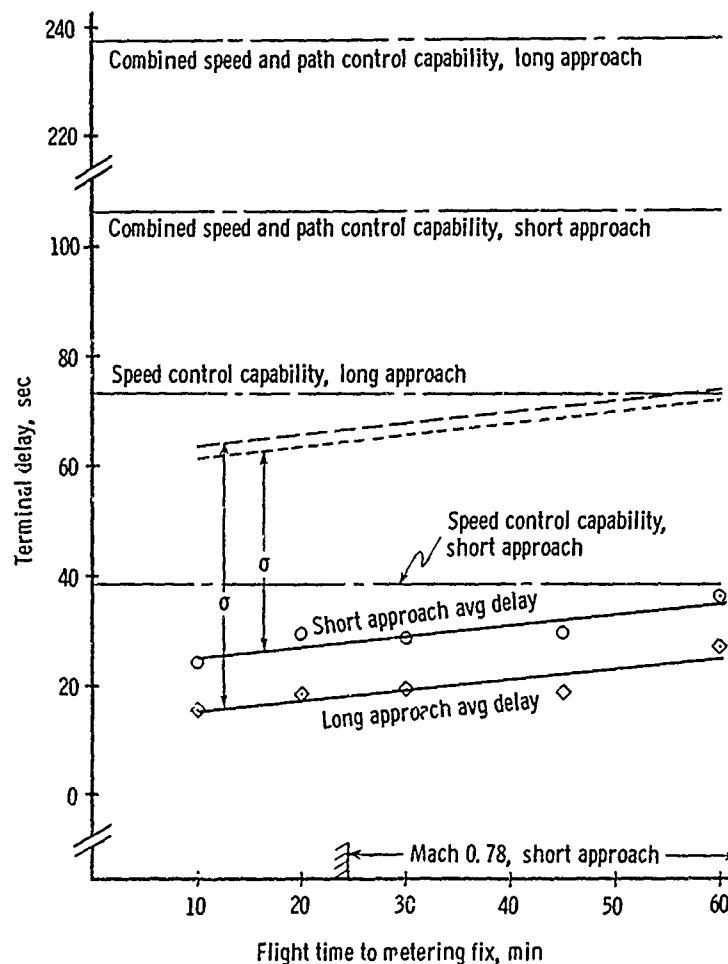


Figure 11: Horizon of control needed to stay within the terminal area nominal delay capability (2/3/4 nautical miles separation).

6.2 Metering Fix Delivery Accuracy

Section 4.0 described how, in concept, the aircraft would be delivered by en route control to the four metering fixes or corner posts with a target time which is computed to meet the aircraft's scheduled landing time. This process is simulated by assigning the aircraft to appear at the metering fix at the scheduler-calculated target time plus a statistical error. The metering fix time error is picked from a normal distribution with mean of 0 and an externally specified variance. Depending on the magnitude and sign (early or late) of the metering fix error, and operating within the boundaries of terminal controllability, the scheduler attempts to minimize the schedule slippage of the following aircraft stream. That means that under certain circumstances an aircraft at the metering fix may have its order in the sequence changed to reduce capacity loss due to its large metering fix time error.

When aircraft arrive at the metering fix earlier than their scheduled time, the application of time delay is used to preserve the schedule by first speed reduction and then path stretching if necessary. The nominal approach routes are shown by the solid lines and the region of path variability is defined by the dashed lines in figure 7. The range of time controllability varies with aircraft type and winds aloft. Table 1 shows the range of terminal controllability for each approach route, without wind, for a B737 aircraft. In a similar manner, the ability to recoup late arrival errors depends on the time catch-up or forward-schedule-slippage capability of the various routes. The eastern routes (KEANN and KIOWA) have only about 18 seconds of time-catch-up capability, relative to their nominal paths, while the western routes (DRAKO and BYSON), because of their "trombone" configuration, have approximately 88 seconds. Figures 12 and 13 show the terminal traffic flow patterns for a metering fix arrival-error standard deviation of 30 seconds and 120 seconds respectively. Figure 13 illustrates the increased use of both path reduction and stretching, relative to the nominal routes, in an attempt to accommodate the larger metering fix arrival errors.

TABLE 1 - SPEED AND PATH TIME CONTROL OF TERMINAL APPROACH ROUTES (B737)

Routes	Delay Control (sec)		Catch-Up Control (sec)	
	Speed	Speed and Path	Path	
KEANN	44	114	18	
KIOWA	38	106	17	
BYSON	73	237	87	
DRAKO	71	237	89	

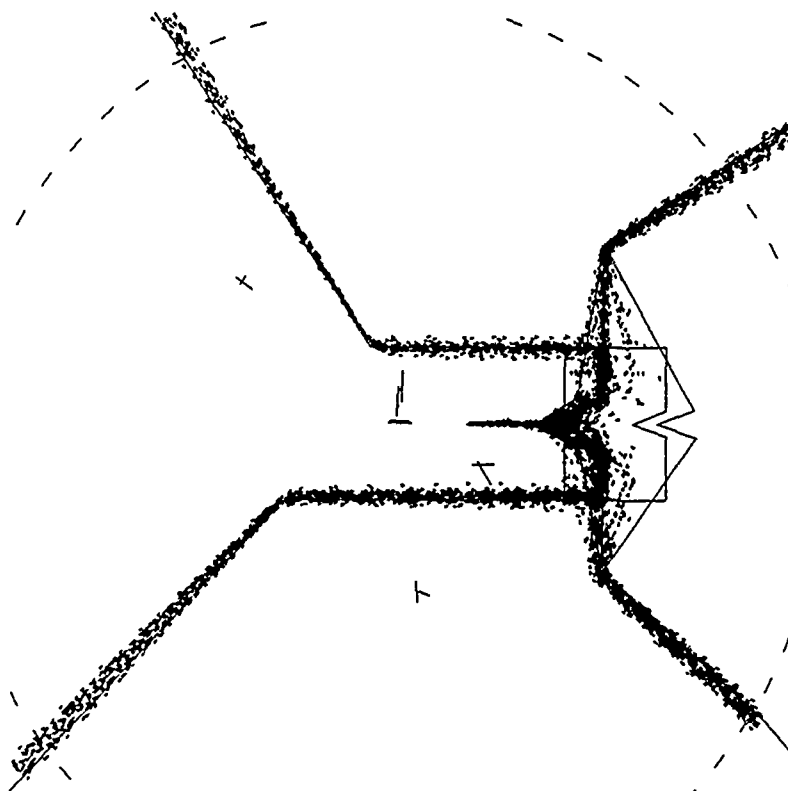


Figure 12: Terminal flow pattern for a metering fix arrival error standard deviation of 30 seconds.

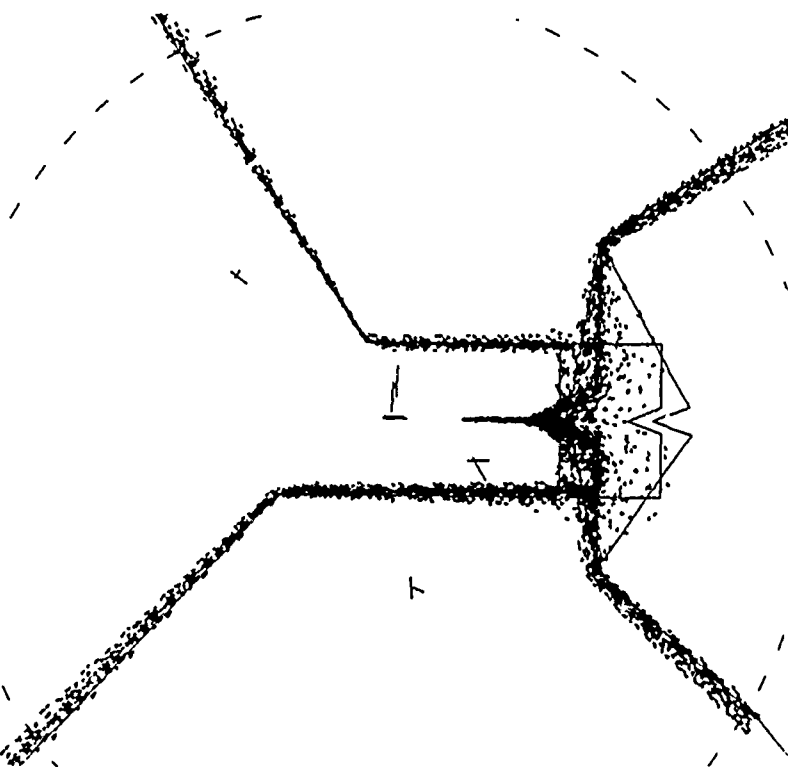


Figure 13: Terminal flow pattern for a metering fix arrival error standard deviation of 120 seconds.

The following factors determine what time loss, if any, results from a metering fix time error: which route the aircraft is on, the route and SLT's of adjacent aircraft in the sequence for swapping, and the magnitude of the metering fix error itself. Figure 14 indicates the cumulative effect of these factor interactions. The figure presents the runway arrival rate of three separation standards plotted for various metering fix arrival-error standard deviations. For an en route/terminal coupled time-based flow control system with the conventional geometry simulated, the plot indicates that en route metering fix delivery-error standard deviations should be kept to less than a number somewhere between 35 to 45 seconds to realize full runway capacity. This is true for all the separations simulated. The system uses the controllability inside the terminal region to prevent the smaller metering fix errors from adversely affecting runway capacity. Figure 15 confirms that less than 35 to 45 seconds is a consistent criteria applicable to different runway delivery accuracies as well as to the various separations shown in figure 14.

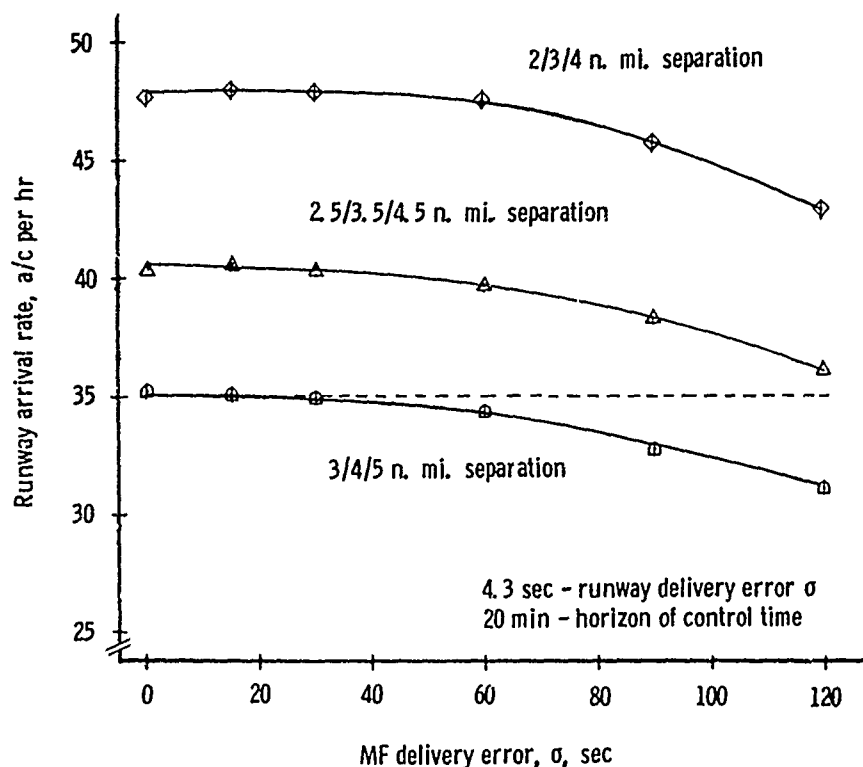


Figure 14: Impact of metering fix error on capacity.

Keeping the metering fix delivery-error standard deviation (σ) below 35 seconds implies the need for ground or airborne assistance to the controller since the manual performance in today's en route metering environment (ERM-1) is in the order of 1.5 minutes (Heimbold, R. L., September 1980). The controller aids described in Section 4 would provide the assistance to improve the delivery performance of aircraft without 4-D capability. The TIMER concept uses representative point-mass models of aircraft to calculate and then indicate to the controller, the Mach cruise speed, start of descent time, and Mach/CAS flight-idle thrust descent speed to be issued in order to meet the scheduled metering fix time. Experiments conducted from the cockpit of commercial airlines (Knox, C. E., May 1985) with a simple model and similar open-loop commands have shown that less than 35 sec σ is achievable in real-world operational conditions.

Airborne, closed-loop, 4-D flight management systems could reduce metering fix error σ 's to considerably less than 35 seconds (Bruckner, J. M. H., July 1977), (Heimbold, R. L., September 1980), (Knox, C. E., October 1980), (Adam, V., October 1982), and (Moor, D. A., December 1984). However, for the terminal area simulated, figure 14 shows that degree of increased precision would do little to improve the arrival rate. For example, there would be no capacity benefit from having closed-loop systems expend extra fuel by manipulating throttles to precisely cross the metering fix with five seconds or less standard deviation. The different curves of figure 15 on the other hand, show that reducing the delivery time error as much as possible is desirable at the runway threshold. This indicates that 4-D flight management system designers should use an accuracy criteria that is a function of the time or distance to the runway.

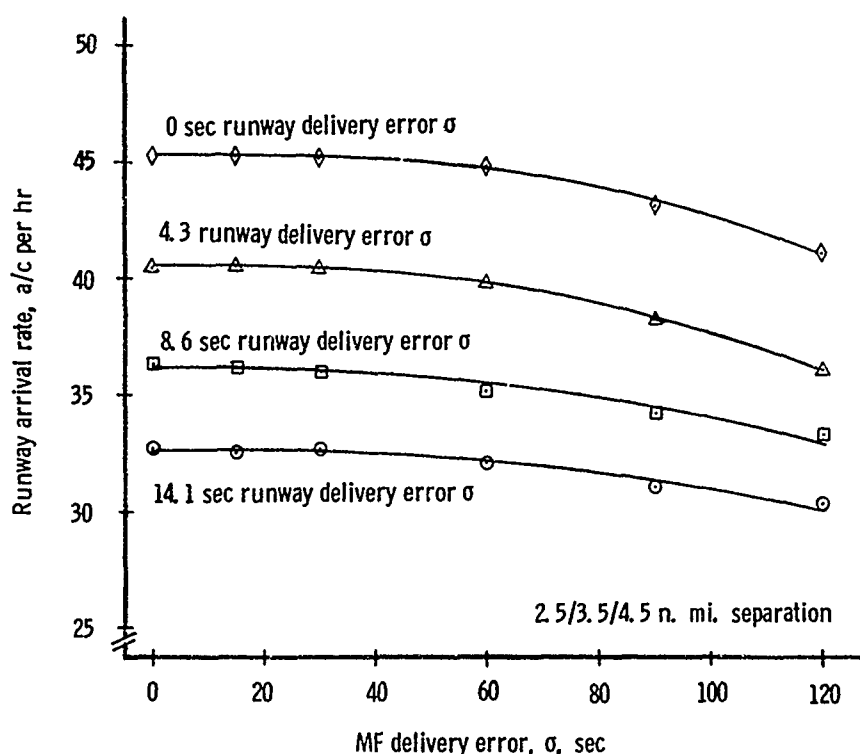


Figure 15: Impact of both metering fix and runway delivery error on capacity.

6.3 En Route Delay Discounting

As shown in the previous section, runway capacity is influenced by large arrival time errors at the metering fixes. The primary factor in this relationship is late arrivals at the eastern metering fixes, KEANN and KIOWA. Whereas late arrival times at the western metering fixes can generally be made up by shortening the downwind leg of the approach, the geometry of the eastern routes allows very little time-catch-up capability. This results in slippage of schedules and subsequent gaps of excessive separation on final approach.

Some of the schedule disruptions caused by large metering fix arrival time errors can be smoothed out by using a technique called delay discounting. This technique, applied during en route control of an aircraft, reduces any calculated en route delay needed to meet its target metering fix time by an amount that is a specified percentage of the delay capability provided by the aircraft's speed reduction capability within the terminal area. The aircraft's terminal path-stretching delay capability is kept in reserve to accommodate errors and uncertainties. For example, aircraft that had delay discounting applied and arrived on time at their metering fix without an assigned landing time change, can expect a delay in the terminal area that is equal to the discounted or postponed amount. Early arrivals at the metering fix are kept on schedule by first using any remaining speed control delay capability not used to accommodate the delay discounting and then by path stretching. The discounting benefit results from having been applied to late arriving aircraft at the metering fix, particularly the eastern routes. The effect of these late arriving aircraft is reduced since the limited time catch-up capability is only needed when the aircraft's metering fix overdue time error is larger than the amount of en route delay that was discounted or postponed. Thus, the schedule impact caused by larger, late, metering fix time errors on the eastern routes is reduced.

As implemented, the specified amount of delay discounted en route for all four corner posts is a constant percentage of each particular route's terminal speed control delay capability. For each aircraft, the terminal controllability is computed and stored at system entry time. Thus, the terminal speed control amount of delay available for discounting is usable throughout the en route phase of control.

Parametric data runs were made using 0, 30, 50, 70, and 100 percent of terminal speed control for en route delay discounting and 30, 90, and 120 seconds standard deviation of metering fix arrival time errors. Figure 16 presents these results showing the runway arrival rate as a function of the upper boundary (percentage of terminal speed control) available for discounting when en route delay was needed. The curves indicate that increasing amounts of discounting recovers about half of the capacity loss due to metering fix arrival errors with large standard deviations. If the system were to operate without any en route controller aids, then delay discounting should be considered. However, if an enhanced en route system and 4-D aircraft are able to restrict metering fix delivery-error standard deviations to approximately 30 seconds or less, there is no capacity benefit to be gained by delay discounting.

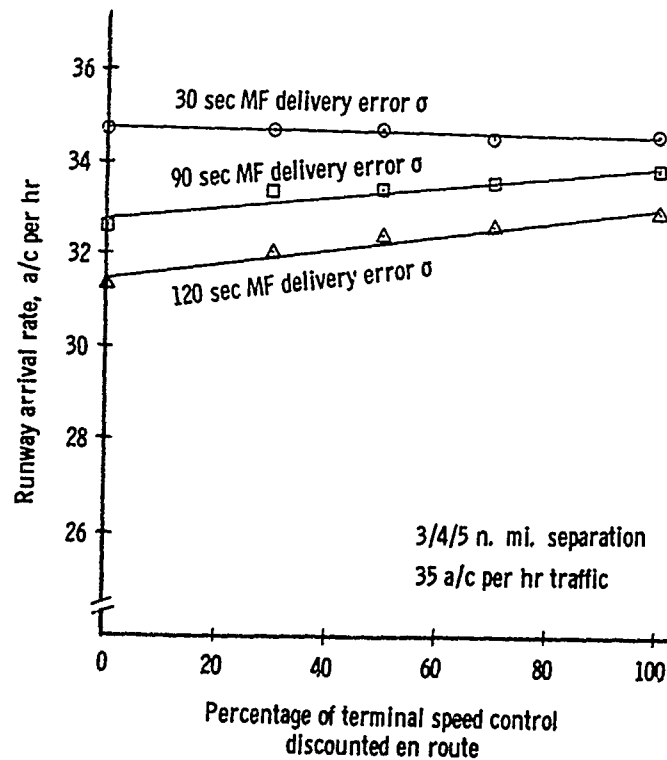


Figure 16: Effect of en route delay postponement on runway arrival rate.

For the 30 seconds metering fix delivery-error standard deviation case, the decrease in average en route delay is matched by an equal increase in average terminal delay as the percentage of delay discounted is increased from 0 to 100 percent. That situation is illustrated in figure 17. Since there is no capacity gain for smaller metering fix delivery-error σ 's, then delay discounting should not be used. When the metering fix delivery-error σ is in the vicinity of 30 seconds or less, applying delay discounting en route will result in increased terminal area delays which could have been taken en route in a more fuel-efficient manner. As would be expected, since delay discounting improved the capacity for the 90 and 120 seconds metering fix delivery-error cases, the reduction in average en route delay is greater than the corresponding increase in average terminal delay when delay discounting is applied to a 35 aircraft per hour traffic sample. Figures 18 and 19 illustrate this significant reduction of average en route delay at the expense of a slight average terminal area delay increase.

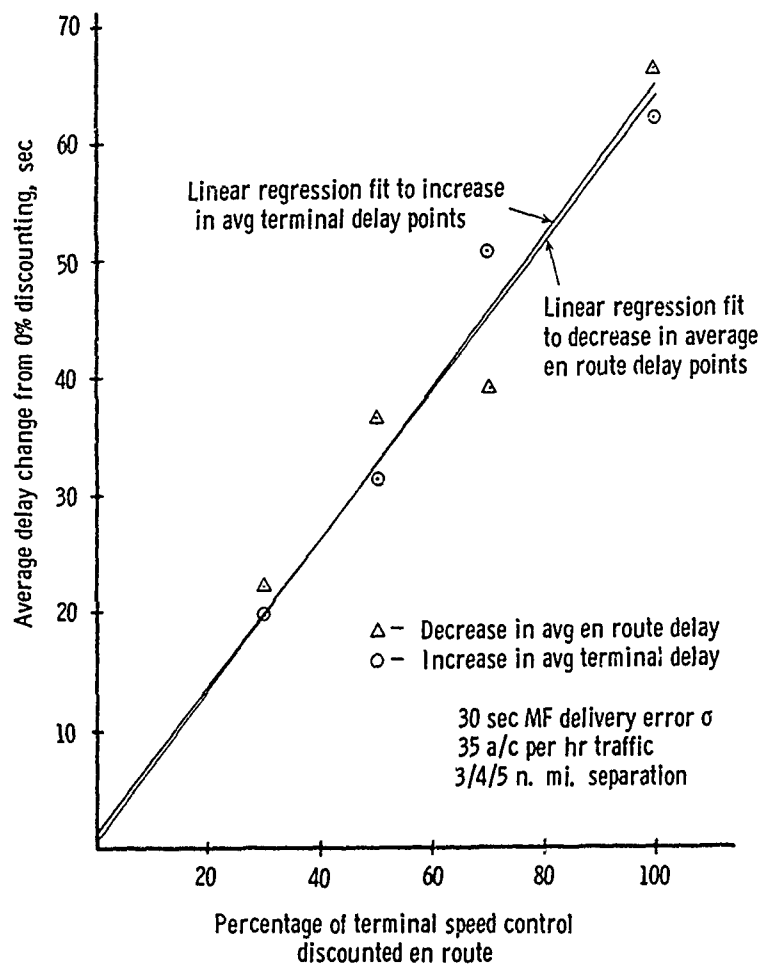


Figure 17: Relationship of both the decrease in average en route delay and the increase in average terminal delay as a function of en route delay postponement for a 30 seconds metering-fix-delivery-error standard deviation.

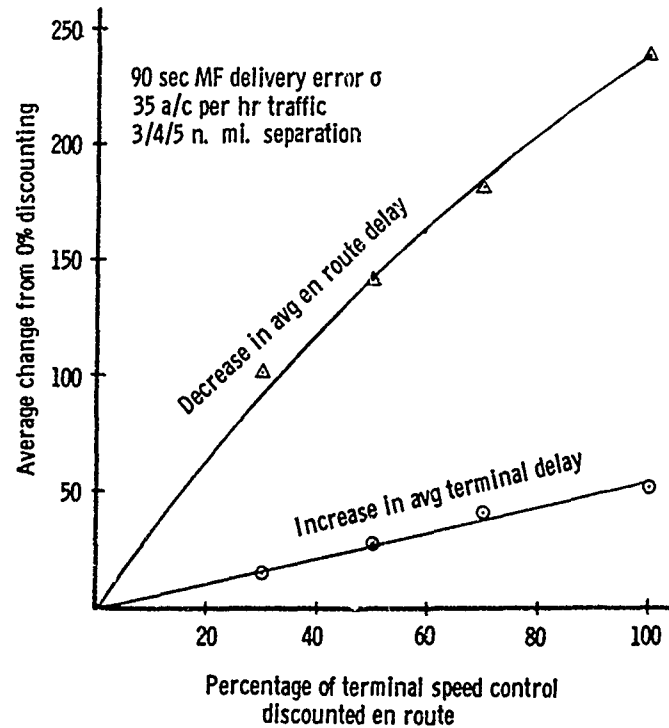


Figure 18: Relationship of both the decrease in average en route delay and the increase in average terminal delay as a function of en route delay postponement for a 90 seconds metering-fix-delivery-error standard deviation.

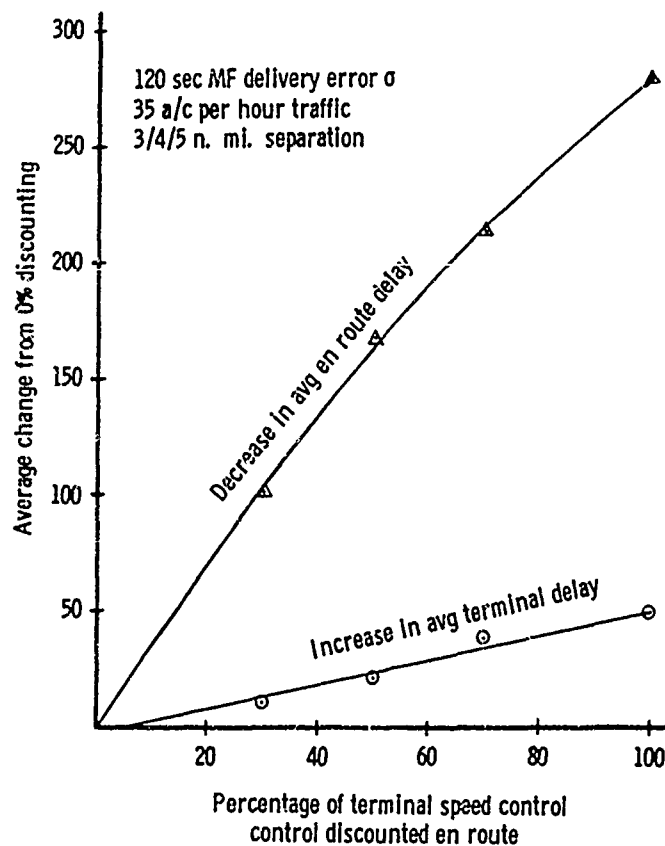


Figure 19: Relationship of both the decrease in average en route delay and the increase in average terminal delay as a function of en route delay postponement for a 120 seconds metering-fix-delivery-error standard deviation.

6.4 Final Approach Delivery Performance

6.4.1 Relation of Separation and Delivery Precision

Like any ATC system that must keep violation of specified separations to a low probability level, TIMER's capacity is sensitive to system final delivery precision. This comes about because a delivery-error-dependent interarrival time buffer must be added to the minimum permitted separation time in order to reduce separation violations to some low probability criteria. The scheduled time separation between two aircraft is illustrated in figure 20. The time relation between single aircraft delivery precision and the buffer added to keep violations between aircraft pairs to less than 5 percent is defined below:

$$\sigma_{RI_{12}}^2 = \sigma_{RD_1}^2 + \sigma_{RD_2}^2 \quad (1)$$

$$T_B = 1.65\sigma_{RI_{12}} \quad (2)$$

where

σ_{RD_1} - runway delivery-error standard deviation of the first of two successive aircraft

σ_{RD_2} - runway delivery-error standard deviation of the second of two successive aircraft

$\sigma_{RI_{12}}$ - aircraft pair runway interarrival-error standard deviation

T_B - buffer time added to minimum separation due to delivery uncertainty

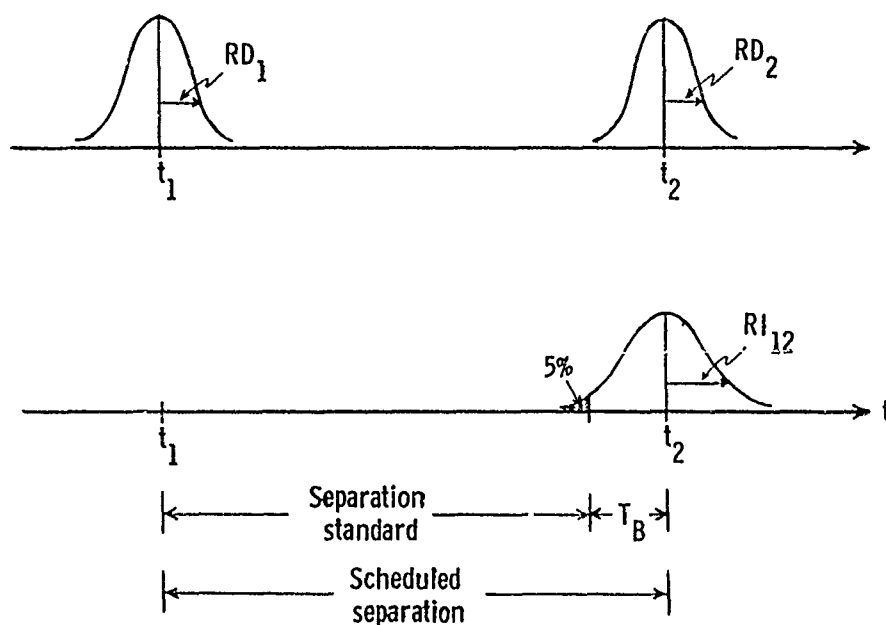


Figure 20: The time relationship between two successive landing aircraft of their individual delivery error, separation standard, and their scheduled separation.

6.4.2 Runway Arrival Rate

Figure 21 shows the simulated TIMER runway arrival rate as a function of system runway interarrival-error standard deviation and runway delivery-error standard deviation for the three separation standards defined in Section 5.0. These data were obtained under the assumption that Runway Occupancy Time (ROT) is not a limiting factor. If current procedure of prohibiting simultaneous occupancy of a runway by more than one aircraft is adhered to, then the maximum mean ROT is 37.6, 50.4, and 63.3 seconds for the 2/3/4, 2.5/3.5/4.5, and 3/4/5 nmi. separation criteria, respectively (Swedish, W. J., August 1979). Runway interarrival-error standard deviation will be the measure used to evaluate the delivery effect of several parameters. However, since 4-D system performance is normally given in terms of aircraft delivery-error standard deviation, that axis was also included in figure 21 for comparison. As figure 21 clearly indicates, final delivery precision is a key issue related to system capacity for all separations although the impact becomes more pronounced as separations are reduced. It is anticipated that when a time-based ATC system is first introduced, many if not most of the aircraft will be non 4-D. Until the bulk of the traffic is 4-D equipped, the performance of a time-based system will be constrained by the runway delivery precision achievable with non 4-D aircraft. A major goal of this study is to determine where, on the figure 21 runway delivery precision axis, the resultant performance of non 4-D equipped aircraft falls when operating together with computer aiding for the controller.

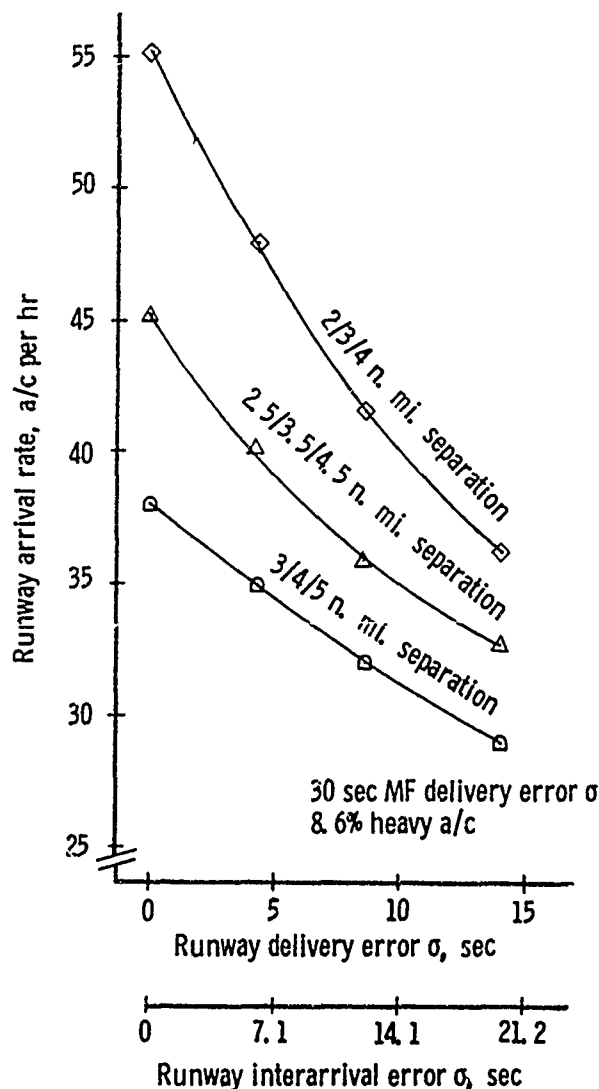


Figure 21: Impact of runway delivery error on capacity.

As a point of reference, the delivery precision (interarrival-error standard deviation) of manual control at the final approach course gate (normally 1 nautical mile outside the final approach fix) is about 18 seconds (Haines, A. L., April 1978). Bear in mind that the delivery precision at the runway threshold is further degraded by variation in aircraft final approach speeds due to varied weight and piloting procedure. Figures 22 and 23 show aircraft separation distributions at the outer markers and at the runway threshold (Mohleji, S. C., April 1987). While these data were collected under conditions of visual aircraft separations, they illustrate the effect that variable final approach speed has on increasing the spread of the separation distribution at the runway as compared to that at the final approach fix. One documented value of runway measured interarrival-error standard deviation, for manually-vectorred aircraft, is 25.6 seconds (Martin, D. A., August 1968).

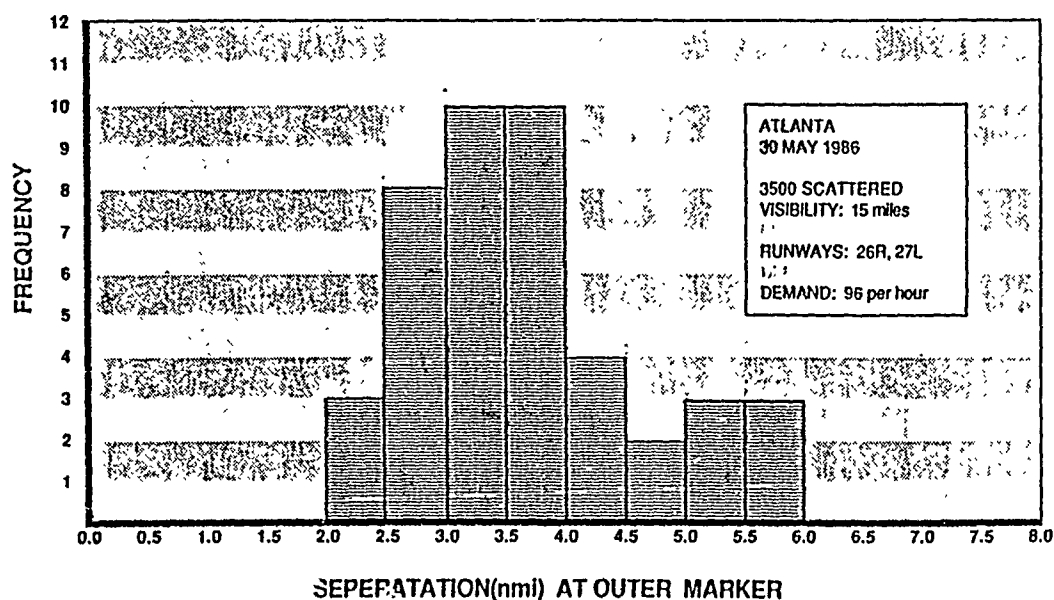


Figure 22: Aircraft pair separation distribution at the Atlanta (ATL) Airport measured when the first aircraft is at the outer marker.

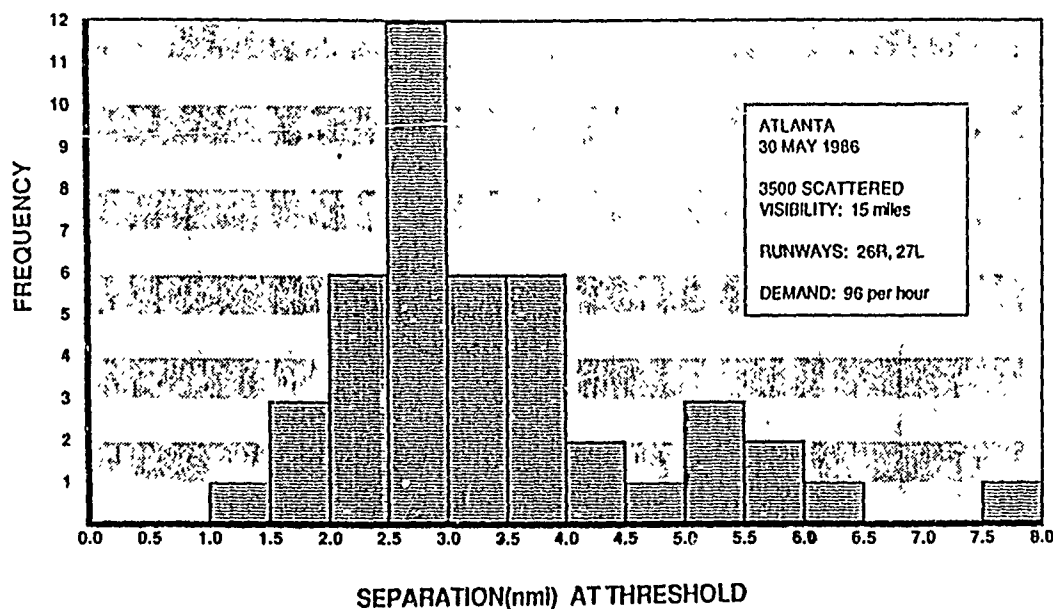


Figure 23: Aircraft pair separation distribution at the Atlanta (ATL) Airport measured when the first aircraft is at the runway threshold.

6.4.3 Non 4-D Equipped Aircraft with Known Expected-Final-Approach Speed

There are several parameters which directly affect the runway delivery performance of non 4-D equipped aircraft in TIMER environments. One of the principal factors is the variability in final approach speed, even within a specific aircraft design class, which is due to variable aircraft load (passengers, freight, and fuel) and differences in piloting procedure. If the final approach speed is known to the flow control system then other factors will determine the lower bounds of delivery precision. Some of these factors are pilot and controller response times, aircraft heading error, heading command resolution, wind velocity, wind velocity error, and piloting procedures.

6.4.3.1 Pilot and Controller Response Time: There is imbedded in the TIMER ETA calculations an assumed time for the controller response to computer generated aids and the pilot response to resultant ATC messages. Clearly a time error will be introduced if either the controller or the pilot react differently. A constant response time error will introduce a bias in the individual aircraft arrival times but the interarrival time error will not be affected. Two successively landing aircraft either early or late by the same amount will be properly separated relative to each other. However, variability in the response time will affect the runway interarrival error. Figure 24 shows the measured runway interarrival-error standard deviation as a function of the combined controller and aircraft system reaction-time-error standard deviation. The nominal value used in the baseline runs was a standard deviation of 3.5 seconds. This value yielded an interarrival-error standard deviation of 6.6 seconds with no winds.

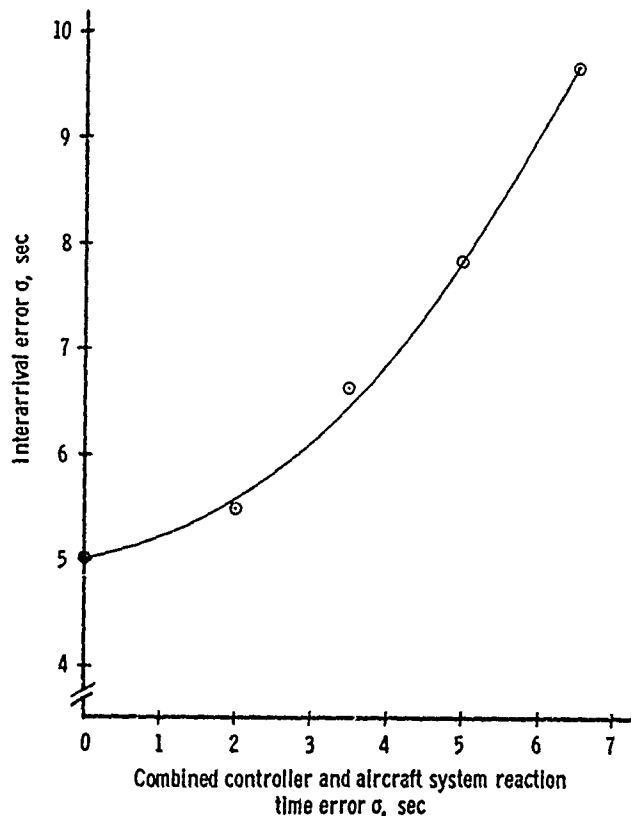


Figure 24: Effect of controller and pilot/aircraft response times on the system's runway interarrival error.

6.4.3.2 Aircraft Heading Error: When an aircraft is given vector instructions in the downwind, base, and turn to final region, the accuracy to which those vectors are followed has some effect on the runway arrival time accuracy. The TIMER calculations are based on a specific trajectory. If the aircraft's path or flight distance is different, then a time error will occur. Figure 25 displays the measured runway interarrival-error standard deviation sensitivity to aircraft-heading-error standard deviation for two wind conditions. The nominal value used in the baseline runs was a heading-error standard deviation of 2 degrees. Increasing the heading error σ to 6 degrees only added about 0.75 seconds to the runway interarrival-error σ for either wind condition.

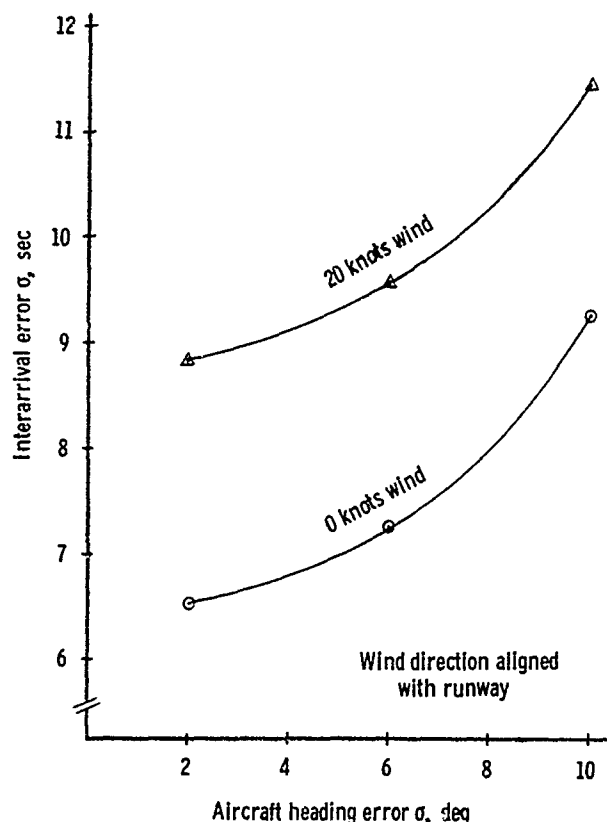


Figure 25: Effect of aircraft heading error on system's runway interarrival error.

6.4.3.3 Heading Command Resolution: The TIMER algorithm calculates a precise heading for the aircraft to follow a desired ground track with the assumed winds. When that heading instruction is displayed and issued to the aircraft, it is rounded to a specified resolution. This causes the heading angle error to vary somewhere between $\pm 1/2$ the resolution angle. Current ATC practice calls for vectors to be issued to the nearest 10 degrees. Figure 26 presents the boundaries of the runway interarrival-error standard deviation as a function of aircraft heading command resolution for two heading-error standard deviations. For non-varying conditions, the resolution rounding or aliasing error is constant for any given ground track. This introduces a fixed bias in the runway delivery time for each aircraft but does not effect the interarrival error. The non-varying condition is represented by the lower boundary of each of the heading error conditions.

On the other hand, variations in the resolution rounding error, caused by factors such as changing winds, altitudes, aircraft speeds, and approach path headings of different routes will affect the runway interarrival error. The upper boundaries plotted in figure 26 show the measured interarrival-error standard deviation as a function of heading command resolution for a uniform distribution model of resolution rounding error. The interarrival-error standard deviation is not very sensitive to heading resolution induced errors if the resolution is kept to 10 degrees or less. For example, the error contribution due to 10 degrees resolution will be somewhere between 0 and 0.75 seconds interarrival-error standard deviation depending on wind and aircraft trajectory variations.

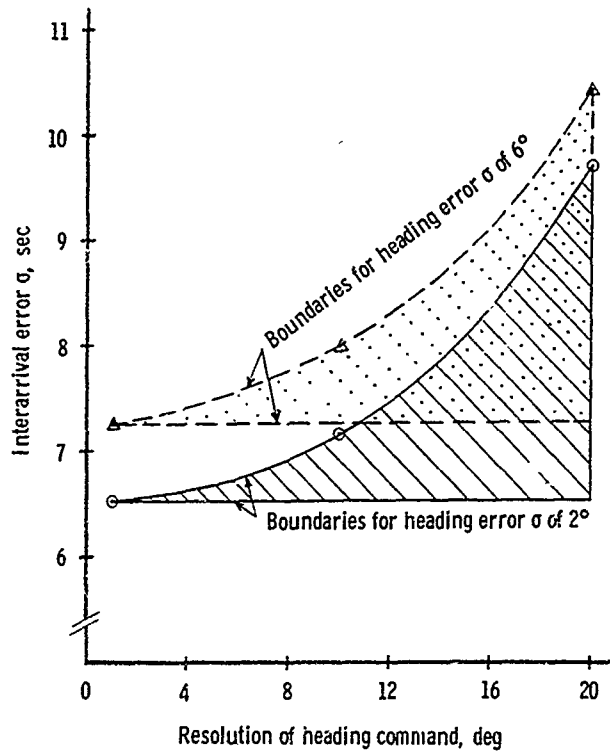


Figure 26: Impact of the heading command resolution on system's runway interarrival error.

6.4.3.4 Wind: As the curves of figure 25 indicated, the TIMER system final approach performance is degraded by winds as well as aircraft-flight-technical-error. Figure 27 shows the measured runway interarrival-error standard deviation as a function of wind strength for the upper and lower bounds of any likely aircraft heading-error standard deviation. Since the TIMER ETA calculation accounts for wind, the interarrival error should not change with wind strength. However, figure 27 indicates that wind strength magnifies the effect of another error or uncertainty. For example, an increase in surface wind from 0 to 20 knots results in an increase of 2.3 seconds interarrival-error σ .

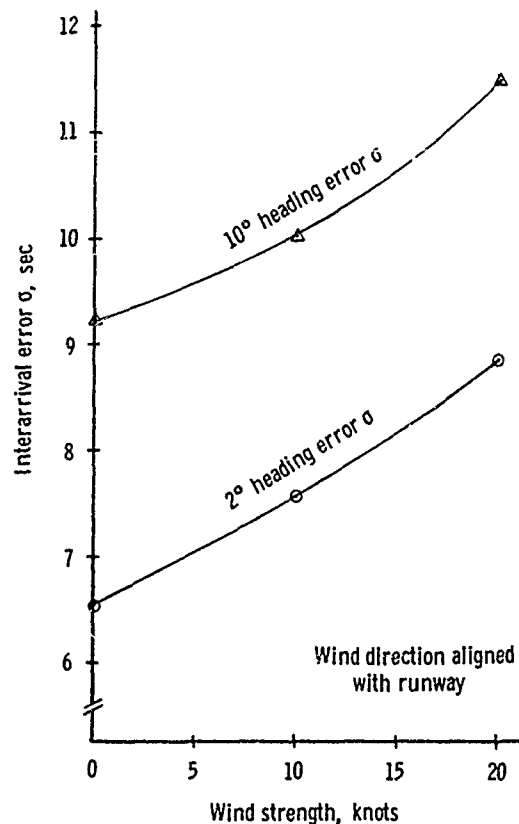


Figure 27: Impact of wind strength on system's runway interarrival error.

In addition to the interarrival-error effect there is a further arrival rate reduction due to reduced groundspeeds caused by the headwind component on final approach. This is characteristic of a system constrained by a distance separation criteria as opposed to a time-based criteria. Figure 28 shows this compounding effect on the runway arrival rate. The dashed curve represents the simulated arrival rate for the given wind condition but for the no-wind interarrival-error buffer value. The interarrival-error standard deviation measured were then used to adjust the separation and project the arrival rates shown by the solid curve.

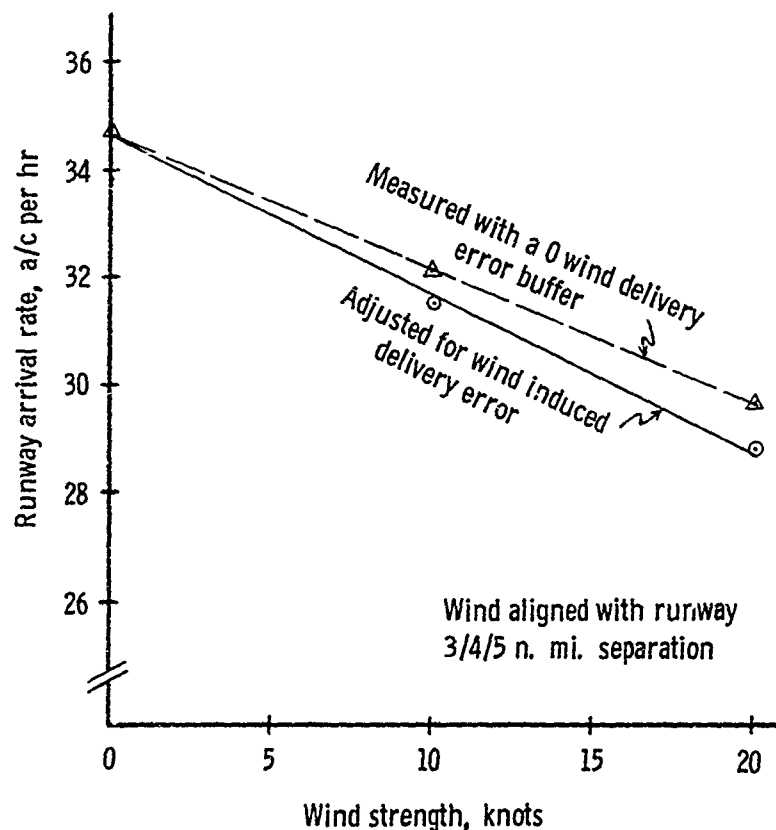


Figure 28: Impact of headwind strength on runway arrival rate.

Another consideration is the contribution of wind strength error. This results from a difference between the actual and predicted value of wind. Figure 29 shows the measured interarrival-error standard deviation for various percentages of wind strength error for a 20 knot surface headwind aligned with the runway. Unfortunately, wind strength errors also affect the final heading vector calculation. Since a particular ground track is desired, there is an interplay between the heading value calculated, the given wind error condition, and the heading resolution to the nearest 10 degrees. This obscures the results somewhat as the data scatter of figure 29 indicates. Nevertheless, for the 20 knot wind condition, it appears that wind strength errors of up to 20 percent have less than a 1 second effect on the interarrival-error σ .

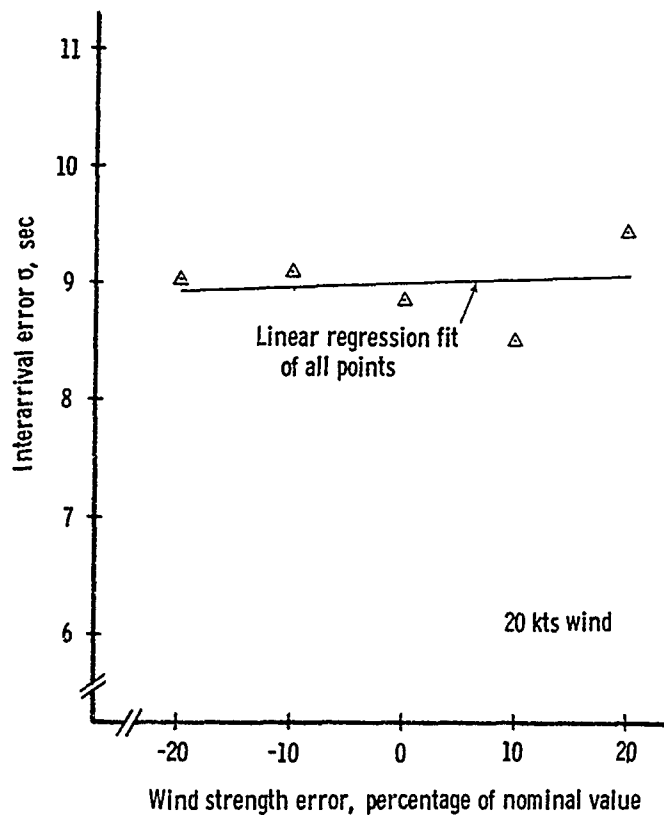


Figure 29: Effect of wind strength error on system's runway interarrival error.

6.4.3.5 Pilot Induced Variation in Expected-Final-Approach-Speed: The final approach speed is defined as the speed flown on an instrument approach between the final approach fix and the runway threshold. For each aircraft type there exists a final approach and landing speed (typically 1.3 times the stall speed) which, for the recommended flap setting, is nearly a linear function of aircraft weight. The speed/weight curves are contained in company and pilot manuals and also in a tabular form in the pilot's take-off and landing speeds flip-chart. Generally, pilots add one-half of the surface headwind plus the gust value to the indicated flip-chart speed. This resultant value will be referred to as the expected-final-approach speed. However, there is some variability in the wind adjustment from pilot to pilot as well as in the precision of flying the selected final approach speed. Other considerations are the type of terminal and traffic load as well as the increasing wind shear concern. These characteristics of higher than expected final approach speeds may be modeled but some variability is inevitable.

The effect of final approach piloting procedure was modeled by adding an additional increment of speed to the expected-final-approach speed, assuming the landing weight of the aircraft was known. This pilot induced uncertainty was represented by a Gaussian distribution of 0 mean and a specified standard deviation. Figure 30 presents measured runway interarrival-error standard deviation sensitivity to the standard deviation of error in the expected-final-approach speed. Variability in actual final approach speed that is different from the expected speed significantly degrades the runway delivery precision. A reasonable pilot induced final approach speed standard deviation in the vicinity of 4 knots (Section 6.4.4) would add about 3.5 seconds to the runway interarrival-error standard deviation as compared to the situation when the prescribed speeds, for the aircraft landing weights, were precisely flown.

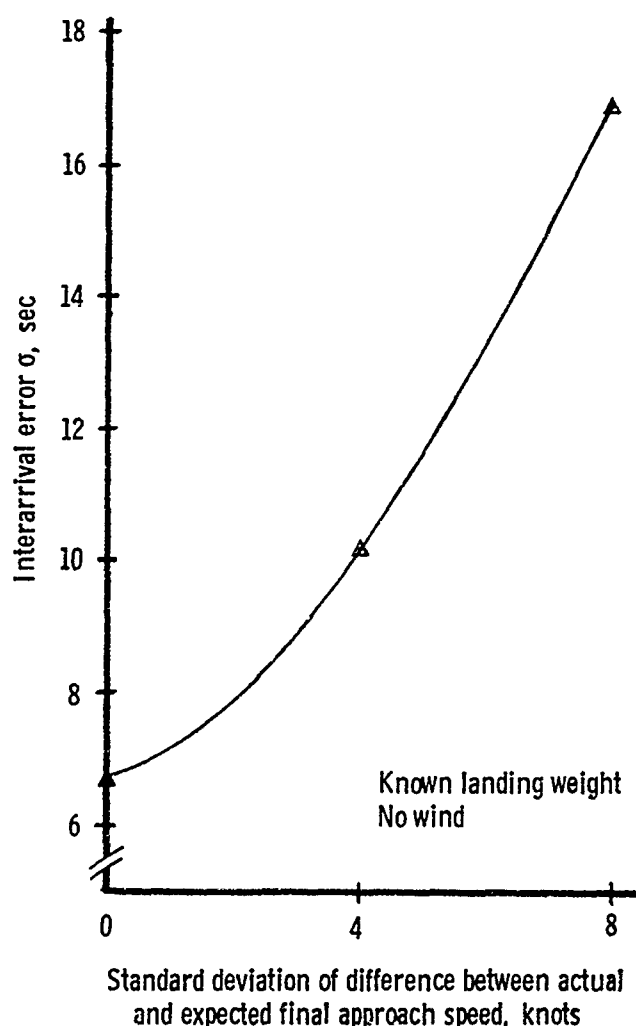


Figure 30: Impact of pilot induced variability in the final approach speed on the system's runway interarrival error.

6.4.3.6 Interarrival-Error with Known Expected-Final-Approach Speed: In the terminal simulation the variability in final approach speed that is due to the aircraft's landing weight is accounted for by varying a quantity called weight factor (W_f). The approach-speed/weight/weight factor relationships are illustrated in figure 31. Weight factor is a normalized value to the particular aircraft type which characterizes the aircraft's actual landing weight. A weight factor of 1 is equivalent to that aircraft's maximum landing weight and 0 is equivalent to the aircraft's operating empty weight. The recommended final approach speed is almost linear over the defined range of weight factor. A straight line approximation to the final approach speed/weight factor relation was used. Therefore, the aircraft's final approach indicated airspeed (V_a) is defined by

$$V_a = V_{am} - (1 - W_f)(\Delta V_a) \quad (3)$$

where

V_{am} = final approach speed at maximum landing weight for the A/C type

$$\Delta V_a = V_{am} - (\text{approach speed at A/C operating empty wt}) \quad (4)$$

$$W_f = \frac{(\text{A/C landing wt.}) - (\text{A/C type operating empty wt.})}{(\text{A/C type max landing wt.}) - (\text{A/C type operating empty wt.})} \quad (5)$$

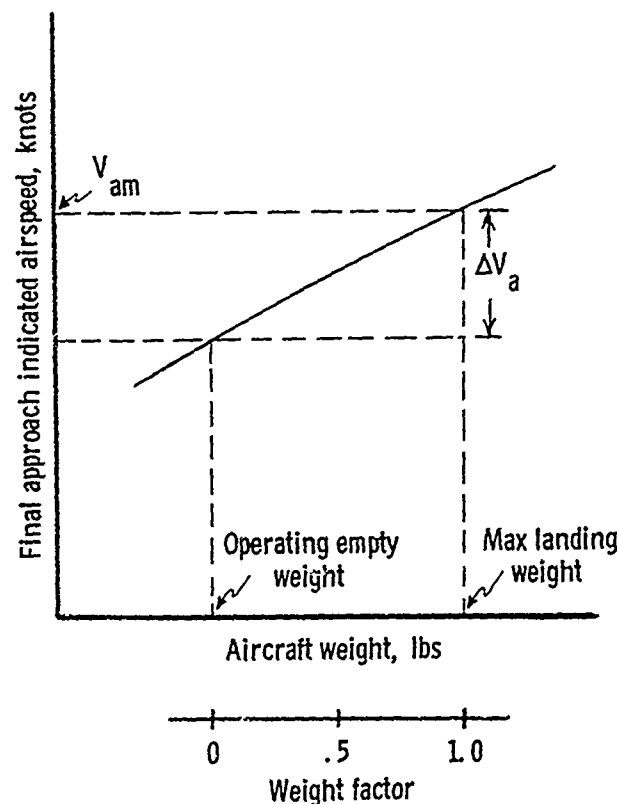


Figure 31: Relationships of aircraft weight, weight factor and final approach landing speed.

If the TIMER system knew the expected landing weight, the specific aircraft's final approach speed could be determined from parameters stored for that aircraft type and equations 3, 4, and 5. One possibility would be to have expected landing weight included as part of the flight plan information entered into the ATC system. A related technique would be to have departure weights entered and then approximate the landing weight using the aircraft fuel-burn rate. The use of data link to convey weight or even the pilot's planned final approach speed will be feasible when that system becomes operationally available. Before data link, a manual entry of the pilot's intended final approach speed into the flow control system might be used instead of calculating the expected speed. This, however, could present some operational problems and additional workload, particularly to the controller.

Another method of knowing the final approach speed would be to request each aircraft of a type to fly a specific indicated airspeed. Either a common speed plus wind correction would be agreed to by pilots and carriers and included in company manuals or it would be requested by ATC. The aircraft-type-specific airspeed would be selected to allow the heavily loaded aircraft of the class to land safely at existing wind conditions. This procedure would simplify the ground system requirements, but would require the lighter loaded aircraft to fly faster than normal final approach speeds. Either a mutually agreed to common final approach speed or an ATC requested final approach speed is a change from current operating procedures and pilot/company acceptance would be a major issue. Other considerations such as tire wear cost, blow-out hazard, runway lengths, and exit locations would influence operational acceptance.

If the aircraft's expected-final-approach speed is known to the TIMER system, the lower bounds of non 4-D equipped aircraft's delivery precision will be determined by several other factors. These factors include pilot and controller response times, aircraft heading error, heading command resolution, wind velocity, wind velocity error and final approach piloting procedure. The parametric evaluation of how these factors degraded runway delivery accuracy indicates that the runway interarrival-error standard deviation for unequipped traffic would be in the region of 8 to 12 seconds with computer aiding to the controller. As referenced in Section 6.4.2, the interarrival-error delivery precision σ of manual control is about 26 seconds at the runway threshold by comparison. Using the same 5 percent violation criteria defined in Section 6.4.1, the improvement of computer aiding over the manual system would theoretically yield an arrival rate increase in the range of 16 to 25 percent when operating under either the 3/4/5 or 2.5/3.5/4.5 nmi separations criteria.

6.4.4 Selected Real-Time Piloted Simulator Results

The real-time version of the Terminal Area Air Traffic Model, TAATM (Credeur, L., August 1981), with the TIMER algorithms embedded, together with a transport cockpit simulator, forms the basis of a total simulation system for real-time crew-in-the-loop experiments. These experiments serve a dual purpose. The first is to verify the fast-time results and refine the model. The second is to provide a baseline operational capability for evaluating and refining controller and display options.

The transport cockpit (figure 32) used in the study is a fixed-based, full-workload, DC-9 simulator. In addition, a television model board provides the out-of-the-window landing scene. The aircraft dynamics modeled were those of the DC-9 Series 30 aircraft. A full complement of cockpit electromechanical instruments was provided, with all major systems functional including autopilot, dual flight directors, navigation and communication radios. Subsystems such as hydraulics and electrical systems were modeled to the extent necessary to provide normal in-flight operations and readouts to the crew. The terminal-area simulation program and the cockpit simulator were run simultaneously on separate computer systems with x, y, and z positions from the DC-9 simulator available to the terminal-area model. The multi-frequency radio communications were simulated with selectable voice link channels between the cockpit radio heads and the ATC controller radar display console of the terminal simulation. Once initialized, the TIMER algorithm treated the DC-9 simulator as if it was one of the terminal simulation's own traffic and reacted to the situations created by the controller/pilot actions.

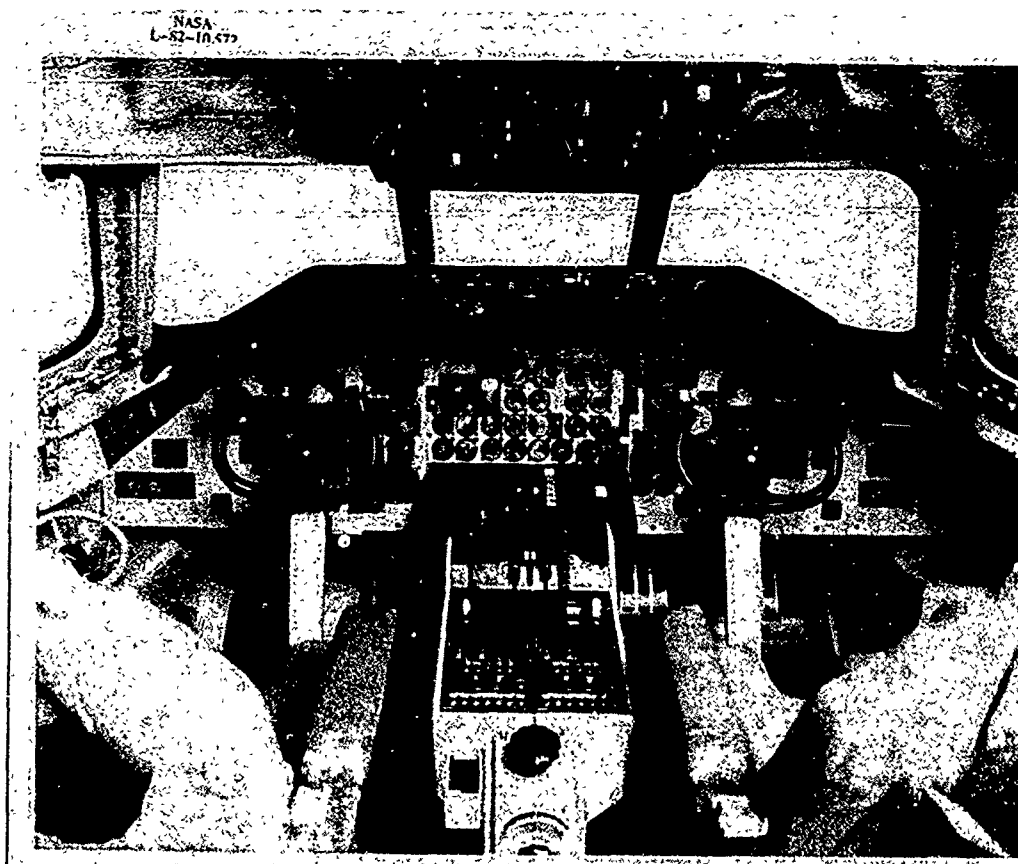


Figure 32: DC-9 cockpit simulator.

The area of interest was the final approach performance of the conventional non 4-D aircraft in the TIMER environment. Approaches from the KEANN and DRAKO routes (figure 7) were randomly selected. A real-time data run was started with the DC-9 simulator initialized and replacing a TAATM aircraft at either 6.5 miles before the downwind leg on the DRAKO route or 6.5 miles before the turn to base on the KEANN approach. Eight professional DC-9 rated crews, four from each of two major U.S. airlines, served as research subjects. A set of runs was made with each crew requested to react to controller instructions as they normally would on an IFR approach. Each crew was then briefed on the TIMER concept and how it was being applied, and another series of simulated approaches was performed. Each run was flown all the way to runway touchdown and terminated after starting the rollout. A full report of the real-time simulation results is in preparation.

Figure 30 indicated that large variations from the expected indicated airspeed, flown by pilots from the final approach fix to the runway threshold, would have a severe impact on runway interarrival error. Therefore, determining the extent of speed variation on final approach from that expected is an important parameter. The pilot's chart listed a speed of 130 knots for the DC-9 simulator configured landing weight of 95,000 pounds. Since the simulated surface headwind was 8 knots, the expected-indicated-airspeed on final approach was 134 knots. Figures 33 and 34 show the frequency distribution of the final approach indicated airspeeds sampled at the category I window (about 200 feet above and 2,800 feet from the threshold for a 3° glideslope), before and after briefing, respectively. The t and F tests at the 6 percent level indicated that the means and standard deviations of the final approach speeds, before and after briefing were not distinguishable. Consequently, the before and after briefing speeds were combined to get the frequency distribution shown in figure 35. This pooled data indicates that, on the average, the final approach speed was 4.8 knots faster than expected, and the standard deviation of the 68 data runs was 3.7 knots.

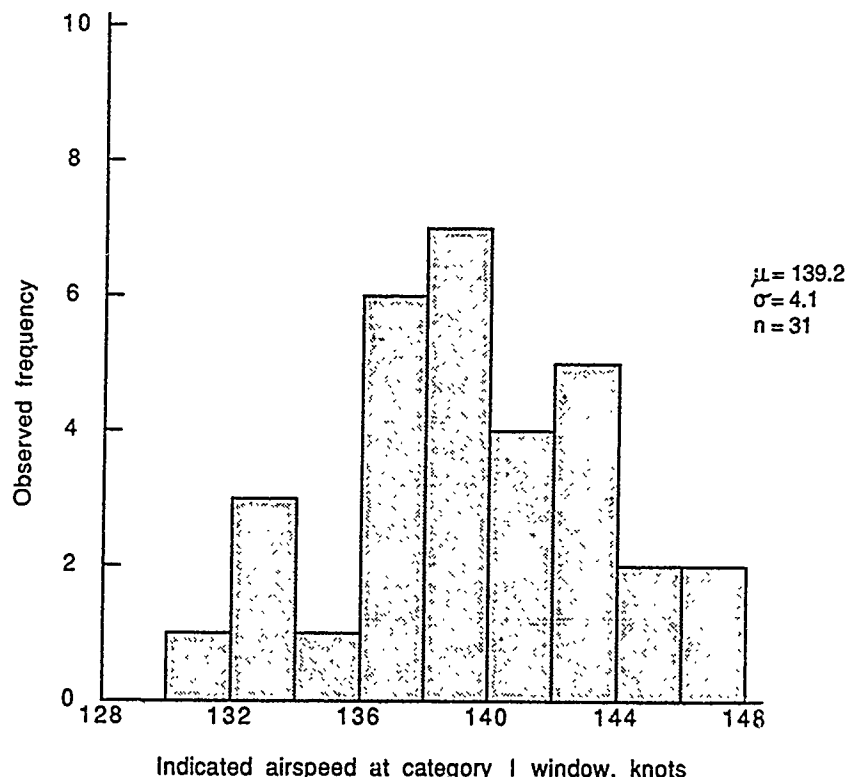


Figure 33: The frequency distribution of the final approach indicated airspeed sampled at the category I window before the TIMER pilot briefing.

As indicated earlier, a key issue related to system capacity is the runway delivery performance of non 4-D equipped aircraft when operating in a time-based environment that provides computer assistance to the controller. This experiment was conducted specifically to quantify the non 4-D pilot/cockpit airborne system's contribution to delivery error. Later experiments in the Langley Research Center total system simulator (Kaylor, J. T., October 1985), with full pseudo-pilot loading of the controller, will assess the ATC controller influence on runway delivery error in a TIMER environment. It should be noted that the DC-9 simulator's landing weight was a known and constant value in all the approaches flown.

Figures 36 and 37 show the frequency distributions of the runway threshold delivery errors before and after pilot briefing. The measured runway arrival-error standard deviation was 9.7 seconds before briefing as compared to 7.0 seconds after briefing. The F test at the 6 percent level, barely indicated the measured runway arrival error standard deviation after briefing was different from that measured before pilot briefing. With no error contribution by the ATC controller and with today's typical airline crew response, the data indicate a non 4-D aircraft-delivery-error standard deviation of about 10 seconds. With pilot knowledge and awareness of the process, i.e., with motivation and attention, the delivery error dispersion could be reduced slightly. Unless the ATC controller error contribution is significantly greater than expected, the real-time piloted simulation outcome after briefing supports the fast-time study conclusions. That is, non 4-D aircrafts' runway interarrival-error standard deviation would be in the range of 8 to 12 seconds, given pilot motivation and ground system knowledge of expected-final-approach speeds.

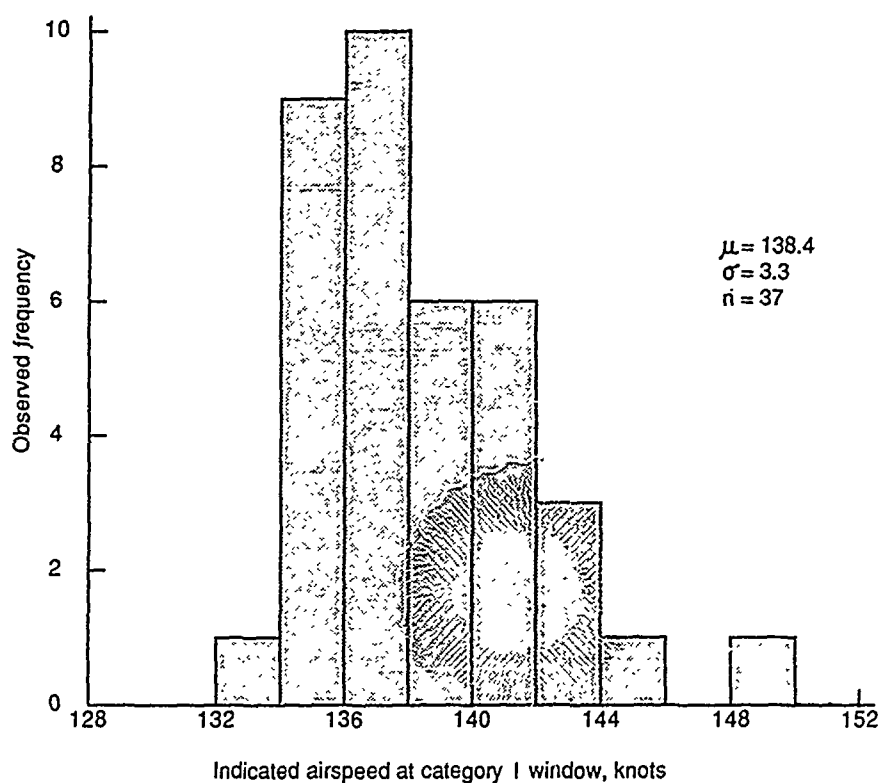


Figure 34: The frequency distribution of the final approach indicated airspeed sampled at the category I window after the TIMER pilot briefing.

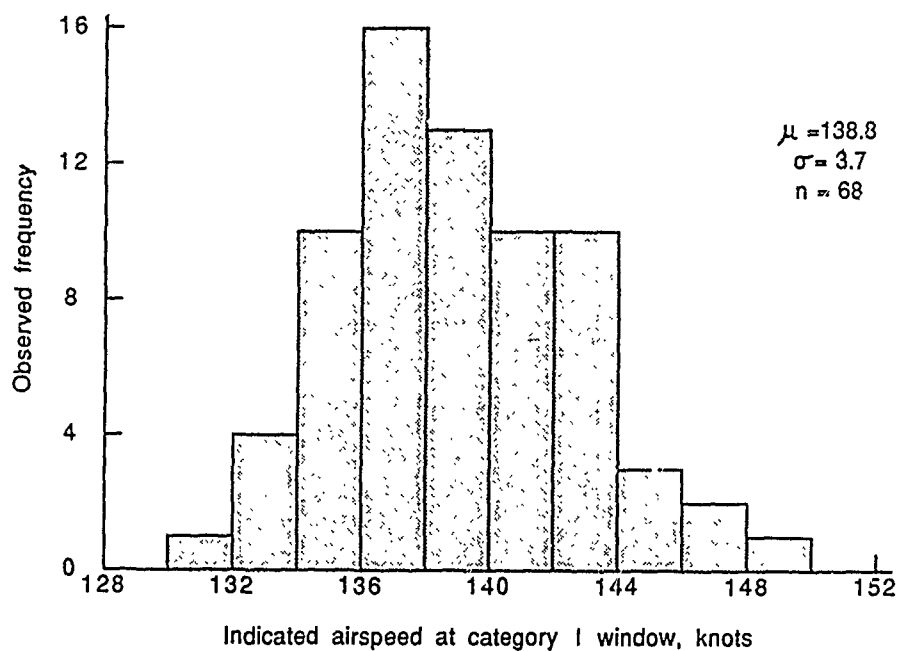


Figure 35: The combined frequency distribution of final approach indicated airspeed for both unbriefed and briefed data runs sampled at the category I window.

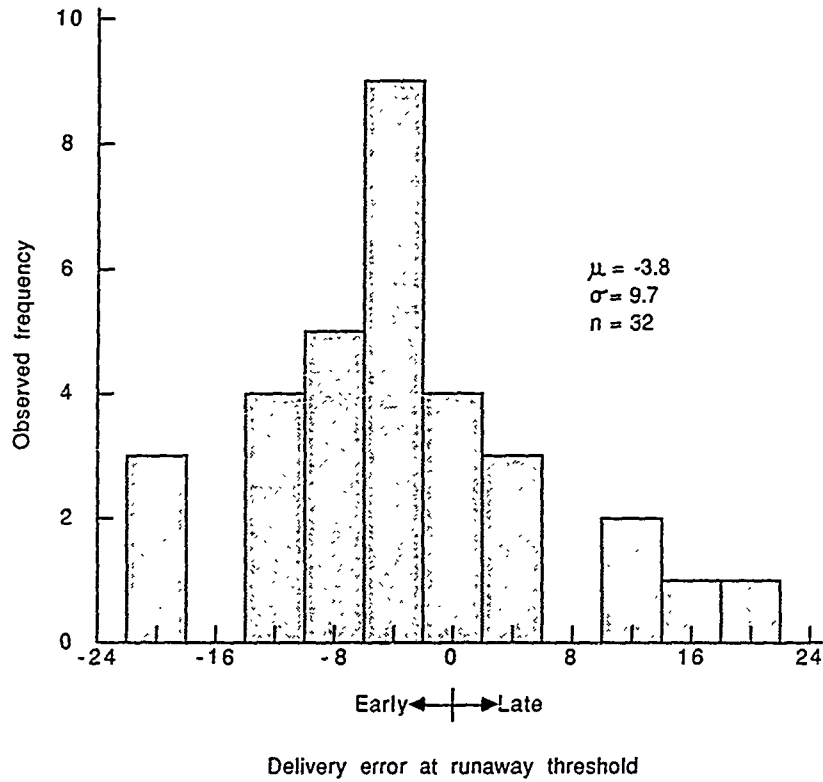


Figure 36: The frequency distribution of the runway-threshold-delivery-error before the TIMER pilot briefing.

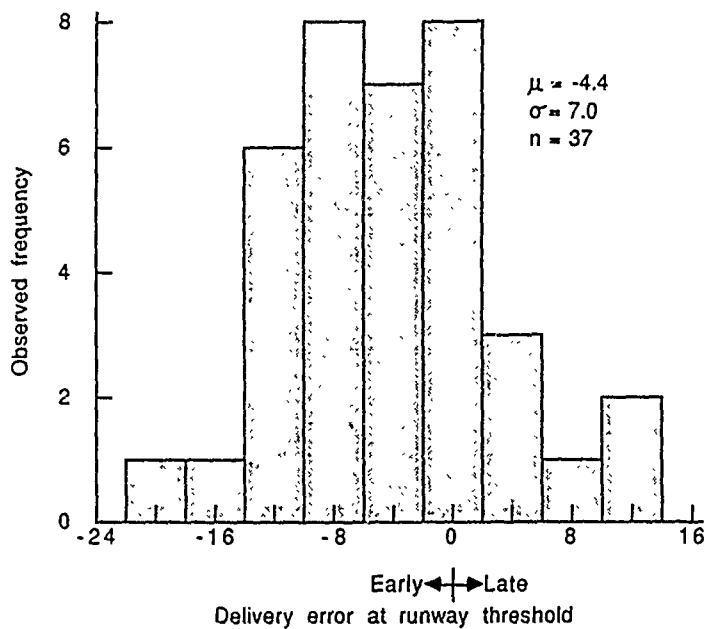


Figure 37: The frequency distribution of the runway-threshold-delivery-error after the TIMER pilot briefing.

6.4.5 Non 4-D Equipped Aircraft with Unknown Expected-Final-Approach Speed

In today's operational environment the weight and thus the expected-final-approach speed of a specific aircraft is not known to the ATC system. Clearly if the expected-final-approach speed is an unknown, variable value then an additional degrading of the delivery precision will result. Flying the last 5 or so miles of the approach at a different speed from that assumed will introduce a significant time error to the runway-threshold crossing time. In the previous two sections the system runway interarrival-error standard deviation was determined to be somewhere between 8 to 12 seconds. The question is how much further reduction in delivery precision will result if the expected-final-approach speed is unknown and should an effort be made to obtain this parameter?

There were 10 types of transport aircraft simulated in the arrival traffic. The value of their possible approach speed variations are shown in table 2. These were compiled from various readily available sources such as "Janes's All the Worlds Aircraft" and Aviation Week's Commercial Transport Table. In calculating ETA's to the runway, when the aircraft's actual landing weight or expected-final-approach speed was not known, the procedure used was to choose the speed value corresponding to the mean of the weight factor distribution. Traffic samples with a weight factor mean of 0.5 and various standard deviations were created to obtain their impact on interarrival delivery precision.

TABLE 2 - FINAL APPROACH SPEED DIFFERENTIAL DUE TO WEIGHT VARIABILITY OF SIMULATED AIRCRAFT

Aircraft Designation	Final Approach Speed Differential (kts)
B720F	14
B727	30
B727-200	32
B737	32
B747	30
DC8	26
DC8 (60, 70 Series)	30
DC9	35
DC9 (30-80 Series)	31
DC10	25

Figure 38 shows the measured interarrival-error standard deviation as a function of different weight factor standard deviations. Under the conditions simulated, operating with unknown expected-final-approach speeds had a significant effect on system interarrival error for landing weight factor standard deviations greater than a value in the range of 0.05 to 0.10. What are the operational weight factor spreads likely to be encountered in the real world? Figure 39 presents the probability distribution of weight factors for all arriving B-737-200A aircraft of a major U.S. carrier landing at Chicago O'Hare Airport (ORD) between January 1, 1986, and April 30, 1987. The weight factor mean for the B-737-200A data was 0.435 and the standard deviation was 0.176. Likewise, figure 40 presents the same information for that carrier's B-737-200 aircraft. The weight factor mean for the B-737-200 data was 0.541 with a standard deviation of 0.196. While these distributions may not represent all situations, the fact that they are for a major carrier means that the distribution characteristics will have a significant impact on total population statistics.

Based on the limited real-world data available, it appears that weight factor standard deviations of greater than 0.1 are likely to be encountered. Figure 38 indicated that operating without aircraft-specific expected-final-approach speed knowledge could add 6 to 10 seconds to the system interarrival error standard deviation. Figure 41 shows the data of figure 27 together with the results when expected-final-approach speed is unknown to the TIMER algorithm. The weight factor distribution of the input traffic had a mean of 0.5 and a standard deviation of 0.15 for both cases. When the detrimental effects of pilot induced final approach speed variability as well as weight factor σ 's that could exceed 0.15 are considered together with the data of figure 41, the overall runway interarrival-error standard deviations would be in the region of 16 to 20 seconds if the final approach speed is unknown to the system. This difference in interarrival-error standard deviation represents about a 10 percent loss in arrival capacity. This magnitude of difference in arrival rate suggests that if there exists an operationally feasible approach to obtaining expected-final-approach speeds, it should be pursued. Some possible techniques were discussed in Section 6.4.3.6.

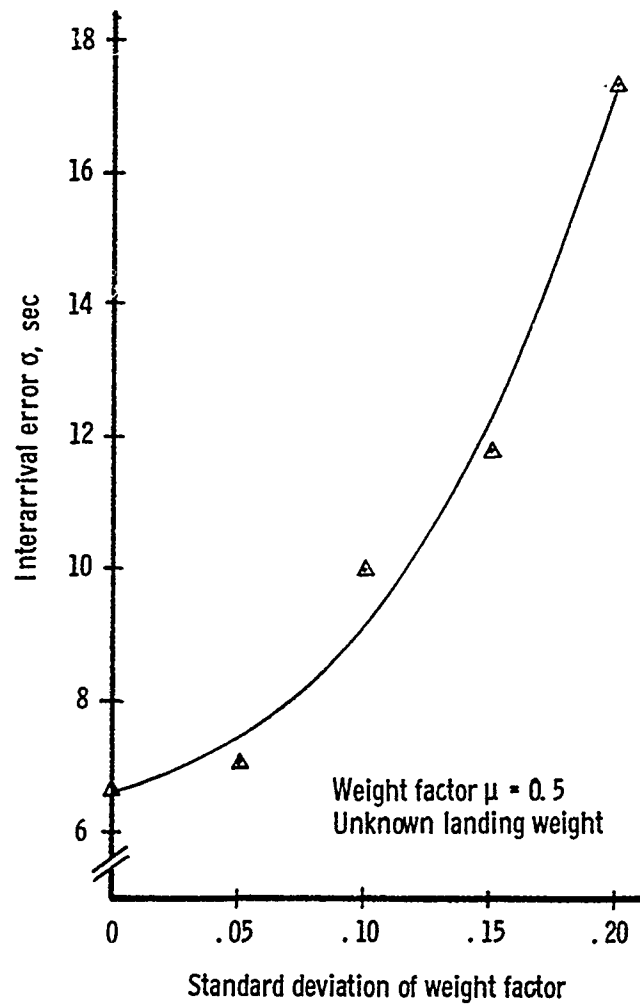


Figure 38: Impact of weight factor's density function on system's runway interarrival error.

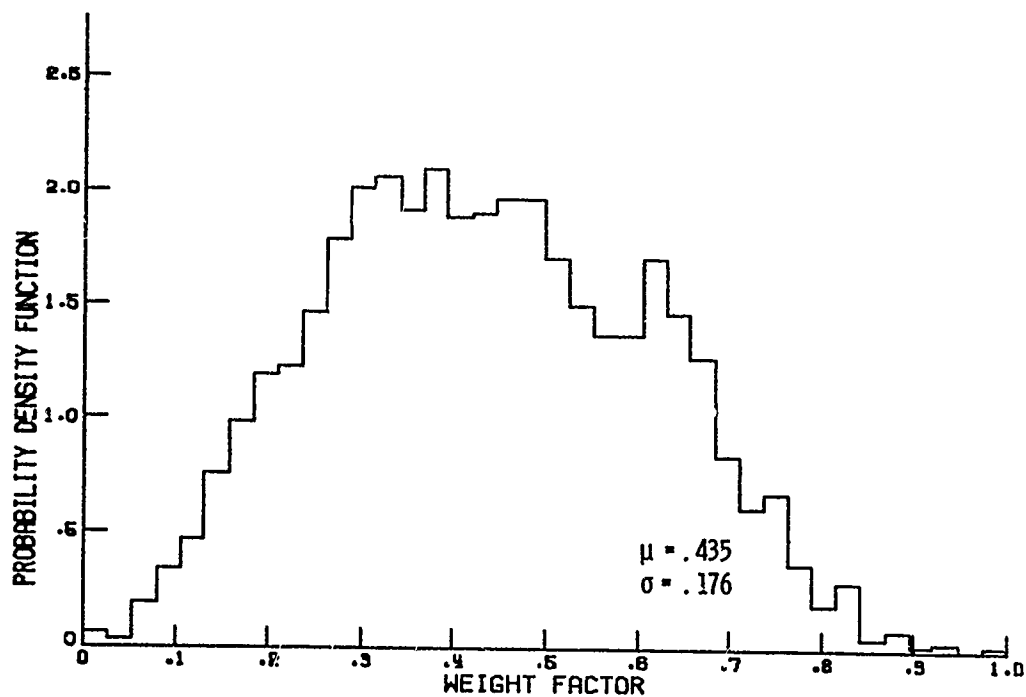


Figure 39: The probability density function of landing weight factor for a major airline's B-737-200A aircraft arriving at O'Hare (ORD) Airport in the period from January 1, 1986, to April 30, 1987. The mean was 0.435 and standard deviation was 0.176.

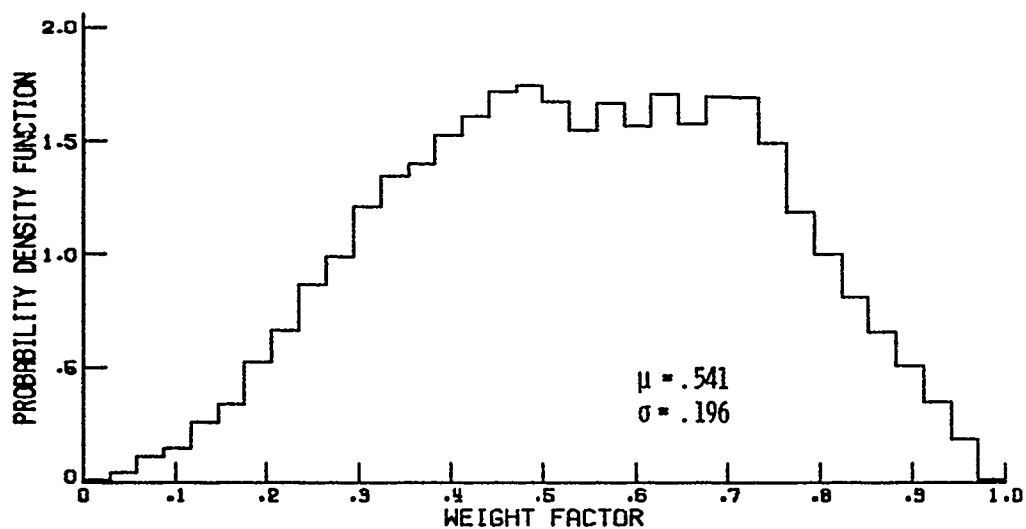


Figure 40: The probability density function of landing weight factor for a major airline's B-737-200 aircraft arriving at O'Hare (ORD) during the period from January 1, 1986, to April 30, 1987. The mean was 0.541 and the standard deviation was 0.196.

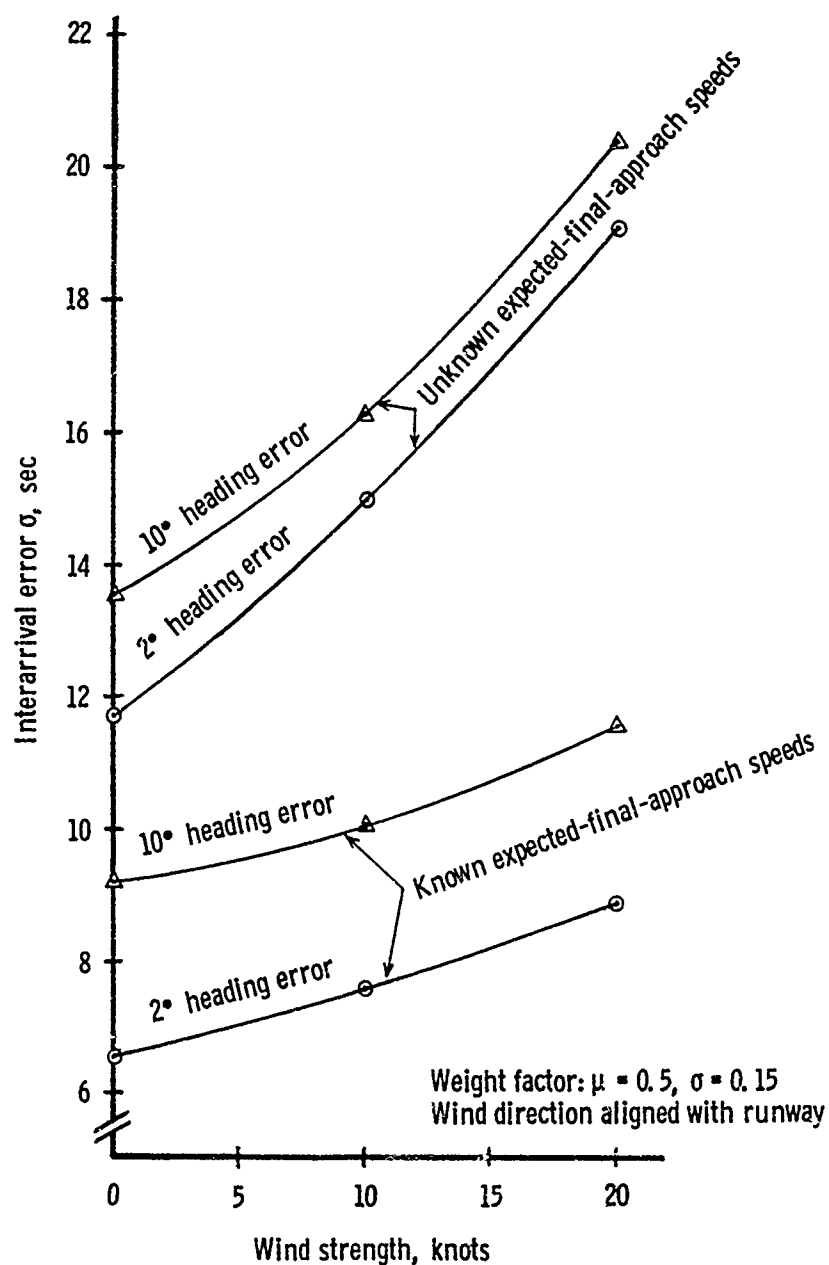


Figure 41: Impact of unknown expected-final-approach speeds, heading error, and wind strength on system's runway interarrival error.

6.4.6 4-D Flight Management System

There is reason to believe that aircraft equipped with advanced 4-D Flight Management Systems (FMS) can achieve delivery precisions of 5 seconds, or less, standard deviation (Bruckner, J. M. H., July 1977), (Heimbold, R. L., September 1980), (Adam, V., October 1982), and (Moor, D. A., December 1984). Figure 42 shows the runway arrival rate as a function of unequipped aircraft runway-delivery error for various mixes of 4-D equipped aircraft. The curves were obtained by a process of mathematical extrapolation, using data from the 2.5/3.5/4.5 separation curve of figure 21, with an assumed delivery-error standard deviation of the 4-D aircraft of 4.3 seconds. The analysis assumed that average interarrival time was the result of three factors: (1) separation standard, (2) schedule gaps due to system inefficiency, and (3) added interarrival buffer to accommodate delivery uncertainty. Since arrival rate is the reciprocal of the average interarrival time, the value of the first two factors can be determined from the data shown in figure 21. If the first two factors are then held constant, one can extrapolate the arrival rate effect of a new weighted buffer. The weighted buffer time value used in the revised average interarrival time is calculated by using equations 1, 2, and

$$T_B' = \sum_{j=1}^2 \sum_{i=1}^2 T_B^{P_i P_j} \quad (6)$$

where

T_B' - weighted buffer time

T_B - buffer time defined in equation (2) for aircraft pair ij .

p - probability that an aircraft is either 4-D equipped or non-equipped depending on the value of i or j .

i - first aircraft of a pair

j - second aircraft of a pair

1 - designates a 4-D equipped aircraft

2 - designates a non 4-D equipped aircraft

Figure 42 indicates that even if the runway interarrival-error standard deviation for non 4-D equipped aircraft is reduced with computer aiding to about 10 seconds, there is still some incremental capacity gains (theoretically 8 percent gain for 100 percent equipage) to be obtained by using high performance 4-D flight management systems.

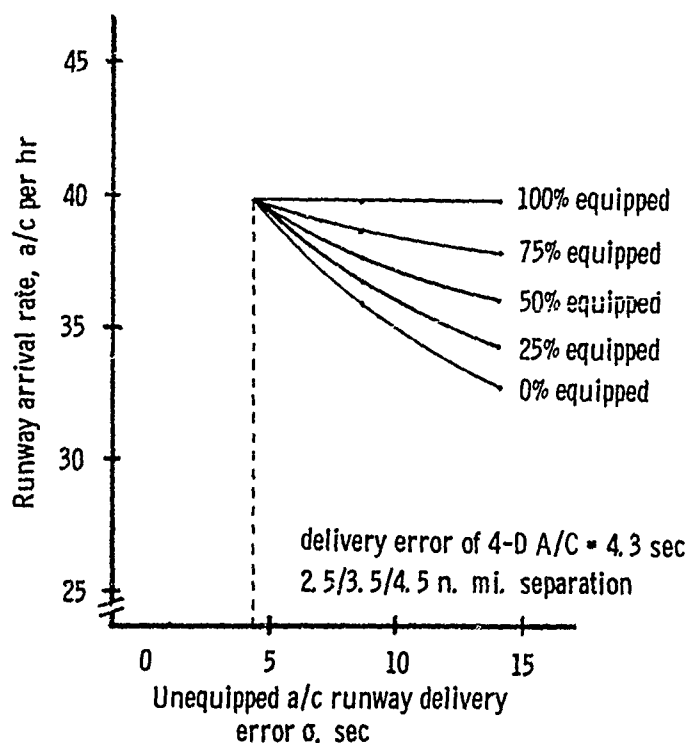


Figure 42: Effect of 4-D equipage on runway arrival rate.

6.5 Final Approach Geometry

It was postulated in Sections 6.2 and 6.3 that capacity may be affected by the limited time catch-up or forward-schedule-slippage capability on the two eastern or short approach routes. In order to test this hypothesis, the final approach geometry was modified in the simulation as shown in figure 43. The dashed lines show the shorter minimum paths obtained by relocating the final approach fix for runway 26L at a distance of 3.5 rather than the normal 5.5 nautical miles from the runway threshold. Such a close-in final approach intercept may be acceptable with MLS navigation.

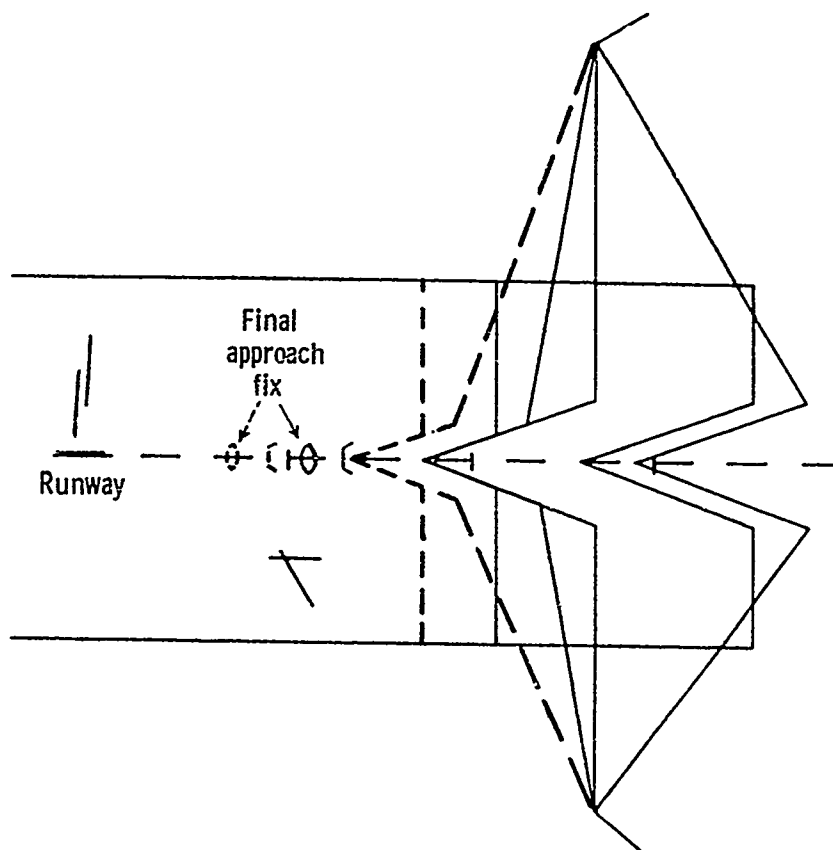


Figure 43: Fine tuning region expanded by dashed lines.

The revised configuration increases the forward-schedule-slippage capability of the eastern routes from about 18 to about 31 seconds. The Western route time-catch-up capability is increased from about 88 to about 160 seconds. The delay capability remains virtually the same as shown in table 1. Figure 44 compares the arrival rate for the nominal and revised geometries. The result of the revised geometry is a slight increase of about 1 aircraft per hour for the 3/4/5 nautical miles separation standard. This suggests that increasing the forward-schedule-slippage capability, particularly on the short approaches, improves the scheduler's ability to accommodate late arrivals at the metering fixes. Although current operational considerations restrict the shortening of the common final approach path, the implementation of the MLS may allow a reconsideration of the constraints (White, W. F., May 1978). A combination of designing as much time catch-up capability as possible in the short routes, together with delay discounting if aircraft are likely to have larger than 30 seconds metering fix errors, are techniques that the ATC system designer can use to reduce the short-route limitation of the conventional four-corner post terminal geometry.

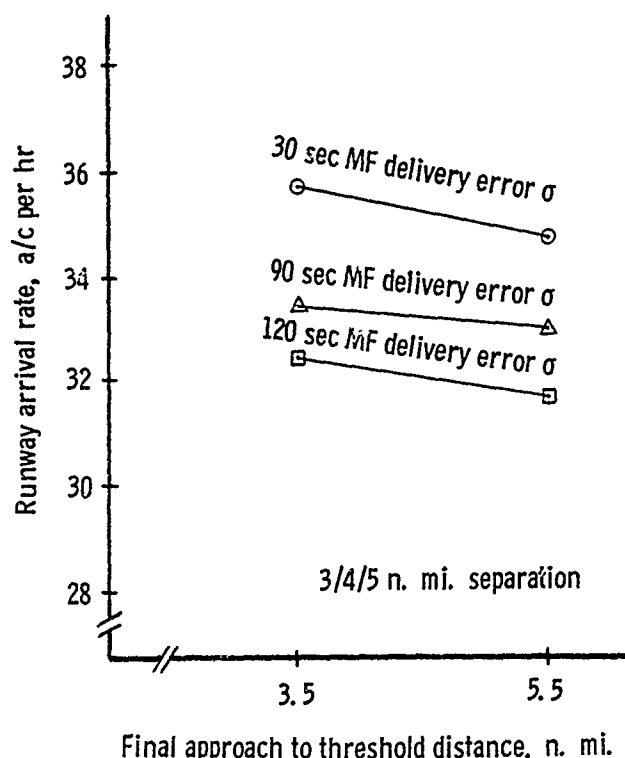


Figure 44: Effect of larger time control as a result of expanding the final approach, fine tuning area.

7.0 MAJOR SIMULATION RESULTS AND CONCLUDING REMARKS

An effort was undertaken, the broad objective of which was to define and evaluate an evolutionary time-based ATC concept called TIMER. The concept is aimed at improving the capacity, reliability, and efficiency of extended terminal operations (en route approach, transition, and terminal flight to the runway) when used with projected ground and avionics upgrades. A fast-time parametric sensitivity evaluation of the basic extended terminal area flow-control concept with non 4-D equipped aircraft was performed using a four corner-post, Denver runway 26L configuration with IFR arrival transport traffic. In addition, a follow-on real-time simulation study was conducted. The results of these studies identify and show the effects and interrelationships of key system variables. The following is a summary of the major findings:

1. A parameter of interest is the horizon of control which, if chosen properly, would enable most of the delays, needed to derandomize arrivals, to be taken en route using cruise speed reduction and fuel-efficient profile descents. Fast-time simulations, with a traffic arrival rate equal to the runway acceptance rate, were run varying the projected flight time to the metering fixes. The desired value of horizon of control depends on the separation standard in use and the airline nominal cruise speeds. The data indicate that a value of 30 minutes to the metering fix is a reasonable working number to use in the design of an extended terminal flow-control design.
2. Data runs indicate that the en route delivery error at the metering fix should be kept to a standard deviation less than somewhere between 35 to 45 seconds in order to realize full runway capacity. Time precision is critical to capacity at the final approach fix and the runway but the impact is considerably less at the metering fix. The system is more robust to metering fix errors because of the speed and fine-tuning control capability within the terminal area. This implies that the metering fix delivery precision design criteria for 4-D Flight Management Systems could be relaxed from the potentially achievable 5 seconds standard deviation. Limiting the metering fix delivery-error standard deviation to 35 seconds or less indicates the need for automated controller aids in the process of controlling aircraft without 4-D capability. The current manual performance in today's en route metering environment (ERM-1) is on the order of 1.5 minutes.
3. Delay discounting, or postponing the execution of some of the en route delays due to terminal scheduling until the aircraft arrive in the terminal area, was shown to be beneficial in reducing the capacity loss of metering fix delivery-error standard deviations significantly larger than 30 seconds. If no en route controller aiding is used, then delay discounting should be applied. However, if automated advisories and 4-D equipped aircraft reduce the metering fix

delivery-error standard deviation to about 30 seconds or less, as expected, then no delay discounting should be used because taking delays en route is more fuel efficient than within the terminal area.

4. As would be expected, the TIMER concept is sensitive to runway delivery precision because a delivery-error-dependent time buffer must be added to the time separation in order to keep separation violations to a low probability. The IFR capacity of a first generation time-based system will be constrained by the delivery precision achievable with non 4-D equipped aircraft. Assuming the expected-final-approach speed is known, there are several other factors such as pilot and controller response time, aircraft heading error, heading command resolution, wind effects, and final approach piloting procedure which will determine the lower bounds of delivery precision. A fast-time and real-time simulation evaluation of these factors indicates that, with computer aiding to the controller, the runway interarrival-error standard deviation for non 4-D traffic could be reduced to the region of 8 to 12 seconds from the approximately 26 seconds that is typical of the current manual control system. This improvement would ideally translate to an "arrival only" increase in the range of 16 to 25 percent in capacity under U.S. IFR separations criteria.

One of the principal factors which affect the runway delivery performance of non 4-D equipped aircraft is the variability in final approach speed as a result of varying landing weights. Fast-time simulations of operations, without aircraft-specific expected-final-approach speed knowledge, indicate that the overall runway interarrival-error standard deviation would be in the region of 16 to 20 seconds. This represents about a 10 percent loss in arrival capacity when compared to the results where the final approach speeds are known. Those results indicate that developing an operational process to determine aircraft expected-final-approach speeds is an important area in the establishment of a precision delivery time-based ATC system.

The introduction of 4-D Flight Management Systems into a time-based ATC system such as TIMER offers further incremental increases in capacity with increases in fleet equipage. With 100 percent equipage, the arrival capacity increases to a theoretical value of about 8 percent over the non 4-D case, even with expected-final-approach speeds known. It should be noted that all the calculated gains given earlier are under conditions where separation distances are rigidly defined and adhered to, which is not the case under VFR conditions.

5. It was postulated that large late arrival time errors at the metering fixes have more impact on capacity than early arrival errors of equal magnitude. The reason is that the four-corner post terminal geometry that was simulated has much greater delay capability to accommodate early errors than it has catch-up or slip-forward capability to accommodate late errors. This is especially true of the two shorter or eastern routes. Shortening the minimum path length by moving the extended runway centerline intercept two miles closer to the threshold slightly improved the capacity by one aircraft per hour. This indicates that increasing the time catch-up capability improves the scheduler's flexibility to handle late metering fix arrival errors. The MLS system may provide an opportunity for the time-based, terminal automation planners to design some additional catch-up capability into the terminal approach geometry in order to reduce the effect of the current short-route limitation.

8.0 ACRONYMS AND ABBREVIATIONS

ATC	Air Traffic Control
ATOPS	Advanced Transport Operating System Program Office
CNS	Communication, Navigation, and Surveillance
4-D	Four Dimensional (x, y, z, and time)
ERM	En Route Metering
ETA	Estimated Time of Arrival
FMS	Flight Management System
IFR	Instrument Flight Rule
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
nmi	Nautical Miles
ROT	Runway Occupancy Time

σ	Standard Deviation
SLT	Schedule Landing Time (at runway threshold)
TAATM	Terminal Area Air Traffic Model
TIMER	Traffic Intelligence for the Management of Efficient Runway-scheduling
VFR	Visual Flight Rules
W_f	Weight Factor

A DESCRIPTION AND EVALUATION OF "TIMER" -- A TIME-BASED
TERMINAL FLOW CONTROL CONCEPT

Credeur, L. - Capron, W.

References

1968

- MARTIN D. A., WILLETT F. M., JR. "Development and Application of a Terminal Spacing System." Final Report, FAA NA-68-25 (RD-68-16), August 1968.

1974

- HOLLAND F. C., GARCEAU T. V. "Genealogy of Terminal ATC Automation." M70-9 REV. 2, MITRE Corporation, March 1974.

1976

- ERWIN R. L., JR. "Strategic Control of Terminal Area Traffic." AGARD-CP-188, February 1976.

1977

- BRUCKNER J. M. H., ET. AL. "3D/4D Area Navigation System Design, Development, and Implementation." FAA-RD-77-79, July 1977.

1978

- HAINES A. L. "Parameters of Future ATC Systems Relating to Airport Capacity/Delay." FAA-EM-78-8, April 1978.
- WHITE W. F., COMPILER "Flight Demonstration of Curved, Descending Approaches and Automatic Landings Using Time Reference Scanning Beam Guidance." NASA TM-78745, May 1978.

1979

- SWEDISH W. V. "Evaluation of the Potential for Reducing Longitudinal Spacing on Final Approach." FAA-EM-79-7, August 1979.

1980

- HEIMBOLD R. L., LEE H. P., LEFFLER M. F. "Development of Advanced Avionics System Applicable to Terminal-Configured Vehicles." NASA CR-3280, September 1980.
- KNOX C. E., CANNON D. G. "Development and Test Results of a Flight Management Algorithm for Fuel-Conservative Descents in a Time-Based Metered Traffic Environment." NASA TP-1717, October 1980.

1981

- CREDEUR L., DAVIS C. M., CAPRON W. R. "Evaluation of Microwave Landing System (MLS) Effects on the Delivery Performance of a Fixed-Path Metering and Spacing System. NASA TP-1844, August 1981.

1982

- ADAM V., LECHNER W. "Investigations on Four Dimensional Guidance in the TMA." AGARD Conference Proceedings No. 340, October 1982.
- BENOIT A., SWIERSTRA S. "Dynamic Control of Inbound Flights for Minimum Cost Operation." AGARD Conference Proceeding No. 340, October 1982.

1984

DEJERNETT F. R.

"Effects of Aircraft and Flight Parameters on Energy-Efficient Profile Descents In Time-Based Metered Traffic." NASA CR-17023, February 1984, Addendum November 1984.

MOOR D. A.

"Time Flies, An In-Service Evaluation of a 4-D Flight Management System." Proceedings of 6th Digital Avionics System Conference, AIAA, December 3-6, 1984.

1985

KAYLOR J. T., SIMMONS H. I.,
NAFTEL P. B., HOUCK J. B., GRAVE, R. D.

"The Mission Oriented Terminal Area Simulation Facility." NASA TM-87621, October 1985.

KNOX C. E., VICROY D. D., SIMMON D. A.

"Planning Fuel-Conservative Descents in an Airline Environment Using a Small Programmable Calculator." NASA TP-2393, May 1985.

1986

CREDEUR L., WILLIAM D. H., HOWELL W. F.,
SPITZER, C. R.

"Advanced ATC, An Aircraft Perspective." AGARD 42nd Symposium of the Guidance and Control Panel, June 10-13, 1986.

GROCE J. L., IZUMI K. H., MARKHAM C. H.,
SCHWAB R. W., TAYLOR J. A.

"An Investigation of TNAV-Equipped Aircraft in a Simulated En Route Metering Environment." NASA CR-178031, May 1986

U.S. DEPARTMENT OF TRANSPORTATION,
FEDERAL AVIATION ADMINISTRATION

"National Airspace System Plan: Facilities, Equipment and Association Development." June 1986

1987

MOHLEJI S. C.

"Operational Data Analysis For Evaluating Benefits of Transition/Terminal Automation." MITRE Corporation briefing to Federal Aviation Administration's Terminal ATC Automation Concept Advisory Group meeting at NASA, Ames Research Center, April 30, 1987.

USE OF 4D RNAV IN TIME-BASED EN ROUTE ARRIVAL METERING

by
R.L. Erwin and K.H. Izumi

Boeing Commercial Airplane Company
P.O. Box 3707 M/S 9W-38
Seattle, Washington 98124-2207
United States

SUMMARY

Arrival metering in en route airspace can match the demand rate to the airport acceptance rate. Air traffic control (ATC) is evolving time-based control techniques to facilitate en route arrival metering. This allows fuel savings by using speed reduction to absorb delay. The logic for en route arrival metering: 1) estimates the undelayed landing time of each arrival, 2) assigns the earliest available landing time, and 3) controls each arrival to its terminal area arrival (feeder) fix according to the common schedule developed for all arrivals.

The airplane flight management system (FMS), used along with the ATC computer as part of a distributed data processing system, can define a minimum fuel cruise and descent flight profile which is consistent with ATC constraints. A study of four-dimensional area navigation (4D RNAV) operational requirements for use in en route arrival metering has determined the functions and time-guidance accuracies needed for ATC-compatible operations. Special investigations have evaluated the use of clean-idle Mach/CAS, constant flight path angle Mach/CAS, and fuel optimal cruise/descent arrival profiles individually and in combination. Significant differences in these descent strategies only appear at high arrival rates.

A 4D RNAV capability is most easily achieved by "wrapping" a time-navigation capability around a 3D FMS. It is estimated that fifty percent of U.S. jet transports will have been delivered with a full 3D FMS by 1995 without any special effort to implement 4D RNAV ATC operations. Inclusion of systems such as performance management systems as candidates for 4D RNAV will bring this estimate well above fifty percent.

Concepts for controlling a mix of 4D RNAV equipped and unequipped aircraft in a time-based en route arrival metering system have been the subject of on-going analyses and simulations by the National Aeronautics and Space Administration (NASA) Ames Research Center. Meanwhile, Boeing on contract to NASA Langley Research Center, used a fast-time simulation to show that even with a small percentage of equipped aircraft, the 4D RNAV user could expect a 4D RNAV clearance a high percentage of the time.

The use of 4D RNAV in en route arrival metering operations can save the operator fuel, reduce both pilot and controller workload, and reduce terminal airspace congestion. Eventually, the extension of 4D RNAV to the runway and 4D RNAV departures can increase airport capacity. ATC operational units have shown enthusiasm toward aircraft capable of precisely achieving assigned fix times. The key issue remains of how to get the jet transport fleet to equip so that 4D RNAV operations can grow.

LIST OF SYMBOLS AND ABBREVIATIONS

3D RNAV	Three dimensional area navigation
4D RNAV	Four dimensional area navigation
ACPH	aircraft per hour
AF	arrival fix
ARTCC	Air Route Traffic Control Center
ASP	Arrival Sequencing Program
ATC	Air traffic control
ATOPS	Advanced Transport Operating Systems
CAS	Calibrated airspeed
CFPA	constant flight path angle
DME	Distance Measuring Equipment
ERM	En Route Metering
ESP	En Route Spacing Program
FAA	Federal Aviation Administration
FL	flight level
FMEM	Flow Management Evaluation Model
FMS	flight management system
ft	feet
gal	gallon
IFR	instrument flight rules
KCAS	knots calibrated airspeed
lb	pound
MF	meter fix
NASA	National Aeronautics and Space Administration

NMi	nautical mile
PMS	performance management system
p_v	probability of overlap
TMA	terminal area
TNAV	time navigation
U.S.	United States
v	common airplane speed
VFR	visual flight rules
δ	minimum horizontal separation
λ	throughput
σ_g	standard deviation of delivery accuracy

1. INTRODUCTION

When the arrival demand equals or exceeds the capacity of an airport it is desirable to meter traffic into the terminal area at a rate which matches the airport acceptance rate. By extending the metering process back into the en route phase of operations, traffic flow can be smoothed and delay absorbed efficiently using speed reduction or high-altitude path stretching and holding.

Modern jet transport aircraft have flight management systems which: 1) have the computational capability to define flight paths in four dimensions, 2) contain detailed real-time airplane performance data, 3) provide precise navigation position data, and 4) use digital flight control systems which accurately control the aircraft to the planned trajectory. Concurrently ATC authorities are developing time-based traffic management and control systems for automating the flow of air traffic. Combined, these airplane and ATC capabilities provide the basis for a time-based ATC system using the airborne 4D RNAV capability with operational benefits to both ATC and the aircraft operator.

A considerable technical background has been developed relative to the use of 4D RNAV for time-based arrival control. Eurocontrol has done extensive analysis and simulation of the use of timed trajectories (Benoit, Swierstra, 1982). The U.S. Federal Aviation Administration (FAA) has implemented time-based arrival control as the en route metering (ERM) system. NASA has analyzed arrival operations using 4D RNAV, simulated ground control of unequipped aircraft, and demonstrated 4D RNAV operation in the Denver ERM system (Tobias, Scoggins, 1987; Knox, Cannon, 1980). Lockheed similarly demonstrated 4D RNAV operation into the Dallas-Fort Worth International Airport (Heimbold, Lee, Leffler, 1980). Boeing has developed the ATC-compatible 4D RNAV requirements and under NASA contract has analyzed 4D RNAV operations and alternative trajectories (descent strategies) (Izumi, Schwab, Groce, Coote, 1986; Groce, Izumi, Markham, Schwab, Taylor, 1986). These are only some of the 4D RNAV efforts.

This paper presents one concept for time-based ATC using 4D RNAV. It is essentially a summation of the principal operational concept, 4D RNAV FMS requirements and trajectory studies which have interested Boeing to date. The general approach to operations is described and a quantifying of the potential benefits is offered.

2. ATC OPERATIONS

The basic functions of time-based arrival metering operations are: 1) determine the time each arriving aircraft should cross the arrival fix and fly a nominal path to the runway such that the arrival demand matches the runway acceptance rate, and 2) control the arriving aircraft along non-conflicting flight paths so that they cross the appropriate arrival fix at the desired (assigned) time. The process should start before flights reach their top-of-descent points. This process works effectively when started at least 30 minutes flight time or 200 NMi out from the airport.

The FAA has for some time used a time-based arrival metering system called "en route metering" (ERM). However, the arrival metering function is now called the "arrival sequencing program" (ASP). This together with the en route spacing program (ESP) make up what is currently the ERM function. ERM is operational for the Denver Stapleton, Minneapolis-St. Paul and Dallas-Fort Worth international airports. It also is used by other Air Route Traffic Control Centers (ARTCC) in various metering applications.

2.1 Arrival- Fix Time Calculation

Figure 1 shows the ERM functional steps in determining the assigned arrival fix time:

- 1) Estimate the time each flight will reach the arrival fix if undelayed.
- 2) Calculate the earliest landing time for each flight by adding the nominal arrival fix to runway transit time to the estimated arrival fix time.
- 3) Assign the earliest available landing time which is later than the earliest calculated landing time.
- 4) Subtract the nominal arrival fix to threshold transit time from the assigned landing time to obtain the assigned arrival fix time.

2.1.1 Undelayed Arrival Fix Time Estimate

The undelayed arrival fix time is obtained by estimating the undelayed flight time of an aircraft from its present position to the arrival fix. Initial ERM operations estimated the meter fix (arrival fix) crossing time by projecting flight progress at radar-measured ground speed during cruise. However, more accurate estimates can be made by representing the descent portion.

One argument has been made that the estimated arrival time at the arrival fix should be based on a fast descent. In high-demand situations, most flights will be delayed. This allows the flights to efficiently absorb delay by slowing down. In the ERM implementation, the arrival fix time estimated from an airplane's normal cruise speed approximated a fast descent.

To illustrate this concept, imagine four arriving flights all positioned 200 NMi from the arrival fix such as to be equal flying time from the arrival fix. They must be sequenced and spaced for a 30 per hour acceptance rate. Figure 2 shows the fuel use from 200 NMi to the arrival fix for: 1) absorbing delay by slowing from an estimated fast descent (curve A) and 2) absorbing delay by descending at a slow speed and then holding (curve B). Table 1 shows the fuel used by each flight under strategy A and strategy B, and the total fuel. In this example, when three or more flights are competing for the same arrival fix time, the fast descent strategy uses less fleet fuel.

DESCENT FUEL (pounds)			
FLIGHT	STRATEGY A	STRATEGY B	DIFFERENCE A - B
	Fast Reference Speed	Slow Reference Speed	
1	1325	985	340
2	1065	1165	-100
3	1005	1330	-325
4	990	1490	-500
TOTAL	4285	4970	-685

Table 1. Total Descent Fuel Calculation for Two Different Reference Speeds

2.1.2 Estimated Landing Time

The earliest estimated landing time is obtained by adding a calculated terminal area transit time to the estimated arrival fix time. The terminal area transit time is calculated as the flight time from the arrival fix to the runway threshold along the nominal four-dimensional terminal area arrival path for that class of aircraft (e.g., jet transport, large propeller, small propeller, etc.).

2.1.3 Landing-Time Scheduler

The scheduling of arrivals to match airport capacity is crucial to efficient time-based arrival operations. The traffic flow at the airport must be scheduled accurately to provide runway utilization equaling or exceeding that provided by conventional manual traffic control, while also providing for efficient flight profiles.

The scheduler must accommodate a mix of arrival airplane performances, unscheduled (pop-up) arrivals, departures on the same or dependent runways, runway changes, and non-standard occurrences (e.g., go-arounds and aircraft emergencies). The scheduler complexity can vary from one for a runway dedicated to jet transport arrivals to one for a runway (or runways) with all types of operations. Since implementation will be different for each airport special operating procedures may need to be developed.

2.2 Time Control

Aircraft can be controlled to meet the assigned arrival-fix time using speed control, path stretching (vectoring) or holding, or a combination of these delay absorption techniques.

Aircraft in a time-based arrival control system can be controlled either from the ground or by using an airborne 4D RNAV capability. The precision of control from the ground is limited by the position measuring accuracy of the

surveillance system, the frequency with which corrective clearances are transmitted, and the response time and accuracy of the corrective actions. 4D RNAV control has been demonstrated to be able to deliver an aircraft over an arrival fix with an accuracy of a few seconds (Knox, Cannon, 1980). The time accuracy of 4D RNAV control is essentially limited only by the position-measuring accuracy of the along-track navigation system. During implementation of time control operations, ground-based control will be used for unequipped flights with some loss in operational benefits.

3. OPERATIONAL CONCEPT FOR USING 4D RNAV

The basic operational concept is for ATC to issue to a 4D RNAV-equipped aircraft a time clearance to the arrival fix while the flight is still some distance from its top-of-descent point. Aircraft would be certified by ATC for 4D RNAV operations and 4D RNAV equipage indicated on the flight plan for the controller. Figure 3 shows a nominal scenario for 4D RNAV flight to the arrival fix in a hypothetical ATC environment using high- and low-altitude sectors separated at flight level 240. The high altitude controller issues an "expected" arrival fix time clearance and a clearance for the pilot to descend to FL240 at his discretion. The pilot then uses the 4D RNAV system to plan the top-of-descent point and trajectory for minimum fuel to the arrival fix. This involves an aim point at or beyond the arrival fix, beyond which the trajectory is fixed by ATC constraints (in this case, the aim point is PALMER). Meanwhile, control has been handed to the low-altitude controller (even though the aircraft is still in the high-altitude sector) and the flight is cleared for a 4D RNAV ALDER arrival.

3.1 Operational Scenario

Figure 4 is the basis for a scenario depicting the use of 4D RNAV in time-based arrival metering when most aircraft are *not* 4D RNAV-equipped. Figure 5 is the basis for a scenario in which all (or most) aircraft are 4D RNAV-equipped.

In a system where most aircraft are unequipped, the use of 4D RNAV can be based on the premise that time clearances would be issued only when ATC concludes that a 4D flight would not conflict with other flights being controlled manually. When metering is in progress and if aircraft are being held, the 4D RNAV aircraft would proceed to the holding fix per ATC instructions. In the absence of holding and with ATC deciding that a conflict was unlikely, the airplane would be given an arrival-fix time assignment. Should the time assignment require more delay than can be absorbed by slowing, the airplane and ATC would negotiate a time clearance including holding at an agreed fix and altitude. A similar negotiation could provide for path stretching to absorb a small amount of excess delay which was less than the minimum absorbable by holding.

When most of the airplanes are 4D RNAV equipped, more of the task could be centralized in ATC with less interaction with the airplane. ATC could use stored performance data to determine the aircraft need for holding, and to specifically calculate and determine non-conflicting trajectories.

An important issue is how much performance data does ATC need to have and how these data will be used to calculate profiles. Ground-based computations will be complicated by the likelihood that no single descent strategy will be employed by all traffic.

4. FLIGHT MANAGEMENT SYSTEM OPERATIONAL REQUIREMENTS

Analysis of 4D RNAV operations in the ATC system has indicated the operational performance time-navigation accuracy and flight profile descent strategies which should be considered as system operational requirements.

4.1 Operational Performance

The 4D path definition algorithm should satisfy the following functional and performance requirements to assure efficient operations.

4.1.1 Airplane Performance

The algorithm must define a path which is within the airplane performance limits. This includes the speed/altitude capability, cabin altitude control requirements, anti-icing, and turbulence penetration. The algorithm should have the capability to define paths ranging from the slowest to the fastest available within the speed/altitude envelope so as to maximize the delay absorption capability.

4.1.2 Arrival Path Geometry

The path must be calculated for the lateral path which the airplane is expected to fly.

4.1.3 ATC Constraints

The path must conform to ATC altitude and speed constraints.

4.1.4 Arrival Fix Time

The 4D path from present position must be defined to place the aircraft over the assigned fix at the assigned time with a specified degree of accuracy and commensurate with a selected descent strategy. This will be discussed later in this section.

4.1.5 Path Accuracy

The 4D path calculation must be based on true geometric height by correcting the pressure altitude. The hydrostatic equation must be solved using the temperature lapse rate and reference temperature. Precise wind data must be used to define airspeeds corresponding to the desired ground speeds so that maximum use can be made of the airplane speed-altitude envelope.

4.1.6 Reinitialization

When the cleared 4D profile is interrupted (e.g., a vector for traffic, reclearance over a different arrival fix, or weather avoidance), the 4D FMS must quickly (or continually) confirm to the pilot the validity of the initial assigned fix time or calculate a new time window within which a new assigned fix time is desired.

4.1.7 Holding and Path Stretching

When the delay to be absorbed exceeds that which can be accommodated by slowing, holding or path stretching must be added to the 4D profile. The algorithm should compute the minimum fuel combination of holding or path stretching and speed control which will meet the assigned fix time. Holding may be at cruise altitude or at a designated fix at lower altitude. Path stretching may be a vector away from and back to the planned 3D path either to a designated or a FMS selected fix. A function which continuously informs the pilot of estimated arrival time at the fix, if he turns toward it, now can provide flexibility in the range of path stretching maneuvers which may be used.

4.2 Time Navigation Accuracy

Recent 4D studies have demonstrated opportunities for increasing flow rate as a result of the 4D RNAV-equipped airplane's capability of absorbing delays precisely and fuel-efficiently through speed control. The precision with which the airplane can make an assigned time at a reference waypoint (e.g., the arrival fix) in a time-based ATC system affords an effective means for increasing throughput.

If no errors in the system are assumed other than delivery accuracy errors which are normally distributed with zero mean, speed differences in traffic consisting of different airplane types are ignored (common speed v), and overlap probability p_v is assumed, the throughput λ (in aircraft per hour) over a common path is given by:

$$\lambda = \frac{1}{\frac{\delta}{v} + \frac{\sqrt{2} Q^{-1} [1 - p_v] \sigma_g}{3600}}$$

where δ is the minimum horizontal separation standard (in nmi), σ_g is the standard deviation of the delivery accuracy error (in seconds), and Q^{-1} refers to the inverse lookup on the standard normal distribution tables.

When the speed at the arrival fix is required to be 250 KCAS (at 10,000 ft) and a separation violation of at most one in a hundred approaches ($p_v = 0.01$) is tolerated, relationships between λ vs. arrival fix delivery accuracy are shown in Figure 6 for four minimum separation standards ($\delta = 3, 5, 7$, and 10 nmi).

The figure suggests that significant improvements in throughput can be achieved if 4D RNAV traffic can make arrival fix times with greater precision. In a DME/DME navigation environment, 4D RNAV is capable of achieving fix-time accuracies as small as 2 to 3 seconds ($1-\sigma$). Manual control to achieve an assigned fix time is expected to be much less accurate, possibly by a factor of ten.

4.3 Flow Management Evaluation Model

The Flow Management Evaluation Model (FMEM) was developed by the Boeing Company's Air Traffic Control Systems Analysis Group to evaluate sensitivities of conflict rate to traffic consisting of varying levels of 4D RNAV equipage in an en route metering (ERM) environment employing a postulated time-based metering component. The study was conducted as part of the NASA Advanced Transport Operating Systems (ATOPS) Flow Management Avionics Research Studies program.

The FMEM is a fast-time simulation, which models the interaction of the ATC system employing ERM with traffic flying in the Denver Center airspace. It provides routing, scheduling, controller clearance generation, conflict checking, and aircraft trajectory generation processes. Model inputs include airspace structure, weather conditions,

traffic characteristics, ATC rules and procedures, flow management parameters, and an aeroperformance data base for airplane trajectory calculations. Statistics are collected over specified time intervals to use in evaluating efficiency of operation both from the airplane and ATC's perspectives.

The air traffic control module keeps track of all "active" aircraft in the simulation, assigns routings, determines present position (radar) data, and monitors conflicts. Ground hold processing is also performed. The ATC module also simulates actions of the controllers in assigning speeds, vectors, or holding to achieve meter-fix times.

The arrival metering module simulates automation software as installed in the NAS Stage A system. The functions performed by the arrival metering software include runway arrival time prediction, runway sequencing and scheduling, delay determination, and creation of meter and freeze lists.

The profile generation module provides aircraft trajectories based on point-mass, steady-state equations of motion. A performance data base is employed for the various commercial turbojet aircraft types modeled, including thrust, drag, fuel flow, and speed envelope data. These trajectories represent the "true" positions of aircraft in the simulation as a function of time.

The FMEM provides data on flow rates and capacity, level-of-delay, fleet fuel burn, controller workload (expressed in terms of number of clearances generated), and safety (numbers of conflicts).

4.4 Flight Profile Descent Strategy

The desirability of having descent profile consistency to minimize the probability of conflicting paths suggests that all traffic employ an identical descent strategy. Furthermore, the unique set of procedures inherent in each strategy implies that one strategy might be preferable to another from the perspective of increasing flow rate and minimizing delays. Following are summaries of recent Boeing investigations of descent strategy trade-offs and their implications for the ATC system and the operator.

4.4.1 Descent Strategy Characteristics

An internal Boeing study of the B737-100 airplane showed that the 3°-constant flight path angle (CFPA) Mach/CAS descent strategy possessed almost identical range of delay absorption capability with an overall increase in fuel usage penalty relative to clean-idle Mach/CAS over a common distance, and for calm winds, ISA conditions, and common initial and final energy states. The explanation for this is that the 3°-CFPA Mach/CAS descent profile closely approximates the clean-idle Mach/CAS but uses some thrust to maintain its geometric constraint. Figure 7 illustrates these fuel vs. delay characteristics for the B737-100. The minimum and maximum elapsed times correspond to fastest- and slowest-speed descents using those strategies. The entire range between these limits constitute the strategy's delay absorption margin. These results prompted similar investigations for other Boeing airplane types. The outcome was the same for the B727-200 (JT9D-7J engines) and the B767-200 (JT9D-7R4), but 2°-CFPA compared more favorably with clean-idle for the B747-200 (JT9D-7J).

These results suggested the possibility that all arrival traffic employing a common descent angle strategy are less likely than clean-idle to provoke conflicts (and, by implication, increase throughput) when both use the same speed schedule, while still enjoying similar delay absorption margins. Recent studies have also identified a technique for minimizing 4D descent fuel by using Pontryagin's Minimum Principle (Chakravarty, 1985) and here in called the "energy-optimal descent strategy."

4.4.2 4D Descent Strategy Evaluation

Intuitively, airplane speed differences would appear to affect system throughput and delay in high-demand situations. An airplane pair in relative proximity requires conflict resolution if the trailing airplane is faster. Throughput is reduced even when a single airplane's descent speed differs from those ahead of and following it. Allowing each aircraft type to descend at its fuel-optimum speed (typically Mach/CAS schedules) may do much for individual airplane efficiencies, but possibly little for system flow rate, in all but low-demand environments. In this light, the Boeing Company under NASA contract has and is continuing to evaluate the system sensitivities to 4D RNAV arrival traffic employing different descent strategies.

The strategy options evaluated for this study were the use of clean-idle Mach/CAS descent, constant flight path angle (CFPA) Mach/CAS descent, and point-mass, energy-optimal descent using variable speed and thrust schedules throughout the descent.

The study assumed traffic consisting of mixtures of three Boeing airplane types (B737-300, B747-200 and B767-200) which were initially flown at the same cruise altitude (37,000 ft), speed (Mach 0.78), and over the same arrival path. An additional assumption was the existence of an advanced, time-based air traffic control system which is postulated to have the ability to maximize the traffic throughput rate, while eliminating conflict-caused delays by adjusting spacings over an arrival fix based on predicted relative separation requirements. This enables ATC to space consecutive arrivals in such a way that no conflicts are projected to occur throughout their descents. Therefore, the definition of throughput implies maximum flow rate for non-conflicting traffic.

Figure 8 shows the effect on system throughput of varying B737, B767 and B747 percentages, for a common 4D time requirement of 1658 seconds and CFPA strategy. The optimal strategy plot is shown in Figure 9, for 1658 seconds. These results demonstrate descent strategy characteristics when airport demand is high, namely, that system throughput is least sensitive to traffic mix when all aircraft use the CFPA Mach/CAS strategy, followed closely by clean-idle Mach/CAS.

Figure 10 shows expected throughputs at some major U.S. airports when the arrival fleet employs the three strategies. Table 2 shows the U.S. domestic traffic arrival distributions according to an airplane-type partitioning (equivalencing), based on data derived from 1984 statistics (Office of Management Systems and Office of Aviation Information Management, 1984).

<u>Airport</u>	<u>Equivalent type</u>		
	<u>B737-300</u>	<u>B767-200</u>	<u>B747-200</u>
John F. Kennedy	42.6	11.5	45.8
Los Angeles	67.9	6.2	25.9
Chicago O'Hare	80.0	7.9	12.1
Atlanta	82.4	11.0	6.6
Denver Stapleton	86.2	11.0	6.6
Dallas/Fort Worth	88.2	4.1	7.7
Minneapolis/St. Paul	90.6	0.8	8.6
Typical ERM Airport	87.9	4.8	7.3
U.S. Average	88.9	4.6	6.5

Table 2. 1984 U. S. Arrival Traffic Distributions (Percent)

A follow-on study that the Boeing Company is currently conducting under NASA contract assumes that aircraft are initially at their optimum flight conditions (long-range cruise speed and altitude as a function of weight).

Table 2 data indicate that the B737 type monopolizes the demand (at least 80%) at all but a few large international airports. At these airports, descent strategy is unimportant in determining system throughput, because only when traffic mixes are more evenly distributed do more conflicts occur, as Figures 8 and 9 demonstrate. For current separation standards, the theoretical maximum throughput (capacity) is just under 60 aircraft per hour (ACPH), so that the study results also suggest that, at most large domestic airports where throughput is almost saturated, no ATC or airline benefits will be achieved by increasing airspace capacity or decreasing the minimum, zero-conflict spacing required between aircraft. At an airport such as J.F.K. International, where the relative proportions of B747 and B737 types are roughly the same, throughput as expected suffers.

The underlying zero-conflict condition on the throughput definition also suggests that as demand exceeds throughput, delays (and, therefore, fuel use) will be greater for more conflict-prone strategies for a fixed arrival rate.

5. CONSIDERATIONS OF PROPORTION OF AIRCRAFT BEING 4D RNAV EQUIPPED

As in any change over in systems, the question arises as to the use of 4D RNAV during the time period when only a portion of the fleet is equipped. Principal questions are: At what rate will the fleet equip? How will ATC handle a mixed fleet? How will 4D RNAV-equipped users benefit during the change over?

5.1 Status of 4D RNAV Implementation

Four-dimensional area navigation capability may be obtained as an integral function in a flight management system, or incorporated into an existing FMS by adding time guidance (TNAV) to the 3D RNAV function. For experimental purposes, a performance management system (PMS) was modified to provide time guidance for NASA demonstrations in en route metering (Heimbold, Lee, Leffler, 1980).

Boeing forecasts that in the U.S. by 1995, 2100 of 4000 large jet transports will have been delivered with a full flight management system (FMS) which will have either an integral 4D RNAV function or a 3D RNAV function suitable for being upgraded to 4D RNAV. In addition, aircraft with other capabilities such as performance management systems can be modified to provide time guidance. ATC's provision of a beneficial environment for the use of 4D RNAV could encourage a high percentage of civil jet transports toward 4D RNAV equipage.

5.2 Control of Mixed 4D RNAV Equipped and Unequipped Traffic

Two methods have been considered for controlling a mix of 4D RNAV equipped and unequipped aircraft in a time-based arrival metering system. The first approach, based on minimum change to existing procedures, is to provide 4D RNAV clearances on a non-conflicting basis. In this procedure, the controller would issue an arrival-fix time assignment clearance to approved 4D RNAV operators if in the controller's judgement there was a high probability that the path of the 4D RNAV airplane would not conflict with that of other traffic. Inherent in this approach is the concept that when an unequipped aircraft follows a 4D RNAV cleared aircraft, the unequipped aircraft would be controlled using the 4D RNAV aircraft for guidance.

The second approach is more complex. In this approach time-based control would be automated to schedule, track and provide advice to the controller for clearances which would keep unequipped flights on their assigned time schedule. Simulations have demonstrated this approach for operations into the terminal area and onto final approach (Erzberger, Chapel 1985).

5.3 Performance of a Partially Equipped Fleet

As a study for NASA, the flow management evaluation model was used to investigate the operation of 4D RNAV equipped aircraft in the en route metering environment. Denver Air Route Traffic Control Center ERM operations were simulated for Denver traffic. The probability of a successful 4D RNAV arrival as a function of percent air carrier jet 4D RNAV equipage was developed for Denver operations (Figure 11). Two criteria for success were considered: 1) the 4D RNAV equipped aircraft completed its flight to the meter fix without any conflicts with other traffic; and 2) the flight was completed without conflict with any preceding flights, while the controller paced the immediately following airplane relative to the 4D RNAV flight to ensure separation. Note that the analysis assumed that when 100 percent of the scheduled air carriers were equipped, there would be additional unequipped jet traffic such that only 72 percent of the total arrivals would be equipped. This analysis suggests that when only a small percentage of the fleet is 4D RNAV equipped, 4D RNAV clearances will be available a high-percentage of the time, especially when the controller paces following unequipped flights on preceding 4D RNAV cleared flights.

A characteristic of hubbing is that in any particular busy period, the majority of flights are often those of the same air carrier. Therefore, if one air carrier equips, it can expect a higher percentage of 4D RNAV operations than indicated by the random equipping analysis. Figure 12 shows proportion of arrivals by air carrier in an example hubbing schedule.

6. BENEFITS OF USING 4D RNAV

The airplane 4D RNAV flight management system can perform some time-based control functions more advantageously than a centralized ATC system. This can provide significant benefits to both the airplane operator and the ATC system.

6.1 Advantages

The operational advantages of 4D RNAV include:

- 1) The ATC system can accurately forecast the future position of the aircraft.
- 2) The pilot knows the profile that will be flown.
- 3) The airplane can more precisely achieve an assigned fix time than can be accomplished by control from the ground.
- 4) The FMS can more precisely determine the optimal flight path for that particular flight's aircraft type and weight.

For the ATC system, the potential benefits accruing from these advantages are:

- 1) Higher throughput by more precise spacing control.
- 2) Reduction of communications and total controller workload through fewer tactical control clearances.

The benefits airplane operators can expect include:

- 1) Reduced pilot workload because of fewer tactical clearances.
- 2) Fuel savings through use of minimum-fuel flight profiles to meet the assigned fix time.

6.2 Fuel Savings

The potential fuel savings have been quantified for 4D RNAV operation in the U.S. en route metering system in an internal Boeing study. Airfield operations simulations were used to determine the delay statistics for the

Denver Stapleton (Figure 13), Minneapolis-St. Paul and Dallas-Fort Worth international airports for forecast 1995 traffic levels. The delay statistics were accumulated for the busy time periods when ERM was assumed to be in use.

The delay statistics for each of the three airports were convolved with the projected fuel savings versus delay for a B737-300 type aircraft (Figure 14). The B737-300 was assumed to represent an average jet transport. This yielded the annual fuel savings for these three airports. These fuel savings rates were then extrapolated for: 1) an additional 15 U.S. airports which are considered principal candidates for ERM use, and 2) all additional U.S. air carrier arrival operations.

Further fuel savings were projected for:

- 1) Precision spacing over the meter fix requiring less terminal area maneuvering.
- 2) Slowing of flights during unmetered periods which would otherwise have arrived early because of more favorable winds.
- 3) Extension of metering along the full en route flight which equates on average to metering from about 600 miles from the destination airport.

Table 3 presents the results of these fuel savings analyses. The calculated estimated fuel savings using en route metering at 18 U.S. air carrier airports in 1995 is a total of 604,600,000 pounds. This equates to 28,650 pounds per airplane per year. The table also lists potential savings from the other considerations resulting from using 4D RNAV for arrival metering.

7. ADDITIONAL 4D RNAV APPLICATIONS

In addition to time-based arrival metering, 4D RNAV is expected to find use for en route flow management, departure spacing, and terminal area arrival spacing control operations.

The en route flow management application is envisioned for situations where ATC wants traffic to flow past a point or boundary with some desired spacing. Examples include whenever:

- 1) A flight has an assigned time or time-window for crossing a Flight Information Region boundary.
- 2) One ATC center is required to provide traffic to an adjacent center with a specified in-trail minimum spacing.
- 3) En route spacing is desired at a fix (or fixes) in one center to meter traffic to an airport in another center.
- 4) En route ATC applies the arrival metering function when all aircraft are still at cruise altitude.

Departure spacing can be used either to: 1) meter (schedule) departures from multiple neighboring airports across common departure fixes, or 2) release a departure such that it can climb to altitude and occupy an otherwise empty slot in a string of in-trail spaced flights.

The implementation challenge is greatest for terminal area arrival spacing, but the benefits are also significant. The principal advantage of using 4D RNAV in time-based terminal area arrival spacing is the increase in runway capacity that can be achieved due to more precise (and thus closer) spacing of the arrivals. The FAA is conducting research to define the future Terminal Area ATC Automation using time as the basis for spacing and control.

Past investigations have indicated that a nominal value for manual interarrival spacing control accuracy is 18 to 20 seconds under IFR conditions, and possible 8 seconds under VFR conditions. Expected 4D RNAV delivery accuracy is 2 to 3 seconds. Figure 15 shows the results of a fast-time simulation of Minneapolis-St. Paul International arrivals in which the average annual delay was estimated for manual control (8/18 seconds), and use of 4D RNAV during IFR only (8/2 seconds) and full-time use of 4D RNAV (2 seconds). When six-minute average annual delay is used as the capacity criterion, the annual capacity could be increased from 390,000 to 470,000 operations. Another way of viewing the results is that the average delay in 1990 could be reduced by 5.2 minutes (an annual saving of 2,246,400 minutes).

Annual Savings (1995)

U.S. EN ROUTE METERING ESTIMATE:

Denver	62,400,000 lb
Minneapolis-St. Paul	39,200,000 lb
Dallas-Fort Worth	43,900,000 lb
15 Additional Airports	459,100,000 lb
TOTAL ERM	604,600,000 lb (28,650 Gal/Airplane)

OTHER POTENTIAL SAVINGS:

Remaining Possible ERM Operations	34,830 Gal/Airplane
Extended Metering to 600 NMI	14,770 Gal/Airplane
Reduced Terminal Area Maneuvering	9,000 Gal/Airplane
Slowing Unmetered Early Flights	4,480 Gal/Airplane

*Table 3. Estimated Fuel Savings with 4D RNAV***8. CONCLUSIONS AND ISSUES**

The research to date suggests potential areas of 4D RNAV application and the future efforts required to reach operational status.

8.1 Conclusions

The following are the principal conclusions which might be drawn from 4D RNAV time-based ATC research to date:

- 1) Aircraft can be equipped for 4D RNAV which has the performance required for time-based arrival control.
- 2) Beneficial operations are potentially available to the 4D RNAV user starting with the first installations.
- 3) Usage of compatible descent strategies will increase system throughput and save fleet fuel.
- 4) More precise arrival fix times by 4D RNAV-equipped aircraft will improve system throughput.

8.2 Issues

Issues that must be resolved to reach practical implementation of time-based metering are deemed to include:

- 1) Find a means to achieve fleet equipage with an appropriate 4D RNAV capability.
- 2) Develop a runway scheduler which with accompanying procedures will provide landing (and departure) times such that runway utilization efficiency will equal or exceed that provided by manual control.
- 3) Develop a ground-based controller for controlling unequipped aircraft in a time-based system.
- 4) Find solutions to the technical challenges in the ATC system design to include calculating operations to the second, planning non-conflicting trajectories involving multiple sectors and systems, and communicating clearances across sector/system boundaries.
- 5) Provide accurate wind data along the arrival trajectory to support full use of the speed/altitude envelope.

"USE OF 4D RNAV IN TIME-BASED EN ROUTE ARRIVAL METERING"

R.L. Erwin - K.H. Izumi

References

1980

Knox C.E., Cannon D.G.

"Development and Test Results of a Flight Management Algorithm for Fuel-Conservative Descents in a Time-Based Metered Traffic Environment", NASA Technical Paper 1717, October 1980

Heimbold R.L., Lee N.P., Leffler M.F.

"Development of Advanced Avionics Systems Applicable to Terminal-Configured Vehicles", NASA Contractor Report 3280, September 1980

1982

Benoit A., Swierstra S.

"The Dynamic Control of Aircraft for Minimum Cost Operation", EUROCONTROL DIVISION E1, Doc 822034, September 1982

1984

Office of Management Systems
(Federal Aviation Administration)
and Office of Aviation Information
Management (Research and Special
Programs Administration)

"Airport Activity Statistics of Certified Route Air Carriers," December 1984

1985

Erzberger H., Chapel J.D.

"Ground Based Concept for Time Control for Aircraft Entering the Terminal Area," Proc. AIAA Guidance and Control Conference, Snowmass, CO, August 1985

1986

Groce J.L., Izumi K.H., Markham C.H., Schwab R.W., Taylor J.A.

"An Investigation of TNAV-Equipped Aircraft in a Simulated En Route Metering Environment," NASA Contractor Report 178031, May 1986

Izumi K.H., Schwab R.W., Groce J.L., Coote M.A.

"An Evaluation of Descent Strategies for TNAV-Equipped Aircraft in an Advanced Metering Environment, ATOPS," NASA Contractor Report 178093, December 1986

1987

Tobias L., Scoggins J.L. Jr.

"Time-Based Air-Traffic Management Using Expert Systems", IEEE Control Systems Magazine, April 1987

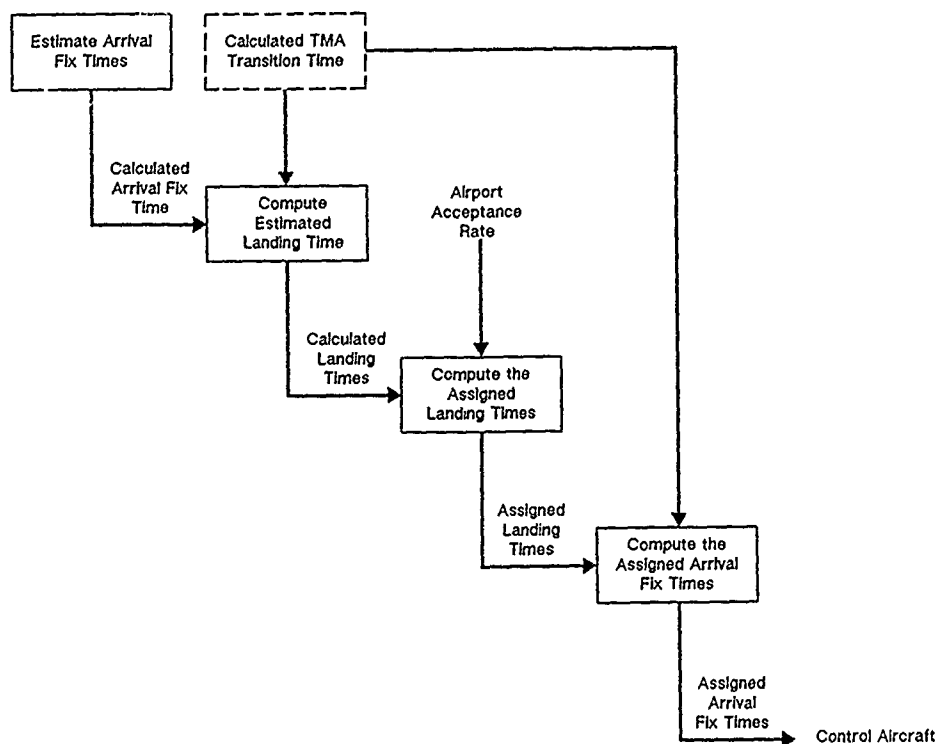


Figure 1. Time-Based Arrival Metering Logic

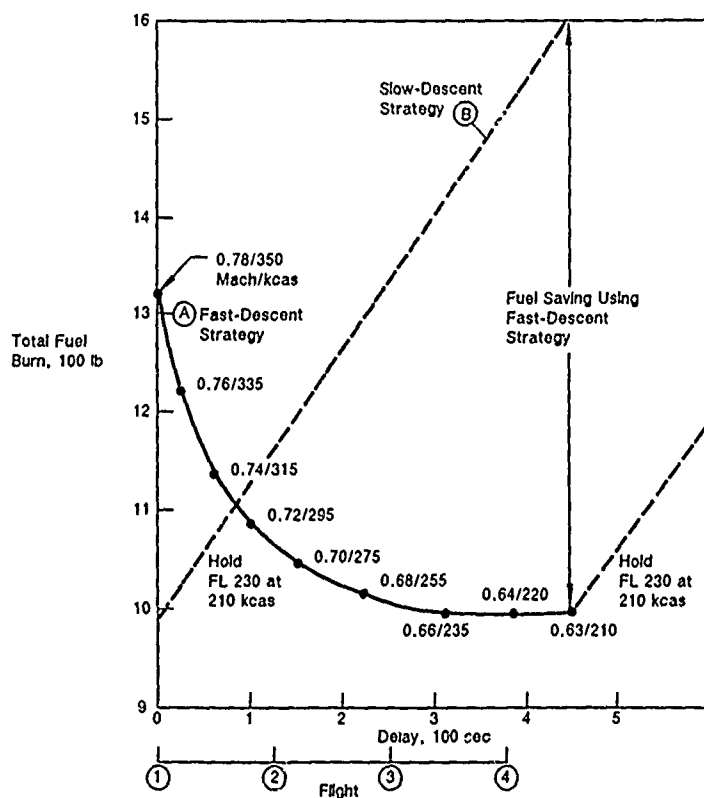


Figure 2. Fuel Saving Using Fast-Descent Speed Strategy for Estimated Undelayed Arrival Fix Time

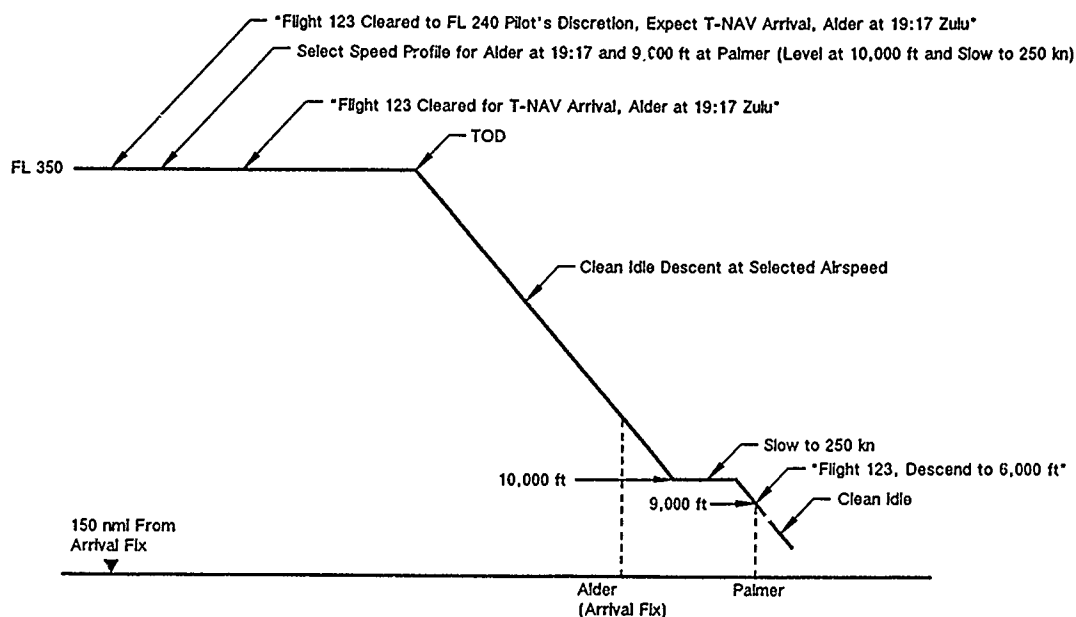


Figure 3. 4D RNAV Minimum Fuel Descent to Arrival Fix

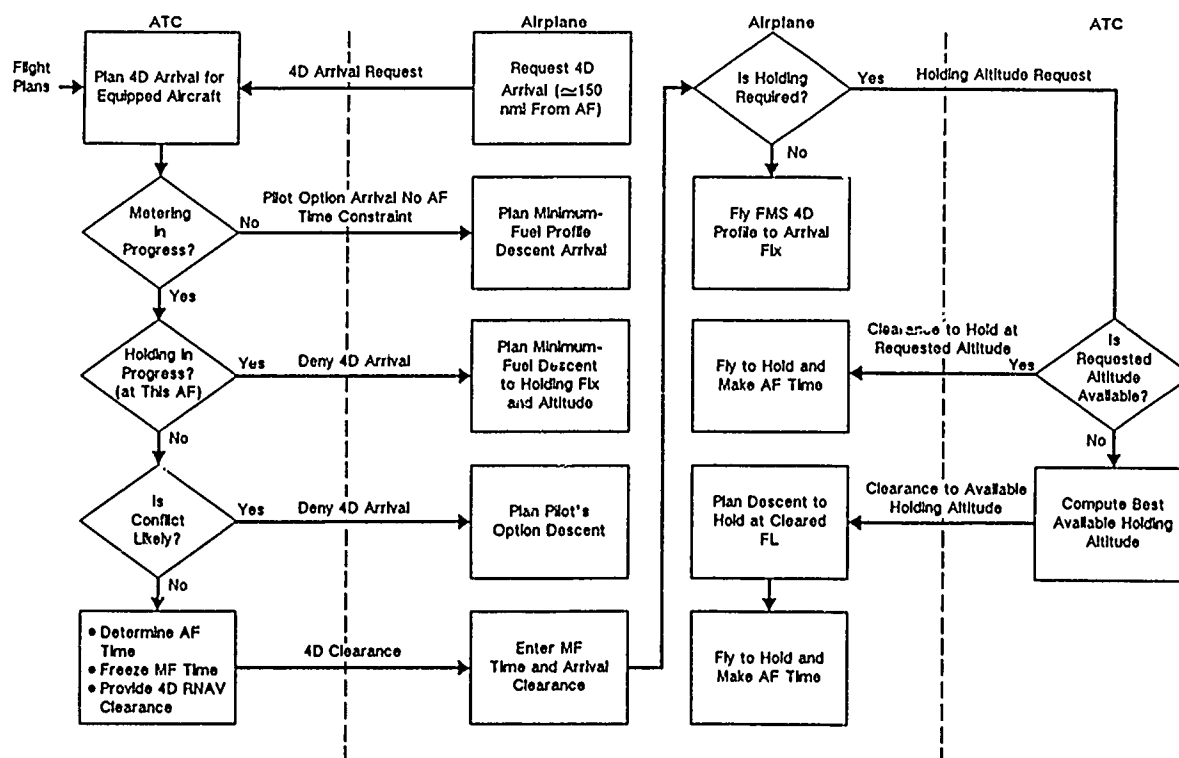


Figure 4. 4D RNAV Use (Most Aircraft Not 4D RNAV Equipped)

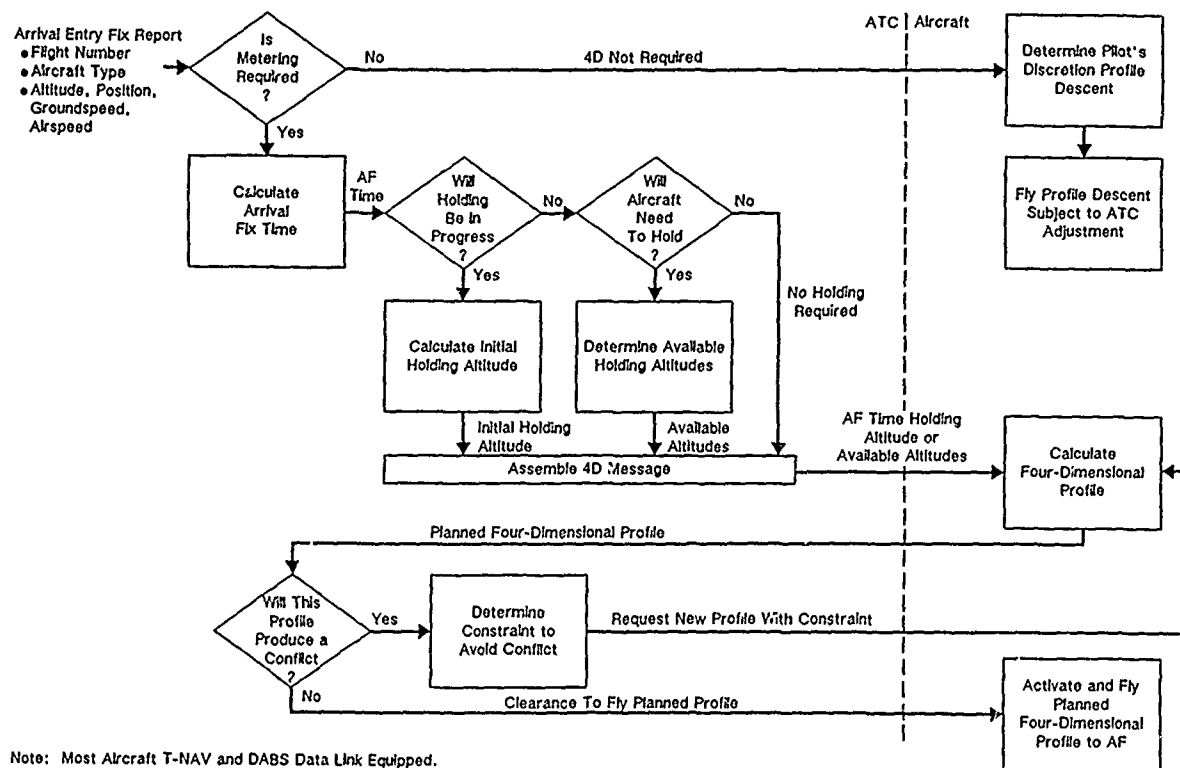


Figure 5. 4D RNAV Use in Time-Based Arrival Metering

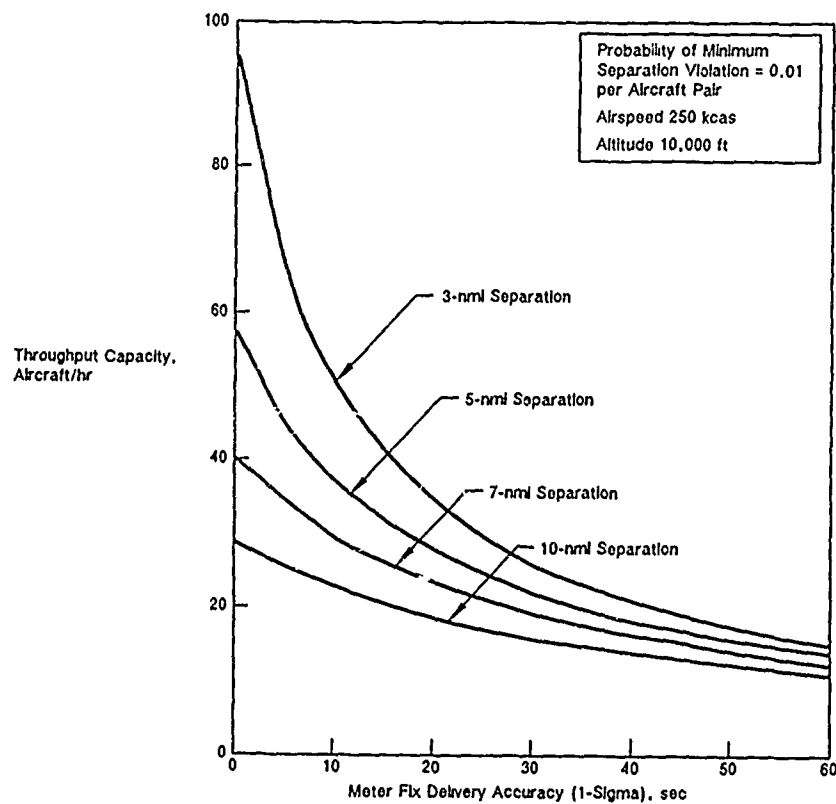


Figure 6. Time-Based ATC Meter Fix Capacity and Control Accuracy Requirements

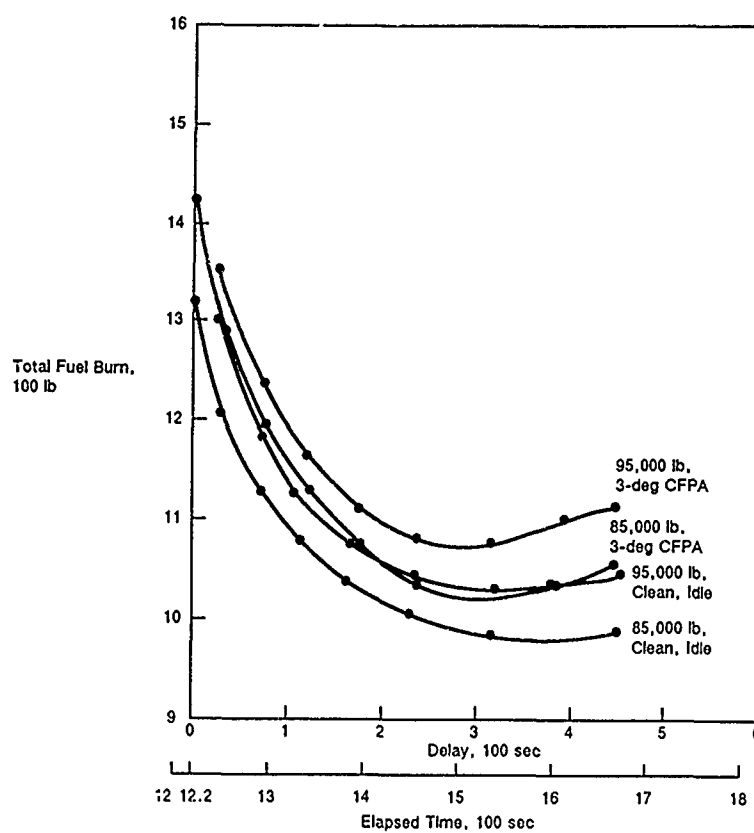


Figure 7. Fuel Versus Delay—Clean Idle Mach/CAS Strategy and 3-deg CFPA Mach/CAS Strategy Gross Weight Variations, B737-100

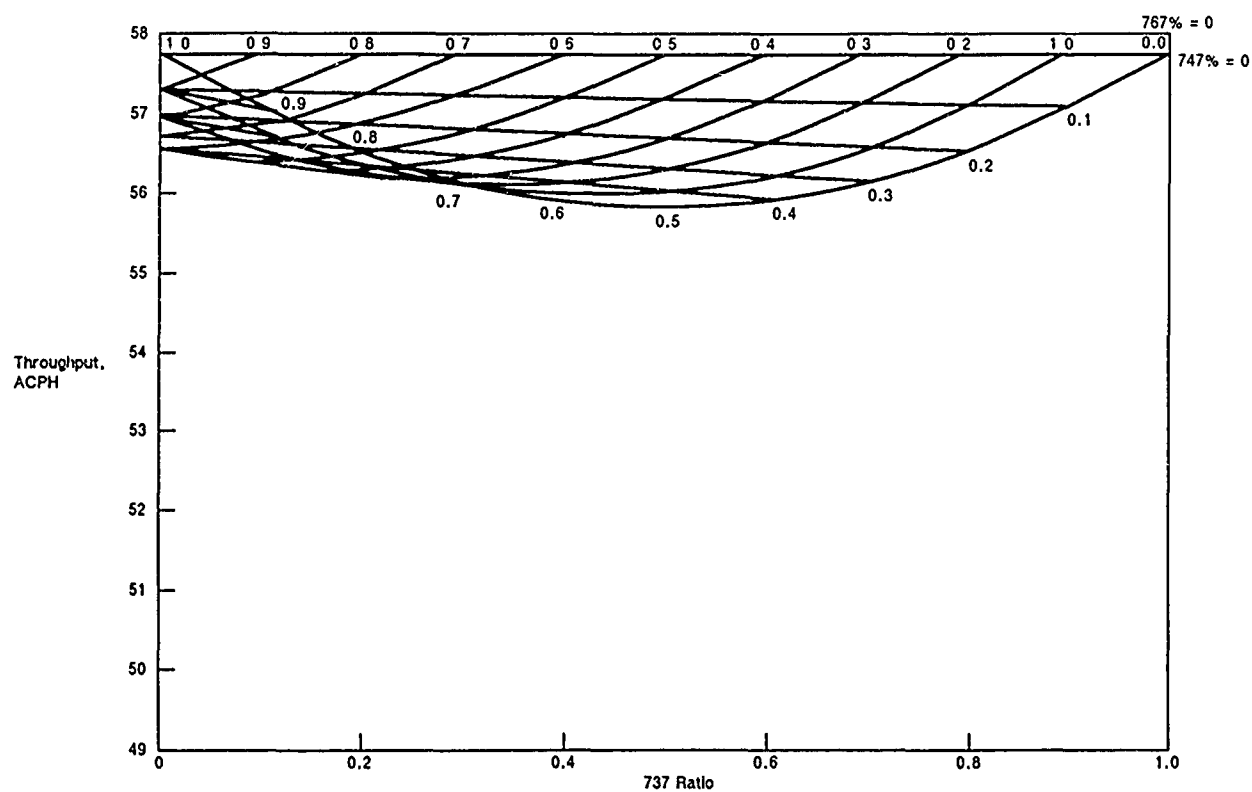


Figure 8. Mixed Traffic Throughput, CFPA Strategy, Elapsed Time = 1658 sec

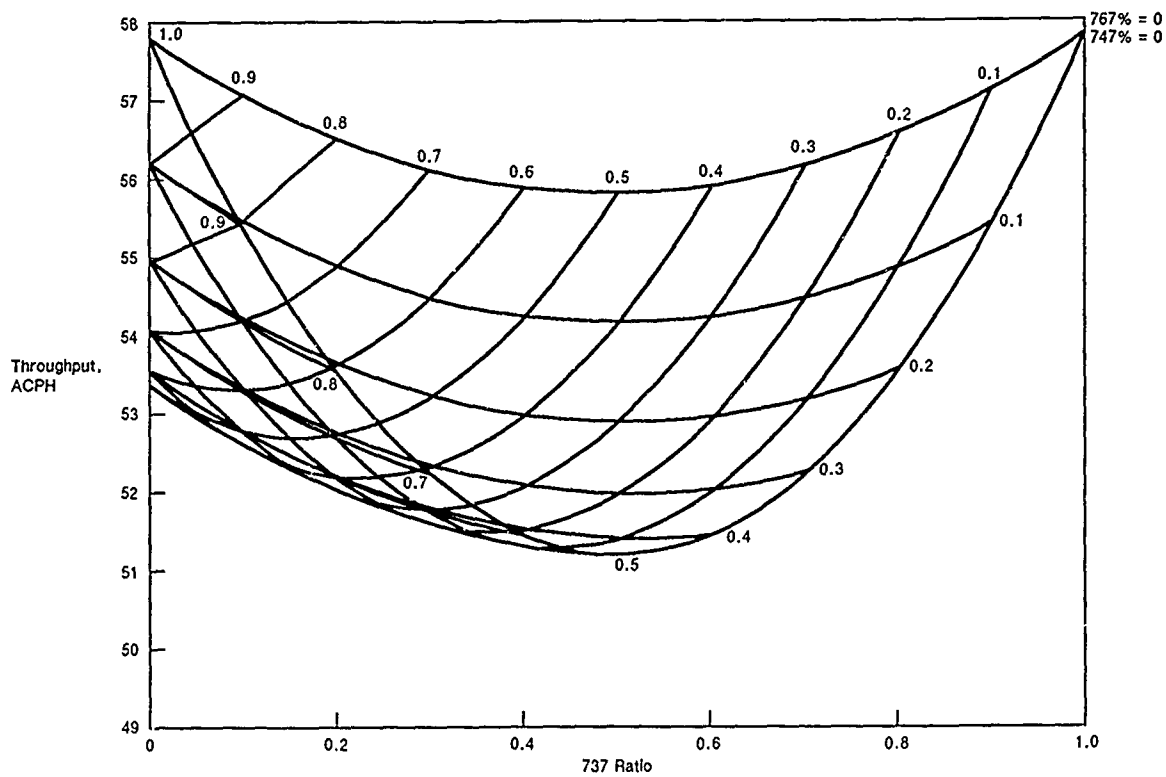


Figure 9. Mixed Traffic Throughput, Optimal Strategy, Elapsed Time = 1658 sec

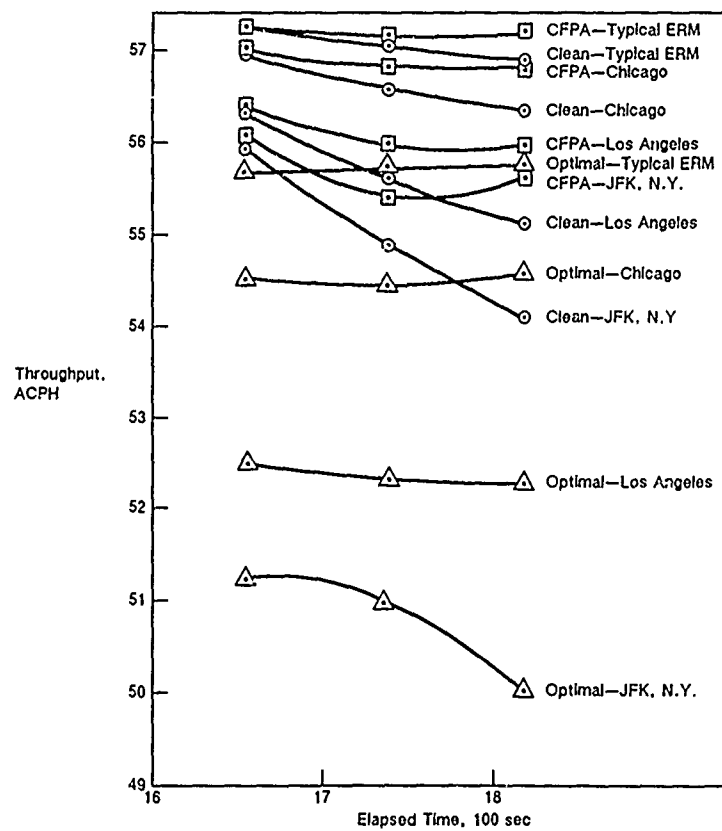
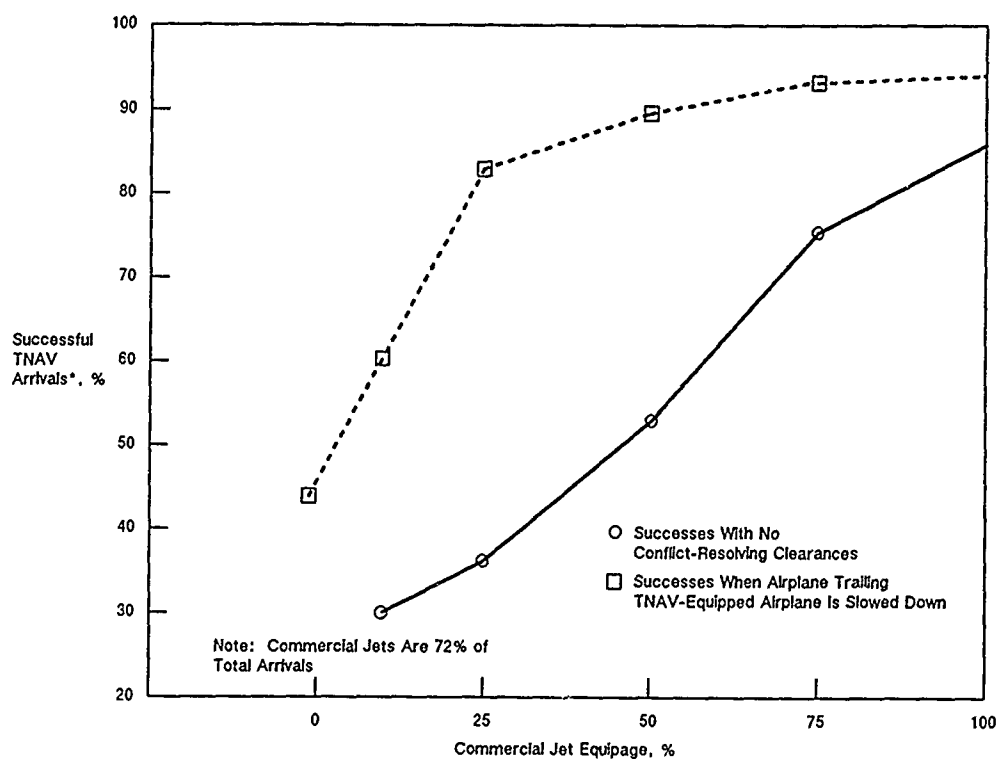


Figure 10. Throughput Performance at Various U.S. Airports



*A Successful 4D RNAV Is One Where 4D RNAV Was Used Throughout Mission.

Figure 11. Probability of Successful 4D RNAV Arrival

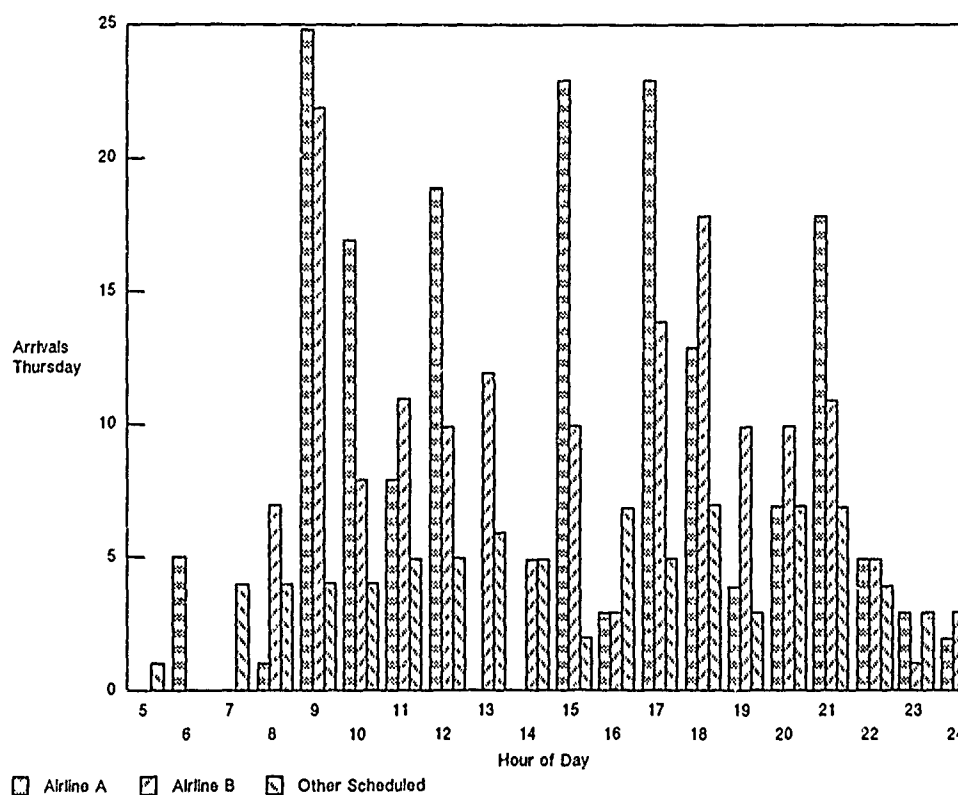


Figure 12. Scheduled Arrival Operations at Denver Stapleton International

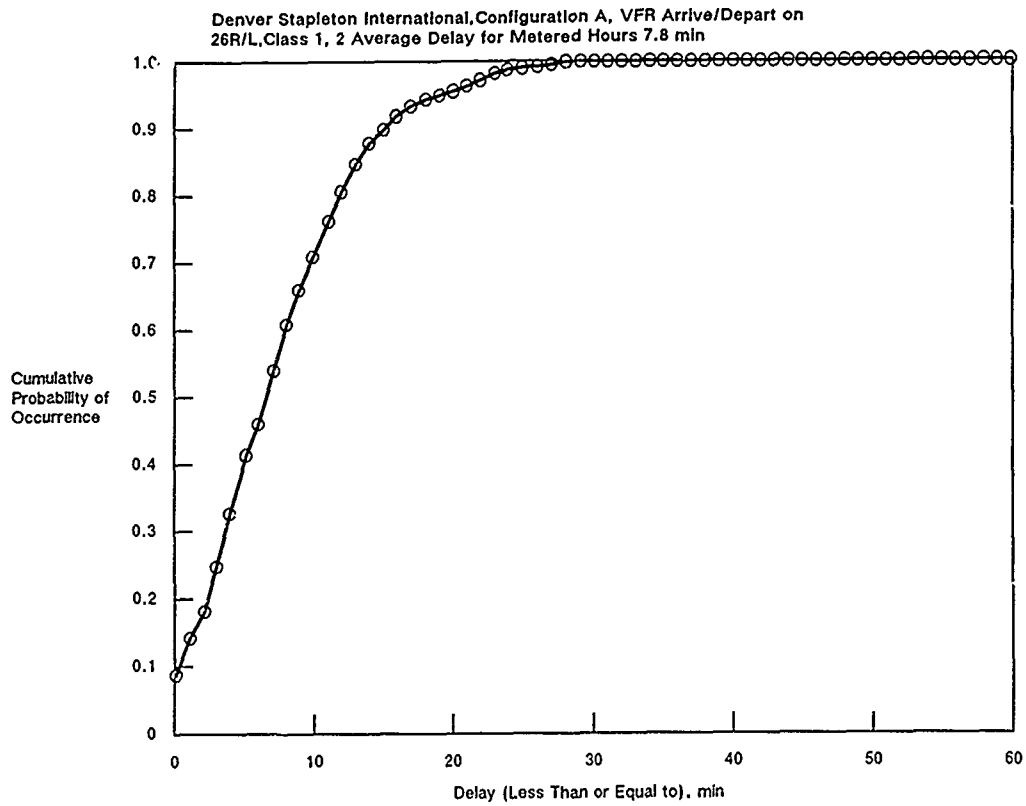


Figure 13. Cumulative Probability of Delay During Metering

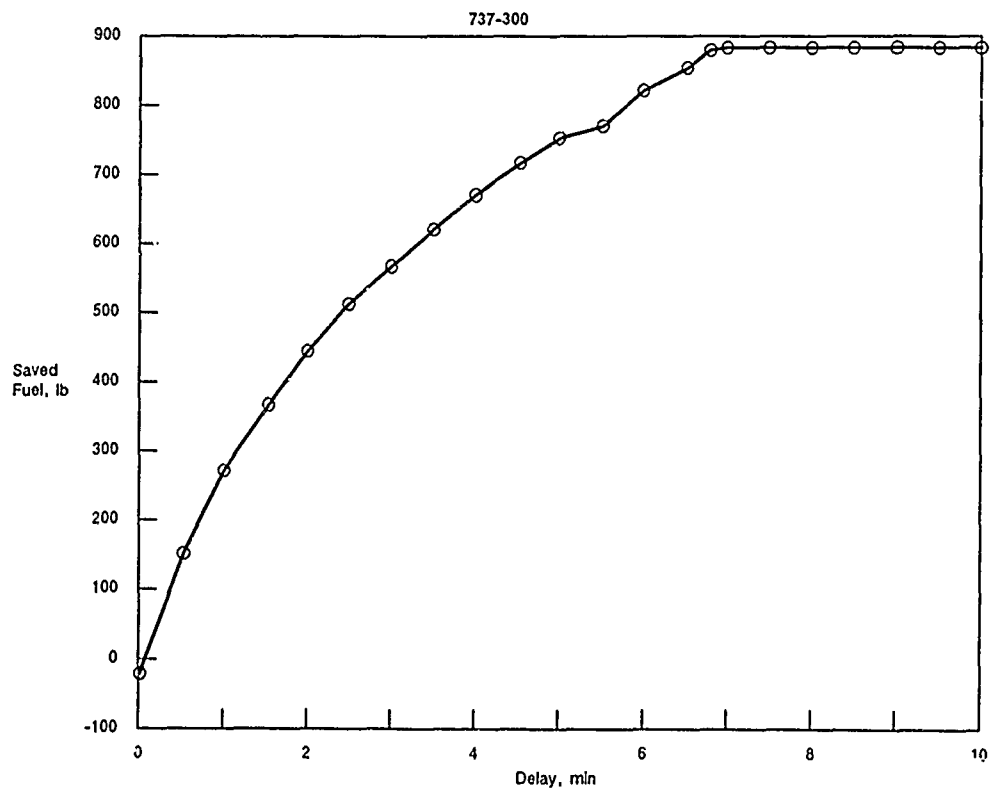


Figure 14. Typical Fuel Saved by Delay Absorption With Speed Reduction

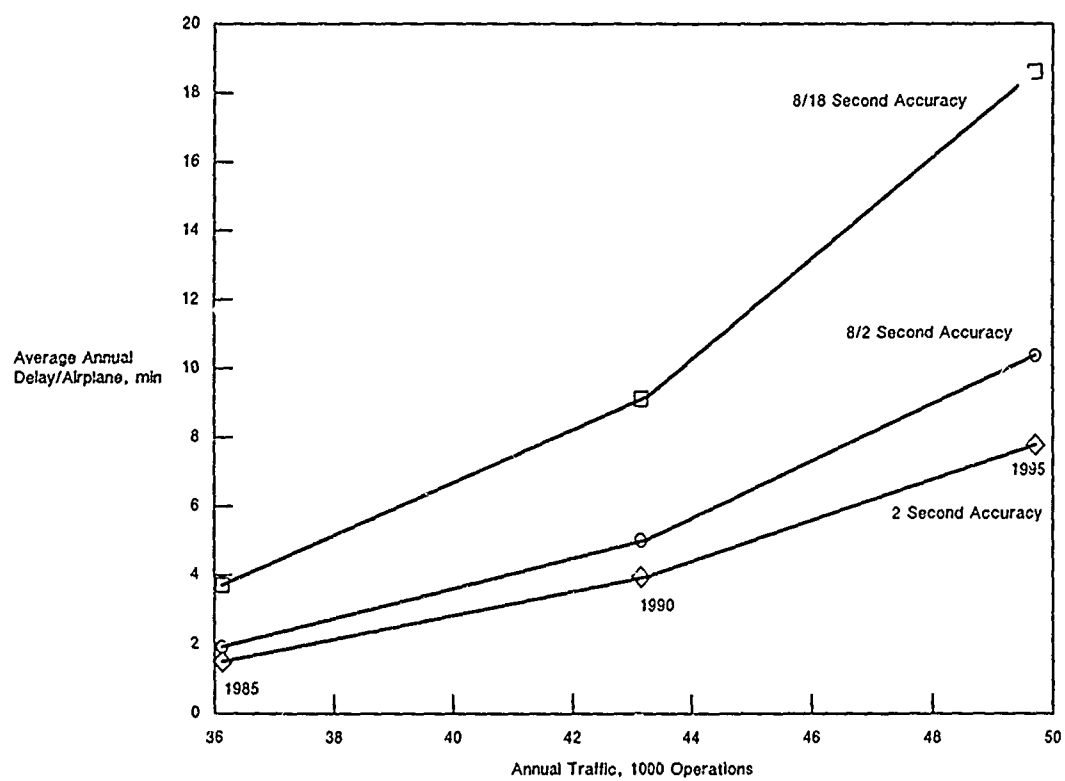


Figure 15. Calculated Average Annual Delay, Minneapolis-St. Paul International Airport

AIR TRAFFIC MANAGEMENT AND AIRCRAFT GUIDANCE IN A ZONE OF CONVERGENCE

by

André Benoît and Sip Swierstra

EUROCONTROL
European Organisation for the Safety of Air Navigation
Engineering Directorate
72, Rue de la Loi, B-1040 Brussels

SUMMARY

The basic principles of air traffic management and guidance of individual aircraft in a Zone of Convergence (ZOC) have been presented in previous papers at successive stages in the development of the project (1978, 1980, 1982, 1984, 1986).

The purpose of this paper is to summarise these principles and to discuss their applicability to the actual operational environment, compatibility with present technology and direct adaptability to future developments, the quality of the interfaces involving the air traffic controller and the aircraft crew and the resultant benefits to the community in terms of economy, use of available capacity and safety.

OBJECTIVES

The ZOC was worked out and developed as a short term concept, an intermediate step towards the efficient integration of air traffic control over all flight phases for all flights. It is a ground-based approach that is consistent with the effort undertaken by aircraft manufacturers and operators aimed at making efficient use of autopilots and more specifically airborne flight management control and guidance systems to determine and fly trajectories meeting airline criteria duly adapted to the numerous constraints resulting from the overall air traffic situation.

In the expected operational context, both the pilot and the controller remain the key elements of the control system. On the ground the controller's prime responsibility is to maintain safe separation among the aircraft in his sector. The ZOC system will advise him how to obtain the maximum utilisation of the available capacity considering the flow of traffic through all sectors of a Centre. In the organisation of the traffic flow, specific objectives of the aircraft operators such as minimum cost, fuel or flight duration are considered, leading to a global minimisation of the deviations from the preferred flight profiles (see below).

In the air, the Flight Management Computer System (FMCS) will assist the pilot in implementing the ATC directives with a very high accuracy, improving the overall control system stability. Future availability of a digital air/ground data link will improve this even further.

Given the presence of human elements in the control loop, the initial planning of the traffic flow will have to be based on an average level of human performance and foreseeable constraints. However, in the ZOC management and control concept, special attention is given to adapting the control strategy to maximise the system throughput. This is done by automatically taking note of above-average controller/pilot performance and adapting the control accordingly. On the other hand, in the event of any setbacks, the system advises the controller how to make the best of the developing situation.

An overall presentation of the approach was made at the AGARD Conference on "Air Traffic Control in face of User Demand and Economy Constraints" organised in Lisbon on 15 October 1982 at the request of the Portuguese authorities (*).

As a consequence, this paper will merely indicate the essential features of the system at its present stage of development. Emphasis will be placed on particular aspects which make it a true ground-based optimum traffic management unit fully in line with advances in airborne guidance, control and flight management.

(*) "Dynamic Control of inbound flights for minimum cost operation"
André Benoît and Sip Swierstra,
AGARD GCP Conference, Lisbon, Portugal, October 15, 1982.
AGARD CP-340, February 1983.
Also EUROCONTROL Report 822041, October 1982.

PRINCIPLES

The ZOC includes and surrounds a main terminal and possibly a series of secondary airports. It extends as far as possible, up to 150, 200, or even 300 nm, from the runway to enable real integration of control over the cruise, descent, approach and landing phases, and possibly also all or part of the climb.

At this point, it may be appropriate to reiterate the notions of preferential and actual trajectories as referred to in the ZOC concept.

Preferential trajectory

(a) Definition

For each aircraft entering the area, from whatever direction, there is one trajectory which meets the operator's requirements in an optimum manner, that is to say for which the control variables are selected (essentially route, altitude and speed) in order to optimise the operating criterion (economy in the wide sense of the term). This will be referred to as the "preferential trajectory". The adjective "preferential" will also be used to qualify its components.

In both the present fixed route network and in any possible future free route system, the route will in practice be determined and assigned according to local considerations (geography, restricted area, availability of ground support, etc.). Consequently, it will play little part in the selection of the preferential profile and can actually be discarded from the control variables. As a result, seen from the ground, the control variables include essentially cruise altitude and speed vector along the path.

(b) Determination and availability

The preferential control variables, altitude and speed, are usually presented for a given route in terms of a sequence of phases, each characterised by a constant indication : indicated airspeed, Mach number, total temperature. Since such conditions can be readily implemented while nevertheless constituting good approximations of the theoretical optima. Aircraft manufacturers and airlines usually make the relevant information easily available to the air traffic services authorities.

In a ground/air/ground data link communications environment, it is possible to envisage on-line receipt of the preferential profile computed on-board at entry, which would accordingly incorporate the impact of local and instantaneous parameters, including aircraft mass and temperature and speed of the air along the route.

Moreover, if the preferential profile is not only determined on-line by a computer (either on-board or ground-based) but also implemented by a computer, the notion of phases characterised by constant indications may be superseded.

Actual trajectories

Clearly, if an aircraft were entering an empty area, it would fly the preferential profile. In reality, the corresponding trajectory will most probably conflict with one or several trajectories of other aircraft already in the area covered by the ZOC control. Accordingly, one or several aircraft will have to depart from their preferential trajectories and fly what are referred to as 'actual trajectories'.

Management of traffic

Too often, in the present operational system, aircraft are allowed to follow their preferential profile until a point where the start of a conflict or problems can become likely or actually be expected : as far as the stack for most aircraft approaching a main airport. The resulting incidental penalties have been quantified and are well known. Furthermore, they increase very rapidly when the density of traffic approaches the maximum runway capacity (saturation effect).

By contrast, ZOC management looks ahead to a horizon which corresponds to the size of the zone concerned (of the order of one hour for a zone covering the whole of Belgium). The management system aims to assign a set of trajectories such that the overall operational criterion (summation extended over all individual criteria for aircraft present in the system and still amenable to control) is satisfied. This set of trajectories is conflict-free at both ends : at entry in accordance with a basic operational rule of control transfer and at the runway threshold as a result of ZOC management action. In short, each inbound aircraft flying through the ZOC area is assigned a trajectory which, on average, is as near as possible to its preferential profile.

Control of individual flights

Once the management component (ROSAS in ZOC terminology) has, on entry of a new aircraft, updated the traffic flow characteristics, the "actual trajectories" are adapted to the new plan by the guidance and control component (CINTIA) and the relevant advisories (or directives depending on the level of automation) are dispatched to the control position(s) concerned for immediate or subsequent implementation.

OVERALL STABILITY

The present system is naturally stable, the stack constituting the regulating reservoir.

In contrast, ZOC management avoids the systematic use of the stacking facilities. It determines the time of arrival and adapts the speed at entry of the aircraft concerned or on entry of another aircraft if applicable. These two operations - associated with the traffic situation and with the characteristics of the aircraft concerned, respectively - are closely coupled. Accordingly, ZOC management is appreciably more efficient than the present operational ATC, but it clearly operates without the reliable, although very costly, buffers constituted by the stacks.

The numerous and varied factors that affect the course of a flight are such that the uncertainty on arrival at the runway threshold could amount to several slots.

This fact was recognised at an early stage of the project and duly taken into account. Indeed, following the first full-scale ATC simulation conducted at the Experimental Centre in 1982, an appreciable effort was devoted to the development of a ground-based 4-D guidance system designed to maintain the assigned time of arrival to within seconds (error less than 10 seconds). This system, which is referred to as CINTIA*, has been tested under a variety of conditions using full-scale flight simulators operated by airline crews. The flexibility, adaptability and accuracy of CINTIA ensure the stability of the overall management and control system in the ZOC area, from entry to touchdown.

MAN/MACHINE INTERFACES

As has been stated previously (Miller, ZOC Video, 1986), the complexity of the ZOC system (as regards both the ROSAS and the CINTIA components) is kept within the computer. The resulting messages are integrated into the aircraft label displayed on the controller's radar screen - without complementary tabular displays or any other addition. The actual messages were defined in conjunction with professional air traffic controllers and they appear to be compatible with real operations. A further discussion on the human aspects involved is presented separately#.

COMMUNICATIONS ENVIRONMENT

A series of exercises has been conducted in order to assess the various components and the overall systems. Full-scale ATC simulations have been conducted satisfactorily in the present radio-telephone (R/T) communications environment.

Nevertheless, the messages and related interfaces have been made directly adaptable to automatic air/ground data communications (D/L). Data link environment exercises are planned in the course of 1990.

ON-BOARD CONTROL/GUIDANCE/NAVIGATION CAPABILITY

The ground-based system under development is intended to accommodate all aircraft allowed to fly in the controlled airspace, without any specific additional requirements. It is essentially based on surveillance information. Guidance directives are expressed in terms of DME distances, of time, or a combination of both*.

IMPLEMENTATION

The ZOC system, incorporating both the CINTIA and the ROSAS components, has been designed in accordance with the principles of distributed processing, i.e. it can be introduced at an experimental or operational centre on a separate small processor, thus avoiding the difficulties inherent in integration into a complex ATC system based on a mainframe computer.

* "The Control of inbound flights : Basic principles"
AGARDograph AG-301, Paper 32. In publication.
Also EUROCONTROL Report 892011-E, December 1989.

"The air traffic controller facing automation : Conflict or Cooperation"
The Royal Institute of Navigation, London, U.K., September 1987.
Also EUROCONTROL Doc. 872008, July 1987.

CONCLUSIONS

In 1982 a full-scale air traffic control simulation of the ZOC concept was conducted at the EUROCONTROL Agency's Experimental Centre (Miller**, 1982). The exercise was extremely instructive and the lessons learnt caused us to reorientate our development work in order to allow for the following factors :

(1) Management position stored in the computer

A virtual management position is always contained in the computer. It can be activated as an on-line traffic manager position. In the simulation conducted subsequently, covering the airspace over the whole geographic area of Belgium, there was no requirement for such a position.

(2) No separate display for presentation of landing sequence

- . A display of the landing sequence and the landing times was introduced into the EEC's 1982 ATC simulation. Where precise guidance advisories were lacking, this information, although presented on a separate display, provided adequate assistance to the approach control, indicating, in particular, the origin of each aircraft approaching the localiser ; such a facility is included in the German COMPAS, to be tested shortly at the operational Frankfurt centre.
- . Nevertheless, the presence of a second, separate tabular or other display can be a source of additional human workload and fatigue. It was accordingly decided to avoid any such additional display. A complete revision of the man/machine interface was undertaken as described in the next paragraph.

(3) Man/machine interface : Integration of all information into the radar label

- . The present ZOC display integrates the guidance advisories into the classic radar label - also the aircraft position in the landing sequence - without any requirement or need for additional tabular or other separate display ;
- . The man/machine dialogue has become a computer -> display -> controller monologue, except where the controller wishes to modify the system configuration.

(4) For convenience of implementation in an operational ATC system, the system has been developed in line with the principles of distributed processing.

In conclusion, these essential factors, introduced at a early stage of the development work, have led to a system sufficiently intelligent to interpret correctly the controller's actions and detect his choices on the basis of the relevant radar observations.

** "Adaptation of simulation tools to the study of fuel consumption problems at the EUROCONTROL Experimental Centre" by W. Miller
Institute of Air Navigation Services,
Luxemburg, October 1982.

GROUND-BASED 4-D GUIDANCE OF FLIGHTS IN STRONG WIND (*)

by

André Benoît and Sip Swierstra

European Organisation for the Safety of Air Navigation
 EUROCONTROL
 Engineering Directorate
 72, rue de la Loi, B - 1040 Brussels (Belgium)

ABSTRACT

In strong wind, groundspeed may vary appreciably during a turn, just as for example in the case of a landing after a U-turn preceding the localiser intercept. Such conditions are critical for maximum use of the runway, and render human estimation of aircraft motion extremely difficult.

This paper summarises the tests conducted using a ground-based 4D-guidance program, developed to assist the air traffic controller in maintaining the predicted landing-time sequence with an accuracy better than 10 seconds for each arrival.

1. INTRODUCTION

In the past, we have tested the ability to predict, guide and control aircraft so as to maintain time of arrival and/or minimum separation at the runway to within seconds, in spite of the numerous perturbations affecting the conduct of a flight (Ref. 1).

In this connection, wind unpredictability was given special attention. Errors in groundspeed of as much as 30 kt were introduced, deriving from both wind inaccuracies and incorrect indicated airspeed, the latter originating in either human errors (on the ground - generated by air traffic controller - or in the cockpit) or transmission defects or both.

The results were within the control system stated tolerances, namely no correction advice where expected time-of-arrival error is less than 10 seconds.

Accordingly, we considered that the model used in the prediction/control programme (CINTIA), performed satisfactorily in a moving atmosphere, whatever the phase of the flight. Nevertheless, the question raised by an experienced airline captain, knowledgeable in aircraft operations and aircraft motion modelling (Ref. 2), cast some doubts on our opinion.

"Have you really tested 'your system' in strong wind conditions ? In a U-shape approach, for instance, an aircraft could be flying with a 50-kt tail wind and encounter a 50-kt head wind on the localiser, that is to say a wind variation of 100 kt over one single turn in the last and most critical part of the flight".

In other words, the control component of CINTIA could very well cope with perturbations resulting from appreciable groundspeed errors, although the impact of wind in the predictive module might not properly be accounted for.

In order to confirm our opinion - or otherwise - it was then decided to conduct experiments in realistic conditions, human aspects included.

The tests were carried out at British Airways Flight Crew Training Centre, in Hounslow, London, on 2nd July 1987. The B-737 and B-757 flight simulators were used simultaneously, operated by two highly experienced British Airways Captains. The Air Traffic Control function was performed by René De Wispelaere, ATS Expert of the Belgian Airways and Airports Agency, with competence for en-route and approach control, currently Head of Approach and Tower Control Units at Brussels National Airport.

This contribution outlines the basic set-up, the scenario followed and the essential conclusions. A detailed description of the tests and results obtained is available in Reference 3.

Ref. 1 : "Next Generation of Control Techniques in Advanced TMA"
 by A. Benoît, S. Swierstra and R. De Wispelaere
 EUROCONTROL Doc. 862016R, June 1986.

Ref. 2 : Critical comments expressed by Captain Y. Delnatte,
 SABENA Belgian World Airlines.

Ref. 3 : "Ground-Based 4-D Guidance of Flights in Strong Wind :
 Tests conducted using British Airways B-737 and B-757 flight simulators"
 EUROCONTROL Doc. 872010, August 1987.

2. FUNDAMENTALS

The trajectory of an aircraft operated in windy conditions is calculated from the integration of the instantaneous vectorial sum

$$\mathbf{V}_e = \mathbf{V} + \mathbf{W}$$

where \mathbf{V} and \mathbf{V}_e are the speed vectors of the aircraft relative to the atmosphere (airspeed) and to the earth (earthspeed) respectively, and \mathbf{W} the velocity of the local air mass relative to the earth (wind vector).

When the wind is considered constant around the aircraft body, any variations - whether time derivatives or space gradients - being slight relative to the aircraft motion scale, the method used to obtain the trajectory in still air is directly applicable, subject to minor amendments affecting in particular indicated speed as against altitude profile near the ground. Indeed, in the present navigation environment, the influence of the wind on the conduct of the flight is mainly sensitive during take-off, approach and landing.

In a ground-based system designed to guide aircraft accurately for precise delivery at the runway threshold, the influence of the wind may become critical since it affects the control advisories the last part of the flight, especially in the course of U or S-shape approaches. Hence the need to assess the calculation, prediction and control of aircraft model algorithms used in CINTIA (Ref. 1) in the presence of strong wind.

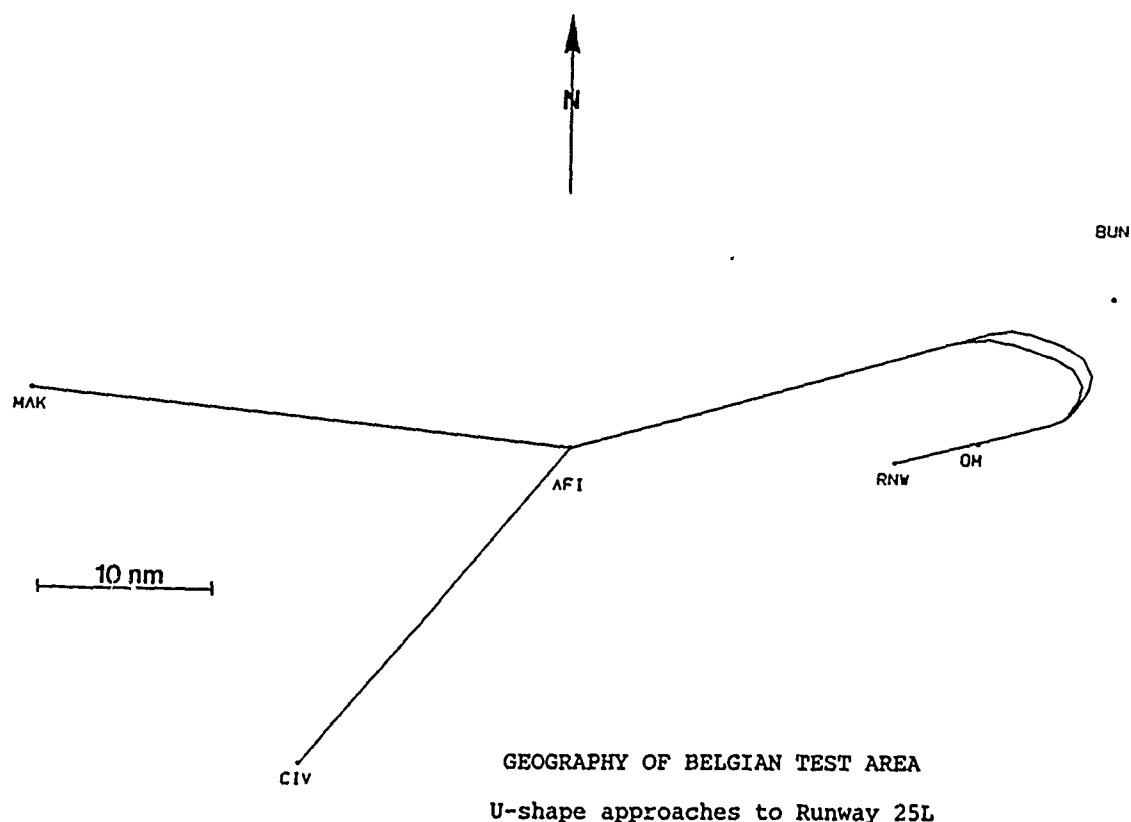


Figure 1

Geography
X, Y

3. EXPERIMENTAL ENVIRONMENT

The experimental facilities used to assess the guidance and control system enable tests to be conducted in realistic conditions from both the atmospheric and human angles.

These particular facilities consist essentially of two full-scale flight simulators (Boeing B-737 B-757), operated simultaneously by British Airways pilots.

The ground-based control unit (ROSAS/CINTIA) receives the position information (radar data) from the two aircraft (Ref. 1). It generates and displays the guidance advisories, which are then transmitted to the aircraft concerned by an actual air traffic controller on the normal R/T channel (Ref. 4).

The experimental facilities used to conduct these tests make it possible to reproduce the most realistic flying conditions, incorporating

- . actual aircraft behaviour - through the use of two full-scale flight simulators ;
- . airline pilot/aircraft interfaces ;
- . pilot/ATC controller interface ;
- . ATC controller/computer interface ;
- . atmospheric motion, wind and turbulence effects included.

Additional information on the experimental facilities used will be available in a separate report dealing with the introduction of specific aircraft control capabilities in air traffic handling simulations.

4. TRAFFIC SCENARIO

The flights took place in the Belgian area depicted in Figure 1. The flights inbound to Brussels were arriving via Mackel (MAK) and Chièvres (CIV). Above the initial points, aircraft were in level flight, at an altitude of 10,000 ft. From there on, the aircraft were proceeding towards Affligem (AFI), following the local Bruno (BUN) approach procedure to land on Runway 25 left.

Two exercises were run, each composed of a series of two flights, the two B-737 and B-757 flight simulators being operated simultaneously. The first exercise was performed in still air, while for the conduct of the second, a 50-kt westerly wind was blowing (260°). For ease of subsequent analysis the windvector was kept constant with altitude. The arrival times at Mackel and Chièvres were selected such that without controller intervention, the aircraft would be "in conflict" over Affligem. Table 1 summarises the general operating conditions.

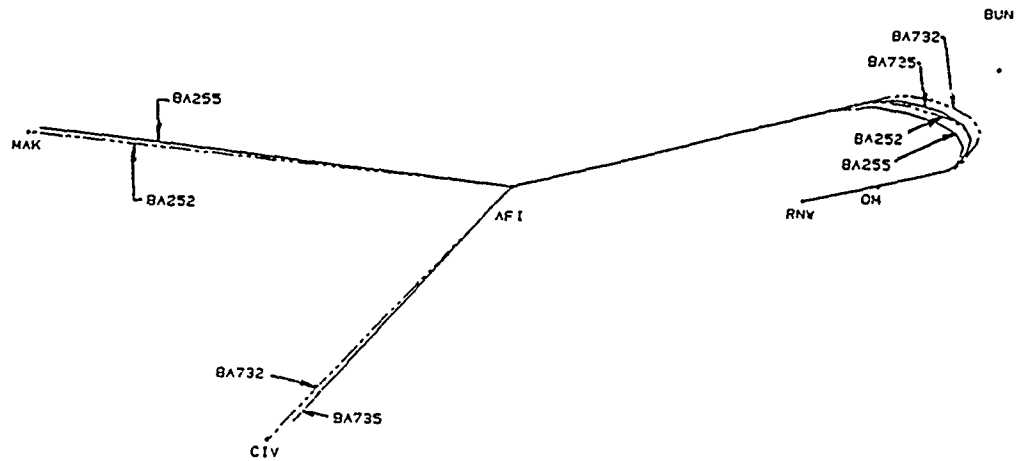
ATMOSPHERE	FLIGHT	AIRCRAFT	PLANNED ROUTE/APPROACH/LANDING
no	BA732	B737	CIV - AFI → BUN - ILS - RW25L
wind	BA252	B757	MAK - AFI → BUN - ILS - RW25L
wind	BA735	B737	CIV - AFI → BUN - ILS - RW25L
50kt/260°	BA255	B757	MAK - AFI → BUN - ILS - RW25L

INBOUND FLIGHTS TO BRUSSELS NATIONAL AIRPORT

General operating conditions

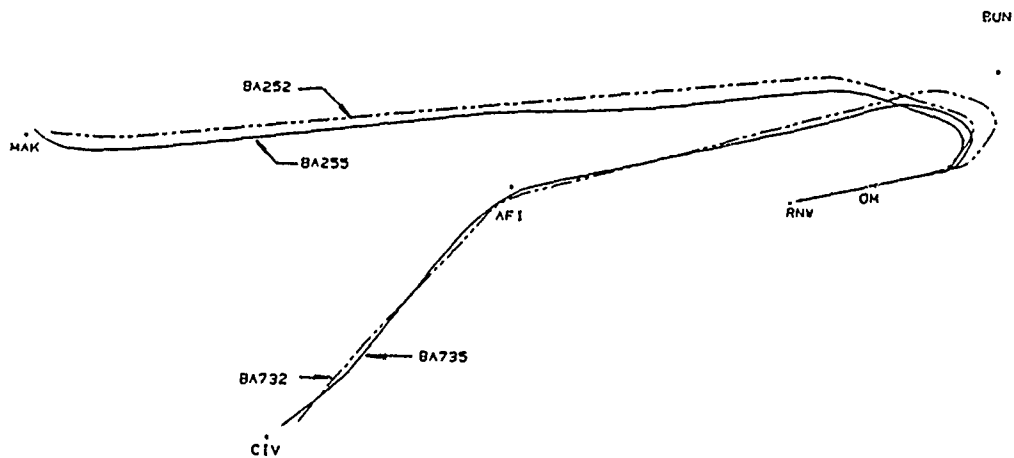
Table 1

Ref. 4 : "The Air Traffic Controller facing Automation : Conflict or Co-operation"
by A. Benoît, S. Swierstra and R. De Wispelaere
EUROCONTROL Doc. 872008, July 1987.



HORIZONTAL PROJECTIONS OF PLANNED FLIGHTS
Initial predictions made at entry into control area

Figure 2.a



HORIZONTAL PROJECTIONS OF ACTUALLY OBSERVED FLIGHTS
Time of arrival maintained as per initial predictions

Figure 2.b

5. CONTROL OF THE FLIGHT

When arriving at the initial point, either Chièvres or Mackel, the aircraft were allocated a landing time based on the

- . nominal route ;
- . aircraft performance capabilities ;
- . airline preferential operation procedure ;
- . standard ATC restrictions ;
- . separation requirements on the localiser ;
- . current meteorological conditions.

The duration of the flights was in all cases of the order of 15 to 20 mn, corresponding to a track length of the order of 60 to 80 nm.

Once a landing time had been allocated, the control of the corresponding flight was exercised in accordance with the ZOC/CINTIA techniques, the control variables including mainly the position of the initiation of the turns, both to base-leg and, to localiser intercept and, to a limited extent, speed at and below 2000 ft.

For these tests, it was decided not to use available speed control in the en-route phases, and accordingly the initial phases of the flights, from Mackel or Chièvres down to 2,000 ft, were conducted at an indicated airspeed of 250 kt.

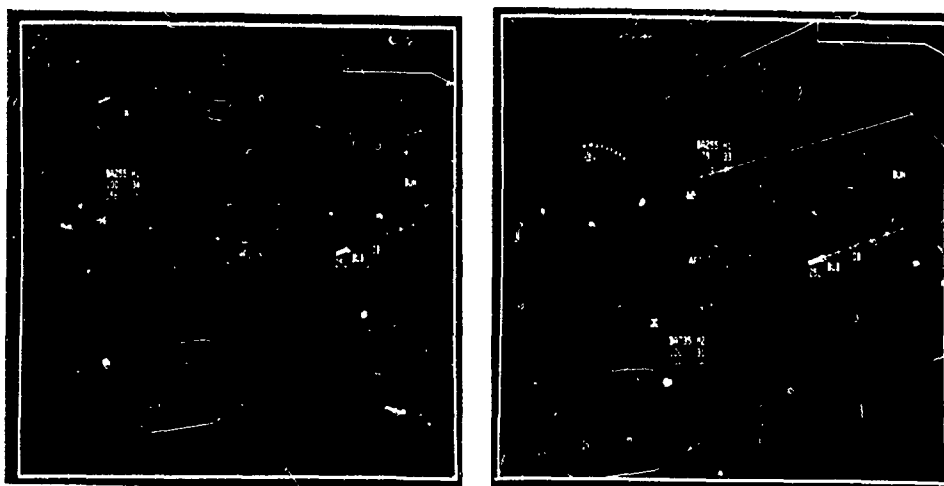
In addition to current perturbations affecting the control of a flight, realistic ATC perturbations were introduced, in particular, actions of the controller aimed at resolving conflicts. These affected the flights in both the vertical and horizontal planes.

A comparison of the horizontal projections of the flights is shown in Figure 2. In the upper part, Figure 2.a gives the ground projections of the trajectories as they were initially computed, aircraft B-757 being over Mackel in the case of flights BA252 and BA255, aircraft B-757 being over Chièvres in the case of flights BA732 and BA735. In the lower part, Figure 2.b shows the corresponding projections for the flights actually observed. It can be seen, for instance, that the controller let both flights BA252 and BA255 go direct towards Bruno to avoid a conflict situation around Affligem. Nevertheless, in all cases the objective was to maintain the time of arrival at the runway threshold as initially predicted. Figures 3 and 4, show clearly the speed control constraint imposed on the tests, namely speed control available only from 2,000 ft downwards.

The ATC ground-based computer having available the preferred airline/aircraft operating procedures for each aircraft, descent, approach and landing speeds, the resultant groundspeed was readily computed : for this exercise, it was assumed that the ATC computer had a correct picture of the atmosphere, the impact of wind inaccuracies having been investigated previously (see for instance Ref. 1). Groundspeed-versus-time relationships initially computed and actually observed are given in Figures 5.a to 5.d, each diagram illustrating a different comparison.

For completion, a perspective view of the trajectories is given in Figures 6 and 7. These diagrams clearly illustrate the efficient cooperation between the human controller undertaking action to avoid conflicts in the neighbourhood of Affligem and the computer maintaining the time of arrival at the runway through adequate guidance advisories.

The control advisories were integrated into the radar labels, as discussed in References 1 and 4. An illustration of the radar screen available to the controller is given in Photographs 1.a and 1.b.

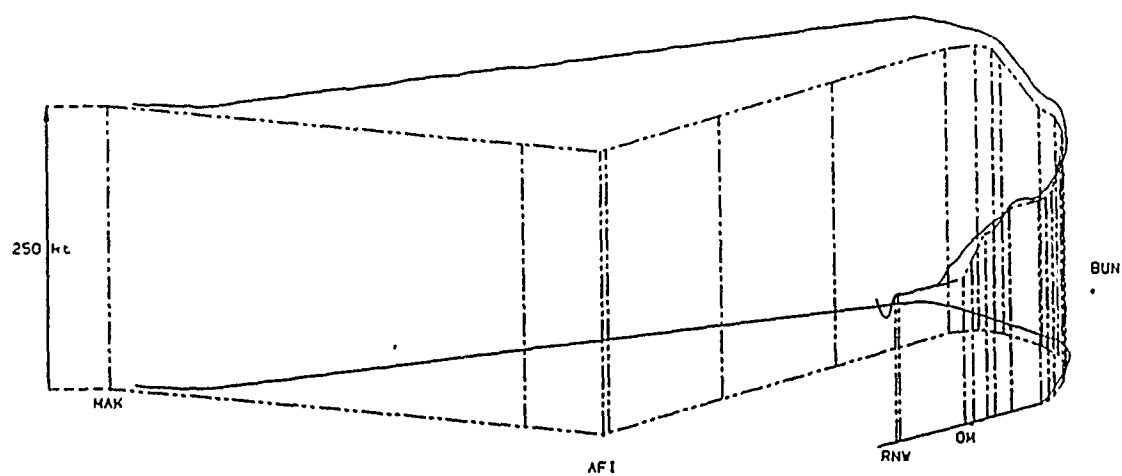
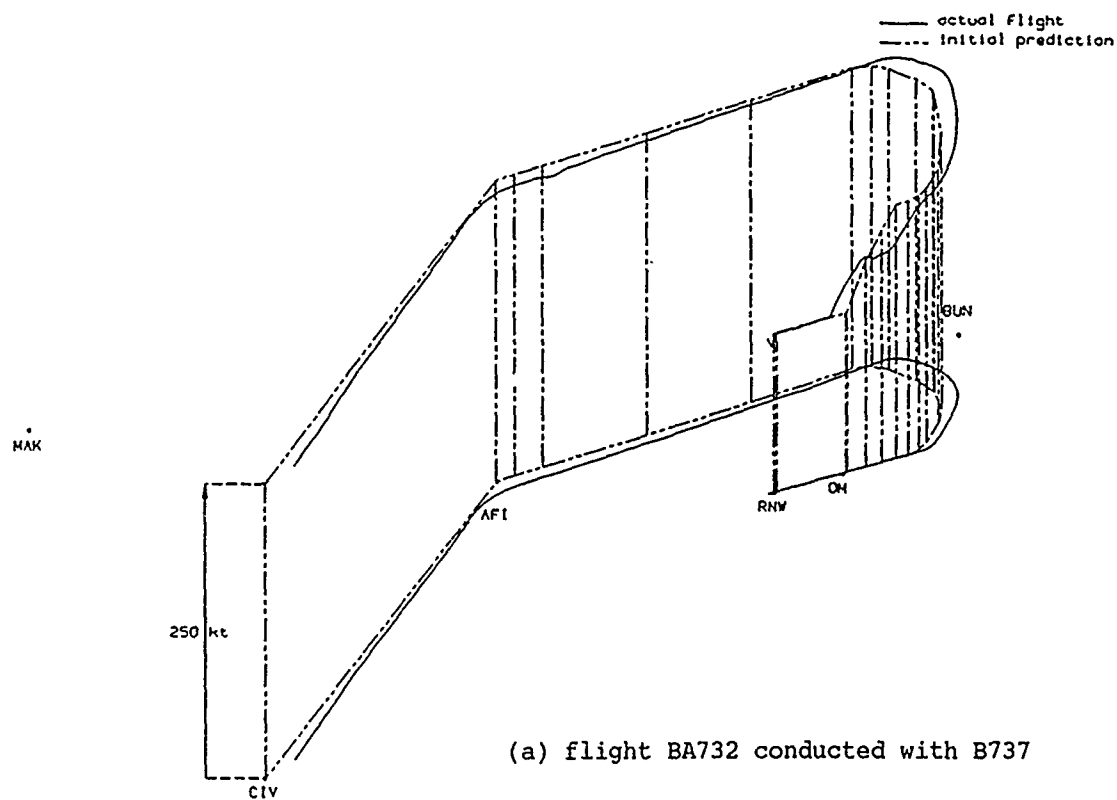


(a)

(b)

DISPLAY OF ADVISORIES TO THE CONTROLLER

Photograph 1



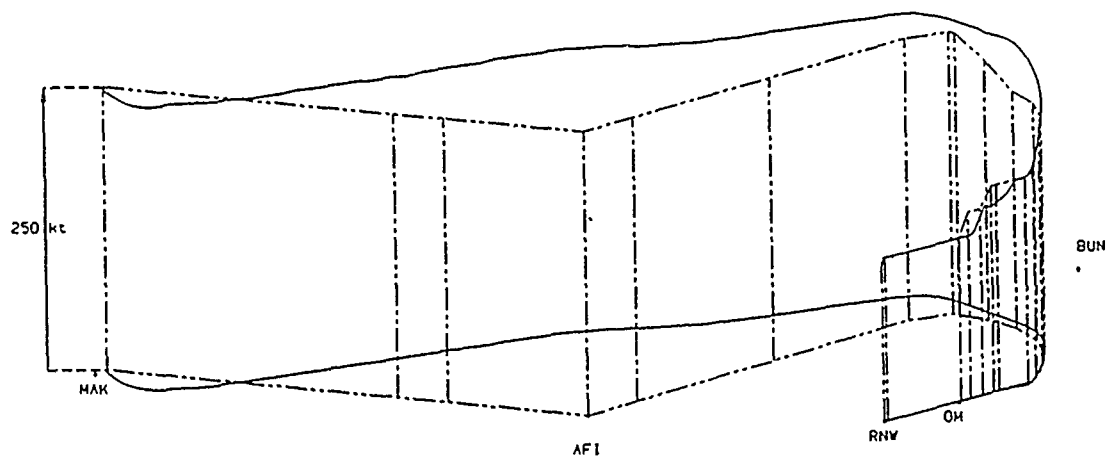
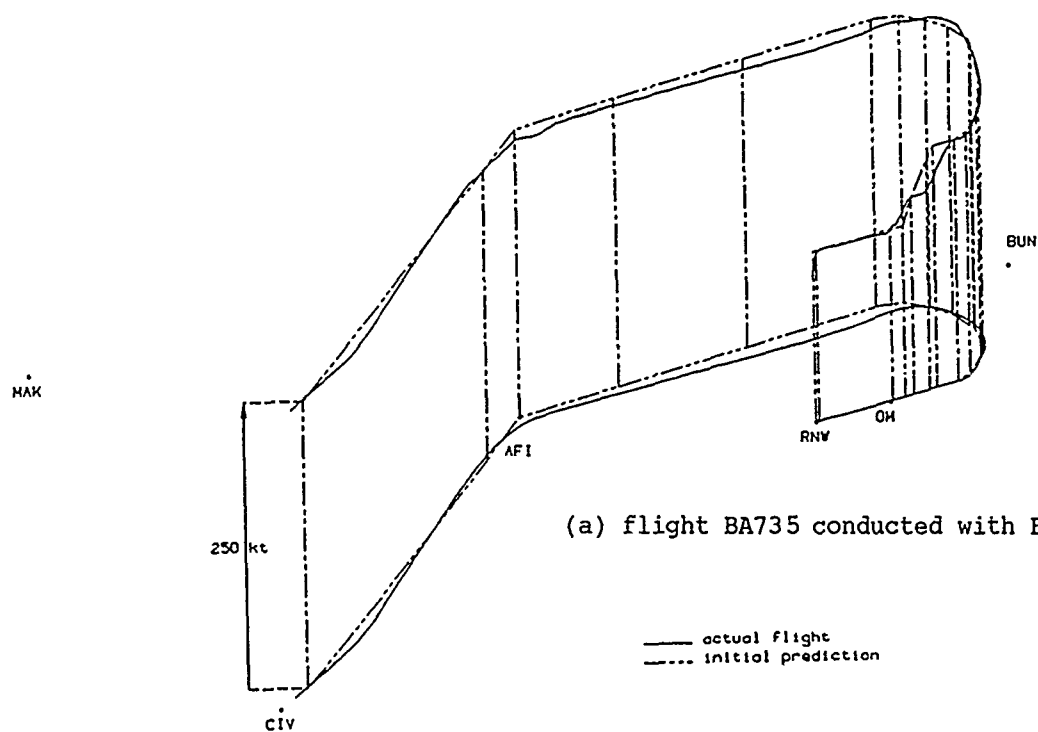
(b) flight BA252 conducted with B757

— actual flight
- - - initial prediction

civ

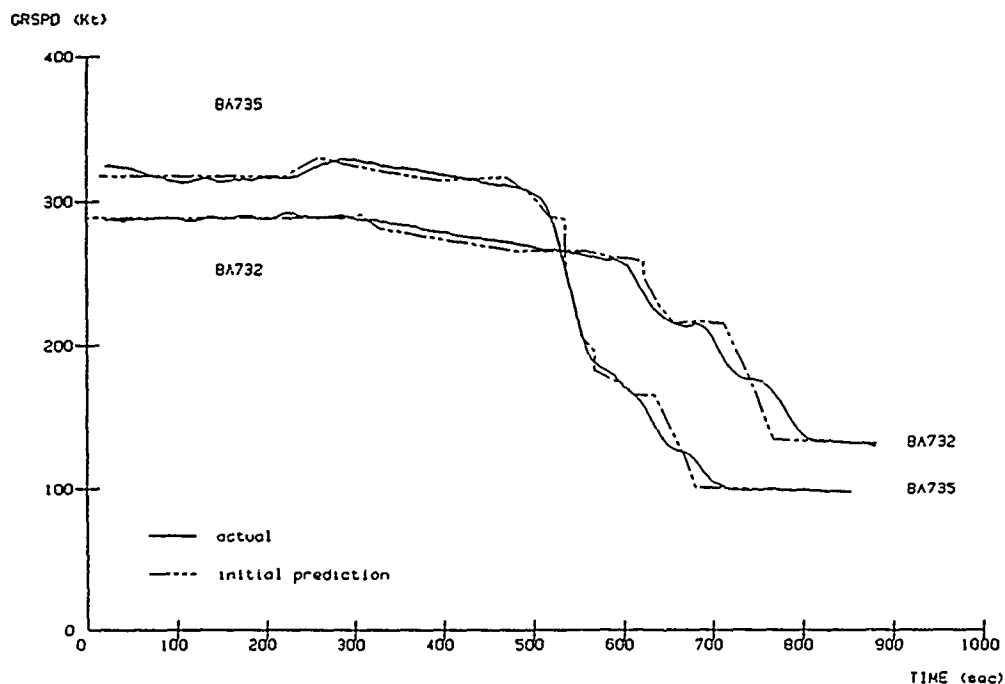
PLANNED AND OBSERVED CAS ALONG THE FLIGHT
Flights conducted in still atmosphere
(a) Flight BA732 (b) Flight BA252

Figure 3

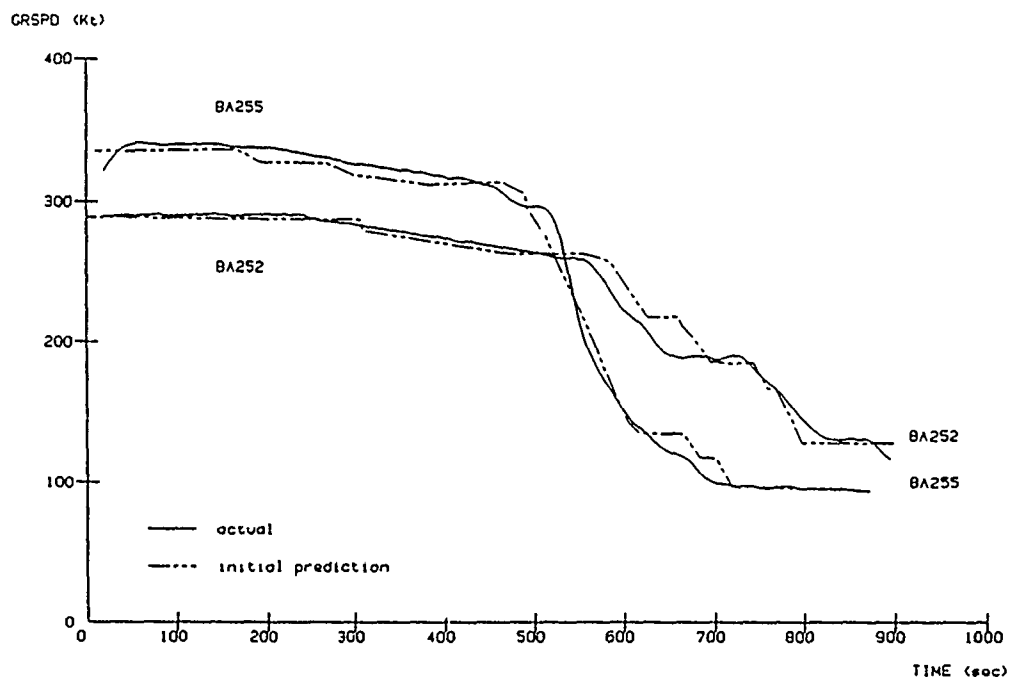


PLANNED AND OBSERVED CAS ALONG THE FLIGHT
 Flights conducted in strong wind
 (a) Flight BA735 (b) Flight BA255

Figure 4



(a) flights conducted with B737 aircraft

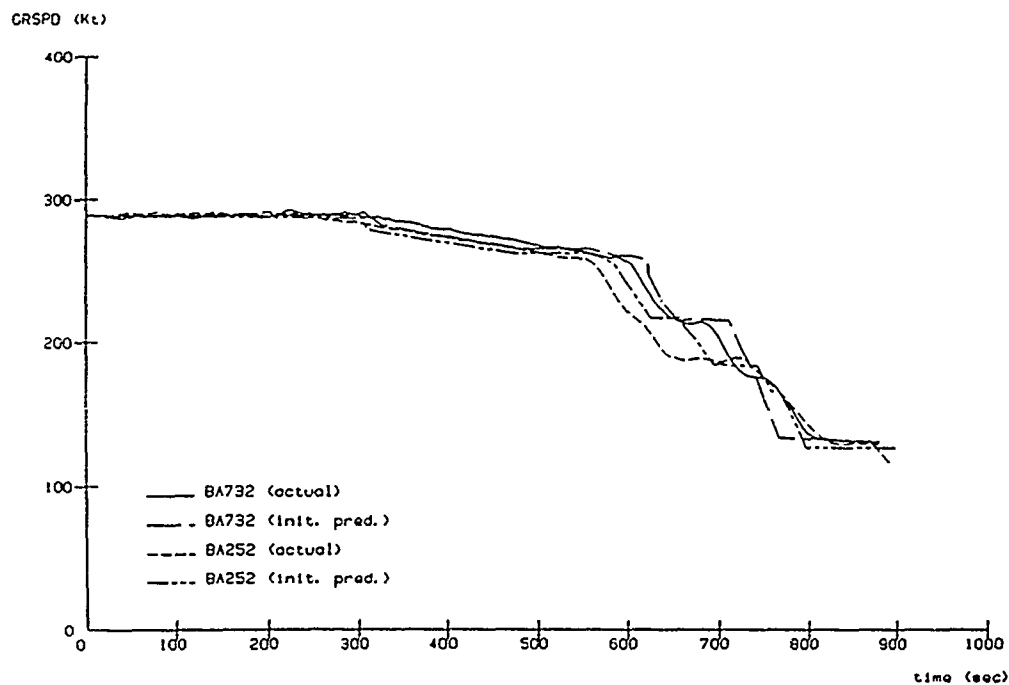


(b) flights conducted with B757 aircraft

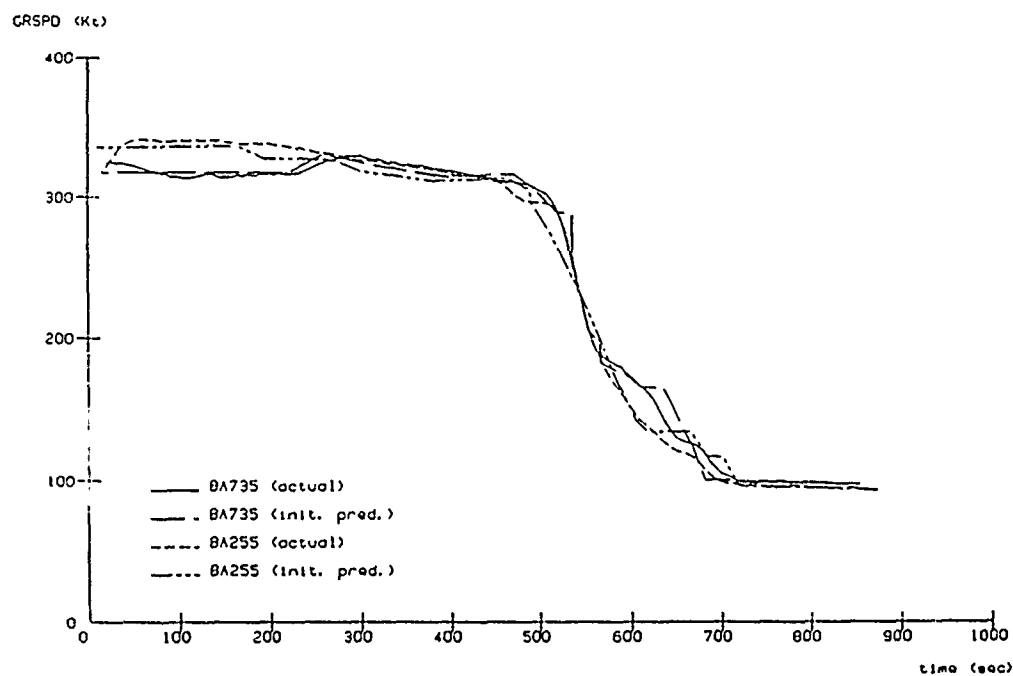
COMPARISONS OF GROUNDSPD VERSUS TIME RELATIONSHIPS
Initial predictions and actual observations
Flights in still atmosphere and in strong wind

Figure 5

(a) and (b)



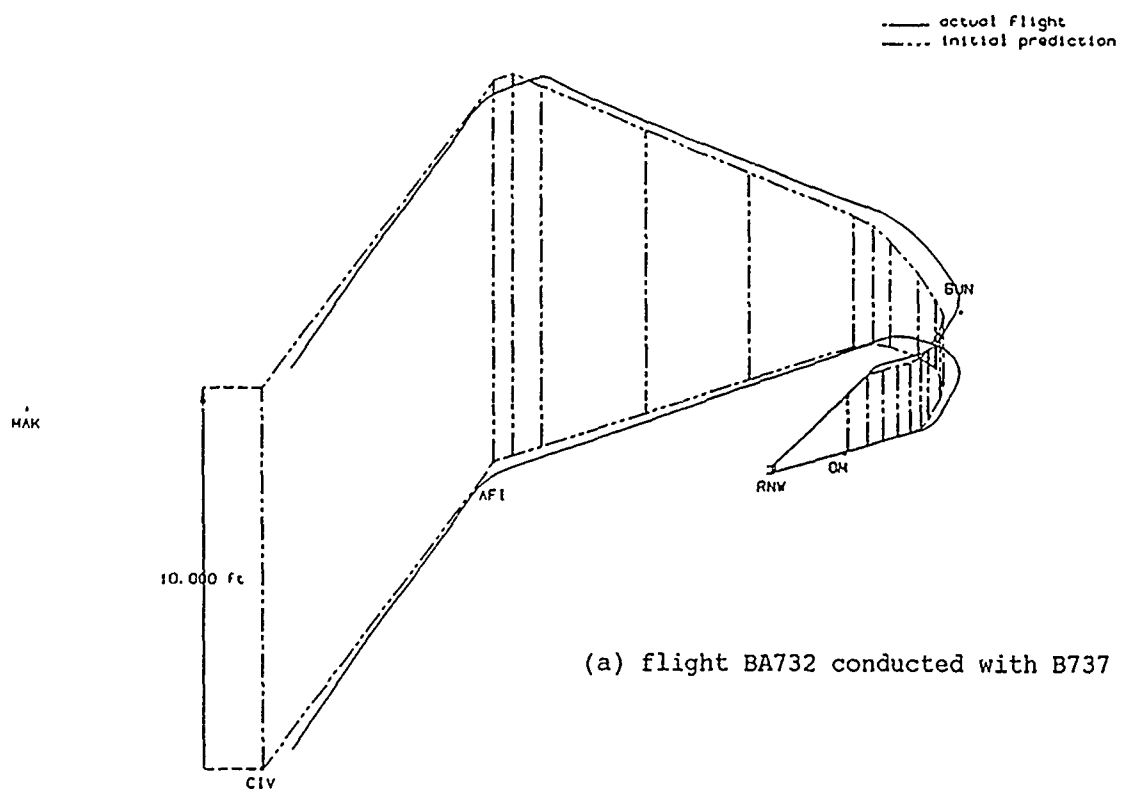
(c) flights conducted in still atmosphere

(d) flights conducted in moving atmosphere
(wind : 50 kt / 260 deg.)

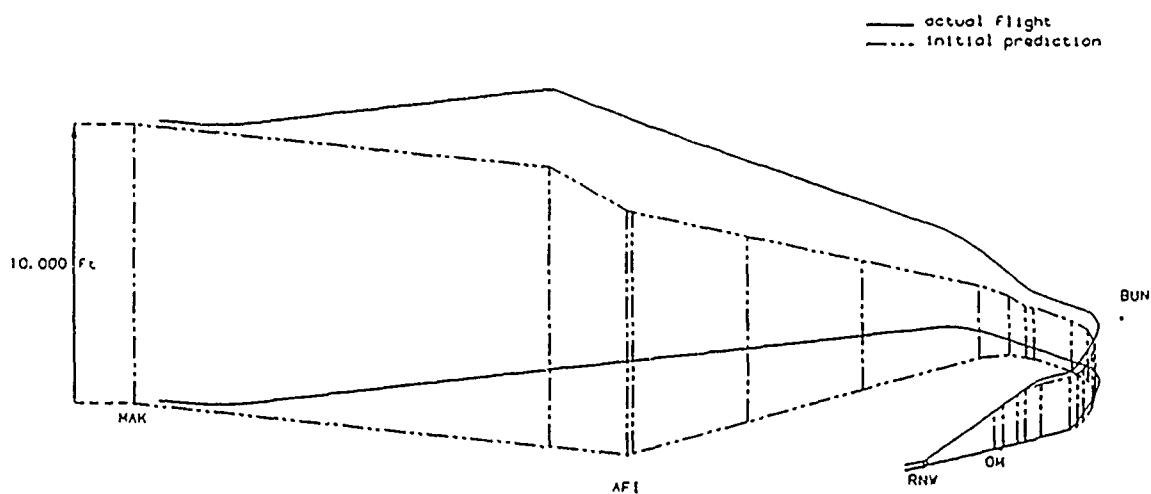
COMPARISONS OF GROUNDSPD VERSUS TIME RELATIONSHIPS
Initial predictions and actual observations
Flights in still atmosphere and in strong wind

Figure 5

(c) and (d)



(a) flight BA732 conducted with B737

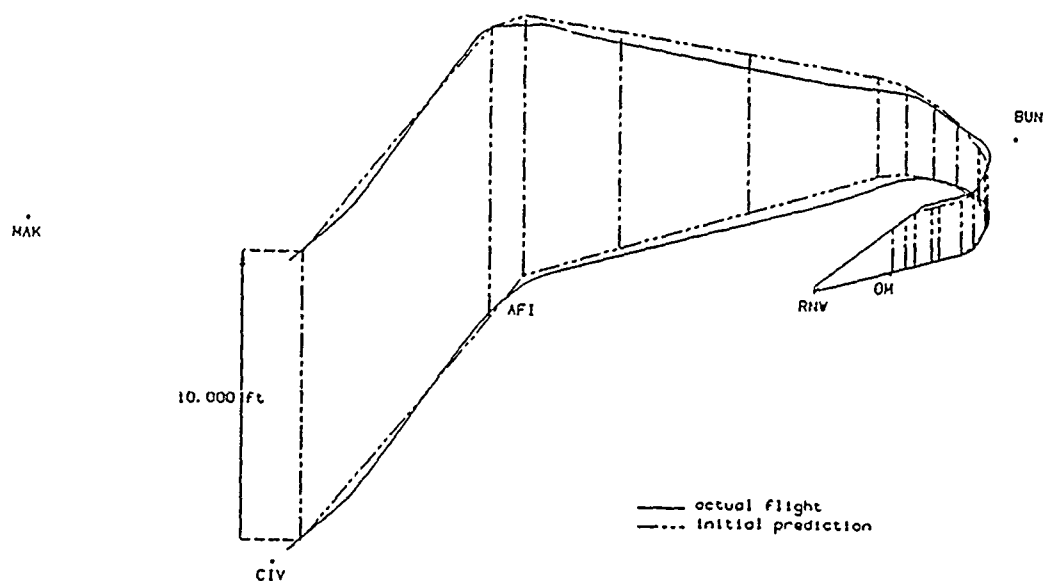


(b) flight BA252 conducted with B757

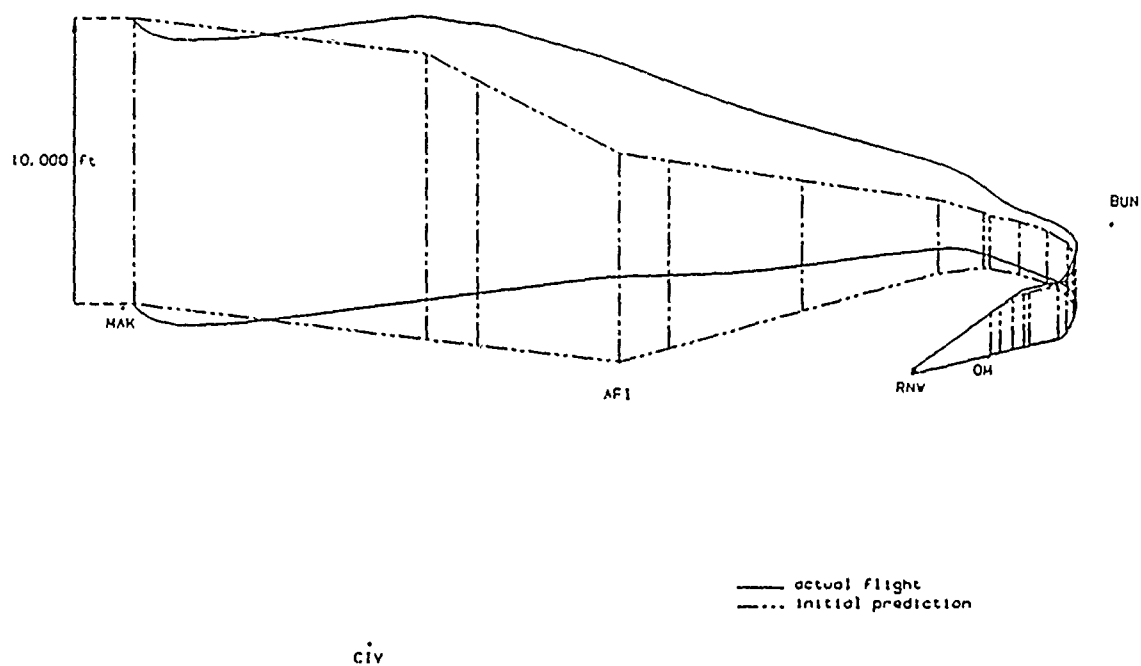
civ

PERSPECTIVE VIEWS OF THE TRAJECTORIES
 Flights conducted in still atmosphere
 (a) Flight BA732 (b) Flight BA252

Figure 6



(a) flight BA735 conducted with B737 aircraft



(b) flight BA255 conducted with B757 aircraft

PERSPECTIVE VIEWS OF THE TRAJECTORIES
 Flights conducted in strong wind
 (a) Flight BA735 (b) Flight BA255

Figure 7

ATMOSPHERE : No wind			
Flight	:	BA-732	BA-252
Aircraft	:	B-737	B-757
Flight duration (sec)			
Predicted	:	881	889
Actual	:	884	880
Error in time of arrival (sec)	:	3 (L)	9 (E)
Error in time at outer-marker (sec)	:	6 (L)	5 (E)
ATMOSPHERE : Wind 50 KT/260°			
Flight	:	BA-735	BA-255
Aircraft	:	B-737	B-757
Flight duration (sec)			
Predicted	:	853	873
Actual	:	857	874
Error in time of arrival (sec)	:	4 (L)	1 (L)
Error in time at outer-marker (sec)	:	2 (L)	1 (E)

E : early L : late

Observed accuracy at runway threshold and at landing

CONTROL OF TIME OF ARRIVAL

TABLE 2

6. CONCLUDING REMARKS

In strong wind, groundspeed may vary appreciably during a turn, as for example in the case of a landing after a U-turn preceding the localiser intercept. Such conditions are critical for maximum use of the runway and render human estimation of aircraft motion extremely difficult.

This paper summarises tests conducted in response to the question whether a ground-based computer program generating advisories fully integrated in the radar label could efficiently assist the air traffic controller in maintaining the predicted landing-time sequence with a accuracy better than 10 seconds for each arrival.

In order to investigate the matter, four incoming flights landing after a U-shape approach were performed in series, two in still air and two encountering a 50-kt head wind on the localiser, that is to say encountering a 100-kt wind variation in the last and most critical part of the flight.

The flights were carried out at British Airways' Flight Crew Training Centre, in London. Simultaneous use was made of the B-737 and B-757 flight simulators operated by professional airline pilots, while the ATC functions were performed by an ATS expert.

The functions of the air traffic controller essentially included the resolution of conflicts over the converging point Affligem - modifying the standard inbound flight path either in the horizontal or in the vertical plane or in both - and the implementation of the computer advisories appearing in the relevant radar labels.

Two sets of two flights, one in still, and the other in moving atmosphere were conducted. At each session, flights were initiated in such a manner that they would conflict over the common waypoint of Affligem; the conflict resolution was left to the human controller, while the advisories to maintain the landing time within 10 seconds were generated by the automatic computer support.

The actual operation of the aircraft was left of the discretion of the pilots, without any request from our side regarding the use of the autopilot or any flight management computer mode ; further, none of the aircraft was equipped for 4-D navigation and the time of arrival predicted at entry (over Mackel or Chièvres as appropriate) was not transmitted to the pilot by the controller.

The results are summarised in Table 2. It can be seen that all flights met the 10-second accuracy criterion at landing (also at the outer-marker), whether in still or fast-moving atmosphere. The respective errors for the B-737 and B-757 were 3 and 9 sec. in still atmosphere and 4 and 1 sec. in moving atmosphere (50 kt head-wind at landing).

In conclusion, the authors feel confident that a true computerised support, such as that derived from CINTIA (Ref.1) and used in these tests, can control with an accuracy of a few seconds the trajectory of aircraft of all types in extreme wind conditions (involving typically about a 100-kt variation during a final U-turn) without the need for special on-board guidance or navigation systems apart from the normal DME equipment. The corollary is that the ATC controller can concentrate on crucial conflict resolution tasks without costly path extensions or systematic holding, in the knowledge that he can rely on an efficient trajectory control support for guidance advice.

* Acknowledgement

The authors would like to express their appreciation to the Royal Institute of Navigation, London, U.K., for publication of an abstract of this work in the Journal of Navigation, Cambridge University Press, Cambridge CB2 2BS, United Kingdom.

GUIDAGE QUADRIDIMENSIONNEL A PARTIR DU SOL DE VOLS OPERANT PAR VENT FORT (*)

par

André Benoît et Sip Swierstra

Organisation européenne pour la sécurité de la navigation aérienne
EUROCONTROL
Direction technique
72, rue de la Loi, B - 1040 Bruxelles (Belgium)

RESUME

Par vent fort, la vitesse-sol peut varier considérablement en virage ; c'est notamment le cas lors d'un atterrissage effectué après un virage à 180° précédant l'interception du faisceau ILS. Ces conditions jouent un rôle crucial au niveau de l'exploitation maximale de la piste, rendant l'appréciation humaine du mouvement de l'aéronef extrêmement difficile.

Le présent document constitue un récapitulatif des essais effectués à l'aide d'un programme de guidage quadridimensionnel asservi, à partir du sol, mis au point dans le but d'aider les contrôleurs de la circulation aérienne à maintenir la séquence prévue des heures d'atterrissage avec une précision de l'ordre de 10 secondes pour chaque arrivée.

1. INTRODUCTION

Par le passé, nous avons testé l'aptitude du système de contrôle à prévoir la trajectoire des aéronefs, à les guider et à les contrôler de manière à maintenir l'heure d'arrivée et/ou l'espacement minimum sur la piste dans une fourchette de quelques secondes et ce, en dépit des nombreuses perturbations susceptibles d'affecter la conduite d'un vol (réf.1).

Dans ce contexte, une attention toute particulière a été accordée à l'imprévisibilité du vent. Des erreurs de vitesse-sol d'une amplitude pouvant aller jusqu'à 30 noeuds on été introduites [provenant soit d'une estimation inexacte du vent, d'un affichage incorrect de la vitesse indiquée imputable soit à des erreurs humaines (au sol - de la part du contrôleur - ou en cabine), soit à des problèmes de transmission, voire à une combinaison des deux].

Les résultats enregistrés se situaient dans les limites de tolérance prévues pour le système de contrôle à savoir, aucun avis de correction lorsque l'erreur de prévision de l'heure d'arrivée est inférieure à 10 secondes.

En conséquence, nous avons considéré que le modèle utilisé dans le programme de prévision de trajectoire et de régulation (CINTIA) fonctionnait de manière satisfaisante en conditions atmosphériques dynamiques, quelle que soit la phase de vol. Néanmoins, la question que nous a posée un commandant de bord chevronné, possédant une longue expérience de l'exploitation des aéronefs et de la modélisation de leurs mouvements (réf.2) nous a amenés à remettre en question notre appréciation du programme : "Avez-vous vraiment testé 'votre système' par vents forts? Dans le cas d'une trajectoire d'approche en U, par exemple, un aéronef évoluant par vent arrière de 50 noeuds affronterait un vent debout de 50 noeuds sur le radiophare d'alignement, soit une variation du vent de 100 noeuds au cours d'un seul virage, pendant la phase finale - et la plus critique - du vol".

En d'autres termes, si l'élément "régulation" du CINTIA est parfaitement en mesure d'absorber les perturbations résultant d'erreurs notables au niveau de la vitesse-sol, l'indice du vent dans le module de prévision de trajectoire pourrait n'avoir pas été suffisamment prise en compte.

Dans le but de confirmer - ou d'infirmer - notre appréciation globale du programme, nous avons décidé de procéder à une série d'expériences dans des conditions - élément humain compris - aussi proches que possible de la réalité.

Ref. 1 : "Contrôle du trafic dans les TMA modernes : Techniques de la prochaine génération"
par A. Benoît, S. Swierstra et R. De Wispelaere
AGARD 42nd GCP Symposium, Bruxelles, 10-13 juin 1986, AGARD CP-410, décembre 1986.
EUROCONTROL Doc. 862016-F juin 1986.

Ref. 2 : Observations critiques du Commandant Y. Delnatte,
SABENA Belgian World Airlines.

Les essais ont eu lieu le 2 juillet 1987 au Centre de formation des équipages de la British Airways (BA Flight Crew Training Centre) à Hounslow, près de Londres. Nous avons eu recours en parallèle aux simulateurs de vol du B-737 et du B-757, desservis par deux commandants de bord chevronnés de la British Airways. Le rôle de contrôleur de la circulation aérienne était assuré par René De Wispelaere, expert ATS de la Régie des Voies aériennes (Belgique), compétent en contrôle en route et en contrôle d'approche et actuellement chef du Service de contrôle d'approche-tour et d'aérodrome/tour à l'aéroport de Bruxelles-National.

Le présent document se borne à décrire la configuration et le scénario retenus pour cette expérimentation, et à formuler les conclusions essentielles qui s'en dégagent. Quant à la description détaillée des essais et des résultats obtenus, elle fait l'objet du document visé en réf.3.

2. NOTIONS FONDAMENTALES

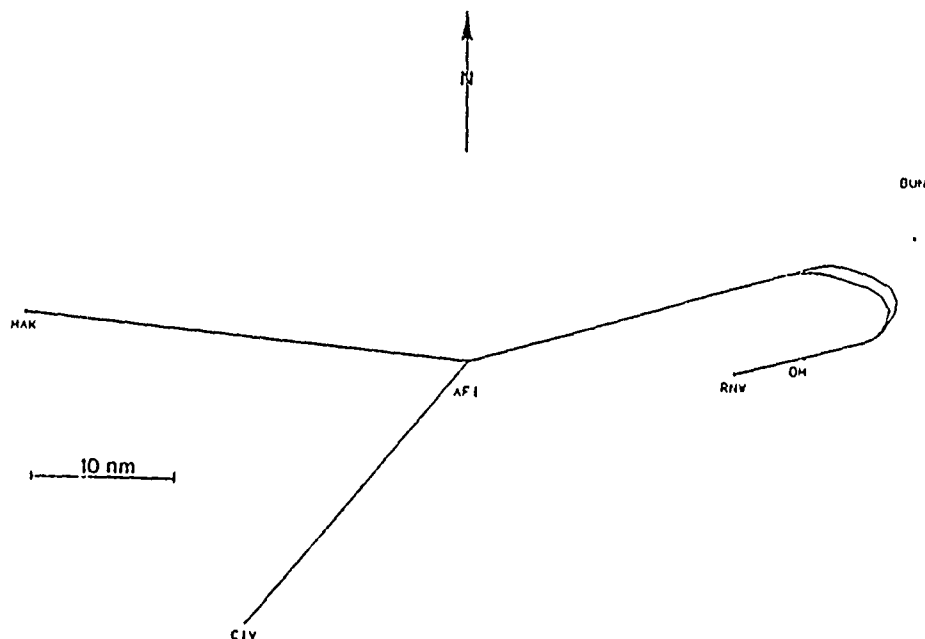
La trajectoire d'un aéronef opérant par vent d'une certaine force est calculée à partir de l'intégration de la somme vectorielle instantanée

$$V_e = V + W$$

où V et V_e correspondent aux vecteurs de vitesse de l'aéronef par rapport à l'atmosphère et à la terre respectivement et où W correspond à la vitesse de la masse d'air locale par rapport à la terre (vecteur "vent").

Si l'on considère que le vent est constant autour du fuselage, toutes les variations - dérivées de temps ou gradients d'espace - étant minimes par rapport à l'échelle de grandeur du déplacement de l'aéronef, la méthode utilisée pour déterminer la trajectoire dans l'air non perturbé est directement applicable moyennant quelques modifications mineures affectant en particulier la vitesse indiquée par rapport au profil d'altitude à proximité du sol. De fait, dans l'environnement qui nous intéresse, l'influence du vent sur la conduite de vol se fait principalement sentir au décollage, pendant l'approche et à l'atterrissage.

Dans le cadre d'un système asservi à partir du sol conçu pour guider les aéronefs avec précision jusqu'au seuil de piste, l'influence du vent peut s'avérer cruciale en ce sens qu'elle entraîne des modifications au niveau des messages de contrôle pendant la phase terminale du vol, en particulier lors d'approches en U ou en S. D'où la nécessité d'évaluer les algorithmes du modèle de calcul, de prévision de trajectoire et de régulation des aéronefs utilisés par le CINTIA (réf.1) dans les conditions de grand vent.



CONFIGURATION DE LA ZONE D'ESSAI EN BELGIQUE

Approches en U vers la piste 25L

Figure 1

3. ENVIRONNEMENT EXPERIMENTAL

Les installations utilisées aux fins d'évaluation du système de guidage et de régulation permettent de procéder à des essais dans des conditions très proches de la réalité tant au niveau des conditions atmosphériques que de l'élément humain.

En l'occurrence, il s'agit de deux simulateurs de vol grandeur nature (Boeing B-737 et B-757) desservis simultanément par des pilotes de la British Airways.

L'unité de contrôle au sol (ROSAS/CINTIA) reçoit la position (données radar) des deux aéronefs (réf.1). Il génère et affiche les messages de guidage qui sont ensuite transmis par un contrôleur de la circulation aérienne à l'aéronef intéressé, via le réseau radiotéléphonique normal (réf.4).

Les installations expérimentales utilisées permettent de recréer des conditions de vol extrêmement proches de la réalité à savoir :

- . comportement de l'aéronef - grâce à l'utilisation de deux simulateurs de vol grandeur nature
- . interfaces pilote/aéronef
- . interface pilote/contrôleur ATC
- . interface contrôleur ATC/ordinateur
- . conditions atmosphériques, y compris les dépôts dûs au vent et les effets de turbulence.

Une information plus complète sur les installations expérimentales utilisées sera publiée sous forme d'un rapport séparé consacré à l'introduction de certaines fonctions de régulation des trajectoires d'aéronefs dans les simulations portant sur la gestion du trafic aérien.

4. SCENARIO DE TRAFIC

Les vols ont eu lieu en Belgique dans la zone décrite à la figure 1. Il s'agissait d'arrivées à Bruxelles via Mackel (MAK) et Chièvres (CIV). A la verticale des points initiaux, les aéronefs se trouvaient en vol horizontal à une altitude de 10.000 pieds. Passés ces points, ils mettaient le cap sur Affligem (AFI) et se conformaient à la procédure locale d'approche via Bruno (BUN) pour atterrir sur la piste 25 L.

Deux exercices ont été organisés consistant chacun en deux vols effectués en même temps, respectivement sur les simulateurs de vol B-737 et B-757. Le premier exercice a été réalisé en atmosphère calme, le second avec un vent d'ouest (260°) de 50 noeuds. Pour simplifier l'analyse des résultats, le vecteur "vent" a été maintenu constant avec l'altitude. Les heures d'arrivée à Mackel et Chièvres ont été choisies de telle sorte que, sauf intervention du contrôleur, les aéronefs devaient inévitablement se trouver en situation de conflit au-dessus d'Affligem. Le Tableau 1 ci-après décrit les conditions générales d'exploitation.

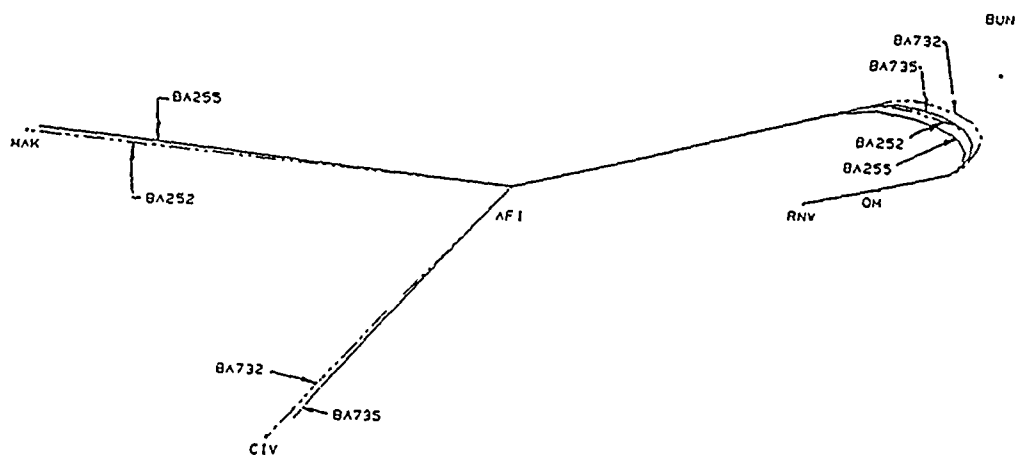
ATMOSPHERE	FLIGHT	AIRCRAFT	PLANNED ROUTE/APPROACH/LANDING
no	BA732	B737	CIV - AFI → BUN - ILS - RW25L
wind	BA252	B757	MAK - AFI → BUN - ILS - RW25L
wind	BA735	B737	CIV - AFI → BUN - ILS - RW25L
50kt/260°	BA255	B757	MAK - AFI → BUN - ILS - RW25L

VOLS A DESTINATION DE BRUXELLES-NATIONAL

Conditions générales d'exploitation

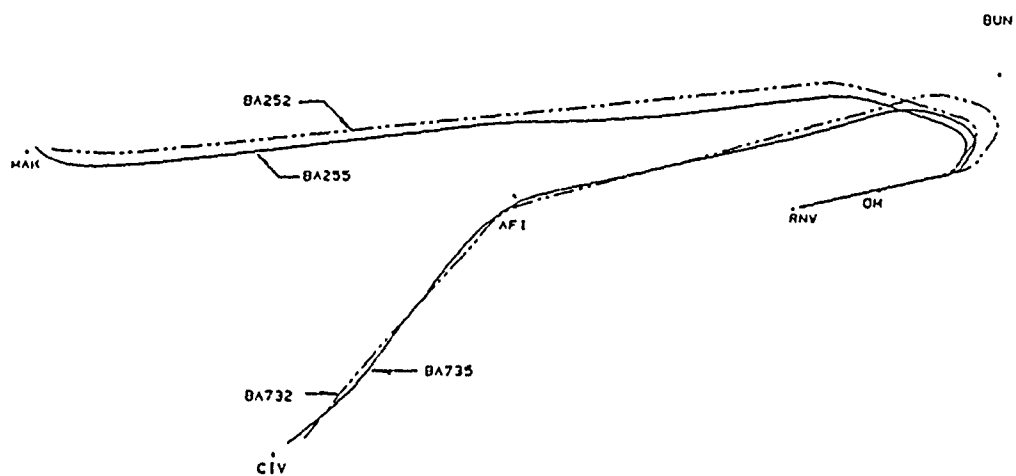
Tableau 1

Ref. 3 : "The Air Traffic Controller facing Automation : Conflict or Co-operation"
 par A. Benoît, S. Swierstra et R. De Wispelaere
 The Royal Institute of Navigation, NAV 87, London, U.K.,
 28,30 September - 1 October 1987.
 Also EUROCONTROL Doc. 872008R, July 1987.



PROJECTION HORIZONTALE DES VOLS PREVUS
Prévisions initiales au point d'entrée dans la région de contrôle

Figure 2.a



PROJECTION HORIZONTALE DES VOLS TELS QU'EFFECTIVEMENT ENREGISTRES
Maintien de l'heure d'arrivée par rapport aux prévisions initiales

Figure 2.b

5. CONTROLE DES VOLS

Lors de leur arrivée au point initial, Chièvres ou Mackel, les aéronefs se virent proposer un instant d'atterrissage calculée sur la base des éléments suivants :

- . itinéraire nominal
- . performances du type d'aéronef
- . procédures de vol préconisées par l'exploitant
- . restrictions ATC d'application générale
- . normes d'espacement requises au passage du radiophare d'alignement de piste
- . conditions météorologiques du moment.

Dans tous les cas, la durée des vols était de l'ordre de 15 à 20 minutes, ce qui correspond à un tronçon de route de 60 à 80 nm.

Une fois l'heure d'atterrissage attribuée, la régulation des vols a été exécutée en application des techniques ZOC/CINTIA, les variables principales étant le point d'amorce des virages, tant pour le parcours de base que pour l'interception du faisceau ILS, et, dans une moindre mesure, la vitesse à 2000 pieds et en-dessous.

Il a été décidé, pour cette série d'essais, de ne pas faire usage de la fonction de régulation de vitesse pendant les phases en route. Les phases initiales des vols - de Mackel ou de Chièvres jusqu'à l'altitude de 2000 pieds - se sont par conséquent déroulées à la vitesse indiquée de 250 noeuds.

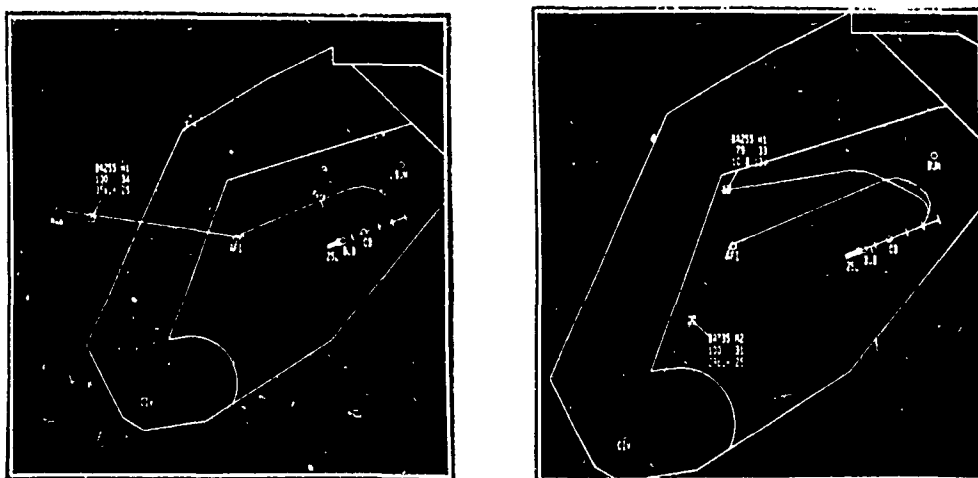
Outre les perturbations usuelles affectant la conduite d'un vol, le scénario comportait un certain nombre de perturbations de nature proprement ATC, notamment une série d'actions de la part du contrôleur aux fins de résolution de conflits. Ces mesures ont eu des répercussions sur le tracé des vols tant dans le plan vertical qu'horizontal.

La figure 2 permet une comparaison des projections horizontales des vols. La figure 2.a montre les projections au sol des trajectoires calculées initialement. Le B-757 assurant les vols BA252 et BA255 passe par Mackel, le B-737 des vols BA732 et BA735 passent par Chièvres. La figure 2.b donne la projection des vols tels qu'ils ont effectivement été enregistrés. On peut constater que le contrôleur a aiguillé les vols BA252 et BA255 directement sur Bruno afin d'éviter une situation de conflit aux alentours d'Affligem. Dans tous les cas, l'objectif demeurait néanmoins de respecter l'heure d'arrivée initialement prévue au seuil de la piste. Les figures 3 et 4 font clairement apparaître la contrainte de vitesse imposée pendant les essais, à savoir, la mise en oeuvre de la fonction de régulation de vitesse à partir de 2000 pieds seulement en descente.

Vu que l'ordinateur ATC situé au sol possède en mémoire les procédures de vol préconisées par l'exploitant ou le constructeur pour chaque type d'aéronef, assorties de tous les paramètres de vitesse pour la descente, l'approche et l'atterrissage, la vitesse-sol résultante a pu être facilement calculée : en l'occurrence, on a supposé que l'ordinateur ATC disposait d'une image correcte des conditions atmosphériques, l'incidence des données de vent inexactes ayant fait l'objet d'une étude antérieure (cf réf.1 par exemple). Les diagrammes des figures 5.a à 5.d montrent l'évolution dans le temps de la vitesse-sol effectivement enregistrée par rapport à la vitesse-sol calculée initialement, chaque diagramme présentant un type de comparaison bien distinct.

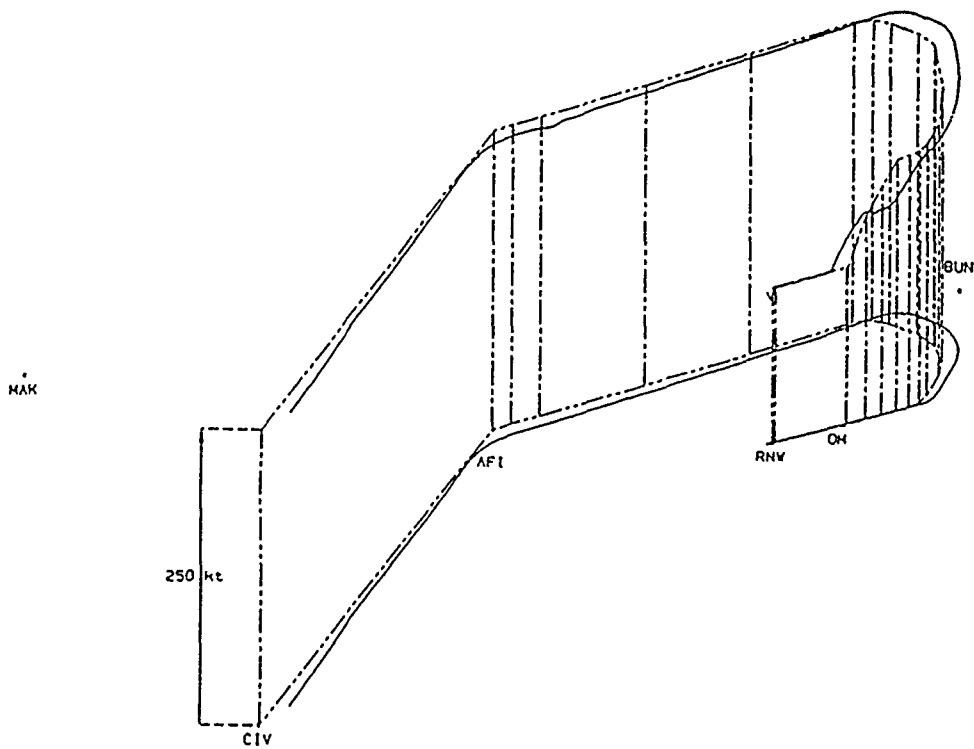
La présente étude est complétée par une vue perspective des trajectoires suivies (figures 6 et 7). Ces diagrammes révèlent l'étroite collaboration entre le contrôleur de la circulation aérienne, qui est intervenu de manière à prévenir des conflits aux alentours d'Affligem, et l'ordinateur, qui a permis de respecter l'heure d'arrivée sur la piste en affichant des messages de guidage ad hoc.

Les messages de guidage étaient intégrés aux étiquettes radar, comme il est expliqué dans les documents cités aux réfs. 1 et 4. Les photographies 1.a et 1.b montrent l'écran radar tel qu'il apparaît au contrôleur.



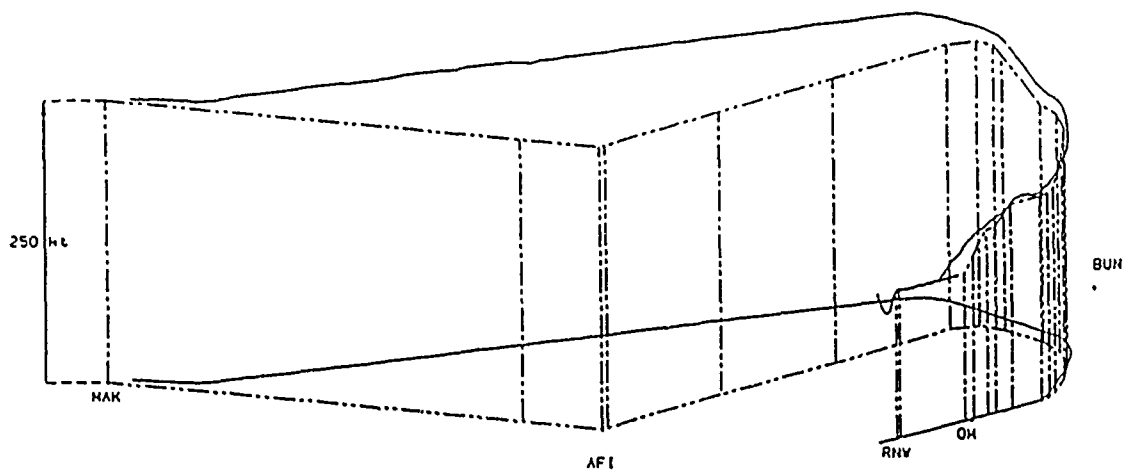
MESSAGE DE GUIDAGE A L'INTENTION DU CONTROLEUR

— Trajectoire de vol réelle
 --- Trajectoire initialement prévue



(a) vol BA732 effectué sur B737

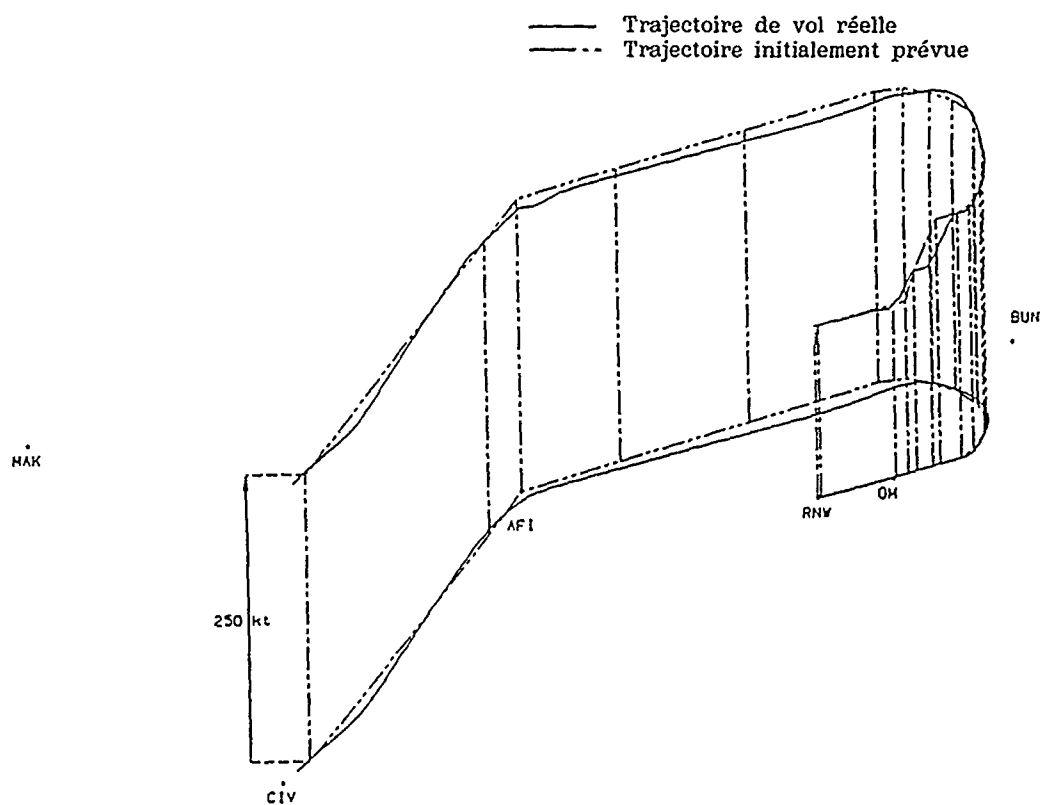
— Trajectoire de vol réelle
 --- Trajectoire initialement prévue



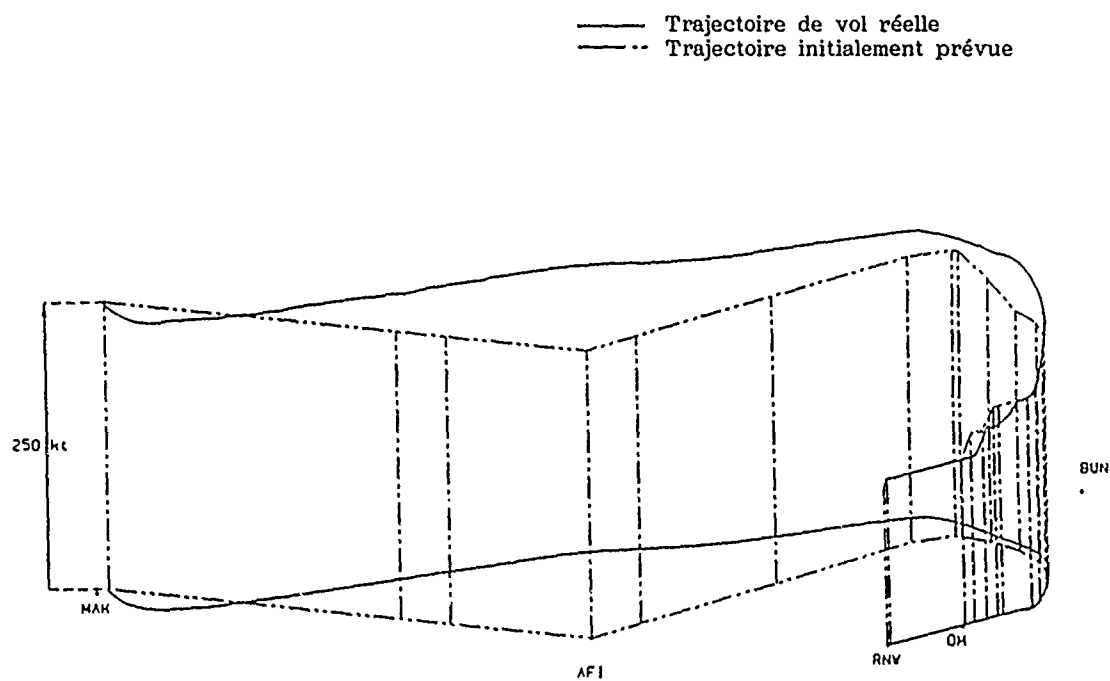
(b) vol BA252 effectué sur B757

V.C. PREVUE ET V.C. RELEVÉE DURANT LE VOL
 Vols effectués en atmosphère calme
 (a) vol BA732 (b) vol BA252

Figures 3



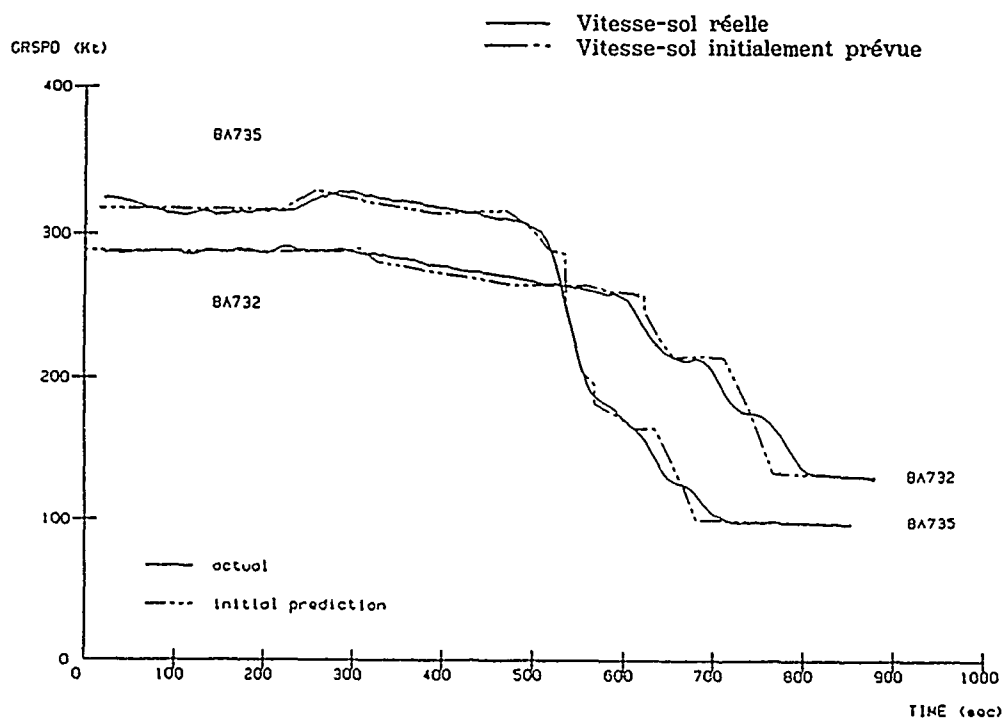
(a) vol BA735 effectué sur B737



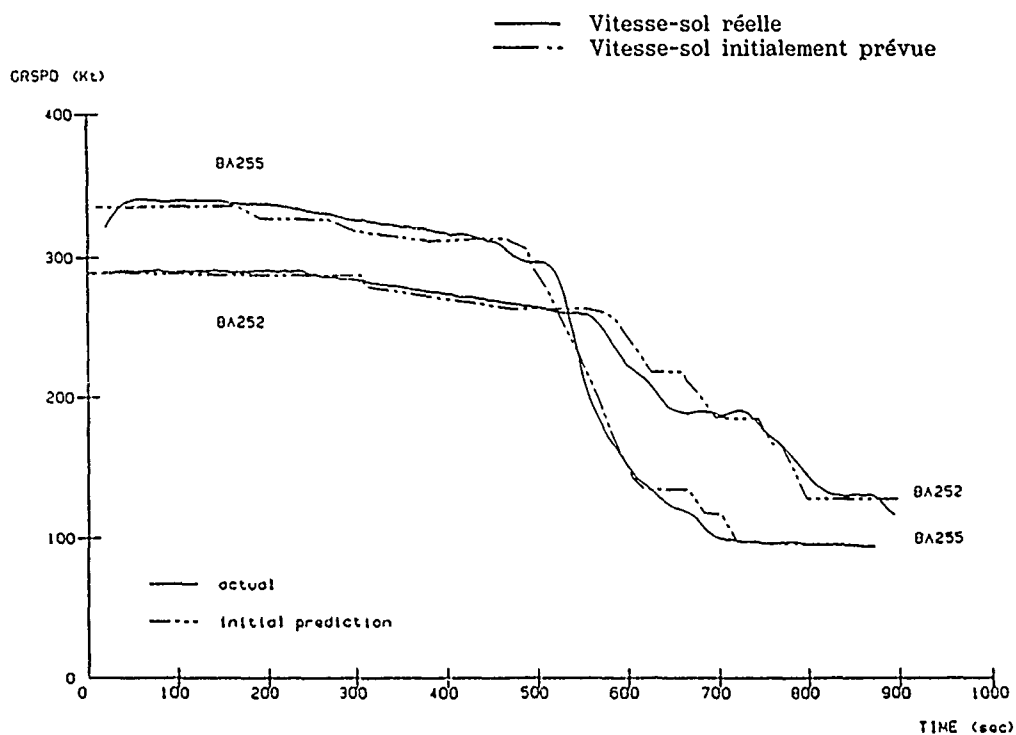
(b) vol BA255 effectué sur B757

V.C. PREVUE ET V.C. RELEVÉE DURANT LE VOL
Vols effectués par vent fort
(a) vol BA735 (b) vol BA255

Figures 4



(a) vols effectués sur B737

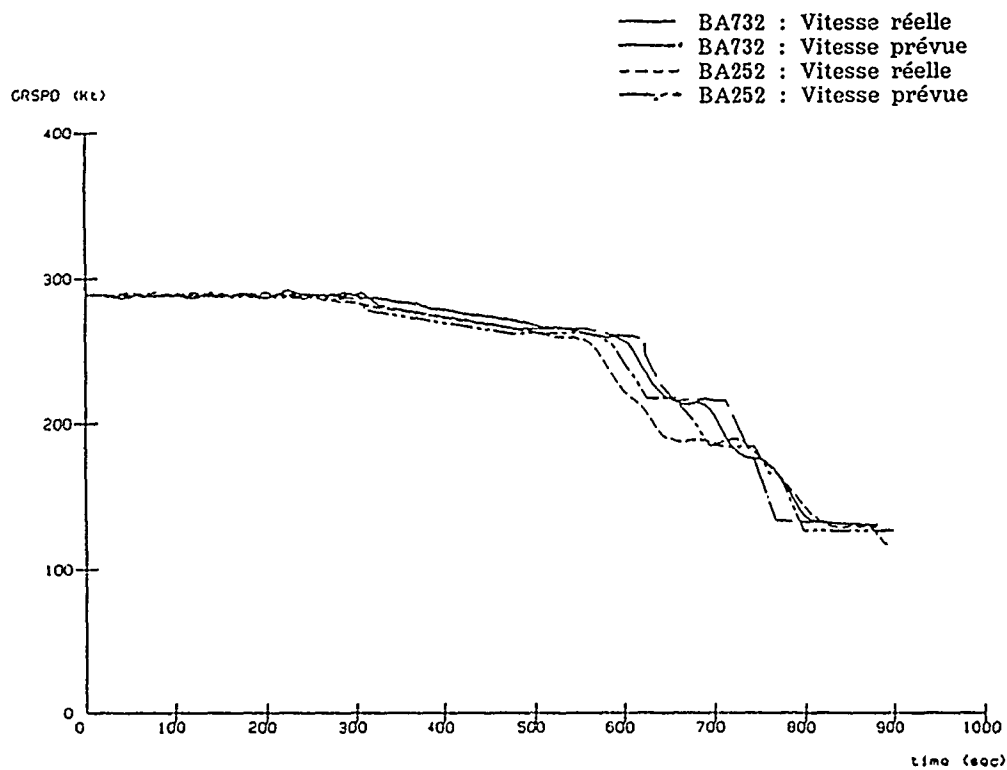


(b) vols effectués sur B757

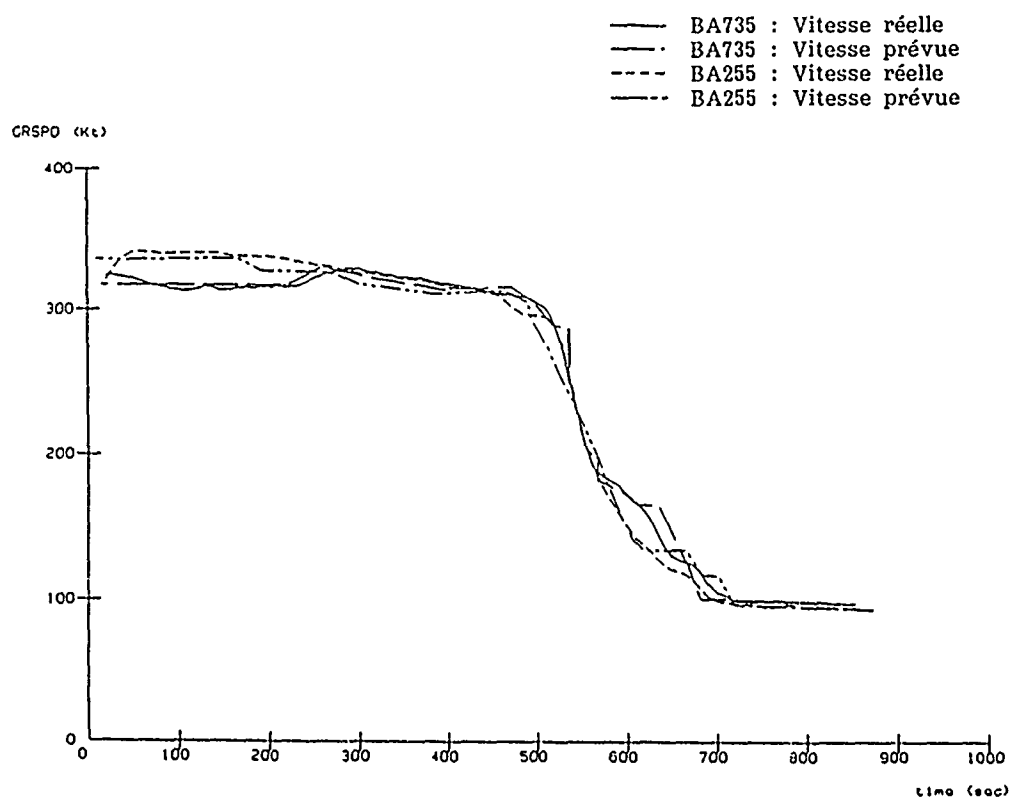
Prévisions initiales et vitesses effectivement relevées
Vols en atmosphère calme et vols effectués par vent fort

Figure 5

(a) et (b)



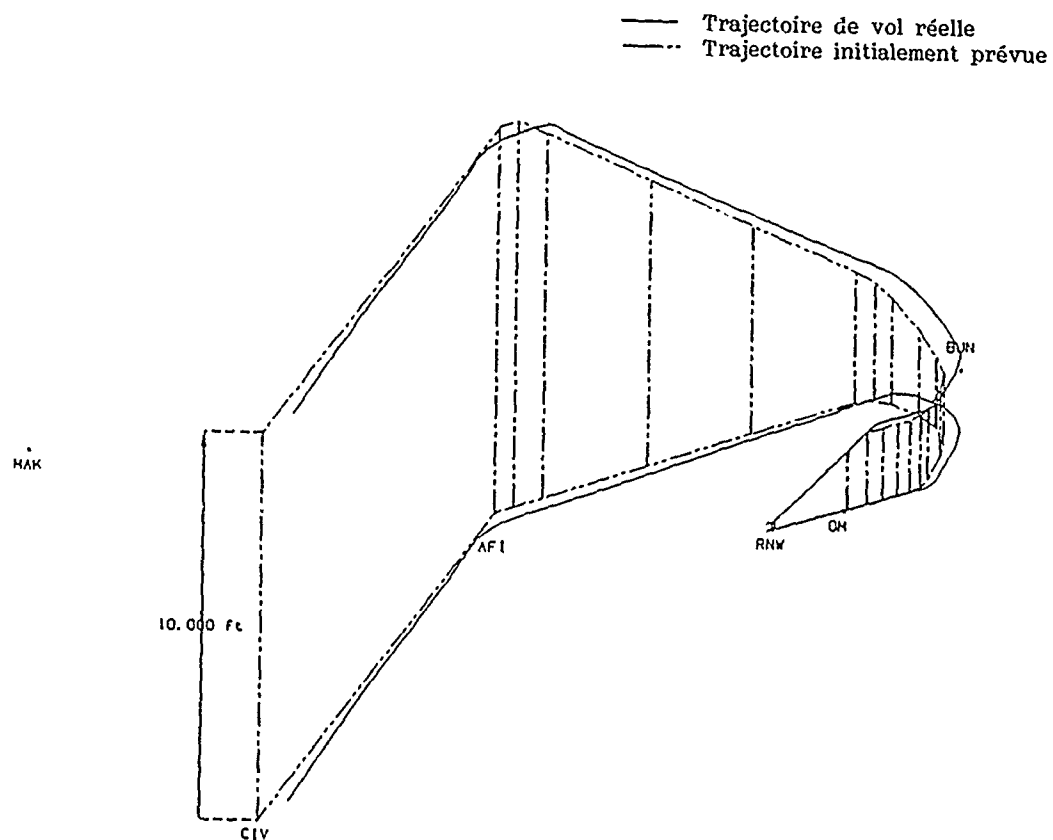
(c) vols effectués en air calme

(d) vols effectués en air perturbé
(vent : 50 noeuds / 260°)

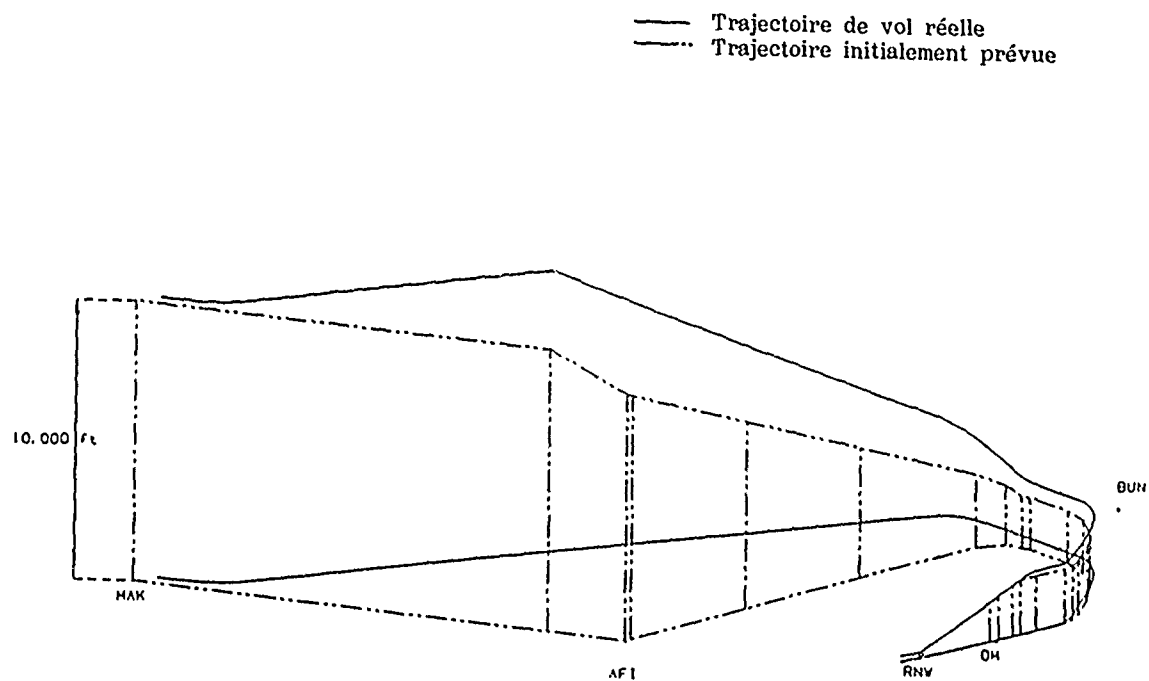
Prévisions initiales et vitesses-sol effectivement relevées
Vols en atmosphère calme et vols effectués par vent fort

Figure 5

(c) et (d)

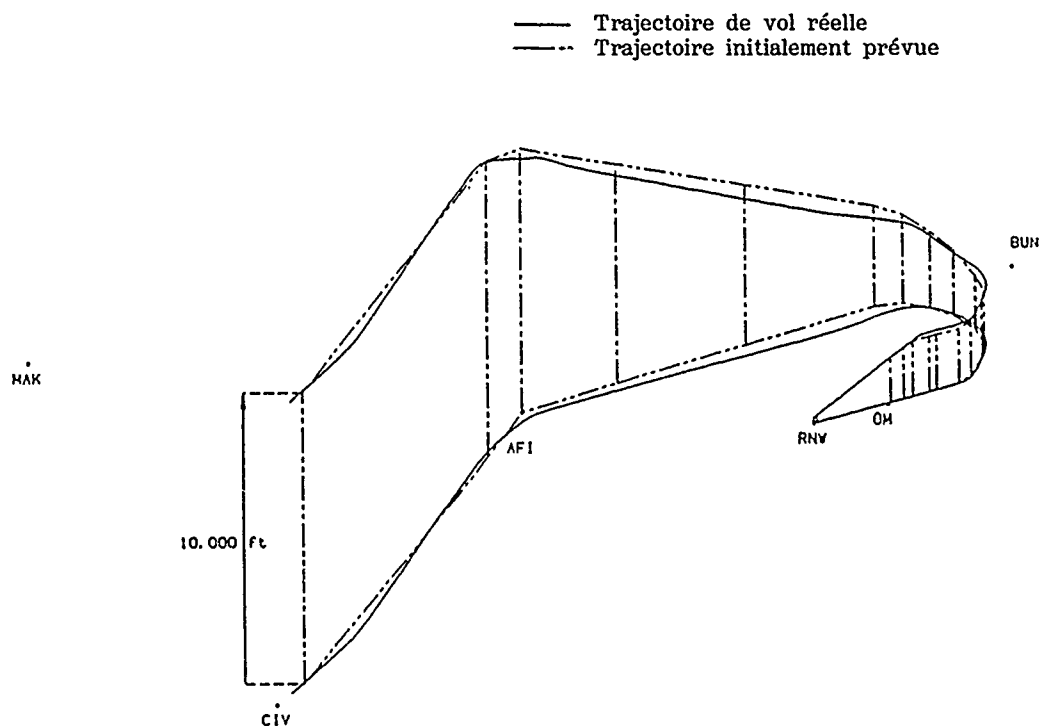


(a) vol BA732 effectué sur B737

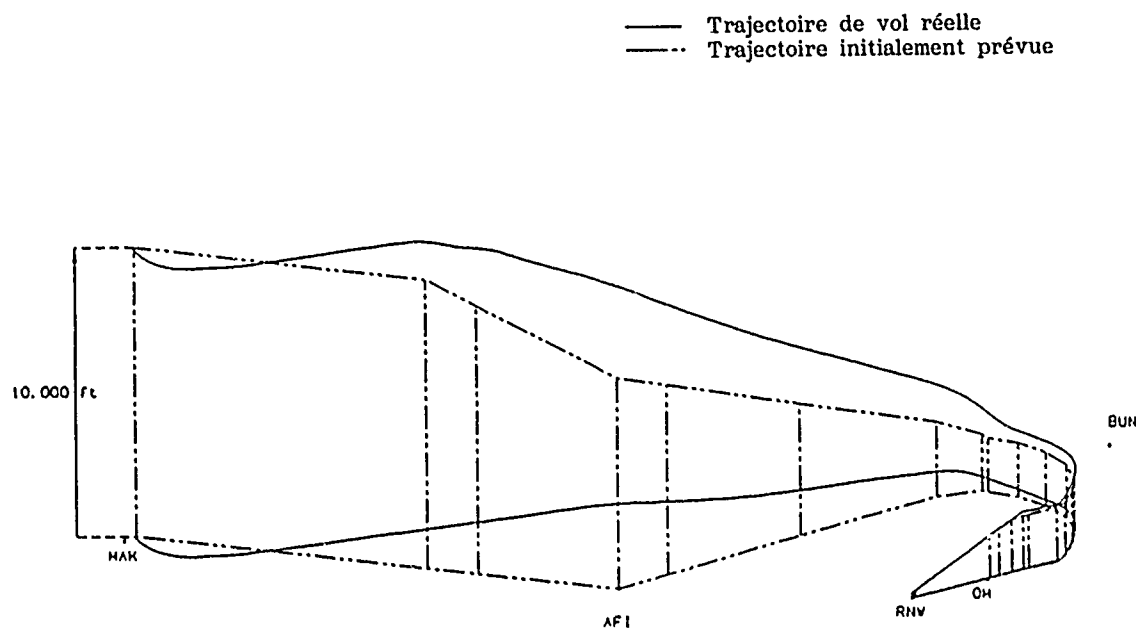


(b) vol BA252 effectué sur B757

VUE EN PERSPECTIVE DES TRAJECTOIRES DE VOL
 Vols effectués en atmosphère calme
 (a) vol BA732 (b) vol BA252
 Figures 6



(a) vol BA735 effectué sur B737



(b) vol BA255 effectué sur B757

VUE EN PERSPECTIVE DES TRAJECTOIRES DE VOL
Vols effectués par vent fort
(a) vol BA735 (b) vol BA255

Figures 7

CONDITIONS ATMOSPHERIQUES : Vent nul			
Vol	:	BA-732	BA-252
Type d'aéronef	:	B-737	B-757
Durée du vol (sec.)			
prévue	:	881	889
réelle	:	884	880
Erreur heure d'arrivée (sec)	:	3 (R)	9 (A)
Erreur à la radioborne extérieure (sec)	:	6 (R)	5 (A)
CONDITIONS ATMOSPHERIQUES : Vent 50 noeuds / 260°			
Vol	:	BA-735	BA-255
Type d'aéronef	:	B-737	B-757
Durée du vol (sec)			
prévue	:	853	873
réelle	:	857	874
Erreur heure d'arrivée (sec)	:	4 (R)	1 (A)
Erreur à la radioborne extérieure (sec)	:	2 (R)	1 (A)

A : en avance

R : en retard

Degré de précision au seuil de piste et à l'atterrissage

CONTROLE DE L'HEURE D'ARRIVEE

TABLEAU 2

6. CONCLUSIONS

Par vent fort, la vitesse-sol peut varier considérablement en virage ; c'est notamment le cas lors d'un atterrissage effectué après un virage à 180° précédant l'interception du faisceau ILS. Ces conditions jouent un rôle crucial au niveau de l'exploitation maximale de la piste, rendant l'appréciation humaine du mouvement de l'aéronef extrêmement difficile.

Le présent document constitue un récapitulatif des essais effectués afin de savoir si un programme de guidage asservi à partir du sol et générant des messages intégrés à l'étiquette radar pouvait effectivement aider les contrôleurs de la circulation aérienne à maintenir la séquence prévue des heures d'atterrissage avec une précision de l'ordre de moins de 10 secondes pour chaque arrivée.

Pour faire, quatre vols à l'arrivée devant atterrir après une approche en U ont été réalisés en série, deux par vent nul et deux par vent debout de 50 noeuds au radiophare d'alignement de piste, soit une variation du vent de 100 noeuds pendant la phase finale - et la plus critique - du vol.

Les vols, effectués au Centre de formation des équipages de la British Airways à Londres, ont été réalisés à l'aide des simulateurs de vol du B-737 et du B-757, utilisés en parallèle et desservis par des pilotes de ligne chevronnés. Les fonctions ATC étaient, quant à elles, assurées par un expert ATS.

Le rôle du contrôleur de la circulation aérienne consistait principalement à résoudre les conflits au-dessus du point de convergence d'Affligem en modifiant la trajectoire standard des vols à l'arrivée, tant dans le plan vertical qu'horizontal, et en mettant en oeuvre les messages de guidage générés par l'ordinateur qui apparaissaient sur les étiquettes radar.

Deux séries de vols ont été effectuées, l'une en atmosphère calme, l'autre par vent de 50 kt. Dans chaque cas, la trajectoire des vols avait été calculée de manière à créer une situation de conflit au-dessus du point de passage commun, Affligem. La résolution des conflits était laissée à l'initiative du contrôleur, tandis que l'ordinateur générait automatiquement les messages permettant de respecter l'heure d'atterrissage à dix secondes près.

La conduite des aéronefs était laissée à la discrétion des pilotes sans aucune exigence de notre part concernant le recours au pilote automatique ou l'exploitation de l'ordinateur de gestion de vol. Aucun des deux aéronefs n'était équipé pour la navigation quadridimensionnelle et le contrôleur ne transmettait pas au pilote l'heure d'arrivée prévue au point d'entrée (Mackel ou Chièvres, selon le cas).

Les résultats des essais sont rassemblés dans le Tableau 2. Il en ressort que tous les vols sont arrivés en respectant la fourchette de 10 secondes imposée à l'atterrissage (et à la radioborne extérieure), quelles que soient les conditions atmosphériques - air calme ou perturbé. Les erreurs enregistrées pour le B-737 et le B-757 étaient respectivement de 3 et 9 secondes en air calme et de 4 et 1 secondes en air perturbé (vent debout de 50 noeuds à l'atterrissage).

En conclusion, les auteurs considèrent qu'un appui informatique effectif, tel que celui dérivé du CINTIA (ref.1) utilisé pour cette série d'essais, permet une régulation des trajectoires de vol de tous les types d'aéronefs avec une précision de l'ordre de quelques secondes même dans des conditions de vent extrêmes (comme par exemple une variation d'une amplitude de 100 noeuds pendant le virage final d'une approche en U) sans qu'il soit nécessaire de prévoir des systèmes spécifiques de guidage et de navigation embarqués autres que l'équipement DME conventionnel. Autre avantage du système, le contrôleur ATC peut se concentrer sur la résolution des conflits sans devoir recourir à des allongements d'itinéraire ou à la mise en attente systématique - deux mesures onéreuses - tout en sachant qu'il peut compter pour le guidage des vols, sur un appui efficace du programme de régulation de trajectoires.

* Remerciements

Les auteurs remercient le Royal Institute of Navigation, Londres, Royaume Uni, pour publication d'un extrait de cette communication dans le Journal of Navigation, Cambridge University Press, Cambridge CB2 2BS, Royaume Uni.

A PILOTED SIMULATOR EVALUATION OF A GROUND-BASED 4D DESCENT ADVISOR ALGORITHM

Thomas J. Davis, Steven M. Green, and Heinz Erzberger

NASA Ames Research Center, Moffett Field, California 94035
USA

ABSTRACT

A ground-based, four-dimensional (4D) descent-advisor algorithm has been developed that combines detailed aerodynamic, propulsive, and atmospheric models with an efficient numerical integration scheme to generate fuel-efficient descent advisories. This paper investigates the ability of the algorithm to provide advisories for controlling arrival time of aircraft not equipped with on-board 4D guidance systems. A piloted simulation was conducted to determine the precision with which the algorithm predicts the trajectories of typical straight-in descents flown by airline pilots under different wind conditions. The effects of errors in the estimation of winds and initial aircraft weight were also evaluated. A description of the algorithm as well as the results of the piloted simulation are presented.

INTRODUCTION

In the past several years, the United States' air traffic control (ATC) system has experienced a continual increase in the congestion of high-density terminal areas resulting in an increase in delays, fuel wastage, and controller workload. Research is currently underway at NASA Ames Research Center to investigate the potential for a time-based, automated air traffic management system to improve the traffic flow into high-density terminal areas. The success of a time-based air traffic management system depends on its ability to handle aircraft equipped with various types of on-board equipment ranging from the basic to the advanced. For example, the near future will bring new commercial aircraft that will be equipped with flightpath management systems capable of generating and flying four-dimensional (4D) trajectories. Although these systems are the essential component of a time-based air traffic management system, there will be a long transition period when there will be a mix of equipped and unequipped aircraft. Thus, to achieve some of the benefits of a time-based air traffic management system during the transition period, a means of controlling the arrival times of unequipped aircraft as well as ATC procedures must also be developed. ATC procedures for controlling a mix of 4D-equipped and unequipped aircraft have already been investigated in a series of simulation studies.¹

This paper describes the development and performance of a ground-based 4D descent-advisor algorithm for controlling the arrival times of unequipped aircraft.* For the purposes of this paper, the arrival time is assumed to be controlled to a position (time-control point) located 30 n. mi. from touchdown at an altitude of 10,000 ft. This position represents an intermediate point between cruise and touchdown where commercial jet traffic transitions from enroute descent to terminal area operation. The desired arrival time accuracy for unequipped aircraft at this position is ± 20 sec.²

Previous work in on-board flightpath management algorithms has laid the foundation for ground-based algorithms. The problem of generating optimum trajectories that minimize direct operating cost for free terminal time was originally solved using an energy-state approximation.³ Sorenson and Waters extended that work to include control of time of arrival.⁴ However, practical use of these optimal flightpaths requires an on-board guidance system to display the guidance commands necessary for the pilot to fly the trajectory. Several flight test programs have addressed this problem and demonstrated the feasibility of controlling arrival time using on-board flightpath management systems.^{5,6} In principle, optimum trajectories could also be calculated on the ground and then uplinked, but data links for sending complex trajectories to aircraft are not currently available in civil aviation. The alternative pursued in this paper is to compromise somewhat on optimality by defining trajectories that can be specified succinctly and flown manually using conventional instrumentation. This compromise resulted in the choice of constant Mach/constant calibrated airspeed (CAS) and idle thrust altitude profiles for the descent trajectories. Such trajectories achieve fuel efficiencies that lie within about 1% of the optimum.

The algorithm described here resides in a microprocessor-based workstation that is interfaced with and receives aircraft surveillance data from the National Airspace System Host Computer. As an unequipped aircraft enters the terminal area, the algorithm calculates the trajectory to meet a specified arrival time. Commands to fly the trajectory are presented to the controller in the form of a descent advisory which the controller issues to the pilot as a clearance. The calculations take into account aircraft type and weight, current atmospheric conditions, and airline operating procedures. Unlike the simple "rules of thumb" pilots currently use in flying descents, the algorithm uses detailed aircraft performance and wind information to determine the position for initiating an idle descent.

A piloted simulation was conducted on a 727 simulator to determine the precision with which airline pilots could fly advisor-assisted descents. In addition, the effect of errors in the estimation of wind

*A modified version of this paper was presented at the August 1987 AIAA Guidance, Navigation, and Control Conference (AIAA Paper 87-2522).

and aircraft weight were also studied. This paper presents a description of the 4D descent advisor algorithm as well as the results of the simulation studies.

ALGORITHM DESCRIPTION

The descent advisor algorithm synthesizes a 4D trajectory in the following way. First, it calculates a nominal descent trajectory based upon the aircraft's current speed. After comparing the nominal arrival time to the desired time, the algorithm then iterates on descent speed until it computes a 4D trajectory which meets the desired time. For each iteration step, a corresponding trajectory is calculated by integrating the aircraft's equations of motion backwards from the time control point to the aircraft's initial position. Finally, the algorithm translates the desired trajectory into an advisory consisting of a top-of-descent point and a descent speed.

1. Descent Procedure

The trajectories generated by the descent advisor algorithm are based upon models of fuel conservative descent procedures currently used in airline operations. These procedures employ a near-idle thrust descent with a constant Mach/constant CAS profile. In general, a descent proceeds in the following way. First, the pilot reduces the throttle to idle and pitches down to maintain the cruise Mach number. When the aircraft has accelerated to the descent CAS, he then changes attitude to track CAS. As the aircraft nears 10,000 ft, the pilot reduces the descent rate to decelerate to 250 knots calibrated airspeed (KCAS), as per Federal Aviation Administration (FAA) regulations, and then continues on down to touchdown. However, some situations require thrust management procedures other than idle throttle. For example, inclement weather may require a minimum thrust level for deicing or turbulence penetration. In addition, some of the older pressurization systems require a minimum thrust level for smooth operation.

2. Equations of Motion

For each speed profile selected in the iteration process, the corresponding descent trajectory is computed by integrating a set of point mass equations of motion. In deriving these equations, no limiting assumptions were made with regard to pilot procedures, aircraft performance, or atmospheric parameters. As a result, the algorithm requires detailed information to model: thrust management; aircraft lift, drag, and thrust performance; and the altitude dependence of winds and temperature. Although this method is computationally intensive, it is highly flexible and is more accurate than schemes which depend on analytical approximations or precomputed trajectories. An additional benefit of this method is the potential to incorporate the preferred operational procedures of individual airlines into the trajectory calculations.

The trajectory equations are derived with respect to an earth-fixed reference frame. It is assumed that the aircraft is flying along a known ground track, thereby simplifying the trajectory to an altitude profile along this track. The descent advisor algorithm incorporates the general case of a curvilinear ground track in the trajectory synthesis process. However, for the purposes of this paper, the ground track is assumed to be a straight line. Defining the variables s and h as distance along the flightpath and altitude, respectively, the equations of motion to be integrated are

$$u \equiv \frac{ds}{dt} = V_T \cos(\gamma_a) + U_{ws} \quad (1)$$

$$w \equiv \frac{dh}{dt} = V_T \sin(\gamma_a) \quad (2)$$

where u and w are defined as the components of inertial velocity in the direction of s and h , respectively, V_T is the true airspeed, γ_a is the aerodynamic flightpath angle, and U_{ws} is the effective wind speed in the flightpath direction. With the wind known as a function of s and h , Eqs. (1) and (2) may be solved once expressions for V_T and γ_a as functions of time are found.

During the constant Mach/CAS segments of the descent, straightforward algebraic expressions for V_T and γ_a may be found. For the constant Mach case, the definition of Mach leads directly to

$$V_T = Ma(h) \quad (3)$$

where a is the speed of sound as a function of altitude and M is Mach number. Making use of the small angle approximation, the corresponding expression for γ_a is

$$\gamma_{aM} = \left(\frac{T - D}{m} \right) \left[V_T \frac{da}{dh} M + g + \frac{dU_{ws}}{dh} V_T \right]^{-1} \quad (4)$$

where T is thrust, D is drag, and g is the acceleration of gravity. For the case of constant CAS, a lengthy expression for V_T can be expressed in the form

$$V_T = V_T(V_{CAS}, h) \quad (5)$$

The corresponding expression for γ_a , analogous to Eq. (4), is

$$\gamma_{aCAS} = \left(\frac{T - D}{m} \right) \left[V_T \frac{dV_T}{dh} + g - \frac{dU_{ws}}{dh} V_T \right]^{-1} \quad (6)$$

For the case of neither Mach nor CAS constant (i.e., acceleration at the top or bottom of descent), V_T must be found by integrating the expression for its time derivative

$$\frac{dV_T}{dt} = \left(\frac{T - D}{m} \right) - g \sin(\gamma_a) - \left(\frac{dU_{ws}}{dt} \right) \cos(\gamma_a) \quad (7)$$

while taking into account

$$mV_T \left(\frac{d\gamma_a}{dt} \right) = L - mg \cos(\gamma_a) \approx 0 \quad (8)$$

where L is lift. Equations (7) and (8) are coupled by the dependence of drag on lift. The approximation of lift equal to weight in Eq. (8) is based on the assumption that the acceleration normal to the flightpath is negligible for normal descent operations.

The evaluation of the T , D , and U_{ws} terms in Eqs. (4), (6), and (7) will be discussed in the following section. The algorithm adopted to integrate Eqs. (1), (2), and (7) is a fourth-order Runge-Kutta scheme, the details of which are discussed in Ref. 2.

3. Descent Advisor Implementation

The descent advisor algorithm has been implemented on a SUN 3 workstation using FORTRAN 77. The information required for the trajectory computations is input both interactively and in file form. For each run, the user is prompted for the aircraft's initial cruise condition (position, altitude, velocity, and weight) and the desired time of arrival. Eventually, the descent advisor will access the cruise state information directly from radar and flight plan data stored in the ATC host computer. In the meantime however, the ability to interactively input the aircraft's initial condition is valuable for research purposes. The information stored in file form includes the aircraft performance models, the thrust management model, the atmospheric data, and the arrival route waypoint structure.

Presently, the descent advisor algorithm models only one aircraft type, a Boeing 727-200. However, the software is structured to accommodate any number of different aircraft types. The performance model, which includes detailed propulsive and aerodynamic information, is used to evaluate the thrust and drag terms just discussed. The propulsive model represents thrust as a function of engine pressure ratio (EPR), Mach, temperature, and pressure. The thrust management model, which will be discussed shortly, defines either the EPR or thrust value required during the descent for a particular thrust management procedure. The Mach number is determined by the speed profile along with temperature, and the temperature and pressure are determined from the atmospheric data. The aerodynamic model represents the drag coefficient as a function of lift coefficient, Mach number, and control surface deflection (speed brake, flaps, and gear). Here, the lift coefficient is determined by employing the approximation that lift is equal to weight. The control surface deflection schedule is based upon speed and position. However, for the purposes of this paper, the aircraft is assumed to be in a clean configuration.

With regard to the modeling of thrust management during a descent, three cases have been identified. The first case is that of a constant thrust setting. The second and third cases involve the variation of thrust to maintain a constant rate of descent and constant inertial flightpath angle, respectively. The actual implementation of the algorithm allows for the assignment of any one of these cases to each distinct segment in a descent (e.g., constant Mach, constant CAS, and so on) along with the corresponding descent rate or flightpath angle for the latter cases. Although a pilot would not actually fly a constant inertial flightpath angle, the combination of the three cases allows for the greatest flexibility in modeling automatic and manual descent procedures.

The atmospheric conditions are modeled in terms of altitude profiles of wind vectors and temperature data. This structure was adopted to take advantage of the Wind Profiler, developed by the Wave Propagation Lab (National Oceanographic and Atmospheric Administration), which reports wind vectors and temperature as a function of altitude on an hourly basis. The accuracy of this system's wind measurement is reported to be within two knots.⁷ Several profiler units have been installed in the Denver area for the purpose of evaluation. For this reason, the Denver Air Route Traffic Control Center is most likely to be the first site for an operational evaluation of the Descent Advisor.

Finally, the arrival route waypoint structure defines the desired aircraft ground track for each arrival route as a set of discrete positions defined in longitude and latitude. Any number of routes may be modeled at one time allowing the controller to select the desired route for each arrival aircraft.

For each aircraft handled, the descent advisor stores data detailing the synthesized 4D trajectory for later comparison with the aircraft's actual trajectory. This information is used to track time error

(defined as the difference between the actual and desired schedules) which may grow during the descent. An example of a synthesized trajectory is given in Ref. 2.

WEIGHT SENSITIVITY

Initially, there was concern about the effect of errors in the estimation of aircraft parameters, especially aircraft weight. Therefore, a study was conducted to determine the sensitivity of an advisor-assisted descent trajectory to an error in the estimation of weight. This section briefly details an analytic investigation of the sensitivity.

It is easily shown that, for a fixed descent speed profile, the time to descend is a function of γ_a . Therefore, the sensitivity, S , of a descent trajectory to a variation in aircraft weight, W , can be defined in the following way:

$$S \equiv \frac{d\gamma_a}{dW} \quad (9)$$

Neglecting the thrust (for an idle descent) in comparison to the drag, it follows from Eq. (6) that

$$\gamma_a \propto \left(\frac{-D}{m} \right) \quad (10)$$

Ignoring compressibility effects, the drag coefficient, C_D , is closely approximated by a second-order polynomial function of the lift coefficient, C_L

$$C_D = aC_L^2 + b \quad (11)$$

where a and b are constants. Equations (9), (10), and (11) may be combined to yield

$$S \propto \frac{d(-C_D/C_L)}{dC_L} = \frac{b}{C_L^2} - a \quad (12)$$

where it is assumed, as in Eq. (8), that lift is equal to weight.

Equation (12) indicates that the sensitivity of γ_a to variations in weight depends inversely on C_L^2 and is zero when the aircraft is operating at maximum L/D. For a given nominal aircraft weight, the sensitivity is a function of descent speed. What remains to be determined is the range of speeds for which a variation in γ_a , caused by a variation in weight, is negligible (i.e., less than 1%). For a 727 aircraft, nominally weighing 140,000 lb, this range was determined by fast-time simulation to be between 250 and 280 KCAS.

It is also of interest to determine the actual variation in time, and therefore γ_a , that is due to a variation in weight for the most sensitive case (i.e., fastest speed profile or smallest C_L). This case was also studied by simulation, the results of which are discussed in the simulation results section.

SIMULATION DESCRIPTION

The ground-based 4D descent advisor was evaluated in a piloted simulation, of a 727-200 aircraft, conducted at the Ames Research Center's Man Vehicle System Research Facility. The simulator, which is FAA certified phase II, has a six-degree-of-freedom motion system and a night-dusk computer-generated-imagery visual system.

A total of 12 pilots were used as test subjects, all of whom were current 727 captains from major U.S. airlines. Before each descent run, the pilot was briefed on current wind and weather conditions. Two wind conditions were tested: a direct tailwind of 70 knots at 35,000 ft linearly decreasing to 0 knots at sea level and a direct headwind of 70 knots at 35,000 ft linearly decreasing to 0 knots at sea level. These two relatively extreme wind conditions were chosen to expose pilots to a fairly difficult flying task, that of minimizing powered flight at lower altitudes, if performed without an advisory. The headwind case forced the trajectory algorithm to keep the aircraft at cruise altitude for a longer time than for a zero wind case, thus requiring a higher descent rate, while the tailwind case caused the aircraft to start down sooner. For each simulation run, the aircraft's initial conditions were: DME range to San Francisco International Airport of 150 n. mi., 35,000 ft altitude, a cruise Mach of 0.8, and heading set for a straight-in approach to runway 28R at San Francisco.

To compare the performance of the 4D descent advisor algorithm with a baseline of current descent procedures, the pilot was initially asked to fly a descent using his airline's standard operating procedure. It turned out that all of the pilots flew a Mach 0.8/280 KCAS descent speed profile. After the baseline descent was completed, the pilot was briefed on the procedures to be used in flying advisor-assisted descents. Following the briefing, the pilot flew several descents, with the aid of advisories,

at speeds spanning the envelope of the aircraft. The descent speeds flown included slow (230 KCAS), nominal (0.8/320), and fast (0.84/350) profiles.

The advisor-assisted descent procedures required that all decelerations be performed in level flight and that all accelerations be performed using cruise thrust (for the case of a descent Mach number greater than the cruise Mach number). In addition, a restriction was imposed on each pilot to limit his descent rate to 3,000 ft per minute (fpm). This was done to study the pilot's ability to follow such a trajectory restriction. The advisory for each descent, generated off-line by the computer algorithm just described, was issued only once at a position approximately 5 n. mi. prior to the top-of-descent. A typical advisory was as follows, "Begin descent procedure at 108 DME; fly a Mach 0.8/320 KCAS speed profile."

RESULTS

A total of 55 descents were flown, 43 of which were advisor assisted. Errors in arrival time, defined as the difference between the actual arrival time and the scheduled arrival time at the time control point (30 n. mi. from touchdown at 10,000 ft) were the major criteria used to evaluate the effectiveness of the 4D descent advisor. Aircraft trajectory data, including altitude, position, time, CAS, Mach number, vertical speed, EPR, and total thrust, were recorded for each descent. Finally, extensive discussions with the subject pilots were conducted in debriefing sessions following the simulation.

1. Arrival Time Accuracy

Figure 1 is a histogram of arrival time errors at the time control point for the 43 advisor-assisted descents flown under both wind conditions. This plot shows that the majority of aircraft arrived within ± 10 sec of their scheduled time. The one-sigma standard deviation was ± 13 sec around the mean value of +6.1 sec. This bias of 6.1 sec is considered small and does not degrade the effectiveness of the algorithm.

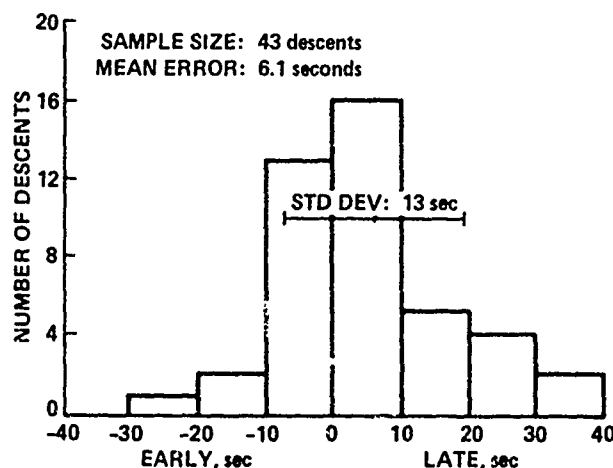


Fig. 1 Histogram of arrival time errors.

Table 1 lists the total variability in arrival time at the time control point, and Table 2 lists the one-sigma standard deviation in arrival time for all 55 descents (baseline and advisor assisted) for both wind conditions.

TABLE 1 TOTAL VARIABILITY OF ARRIVAL TIME IN SECONDS

	Baseline	Advisor assisted			
		Nominal	Slow	Fast	Fast-idle
Tailwind	195	42	12	21	
Headwind	88	24	13	55	22

Figures 2-6 are composite plots of altitude versus range for the baseline and advisor-assisted descents for the headwind case. These figures illustrate the trends which cause the time variability listed in Tables 1 and 2.

For the baseline descents, there were significant differences in arrival time at the time control point (88 and 195 sec for the headwind and tailwind conditions, respectively). The reason for this, a wide variation in the top-of-descent point, is illustrated in Fig. 2. Although each of the pilots used the glide ratio rule of thumb of 3 n. mi./1,000 ft, the correction they used for wind varied from pilot to

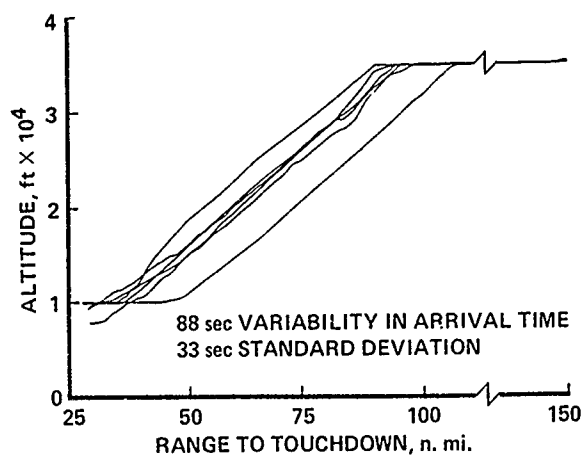


Fig. 2 Baseline descents.

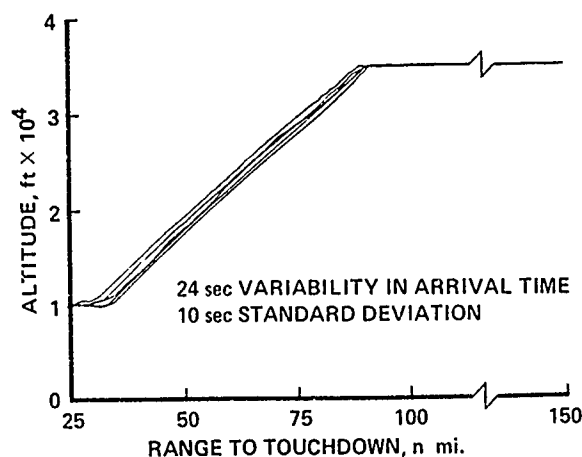


Fig. 3 Advisor assisted descents: nominal (0.80/320).

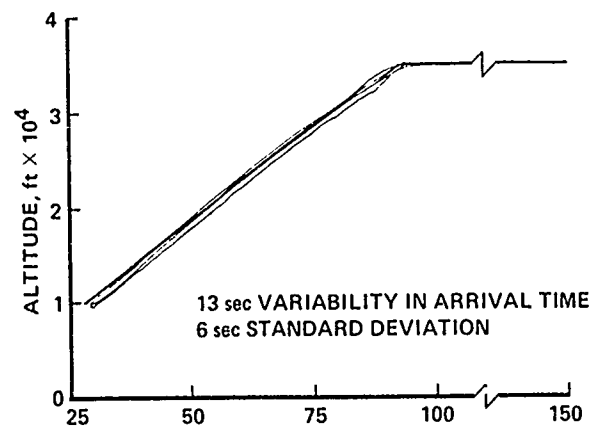


Fig. 4 Advisor assisted descents: slow (230).

pilot. The advisor-assisted descent using the nominal speed profile (0.8/320), the profile most similar to the baseline profile, resulted in a dramatic decrease in the arrival time variability. This is due to the consistent top-of-descent point used in the advisor assisted runs (Fig. 3). The slow profile (230 KCAS), which represents the low-speed boundary of the 727, yielded the lowest variability in arrival time. This profile (Fig. 4) was the simplest for the pilot to fly because he only tracked a single speed (CAS) throughout the entire descent; i.e., there was no constant Mach segment. Although there were good results for the fast (0.84/350) profile with the tailwind, the fast profile with the headwind presented problems for the pilots. The large variability for the headwind case (55 sec), which contrasts strongly with that for the tailwind case (21 sec), is due to the extremely difficult task of limiting the descent rate for this set of conditions. The maximum idle-thrust descent rate for the fast profile is approximately 6,000 fpm for the headwind case as opposed to 3,000 fpm for the tailwind case. The difficulty of

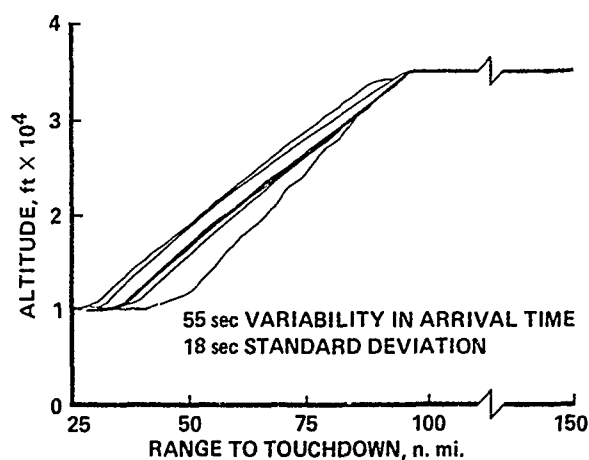


Fig. 5 Advisor assisted descents: fast (0.84/350).

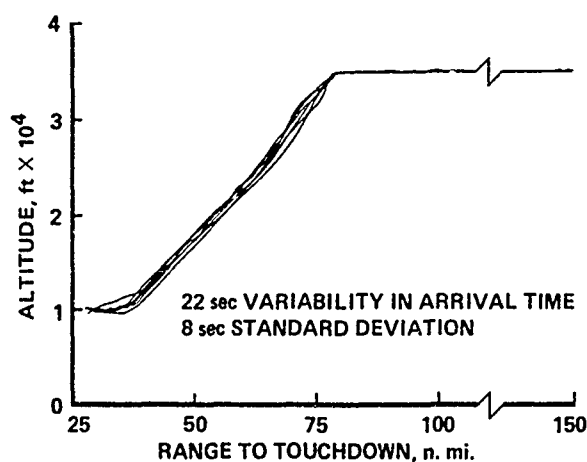


Fig. 6 Advisor assisted descents: fast-idle (0.84/350).

TABLE 2 ONE-SIGMA STANDARD DEVIATION OF ARRIVAL TIME IN SECONDS

	Baseline	Advisor assisted			
		Nominal	Slow	Fast	Fast-idle
Tailwind	±64	±16	±4	±10	
Headwind	±33	±10	±6	±18	±8

the descent rate limit task is due to two factors. First, the large difference between the idle thrust descent rate and the descent rate limit varies as a function of altitude. This forces the pilot to continually vary thrust to meet the limit. Second, there is a significant time lag in the vertical speed indicator and the thrust response of the aircraft is slow. As a result, there is a large variation in the altitude versus range profiles from pilot to pilot (Fig. 5). For the purposes of comparison, additional fast profile descents (with headwind) were flown without the descent rate limit (i.e., idle thrust). Figure 6 illustrates the relatively small variability in the altitude versus range trajectories for this case. These runs resulted in a 22-sec variability in arrival time which is very close to the result for the tailwind case.

The effect of the descent rate limit on time variability (as a function of speed profile) is best illustrated in Fig. 7. This figure plots the one-sigma standard deviation time versus range to touchdown for the advisor-assisted descents flown with the headwind condition. For the slow descent (230 KCAS), there is little variation in time over the trajectory because the aircraft never approaches the descent rate limit thus enabling the pilots to fly consistent trajectories. The same is partially true for the nominal profile (0.8/320) in that the idle-thrust rate of descent exceeds the limit only during the constant Mach segment of the descent. However, for the fast profile (0.84/350), the time variation is large because the idle thrust descent rate exceeds the 3,000-fpm limit over the entire trajectory.

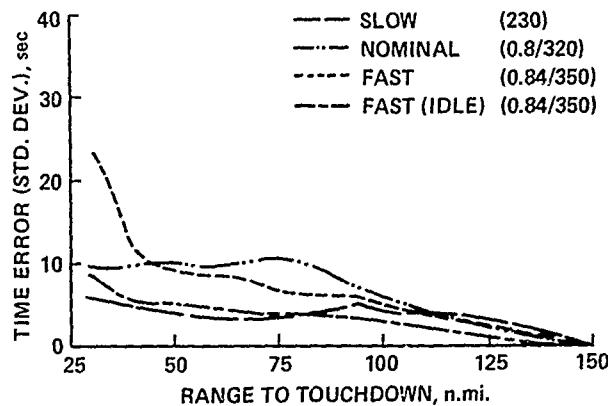


Fig. 7 Effect of descent rate limit on time variability.

A comparison of the plots for the nominal and fast profiles in Fig. 7 reveals an interesting phenomenon. Toward the end of the fast descent, within 45 n. mi. to touchdown, there is a noticeable increase in time variability. This is due entirely to the large variation in the flightpath angle, from one run to another, seen in Fig. 5. These variations in flightpath angle result in a wide range of positions at which the aircraft arrives at 10,000 ft (approximately 15 n. mi.). The large increase in time variability occurs inside 45 n. mi. because some aircraft are decelerating to 250 KCAS in level flight while others are still descending at 350 KCAS. Figure 7 also shows that when the descent rate limit is removed (fast-idle case), the time variability is dramatically improved. This improvement translates into a 56% reduction in the one-sigma standard deviation of arrival time. Therefore, to minimize errors in a descent advisory system, the procedures employed must avoid the necessity for large variations in thrust.

2. Effect of Wind Estimation Errors

Also studied was the effect of an error in the estimate of winds aloft on the time accuracy of an advisor-assisted descent. Five additional piloted descents were flown with descent advisories based upon an incorrect estimate of the wind. The initial conditions for this test were the same as just described. The descent advisory for each descent was Mach 0.8/320 KCAS with the top of descent based upon an estimated wind aloft of 70 knots at altitude linearly decreasing to 0 knots at sea level in the tailwind direction. However, the actual wind aloft programmed into the simulator was 90 knots at altitude linearly decreasing to 10 knots at sea level in the tailwind direction.

Figure 8 presents the time and altitude trajectories for the five piloted descents. The scheduled trajectory, synthesized by the descent advisor for the estimated wind condition, is superimposed on these figures. A 10- to 40-sec difference in descent duration exists between the piloted descents under the actual wind condition and the synthesized trajectory for the estimated wind condition. Although there were not enough runs performed for a reliable statistical analysis, two important trends may be observed. First, the variability in arrival time at 30 n. mi. for the piloted descents (30 sec) is within that found for the pilot performance studies just discussed. More importantly, the arrival time error (the difference between the actual and scheduled arrival times) exceeds the desired time accuracy of ± 20 sec. These results tend to indicate the need for a "mid-descent" correction procedure which would allow a controller to correct a descent trajectory for any significant errors that may develop. However, it is important to note that the error in wind estimate studied is large compared to the ± 2 -knot accuracy of the Wind Profiler.

3. Effect of Weight Estimation Errors

The descent advisor algorithm was used to simulate the 4D trajectories resulting from a variation in aircraft weight. The initial conditions were the same as for the piloted simulation just described, except that the wind was set to zero. The trajectories were simulated to the time control point, for a variety of descent speeds spanning the aircraft's speed envelope. The baseline run incorporated a descent profile (at idle thrust) which would deliver a 140,000-lb aircraft to the final position at 10,000-ft altitude and decelerated to 250 KCAS. The same descent profile was also simulated for aircraft weights 10,000 lb above and below the baseline weight. This difference in weight represents a 10% error in the estimation of the aircraft's actual useful load (fuel plus payload) for a typical medium range flight. A survey of airline pilots showed that their airlines' estimates of enroute weight are accurate to within at least 5%.

The results of the fast-time simulation confirmed the earlier analysis that the sensitivity of flightpath angle to variations in weight is highly dependent on descent speed. For the descent speeds between 250 and 280 KCAS, there was no appreciable difference in flightpath angle for the various weights tested. However, for greater speeds, there were distinct differences in flightpath angle for the various weights. Figure 9 illustrates the variation in the altitude-versus-range trajectory for the worst case (highest descent speed profile, Mach 0.84/350 KCAS). The lighter aircraft arrived 12 sec later than the baseline while the heavier aircraft arrived 9 sec early. Although the lighter aircraft was able to meet

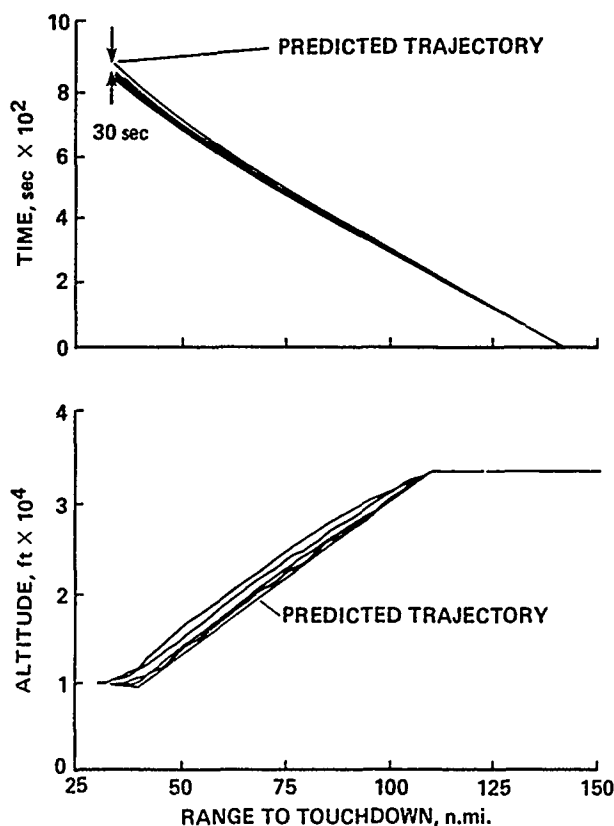


Fig. 8 Effect of errors in wind estimation.

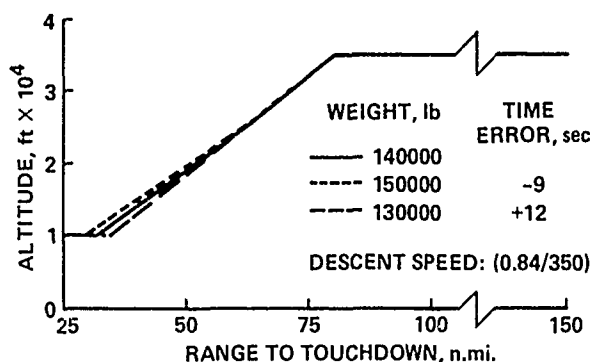


Fig. 9 Effect of errors in weight estimation.

the desired final condition of 250 KCAS at the time control point, the heavier aircraft was still decelerating through 280 KCAS at this point. This difference in final condition translates directly into an additional time error of 2 sec. It is interesting to note that nearly all of the time error, for both the lighter and heavier aircraft, occurs after the level-off at 10,000 ft. The difference in γ_a , between the baseline and off-weight cases, has little effect on the true airspeed profile for a given descent Mach/CAS. Once the aircraft reach the level-off altitude though, the variation in γ_a translates directly into a stretched or shortened level flight segment to the 30 n. mi. point.

4. Pilot Debriefing

Pilots were pleased that the procedures used in flying the descents were the same as they are currently using to fly unassisted descents. They felt that most line pilots would not resist following descent advisories issued by a controller if the advisories would lessen the chance of delays. All of the pilots were supportive of the descent advisor concept as a method for saving fuel and reducing delays.

CONCLUDING REMARKS

A ground-based 4D descent advisor algorithm has been developed and tested in a piloted simulation. The algorithm has significant potential for accurately controlling arrival times of aircraft not equipped with on-board 4D flightpath management systems. An accuracy at the time control point of ± 20 sec, which is necessary for a time-based ATC system to be effective, appears attainable with the descent advisor. It was determined that to minimize time error, the descent procedures employed must avoid the necessity for

large variations in thrust over the descent. It was also found that errors in the estimation of weight do not have a significant effect on the algorithm's performance. However, wind errors of 20 knots or more do have a significant effect and will require a mid-descent correction procedure if encountered. Subject pilots who participated in the simulation were able to fly the advisor-assisted descents without prior training and were enthusiastic about the potential use of the descent advisor. Current plans call for a more extensive evaluation of the algorithm to study its performance in handling descents with turns. In addition, a series of ATC simulations will be performed (in conjunction with piloted simulations) to evaluate the descent advisor's effectiveness as a controller tool. If these tests are successful, the FAA and NASA plan to conduct an operational evaluation of the descent advisor at an enroute traffic control center.

REFERENCES

1. Tobias, L., Erzberger, H., Lee, H. Q., and O'Brien, P. J., "Mixing Four-Dimensional Equipped and Unequipped Aircraft in the Terminal Area," J. Guidance, Control, and Dynamics, Vol. 8, May-June 1985, pp. 296-303.
2. Erzberger, H. and Tobias, L., "A Time-Based Concept for Terminal Area Traffic Management," AGARD 42nd Symp. Guidance and Control Panel on Efficient Conduct of Individual Flights and Air Traffic, Brussels, Belgium, June 1986.
3. Erzberger, H. and Lee, H., "Constrained Optimum Trajectories with Specified Range," J. Guidance and Control, Vol. 3, Jan.-Feb. 1980, pp. 78-85.
4. Sorensen, J. A. and Waters, M. H., "Airborne Method to Minimize Fuel with Fixed Time-of-Arrival Constraints," J. Guidance and Control, Vol. 4, May-June 1981, pp. 348-349.
5. Lee, H. Q., Neuman, F., and Hardy, G. H., "4D Area Navigation Systems Description and Flight Test Results," NASA TN D-7874, Aug. 1975.
6. Knox, C. E. and Cannon, D. G., "Development and Test Results of a Flight Management Algorithm for Fuel Conservative Descents in a Time Based Metered Traffic Environment, NASA TP 1717, Oct. 1980.
7. Hogg, D. C., Decker, D. M. T., Guiraud, F. O., Earnshaw, K. B., Merritt, D. A., Moran, K. P., Sweezy, W. B., Strauch, R. G., Westwater, E. R., and Little, C. G., "An Automatic Profile of the Temperature, Wind and Humidity in the Troposphere," J. Climate and Applied Meteor., May 1983, pp. 807-831.

THE AIR TRAFFIC CONTROLLER FACING AUTOMATION : CONFLICT OR CO-OPERATION (*)

by

André Benoît and Sip Swierstra

Engineering Directorate
European Organisation for the Safety of Air Navigation
EUROCONTROL
72, rue de la Loi, B-1040 Bruxelles

and

René De Wispelaere
Belgian Airports & Airways Agency
Air Traffic Services
80, Rue du Progrès, B-1210 Bruxelles

SUMMARY

Today, developments in ground-based and on-board computers, navigation and digital air/ground/air communications make it possible to envisage for tomorrow extensive automation of the overall air traffic control process, always provided that reliability, safety and responsibilities can be absolutely covered in all possible eventualities, however remote.

Accordingly, before "tomorrow", an appreciable amount of traffic will cross our skies and be handled by air traffic controllers without the support of advanced automated tools. Nevertheless, at the same time, the potential of automation will continue to increase.

Its inherent benefits for the overall community may be refused and lost for a long period; in contrast, it may contribute to the production of more sophisticated and powerful tools and assist the controller in achieving a degree of efficiency which he could never have dreamed of before. What is it which will tip the scales in favour of one or the other option?

This subject will be discussed in the light of the experience gained during the development of an approach to the definition, assessment and testing in an operational environment of a procedure suitable for guiding aircraft along 4-D trajectories illustrative of the next system generation of ATC. The paper will cover the essential aspects of the computer/controller/pilot/aircraft chain of dialogues, placing the emphasis on the connivance between the computer and the controller, the intelligent interpretation of the surveillance information by the computer, the definition and generation of guidance directives, their relay to the pilot and finally, the use of navigation aids.

The paper concludes by showing the integration of the ground-based 4-D guidance and control system messages on a standard ATC radar display, illustrating this for the guidance of flights conducted by SABENA crews operating B-737 and DC-10 aircraft.

1. INTRODUCTION

In poor visibility and for night operations, pilots have for several decades now trusted automatic guidance directives to bring transport air-carriers safely to the ground. Today, it is conceivable to input a detailed flight plan in a computer for the resulting flight to be conducted automatically. Nevertheless, the captain remains in charge and ultimately responsible for safe operation.

In Air Traffic Control, the situation is still appreciably different. Certainly modern technology plays a role, but essentially to assist in the performance of ancillary tasks and the presentation of available information. The processing of flight plans and the display of synthetic radar data are examples of such contributions. Clearly, technology provides aircraft position, but in contrast with aircraft operation, no automatic system has yet been introduced to generate solutions resulting from an assessment of the overall traffic situation and suitable for the safe conduct of each individual flight accordingly.

This difference between air and ground situations probably results from a range of historical, motivational, psychological, commercial and other general and particular reasons which we do not intend either to analyse, explain, deplore or justify. Nevertheless, as automation in air traffic handling becomes a reality, and will undoubtedly change the face of air traffic control, it may now be appropriate to derive counsel from some observations.

(*) This paper has been presented at the International Conference NAV 87
"Data dissemination and display" organised by
The Royal Institute of Navigation, London, U.K., 29, 30 September - 1 October 1987

Increased aircraft performance has always been a challenge motivating both qualified engineers and skilled pilots, whatever the performance aspects were: speed (whether high or low), manoeuvrability (stability, terrain following, interception), all-weather and night operations, or more recently, low noise and fuel economy.

Clearly, pilots have always been closely associated with engineers in the development of new aircraft and the implementation and use of automation. In the field historically known as Air Traffic Control, there is no equivalent to a test pilot, and the general attitude appears rather conservative in contrast with the aviation community, where the next generation of aircraft remains a perennially fascinating theme. The situation may and probably will evolve.

Accordingly, we trust the controllers to work jointly with the engineers to develop reliable and powerful tools suitable to yield a high level of efficiency in terms of economy, use of available capacity and comfort of passengers, which could never be achieved without the introduction of an automated decision process. The following paragraphs will illustrate this further in the case of a 4-D guidance program.

Further, to derive full benefit of the automation potential - on-board and on the ground -, "it is obvious that future development in the ATM field must entail close co-operation between aircraft and avionics manufacturers, aircraft operators, and the authorities - ATC engineers and controllers - responsible for Air Traffic Management", as already advocated previously (V. Vachéry, AGARD - GCP Symposium, June 1986, AGARD-CP 410).

2. OUTLINE OF ZONE OF CONVERGENCE CONCEPT

The Zone of Convergence (ZOC) concept has been described elsewhere (see Ref. 1 and enclosed bibliography) and in this paper it will be sufficient to state that it was suggested and developed as an efficient short-term measure to bring about a significant improvement in the handling of air traffic in Western Europe. It integrates the control components for all flights and each flight is considered as a whole - not as a succession of disconnected phases - and it provides the optimum flying conditions in the area concerned in terms of economy, capacity, expedition and, as a consequence, crew and passenger comfort.

The area covered must be sufficiently large compared with the size of a present terminal; hence the introduction of the term Zone of Convergence (André Benoît and André Fossard, 1977) to avoid any ambiguity with current practice. Applications to Brussels and London treated as Zones of Convergence have shown quantitatively the advantages which may be expected, and clearly indicated the critical path in the development prior to implementation.

Among these, the ground-based 4-D guidance of individual aircraft following the directives resulting from the assessment of the overall traffic situation constitutes a prerequisite for which no illustrative example is available elsewhere.

The relevant technique aims at guiding aircraft accurately through the area so as to achieve an allocated landing time within seconds of the values determined at entry, i.e. 15 to 60 minutes beforehand. The following paragraphs will show the level of automation and the roles of the controllers and pilots in such a guidance process, illustrating a characteristic component of the next generation of air traffic handling techniques.

3. 4-D CONTROL OF AIRCRAFT TIME-OF-ARRIVAL CONSTRAINED TRAJECTORY

When an aircraft enters the jurisdiction of the ZOC control, the ZOC management unit (optimiser) re-assesses the overall traffic situation and determines the option landing sequence and consequently the landing times and in a second step defines the trajectories which meets these constraints in a way closest to the pilot requirements.

For the system to be stable, this trajectory must be "implemented" in accordance with its initial definition, and the time of arrival at the runway threshold controlled within seconds. In present operations, the ATC controller cannot achieve these twin aims, on account, inter alia, of airspace structuring, traffic handling complexity, lack of adequate predictive tools, etc.

It was accordingly decided to place particular emphasis on the design of a ground-based 4-D control module suitable for accurate on-line guidance of aircraft throughout the flight, whatever the perturbations affecting its conduct. A summary of the objectives, status and plans is presented in Reference 2.

Since the initial phase of the assessment of the methods and techniques proposed or considered, airline pilots and professional air traffic controllers have been playing their own role in the experiments (see Refs. 3 to 9), such as defining from the start interfaces not only compatible with, but also highly suitable for practical operation.

4. INTERFACES

4.1. Experimental facilities

The experimental facilities used to assess, test and validate the ground based 4-D control of aircraft techniques and procedure are described elsewhere (Ref. 9). The main components include :

- (a) an Air Traffic Control unit implementing the directives generated by ROSAS, the Regional Organisation of the Sequencing and Scheduling of Aircraft System, namely the central traffic on-line management unit covering the Zone of Convergence concerned. The main tool available for the efficient conduct of this task is the CINTIA system (Control of Inbound Trajectories of Individual Aircraft) which provides the sector controllers with precise guidance directives and all relevant information pertaining to the flights falling within this sector unit's jurisdiction. In the series of tests conducted to date, this unit has been operated by one or two professional controllers from the Belgian Airports & Airways Agency.
- (b) full scale airline flight simulators, operated by qualified airline crews and semi-automatic computer flight simulators used to increase the overall work-load. Recent tests (1987) were made using simultaneously two airline flight simulators (British Airways B-737 and B-757 and SABENA DC-10 and B-737).
- (c) a processing unit which receives the information from the aircraft simulators involved and transmits the collected information as simulated radar data to the Air Traffic Control Unit.
- (d) the R/T ground/air/ground communication channels as available today will be the only mode of communication discussed in this paper. Nevertheless, the system proposed is directly adaptable for use in a future automatic data link environment.

4.2. Main interfaces

Two essential categories of interface can be envisaged, viz those involving automatic exchanges only, such as the generation, transfer and receipt of radar data, and those involving human participation. The latter will be the only one considered here.

4.2.1 Computer / controller

This interface involves several paths:

(a) Computer → display → controller :

firstly for guidance directives generated and displayed automatically by CINTIA and secondly for provision of information requested by the controller either directly on his own initiative or following requests expressed by the aircraft;

(b) Controller → keyboard/mouse → computer :

only required for change in presentation of information or to express requests for additional data or to alter the arrival time proposed by ROSAS ; never for actual control or guidance of aircraft, even in cases of trajectory alterations.

4.2.2 Controller / aircraft crew

This R/T supported interface will transmit two essentially different types of message, namely :

(a) display → controller/aircraft crew :

4-D guidance directives generated by CINTIA, displayed on the radar screen, translated into current ATC terminology and sent to the aircraft with acknowledgement or otherwise.

(b) controller/ aircraft crew :

for all other non-guidance messages the crew and the controller used standard phraseology.

4.2.3 Aircraft crew / aircraft control

In this context, this interface corresponds to the implementation of the CINTIA's 4-D guidance directives at the discretion of the Captain - within of course the possibilities offered by the onboard equipment -, this can be done in several ways depending on the phases of flight and local/instantaneous conditions :

- (a) manually ;
- (b) using the auto-pilot in the ad hoc mode;
- (c) using the flight management computer system ;
- (d) combining the above modes of operation.

5. DESIGNER/PILOT/CONTROLLER CO-OPERATION

5.1. Initial experiments in real life operation

Once the basic principles of a groundbased guidance of aircraft were established, preliminary feasibility tests were conducted on line, in the Autumn of 1979, during actual operations in conjunction with British Airways, Engineering Operations, air crew, and Air Traffic Control Authorities providing Belgian en-route and approach controllers for the conduct of the flights and adequate co-ordination between London Air Traffic Control, EUROCONTROL UAC and the Brussels FIR (see Ref. 3).

5.2. Assessment of CINTIA operating procedure

Since the techniques have evolved but the co-operation with both the users of the system, namely the air traffic controllers on the one hand, and the users of the airspace, the airline pilots on the other hand, has continued. After a series of tests conducted with aircrews of British Airways, Deutsche Lufthansa, NLM City Hopper, SABENA Belgian World Airline and of the NLR, National Aerospace Laboratory, Amsterdam, and professional en-route and approach controllers of the Belgian Airports & Airways Agency, the results obtained make it possible to draw essential conclusions with respect to the acceptability of the procedure translating CINTIA's directives into aircraft control commands, and its compatibility with current operation.

The tasks referred to, using full scale flight simulators, have been made in different Flight Simulation Departments (Fokker and National Aerospace Laboratory, Amsterdam; SABENA, Brussels; Deutsche Lufthansa, Frankfurt; Finnair, Helsinki; British Airways, London).

For each session, the simulator was operated by a different crew. Accordingly, the procedure was exposed to a reasonably wide range of captains, first officers and flight engineers. Their reactions, critical comments and advices have been analysed, discussed and the conclusions integrated in the procedure presently available.

In contrast, the ATC Unit was always operated by the same two controllers, both experts in en-route and approach control. Occasionally, additional controllers joined the simulation for familiarising themselves with this concept, illustration of the next generation of control techniques.

5.3. General conclusions

5.3.1 Airlines crews

It is fair to say that the directives generated by CINTIA for an accurate 4-D guidance of the aircraft appear adequate whatever the mode of operation (manual, auto-pilot, FMS). Obviously, CINTIA's guidance relies on the availability of DME information on the flight deck.

The stage has been reached where briefing of the crew prior to the flight is no further necessary; the aircraft receives guidance messages from entry into the zone as would be the case in current operation.

In conclusion, the crew do not need particular training to implement satisfactorily and closely follow CINTIA's 4-D guidance directives.

5.3.2 Air traffic controllers

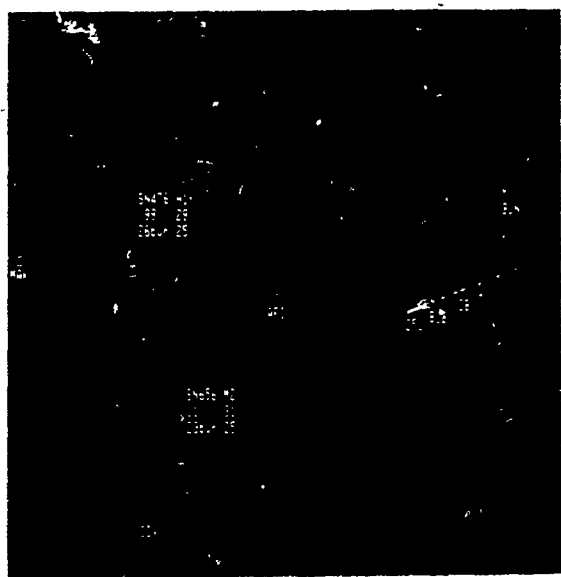
In this respect the situation is different.

- (a) In most of the tests there were only two controllers actually involved, precisely those who contributed to the definition of the guidance messages.
- (b) During familiarisation sessions, when use of the system was demonstrated to a group of some ten controllers, the general reaction was positive, most enthusiastic comments originated from representatives of the young generation.
- (c) From our limited experience, it is nevertheless clear that, in contrast with pilots, the ATC controllers will need reasonable training before being able to play their role with full efficiency.

6. CINTIA MESSAGES IN RADAR DISPLAY

The prediction, guidance and control data generated by the CINTIA system are converted into messages suitable for traffic and aircraft control. Their messages have been integrated in the standard ATC radar display as shown in Figure 1.

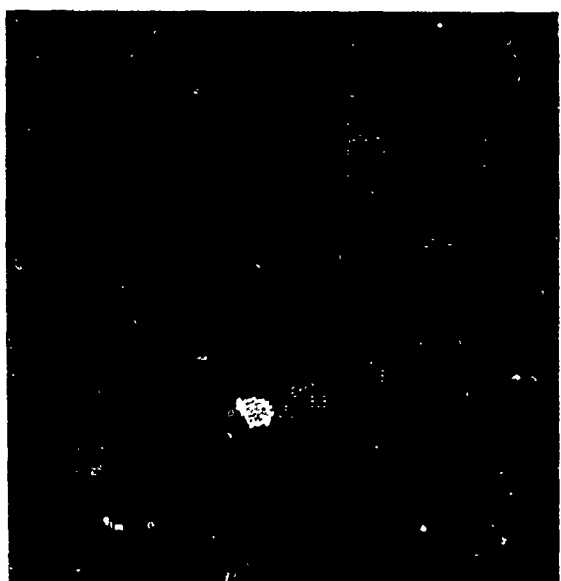
This figure presents a sequence of four pictures of the controller's screen, when two aircraft approach Brussels to land on Runway 25L. Let us follow these two flights, through Pictures (a) to (d).



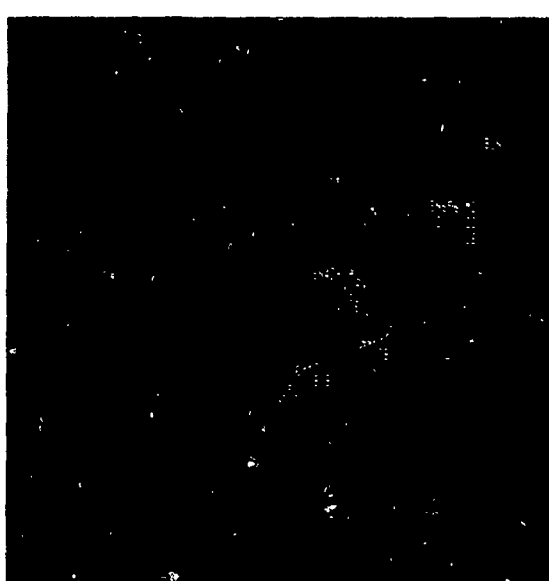
(a)



(b)



(c)



(d)

CINTIA MESSAGE INTEGRATION IN STANDARD ATC RADAR DISPLAY

Figure 1

Picture (a)

Flight SN 476 comes from Mackel (MAK), it is a "heavy" aircraft, in fact a SABENA DC-10, and according to the on-line ROSAS management system it is presently number one in the landing sequence. This information appears in the first line of the label : identification (SN 476), mass category [heavy (H); medium (M); light (L)]. The second line provides the mode C altitude expressed in flight levels (99) and the ground speed rounded off to the closest multiple of 10 kt(29). This information is derived from radar data. The third line contains the CINTIA directives (warning or positive, the transition from one mode to the other corresponding either to flashing or change of colour or both). In this case, SN 476 is expected to initiate descent at 26 nm from Bruno DME (BUN), and to conduct the descent at 250 kt, IAS, at idle power.

Similarly, Flight SN 656 comes from Chèvres (CIV), it is "medium" in terms of weight, a SABENA B-737 aircraft, is presently second in the landing sequence, it is at FL 110 and its ground speed is estimated to be 310 kt. The aircraft is expected to (a) initiate descent at 23 nm-DME, Bruno, and (b) to descent at 250 kt, IAS.

Picture (b)

Both aircraft are now descending and heading towards Bruno. SN 476 is expected to turn right, at 5.3 nm-DME Bruno onto heading 140 degrees. Similarly, SN 656 may expect to turn at 2.5 nm-DME Bruno onto heading 210 degrees.

Picture (c)

SN 476 will now be advised to turn onto heading 220 degrees for intercepting the localiser. The indication to the right gives the precise information on when the directive should be transmitted to the cockpit.

Picture (d)

SN 476 has just passed the outer marker beacon. SN 656 will intercept the localiser. For both aircraft, the symbol "... " indicates that the expected landing time is still within CINTIA acceptable tolerance (presently 10 sec.). Further, the information ".3E" and ".2E", respectively, indicate to the controller that the arrival time error would correspond to .3 and .2 nm respectively, (E for early ; L for late).

7. CONCLUSIONS

The principles of a ground-based 4-D control technique suitable to guide aircraft accurately through a zone of convergence have been established. The control accuracy such as the time-of-arrival allocated some 15 to 60 minutes in advance can be maintained within seconds in spite of the numerous perturbations effecting the actual trajectories of aircraft.

From the initiation of the experimental phase a close co-operation between the engineers, professional air traffic controllers and airline pilots existed. This made it possible to define precise, realistic and reliable guidance and control messages on the basis of the data generated by the ground guidance and control system (referred to as CINTIA). Presently, these messages as generated by CINTIA have been integrated in the ATC radar display. The experiments conducted to date indicate that the control and guidance directives definition and presentation is adequate for both the air traffic controller and the airspace users.

Further, it seems that the crew could receive acknowledgement and implement the guidance directives correctly without prior familiarisation with the system, while the ATC controller will need adequate training to gain full benefit of such tools, representative of the next generation of control techniques.

8. REFERENCES

The documents listed below refer to the 4-D guidance and control of aircraft project undertaken at the Engineering Directorate of EUROCONTROL with the participation of air traffic controllers of the Belgian Airports & Airways Agency and the co-operation of European Airlines (British Airways; Belgian World Airline, SABENA; Deutsche Lufthansa; NLR City Hopper).

The first reference places the ground-based 4-D guidance of aircraft in the overall context of air traffic handling in Western Europe. The second paper summarises the situation as it was at the end of 1985. These two first papers also include bibliographical information. References 3 to 9 constitute reports on actual tests of the prediction, guidance and control system, CINTIA, at several stages of the development.

- (1) Benoît, A.: "On-line management and control of air traffic". Lecture delivered at the Advanced Workshop on "Flow Control of Congested Networks: The Case of Data Processing and Transportation". Consiglio Nazionale della Ricerche, Capri, Italy, 12-17 October 1986. NATO ASI Series, Vol. F38, Springer-Verlag Berlin Heidelberg 1987. Also EUROCONTROL Report 872005, April 1987.
- (2) Benoît, A.: "4-D Control of current air carriers in the present environment. Objectives - Status - Plans". Paper presented at the Seminar on "Informatics in Air Traffic Control". Consiglio Nazionale della Ricerche, Capri, Italy, October 1985. Also EUROCONTROL Report 862013, March 1986.
- (3) Benoît, A. and Swierstra, S.: "On-line assessment of 4-D trajectory prediction techniques (OLEVAT-I)". EUROCONTROL Report 802009, February 1980.
- (4) Benoît, A. and Swierstra, S.: "The control of cruise-descent profiles. Experiments using B-737 and Airbus A-300 flight simulators". EUROCONTROL Report 812020, August 1981.
- (5) Benoît, A. and Swierstra, S.: "The dynamic control of inbound flights. Experiments conducted on the SABENA DC-10 flight simulator". EUROCONTROL Report 822028, June 1982.
- (6) Benoît, A.; Garcia, C. and Swierstra, S.: "Ground-based coordinated control of time of arrival. Part 1: Integration of cruise and en-route descent (Tests conducted using airlines (B-737, A-300, DC-10) flight simulators". EUROCONTROL Report 832028, December 1983.
- (7) Benoît, A. and Swierstra, S.: "A cost-efficient control procedure for the benefit of all airspace users". AGARD GCP Symposium, Cesme, Izmir, Turkey, 16-19 October 1984. AGARD CP-360 February 1985. Also EUROCONTROL Report 842011, August 1984.
- (8) Benoît, A. and Swierstra S.: "A ground/air coordinated procedure for minimum cost operation over an extended area". Conference on "Today and Tomorrow Mini & Micro Computers in Airline Operations". RAeS, London, U.K., 21-22 October 1982. Also EUROCONTROL Report 822036, September 1982.
- (9) Benoît, A.; De Wispelaere, R. and Swierstra S.: "Next generation of control techniques in advanced TMA. Automatic Assistance for the Controller/Pilot dialogue". AGARD GCP Symposium, Bruxelles, Belgium, 10-13 June 1986. AGARD CP-140, December 1986. Also EUROCONTROL Report 862016-R, June 1986.

LE CONTROLEUR DE LA CIRCULATION AERIEENNE ET L'AUTOMATISATION :

CONFLIT D'INTERETS OU CONVERGENCE ? (*)

par

André Benoît et Sip Swierstra

Organisation Européenne pour la Sécurité de la Navigation Aérienne
EUROCONTROL
Direction Technique
72, rue de la Loi, B-1040 Bruxelles (Belgium)

et

René De Wispelaere

Régie des Voies Aériennes
80, rue du Progrès, B-1210 Bruxelles

SOMMAIRE

Les progrès réalisés dans le domaine de l'ordinateur aéronautique (qu'il s'agisse de l'infrastructure au sol ou de l'élément embarqué), des systèmes de navigation et des télécommunications numériques air sol-air nous autorisent à imaginer pour "demain" un processus de contrôle de la circulation aérienne hautement automatisé pour autant que dans toutes les éventualités - même dans les moins probables - la fiabilité, la sécurité et la stricte délimitation des responsabilités soient totalement garanties.

Mais bien avant cela, nos cieux auront été traversés d'innombrables vols que les contrôleurs de la circulation aérienne auront pourtant dû prendre en charge sans l'aide de ces techniques de pointe. Entre-temps, toutefois, les possibilités qu'offre l'automatisation ne cesseront de croître.

On pourrait certes vouloir se passer des avantages intrinsèques qu'elle présente pour toute la communauté aéronautique, mais on en perdrait alors le bénéfice pour longtemps ; à l'opposé, on peut en tirer parti pour l'élaboration de moyens plus perfectionnés et plus puissants et aider ainsi le contrôleur à atteindre un niveau d'efficacité dépassant tout ce qu'il aurait pu concevoir.

Quel est donc l'élément qui déterminera le choix de l'une ou l'autre option ?

Tel est précisément le problème que nous nous proposons d'aborder ici, à la lumière de l'expérience acquise dans la mise au point, l'évaluation et la mise à l'épreuve, en conditions réelles d'exploitation, d'une procédure qui permet de guider les aéronefs sur des trajectoires quadridimensionnelles et qui est représentative de la prochaine génération de systèmes ATC. Nous décrirons par ailleurs les principaux aspects des maillons calculateur/contrôleur/pilote/aéronef constitutifs de la chaîne du dialogue (en nous attachant particulièrement à l'alliance ordinateur-contrôleur), l'interprétation intelligente, par l'ordinateur, des informations destinées à la surveillance, la définition et la production de directives de guidage, la transmission de celles-ci au pilote et, enfin, l'emploi des aides à la navigation.

Dans la conclusion, nous montrons comment on intègre les messages du système sol de guidage et de contrôle quadridimensionnels au dispositif sur les écrans standard de visualisation radar dont sont dotés les services ATC ; les exemples choisis pour les besoins de la démonstration sont des vols exécutés par des équipages de la SABENA sur B-737 et DC-10.

1. INTRODUCTION

Depuis plusieurs décennies, les pilotes s'en remettent à des moyens automatisés de radiocommunication pour faire atterrir leurs appareils en toute sécurité lorsqu'ils opèrent en mauvaises conditions de visibilité ou la nuit. De nos jours, il est de surcroît tout à fait concevable de mettre sur ordinateur toutes les données détaillées d'un plan de vol. La conduite de ce vol peut alors être entièrement automatique, mais en dernier ressort, ce n'en est pas moins le commandant de bord qui reste seul responsable de la sécurité du vol.

Pour le moment, il en va tout autrement dans les services de contrôle de la circulation aérienne. Bien sûr, la technologie moderne y laisse son empreinte, mais elle se borne essentiellement à apporter une assistance dans l'exécution de certaines tâches secondaires et dans la visualisation de l'information disponible. Le traitement des plans de vol et l'affichage des données radar synthétiques en sont une illustration. Certes, la technologie permet de bien connaître la position des aéronefs, mais à la différence de ce qui se passe pour la conduite d'un avion, il n'existe encore aucun système automatisé susceptible de fournir une solution précise à partir d'une appréciation de la situation de trafic dans son ensemble et permettant donc l'exécution, en toute sûreté, de chaque vol.

Le contraste entre ces deux états de fait tient probablement à une foule de raisons tant générales que particulières, à la fois d'ordre historique et relevant de motivations psychologiques et commerciales, que nous n'avons l'intention ni d'analyser, ni d'expliquer, ni de déplorer, ni encore de justifier d'aucune

(*) Cette communication fut présentée à la Conférence internationale NAV 87
"Data dissemination and display"

organisée par

The Royal Institute of Navigation, Londres, Royaume-Uni, 29 sept. - 1er oct. 1987.

façon. Mais, l'automatisation dans l'exercice du contrôle de la circulation aérienne devenant bel et bien une réalité, le paysage du Contrôle s'en trouvera sans nul doute bouleversé. Dès lors, le moment est peut-être venu de faire certaines constatations et d'en tirer des enseignements utiles.

L'amélioration des performances de vol n'a jamais cessé d'être un défi stimulant, à la fois pour les ingénieurs spécialisés et pour les pilotes chevronnés. C'est ainsi qu'elle a porté tantôt sur la vitesse (plus rapide ou plus lente), tantôt sur la maniabilité (stabilité, aptitude à serrer les obstacles naturels, interception), tantôt sur les opérations tout temps ou de nuit, ou encore - plus récemment - sur la réduction du bruit et les économies de carburant.

De fait, pilotes et ingénieurs ont toujours travaillé en étroite coopération lorsqu'il s'est agi de concevoir de nouveaux appareils ou de mettre en oeuvre des techniques ou des systèmes automatisés. Dans le domaine que l'histoire a fait connaître sous le nom de Contrôle de la circulation aérienne, l'alter ego du pilote d'essai n'existe pas et, d'une manière générale, les esprits sont beaucoup plus conservateurs que dans le monde de l'aéronautique, qui porte à chaque génération successive d'aéronefs un intérêt sans cesse renouvelé. Il est possible et, au demeurant, probable que les mentalités évolueront sur ce point.

C'est pourquoi nous ne doutons pas que les contrôleurs se joindront aux ingénieurs pour mettre au point des moyens fiables et puissants, dont l'utilisation offrirait la perspective d'un très haut niveau d'efficacité non seulement sur le plan économique, mais encore sur celui de l'exploitation du potentiel disponible et du confort des passagers, ce qui ne saurait s'imaginer sans le recours à un processus automatisé de prise de décision. Les paragraphes qui suivent s'attacheront à en donner la démonstration, en prenant comme exemple le processus de guidage des aéronefs dans les quatre dimensions.

En outre, si l'on veut tirer le parti maximum du potentiel que recèle l'automatisation - tant à bord qu'au sol - "il est évident que les perfectionnements futurs dans le domaine de la gestion du trafic aérien nécessitent absolument une étroite coopération entre les avionneurs, les fabricants d'équipements aéroélectroniques, les exploitants d'aéronefs et les services (ingénieurs ATC et contrôleurs) chargés de la gestion du trafic aérien", comme le soulignait V. Vachiéry (Symposium AGARD-GCP, Juin 1986, AGARD-CP-410).

2. LE CONCEPT DE LA ZONE DE CONVERGENCE

Le concept de la zone de convergence (ZOC) a fait l'objet d'une publication séparée (voir réf. 1 et bibliographie incluse). Nous nous bornerons dès lors à rappeler ici que sa réalisation a été proposée comme moyen efficace d'améliorer sensiblement à court terme l'écoulement du trafic aérien en Europe occidentale.

Il s'agit d'intégrer, pour l'ensemble des vols, les différents éléments constitutifs du contrôle, chaque vol étant considéré comme une entité et non plus comme une succession de phase distinctes ; les conditions d'exploitation offertes dans la région considérée sont donc optimales à plusieurs titres : économie, capacité, rapidité d'écoulement et par voie de conséquence confort, des équipages comme des passagers.

La région d'exploitation d'un tel concept doit être relativement vaste, comparée à une région terminale classique, d'où la notion de "Zone de convergence" (André Benoît et André Fossard, 1977) afin d'éviter toute confusion avec la pratique actuelle. Les applications réalisées pour Bruxelles et Londres ont permis de préfigurer les avantages quantitatifs de la ZOC, tout en mettant en évidence le "chemin critique" des diverses étapes à mettre au point avant sa mise en oeuvre réelle.

Parmi ces avantages, on peut citer le guidage, quadridimensionnel depuis le sol, de chaque aéronef suivant les directives auxquelles aboutit l'appréciation de la situation du trafic dans son ensemble ; un tel guidage est un préalable dont il n'existe aucun autre exemple ailleurs.

La technique utilisée permet de guider les aéronefs avec précision tout au long de leur itinéraire dans la zone de convergence, de manière que l'atterrissage se produise, à quelques secondes près, à l'heure qui leur a été assignée au moment où ils pénètrent dans cette zone (soit 15 à 60 minutes auparavant). Les paragraphes qui suivent s'attacheront à décrire le niveau d'automatisation requis, ainsi que les rôles respectifs du contrôleur et du pilote dans le processus de guidage, afin d'illustrer l'une des composantes caractéristiques de la prochaine génération des techniques de contrôle du trafic aérien.

3. CONTROLE DES AERONEFS DANS LES QUATRE DIMENSIONS DETERMINATION DE LA TRAJECTOIRE EN FONCTION D'UNE HEURE D'ARRIVEE IMPOSEE

Lorsqu'un aéronef pénètre dans la région relevant des services de Contrôle de la ZOC, l'organisme de gestion de la ZOC (le service "optimiseur") réévalue la situation globale de trafic ; il détermine la meilleure séquence d'atterrissage possible - et donc les heures prévues d'atterrissage - et, dans un second temps, définit la trajectoire qui tient compte de ces références horaires tout en répondant le mieux possible aux exigences du pilote.

Pour que le système conserve sa stabilité, cette trajectoire doit être suivie en conformité de sa définition initiale et l'heure de franchissement du seuil de piste respectée à quelques secondes près. Dans les circonstances actuelles, le contrôleur ATC ne saurait atteindre simultanément ces deux objectifs, notamment en raison de la structure de l'espace aérien, de la complexité des procédures de contrôle, du manque de moyens de prévision adéquate, etc.

C'est pourquoi il a été décidé d'accorder une importance toute particulière à la conception d'un module "sol" de contrôle quadridimensionnel, se prêtant au guidage précis, en direct, du vol tout au long de son itinéraire, quels que soient les éléments extérieurs susceptibles d'influer sur son exécution. L'ouvrage cité en référence n° 2 fait la récapitulation succincte des objectifs, de la situation actuelle et des projets existant dans ce domaine.

Dès le moment où a commencé l'étude des méthodes et techniques proposées ou envisagées, les pilotes de ligne et les contrôleurs aériens ont apporté leur part à la conduite des expérimentations (voir références 3 à 9), par exemple pour la définition, d'entrée de jeu, d'interfaces qui, loin d'être simplement compatibles avec les opérations réelles en vol, y soient parfaitement adaptées.

4. INTERFACES

4.1. Moyens d'expérimentation

Les moyens qui ont servi à l'évaluation, à l'expérimentation et à la validation des techniques "quadridimensionnelles" de contrôle aérien sont décrites dans l'ouvrage visé en référence 9. En voici cependant les principaux éléments constitutifs :

- (a) un organisme de contrôle de la circulation aérienne appliquant les directives produites par le système ROSAS (Regional Organisation of the Sequencing and Scheduling of Aircraft System), c'est-à-dire l'organisme central de gestion en direct du trafic aérien desservant la zone de convergence considérée. Actuellement, l'outil le plus efficace dont on dispose pour cette tâche est le système CINTIA (Control of Inbound Trajectories of Individual Aircraft), qui donne aux contrôleurs de secteur des directives de guidage précises, ainsi que toutes les données utiles concernant les vols relevant de la juridiction de cet organisme. Dans tous les essais réalisés à ce jour, celui-ci a été desservi par deux contrôleurs chevronnés de la Régie belge des Voies aériennes.
- (b) des simulateurs de vol en vraie grandeur, avec, aux commandes, des équipages de ligne qualifiés, et des simulateurs de vol semi-automatisés afin d'augmenter la charge de travail globale. Des essais ont été réalisés récemment (1987), à l'aide de deux simulateurs de vol (en l'occurrence celui d'un B-737 et B-757 de la British Airways, ainsi qu'un DC-10 et B-737 de la Sabena) utilisés simultanément ;
- (c) un dispositif de traitement, qui reçoit les données transmises par les simulateurs et les renvoie, sous forme de données radar simulées, à l'organisme de contrôle de la circulation aérienne ;
- (d) les voies de communication radiotéléphoniques sol-air-sol, telles qu'elles existent aujourd'hui, sont le seul mode de communication qui sera évoqué dans le présent exposé. Le système proposé peut néanmoins s'adapter directement à une infrastructure où les échanges de données seraient automatisés.

4.2. Interfaces

Les deux principaux types d'interfaces envisageables sont ceux qui donnent lieu exclusivement à des échanges automatisés (par exemple pour la production, le transfert ou la réception de données radar), et ceux où intervient un élément humain. Ce sont ceux-ci qui retiendront notre attention.

4.2.1. Ordinateur/contrôleur

Ce rapport comporte plusieurs filières :

(a) Ordinateur → dispositif de visualisation → contrôleur

Sert, en premier lieu, à l'acheminement des indications de guidage produites et affichées automatiquement par le système CINTIA et, en second lieu, à la fourniture des informations demandées par le contrôleur soit de sa propre initiative, soit à la requête d'un pilote.

(b) Contrôleur → clavier/souris → ordinateur

Cette liaison est utilisée uniquement pour changer la présentation des données, demander un supplément d'information ou modifier l'heure d'arrivée proposée par le système ROSAS ; elle ne sert donc jamais au contrôle ou au guidage des aéronefs, pas même en cas de changement de trajectoire.

4.2.2. Contrôleur/équipage

Cette liaison, réalisée en radiotéléphonie, sert essentiellement au transfert de deux types de messages :

(a) écran → contrôleur/équipage

directives de guidage dans les 4 dimensions, produites par le système CINTIA, affichées sur l'écran radar, produites en termes et sigles ATC consacrés et transmises à l'aéronef avec ou sans demande d'accusé de réception ;

(b) contrôleur/équipage

messages autres que ceux qui comportent des directives de guidage ; l'équipage et le contrôleur utilisent ici les expressions conventionnelles habituelles.

4.2.3. Equipage/service ATC

Dans le contexte qui nous occupe, cette liaison correspond à la mise en application des directives de guidage quadridimensionnelles du Système CINTIA, selon la décision qu'aura prise le commandant de bord en fonction, bien entendu, des diverses solutions que lui proposera l'équipement embarqué. Il existe en l'occurrence plusieurs modes d'intervention, selon la phase de vol et les conditions locales ou ponctuelles :

- (a) intervention manuelle ;
- (b) pilotage automatique, dans le mode qui convient ;
- (c) système automatisé de gestion de vol ;
- (d) combinaison de deux ou des trois modes précédents.

5. COOPERATION ENTRE CONCEPTEURS, PILOTES ET CONTROLEURS

5.1. Applications expérimentales en conditions d'exploitation réelles

Une fois établis les principes fondamentaux d'un système "sol" de guidage des aéronefs, les premiers essais de faisabilité ont été réalisés en direct, à l'automne 1979, à l'occasion de vols réels et avec l'assistance de la British Airways, des services d'exploitation technique, d'équipages et des autorités ATC belges qui avaient fourni les contrôleurs en route et les contrôleurs d'approche nécessaires à l'exécution des vols, ainsi qu'à la bonne coordination entre les services de contrôle de Londres, l'UAC de Maastricht (EUROCONTROL) et la FIR de Bruxelles (voir réf. 3).

5.2. Evaluation de la procédure CINTIA

Depuis lors, les techniques ont évolué et la coopération avec les deux parties prenantes au système, c'est-à-dire les contrôleurs de la circulation aérienne, d'une part, les utilisateurs de l'espace aérien et les pilotes de ligne, d'autre part, s'est poursuivie. C'est ainsi qu'une série d'essais, réalisés avec l'assistance d'équipages de la British Airways, de la Deutsche Lufthansa, de la NLM City Hopper, de la Sabena et du NLR (Laboratoire aérospatial des Pays-Bas), ainsi que de contrôleurs en route et d'approche de la Régie belge des Voies aériennes (RVA) a permis de dégager des conclusions essentielles quant à l'acceptabilité de la procédure pour la transposition des directives CINTIA en instructions de contrôle destinées à l'aéronef, ainsi qu'à la compatibilité de cette procédure avec les modes d'exploitation actuels.

Ces essais, pour lesquels il a été fait appel à des simulateurs de vol en vraie grandeur, ont été exécutés avec le concours des services spécialisés de Fokker, du Laboratoire aérospatial national des Pays-Bas (Amsterdam), de la Sabena (Bruxelles), de la Deutsche Lufthansa (Francfort), de la Finnair (Helsinki) et de la British Airways (Londres).

Pour chaque session de travail, le simulateur était desservi par un autre équipage, de sorte que l'application de la procédure a été laissée à l'appréciation d'un nombre relativement élevé de commandants de bord, de co-pilotes et d'officiers mécaniciens de bord différents. Leurs réactions, observations, critiques et avis ont fait l'objet d'analyses et d'échanges de vues, dont les conclusions ont été intégrées à la procédure telle qu'elle existe aujourd'hui.

En revanche, l'équipe ATC a toujours été composée des deux mêmes contrôleurs, tous deux détenteurs de licences de contrôle en route et d'approche. Parfois, d'autres contrôleurs ont participé aux exercices de simulation pour se familiariser avec le concept, qui est un exemple démonstratif de la prochaine génération des techniques de contrôle.

5.3. Conclusions générales5.3.1. Equipages de ligne

En toute honnêteté, on peut affirmer que les directives produites par le système CINTIA pour le guidage précis de l'aéronef dans les quatre dimensions donnent satisfaction quel que soit le mode d'exploitation choisi (manuel, pilotage automatique, FMS). Bien entendu, le guidage CINTIA ne peut s'exercer que si l'on dispose, dans le poste de pilotage, des informations du DME.

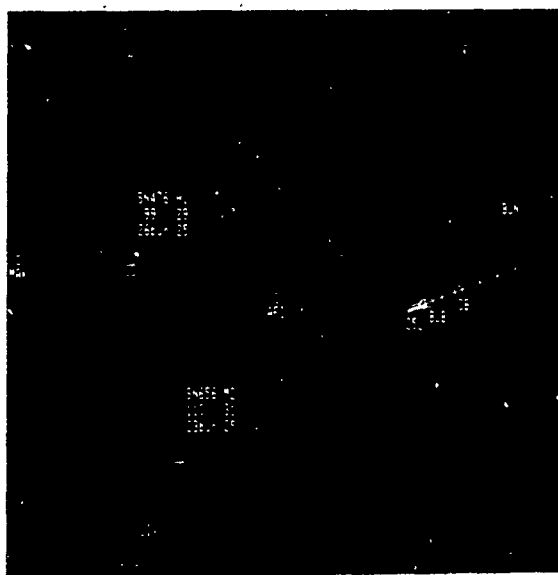
Nous avons maintenant atteint le stade où le "briefing" des équipages avant le vol n'est plus nécessaire ; l'équipage reçoit les messages de guidage dès que l'aéronef pénètre dans la zone, à l'instar de ce qui se passerait dans les conditions opérationnelles réelles.

En conclusion, il est permis de constater que les équipages n'ont besoin d'aucune formation particulière pour pouvoir appliquer correctement les directives de guidage quadridimensionnelles du CINTIA.

5.3.2. Contrôleurs de la circulation aérienne

Il en va différemment des contrôleurs :

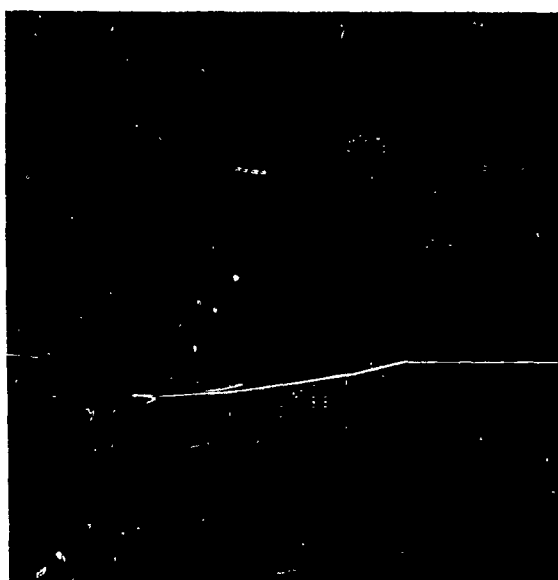
- (a) La majorité des essais ont été réalisés avec l'assistance de deux contrôleurs seulement, en l'occurrence ceux qui avaient contribué à la définition des messages de guidage.



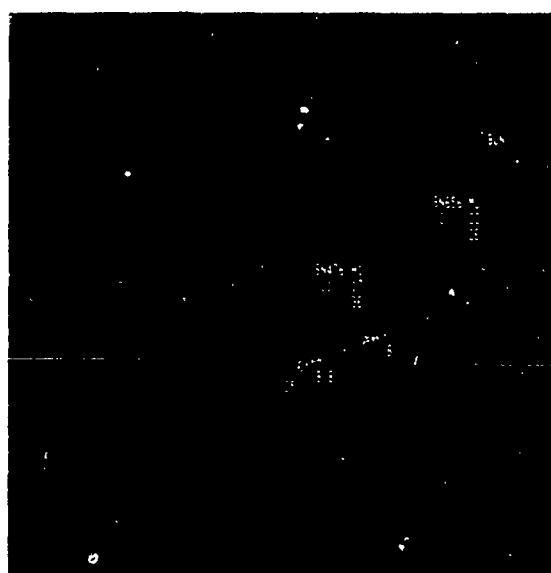
(a)



(b)



(c)



(d)

INTEGRATION DES MESSAGES CINTIA DANS L'AFFICHAGE RADAR

Figure 1

- (b) Pendant les exercices de familiarisation, où était faite la démonstration pratique de l'application du système à l'intention d'un groupe de quelque dix contrôleurs, les réactions étaient, d'une manière générale, positives, les représentants de la jeune génération étant aussi les plus favorables.
- (c) Il ressort néanmoins de cette expérience, il est vrai limitée, qu'à l'inverse des pilotes, les contrôleurs devront bénéficier d'une certaine formation avant de pouvoir assumer leur rôle avec un maximum d'efficacité.

6. AFFICHAGE RADAR DES MESSAGES CINTIA

Les données de prévision, de guidage et de contrôle produites par le système CINTIA sont traduites en messages se prêtant au contrôle, tant global qu'individuel, du trafic aérien ; les messages ATC sont à leur tour intégrés à l'affichage radar habituel, comme le montre la figure 1.

Cette figure reproduit une séquence de quatre images de l'écran du contrôleur, représentant l'approche de deux aéronefs en vue de l'atterrissage sur la piste 25L de l'aéroport de Bruxelles. Voyons, image par image, comment ces vols se déroulent.

Image (a)

Le vol SN 476, en provenance de Makel (MAK), est effectué par un gros porteur (DC-10 de la Sabena) ; en application du système ROSAS de gestion en direct, il devrait être le premier à atterrir. C'est ce qui apparaît à la première ligne de l'étiquette : identification (SN 476), catégorie de poids (lourd : (H), moyen (M), léger (L)). A la deuxième ligne, on trouve les données d'altitude en Mode C exprimées en niveau de vol (99) et la vitesse-sol arrondie au plus proche multiple de 10 noeuds (29). Ces informations sont tirées des données radar. La troisième ligne contient les directives CINTIA (avertissement, autorisation, transition d'un mode à un autre, si le voyant lumineux clignote ou s'il y a changement de couleur, ou les deux). Dans le cas considéré, le vol SN 476 est censé amorcer sa descente à 26nm du DME Bruno (BUN) et effectuer cette descente à 250 noeuds VI et à puissance réduite.

Le vol SN 656, en provenance de Chièvres (CIV), de "moyen" tonnage - (B-737), est classé deuxième dans la séquence des atterrissages ; il évolue au niveau FL 110, à une vitesse estimée à 310 kts. Il est supposé amorcer sa descente à 23nm du DME Bruno et exécutera sa descente à 250 noeuds VI.

Image (b)

Les deux aéronefs sont maintenant en descente et se dirigent vers le DME Bruno. Le SN 476 devrait virer à droite, à 5,3 nm du DME Bruno et prendre le cap 140°. De même, le SN 656 peut s'attendre à virer au cap 210° à 2,5 nm du DME Bruno.

Image (c)

Au vu de cette image, il sera conseillé au SN 476 de virer au cap 220 pour intercepter l'alignement. Les indications sur la droite précisent, très exactement, le moment auquel la directive correspondante doit être transmise au poste de pilotage.

Image (d)

Le SN 476 vient de dépasser la radioborne extérieure, et le SN 656 n'a pas encore intercepté l'alignement. Pour les deux aéronefs, le symbole "... " indique que l'heure attendue d'atterrissage est toujours conforme aux tolérances CINTIA (en l'occurrence 10 sec.). De plus, les indicateurs ".3E" et ".2E" montrent au contrôleur que l'erreur sur l'heure d'arrivée se traduirait par 0,3 nm et 0,2 nm respectivement (E : en avance ; L : en retard).

7. CONCLUSIONS

La technique à suivre pour contrôler les aéronefs dans les quatre dimensions, à partir du sol, pour les guider avec précision dans leur traversée d'une zone de convergence est bien établie dans ses principes. La précision de ce contrôle peut être maintenue à quelques secondes près, par exemple en ce qui concerne l'heure d'arrivée assignée 15 à 60 minutes plus tôt, en dépit des nombreux éléments influant sur les trajectoires réellement suivies.

L'étroite coopération qui s'est instaurée depuis les tout débuts de la phase expérimentale entre les ingénieurs, les contrôleurs aériens et les pilotes de ligne a permis de définir des messages de guidage et de contrôle précis, réalistes et fiables sur la base des données produites par le système sol de guidage et de contrôle connu sous l'appellation CINTIA.

Aujourd'hui, l'intégration des messages CINTIA aux dispositifs de visualisation des données radar est chose faite, et les expérimentations réalisées à ce jour donnent à conclure que la définition et la présentation des directives de guidage et de contrôle conviennent tant au contrôleur de la circulation aérienne qu'à l'utilisateur de l'espace aérien.

Enfin, il semblerait que les équipages de conduite puissent recevoir, confirmer et mettre correctement en application les directives de guidage sans avoir dû se soumettre au préalable à une formation spécialisée, tout à l'inverse des contrôleurs ATC si l'on veut que ceux-ci puissent tirer pleinement parti de ce nouveau concept, représentatif de la prochaine génération des techniques de contrôle.

8. REFERENCES

Les documents mentionnés ci-après se réfèrent au projet de guidage et contrôle quadridimensionnels des avions entrepris à la Direction technique d'EUROCONTROL avec la participation des contrôleurs de la circulation aérienne de la Régie Belge des Voies Aériennes et la collaboration des compagnies aériennes européennes (British Airways ; Belgian World Airline, Sabena ; Deutsche Lufthansa ; NLM City Hopper, Amsterdam).

La première référence situe le guidage quadridimensionnel de l'avion à partir du sol dans le contexte général de la gestion du trafic en Europe occidentale. La deuxième communication citée résume la situation telle qu'elle se présentait à la fin de l'année 1985. Ces deux articles comportent une bibliographie détaillée. D'autre part, les références 3 à 9 constituent des rapports sur les essais du système de prédiction, guidage et contrôle, CINTIA, à différents niveaux de son développement.

- (1) Benoît, A : "On-line management and control of air traffic". Lecture delivered at the Advanced Workshop on "Flow Control of Congested Networks : The Case of Data Processing and Transportation".
Consiglio Nazionale della Ricerche, Capri, Italy, 12-17 October 1986.
Also EUROCONTROL Report 872005, April 1987.
- (2) Benoît, A : "4-D Control of current air carriers in the present environment. Objectives - Status - Plans". Paper presented at the Seminar on "Informatics in Air Traffic Control".
Consiglio Nazionale della Ricerche, Capri, Italy, October 1985.
Also EUROCONTROL Report 862013, March 1986.
- (3) Benoît, A. and Swierstra, S. : "On-line assessment of 4-D trajectory prediction techniques (OLEVAT-I)". EUROCONTROL Report 802009, February 1980.
- (4) Benoît, A. and Swierstra, S. : "The control of cruise-descent profiles. Experiments using B-737 and Airbus A-300 flight simulators". EUROCONTROL Report 812020, August 1981.
- (5) Benoît, A. and Swierstra, S. : "The dynamic control of inbound flights. Experiments conducted on the SABENA DC-10 flight simulator". EUROCONTROL Report 822028, June 1982.
- (6) Benoît, A. ; Garcia, C. and Swierstra, S. : "Ground-based coordinated control of time of arrival. Part 1 : Integration of cruise and en-route descent (Tests conducted using airlines (B-737, A-300, DC-10) flight simulators)". EUROCONTROL Report 832028, December 1983.
- (7) Benoît, A. and Swierstra, S. : "A cost-efficient control procedure for the benefit of all airspace users". AGARD GCP Symposium, Cesme, Izmir, Turkey, 16-19 October 1984.
AGARD CP-360, February 1985.
Also EUROCONTROL Report 842011, August 1984.
- (8) Benoît, A. and Swierstra, S. : "A ground/air coordinated procedure for minimum cost operation over an extended area". Conference on "Today's and Tomorrow's Mini & Micro Computers in Airline Operations". RAeS, London U.K., 21-22 October 1982.
Also EUROCONTROL Report 822036, September 1982.
- (9) Benoît, A. ; De Wispelaere, R. and Swierstra, S. : "Next generation of control techniques in advanced TMA. Automatic Assistance for the Controller/Pilot dialogue". AGARD GCP Symposium, Bruxelles, Belgium, 10-13 June 1986.
AGARD CP-410, December 1986.
Also EUROCONTROL Report 862016-R, June 1986.

PART VI

Surveillance

AIRCRAFT TRAJECTORY RECONSTITUTION

on the basis of

MULTI-RADAR PLOT INFORMATION

by

P. van der Kraan

European Organisation for the Safety of Air Navigation
EUROCONTROL
Engineering Directorate
72, Rue de la Loi, B-1040 Bruxelles (Belgium)

EXECUTIVE SUMMARY

1. WHY RADAR SYSTEM PERFORMANCE ANALYSES?

Present day ATC Systems rely to a great extent on the radar derived aircraft positions displayed to the controller. The displayed positions should represent as accurate as possible the actual 3 dimensional aircraft position at the display time. In order to safely separate aircraft, thereby respecting as much as possible an economic dynamic behaviour of aircraft, also the availability of accurate speed information is of importance. For the correct vectoring of aircraft in the Approach function the availability of an accurate speed vector is extremely valuable.

Furthermore several functions associated with the Radar Data Processing System, assisting controllers in their tasks, make use of the radar derived position and speed information. An important one is the so-called Short-Time Conflict Alert function, which, by making use of the actual positional and speed information in most cases, supplemented by Flight Plan information, provides predictions for possible near future conflicts (e.g. infraction of the radar separation minimum within the forthcoming 2 minutes). Information on e.g. along-track and across track accelerations or on changes in the vertical speed could increase considerably the accuracy of prediction of this function.

It is, therefore, very important that the capability of the total radar system for the accurate derivation of the aircraft position and speed, and to a certain extent of its accelerations, is assessed.

This assessment forms part of an assembly of radar performance analyses which are made prior to putting a radar system into operational use or as part of the monitoring and control actions protecting the radar system from performance degradation. An important pre-requisite for executing radar performance assessment is the availability of accurate positional and time information on the actual aircraft trajectory.

2. POSSIBLE WAYS TO OBTAIN RECONSTITUTED TRAJECTORIES

Classical ways of measuring aircraft trajectories consisted either of the use of special test aircraft with accurate on-board measurement equipment or of the measurement of aircraft positions with special tracking radars (lock-follow) with a high positional update rate. Both measurement methods suffer of some severe drawbacks such as high costs and relatively low traffic samples, which are furthermore restricted to small geographical areas and/or to the use of limited numbers of aircraft types.

Therefore methods have been developed by EUROCONTROL in cooperation with the National Aerospace Laboratories in Holland for the accurate reconstitution of the aircraft trajectory data from multi-radar plot data. Radar plot data are the radar derived extractor messages which are transmitted from the radar extraction systems to the ATC Centres (often via telephone lines) for further processing in the Centre's Radar Data Processing System.

3. AIRCRAFT TRAJECTORY RECONSTITUTION FROM MULTI-RADAR PLOT DATA

3.1. Reconstitution of the aircraft position

The successive steps necessary for an a-posteriori aircraft trajectory reconstitution from radar plots are the following :

- i) As a first step the total number of collected multi-radar plot data (typically consisting of 1 to 3 hours of data) are subjected to a chaining process (sometimes referred to as Object Correlation). This process organises the data in such a way that correct plots belonging to a particular trajectory receive a particular Aircraft Identity (AI). Plots not receiving an AI are considered to be so-called "false-plots" (e.g. derived from SSR reflections, antennae sidelobe or PR clutter).

A chainer is an a-posteriori device (i.e. has at any given time both history and future plot information available) and can, therefore, operate more accurately than a real-time tracker.

- ii) As a next step, all radar data are evaluated for systematic radar errors. The following error sources are evaluated per radar :

- Positional errors in the radar station position (latitude, longitude)
- Bias error in the reported plot azimuth
- Bias error in the reported range information
- Possible range dependent range error (e.g. wrong range unit, extractor clock error)
- Time stamping bias
- Alignment error between SSR and PR element of a radar station.

Prior to the actual trajectory reconstitution, an assessment per aircraft is made of a possible bias-error in the SSR range information due to an error in the aircraft transponder delay, which occurs when preparing a reply on an interrogation.

- iii) As a last step the multi-radar plot information is corrected for systematic errors and is subjected to a process of curve fitting through the corrected plot data by the use of so-called B-spline functions.

The B-splines used are of the order 4 and the time is sub-divided in dynamically adaptable time-intervals. The length of the time-intervals depends on the amount of manoeuvring of the aircraft.

Continuity of position and speed is imposed at the end and start of intervals. Reconstituted trajectories are stored in the form of B-spline coefficients (data reduction) for which optimum values are found by a least-square approximation. One coefficient is required per interval and per dimension.

The estimation of systematic errors is only sufficiently accurate if sufficient radar overlap exists between the coverage of participating radars (preferably some areas with triple radar overlap). Normally such multiple coverage exists for regions with a high density of air traffic.

Tests and operational experience with the position reconstitution program at the EUROCONTROL Experimental Centre have shown that absolute positional accuracies between 50 and 100 m. may be obtained. Some difficulties exist still with the speed of convergence of the systematic error estimation process.

3.2. Reconstitution of the speed and accelerations

Elsewhere in this AGARDograph, Mr Blom has presented a paper on the application of Markov Jump-diffusion models of manoeuvring aircraft for radar tracking and trajectory reconstitution.

Although the use of B-splines provides a good means for the reconstitution of the aircraft position, it has been found that the reconstituted speed and as a result of course also the reconstituted accelerations are rather inaccurate. The use of models as described in Mr. Blom's paper promise much better results. His method permits as a supplementary advantage the classification of trajectory parts according to the so-called Mode-of-Flight (uniform motion, along-track acceleration/deceleration, unintentional manoeuvres, normal and expeditious turns etc.). This classification is necessary for the accurate evaluation of radar tracking algorithms. A facility based on the principles outlined in Mr Blom's paper will be developed in the near future.

4. ADDITIONAL APPLICATIONS OF THE USE OF RECONSTITUTED AIRCRAFT TRAJECTORIES

The use of reconstituted trajectories and the associated assessment of systematic errors has, in addition to the use for radar performance analyses, a number of other applications such as :

- Aircraft accident and incident investigations
- On-line Quality Control and alignment of radars
- Simulation of realistic aircraft trajectories for any desired aircraft type in any desired environment.

5. CONCLUSION

The radar system is a very critical element of the present ATC System and will be this for the forthcoming 10 to 20 years. Due to its importance and complexity, evaluations of the radar system performance are required both prior to the operational use of a new system as well as during its operational life.

The availability of detailed information on the aircraft position, speed and accelerations at any given time for comparison with the displayed radar information is an important pre-requisite for execution of radar performance analyses. Methods have been developed and are now in use which permit the accurate reconstitution of the aircraft position from multi-radar plot information. Methods for the accurate reconstitution of the aircraft speed and accelerations, as well as of the so-called Mode of Flight, will be developed in the near future.

BAYESIAN MULTI-SENSOR TRACKING FOR
ADVANCED AIR TRAFFIC CONTROL SYSTEMS

by

H.A.P. Blom, R.A. Hogendoorn and F.J. van Schaik

National Aerospace Laboratory NLR
P.O. Box 90502
1006 BM Amsterdam
The Netherlands

ABSTRACT

An overview is given of a Bayesian tracking system for a multi-sensor environment. The main modules perform track initiation, track continuation and systematic error estimation, respectively. The track continuation module plays for Air-Traffic Control the most important role. It consists of a combination of those approximate Bayesian methods that proved to be the most efficient for the main problems of track continuation: Extended-Kalman filtering for non-linear dynamics, Probabilistic Data Association for unassociated measurements and Interacting-Multiple-Model filtering for sudden manoeuvres. Comparisons of this new tracking system with α - β , Kalman based and state-of-the-art tracking systems show its superiority for application to Air-Traffic-Control surveillance. It provides better track continuity, more accurate expectations of position and velocity and more complete additional information in the form of probabilities of modes of flight (turning, accelerating and straight modes) and consistent estimates of its own accuracy. With this track information, advanced Air-Traffic-Control systems may better cope with the many uncertainties that are inherent to air traffic.

The results in this paper were obtained partly under contract with the Dutch Organization of Civil Aviation (RLD).

1. INTRODUCTION

During recent years an extensive study on aircraft tracking for civil ATC (Air-Traffic-Control) has been done at NLR. The objective was to develop a tracking system, which can provide far better aircraft state information (tracks) than is presently the case. The desired improvements are more accurate state estimates and additional state information. With the first, we mean better track continuity and smaller errors in the estimates of position, velocity and acceleration. With the additional state information we mean:

- Probabilities of track types, such as aircraft track, flying angle track or false track.
- Probabilities of the mode of flight, such as manoeuvring, accelerating or straight flight.
- Reliable indication of the accuracy of the state estimates.

The provision of such additional state information to an ATC system seems particularly important in view of the growing need of air-traffic-controller-friendly systems for planning, conflict alert and conflict resolution. These systems can only be made more friendly if they are provided themselves with more complete state information. This can be done by installing better sensors, better extractor systems, better tracking systems and better aircraft transponder systems. As new sensor, extraction and transponder systems have already the full attention of the ATC community, the present study concentrates on improvements of the tracking system, with the requirement that measurements, using new types of transponders, sensors or extractors can easily be incorporated into the new tracking set-up. To reach the objectives, the theoretically well-known Bayesian approach was used in the study. The elaboration of this approach started shortly after the invention of the Kalman filter and it has led to a steadily growing number of Bayesian tracking methods (Jazwinski, 1970; Farina and Studer, 1985; Blackman, 1986; Bar-Shalom and Fortmann, 1988). The result of the NLR tracking study is a Bayesian multi-sensor tracking system, which is practically implementable and makes high-quality tracks from measurements of only a single primary surveillance radar system.

This paper gives an overview of the design, the theoretical background and the performance of this tracking system. First, in section 2, we present the main modules of the tracking system. Next, in section 3, we take a look at the module that executes the, for ATC most critical, function of track continuation. Then, in section 4, we give an impression of the performance of this tracker for measurements of a single primary en-route surveillance radar, and make some comparisons with other trackers. In section 5, we draw a number of conclusions.

2. MULTI-SENSOR TRACKING MODULES

The task of a multi-sensor tracker is to provide track information about aircraft in the ATC surveillance area. This area is covered by one or more sensors, possibly of different type. To perform the tracking, we developed a modular system, of which we give a short outline of this section.

The heart of the system is the track continuation module. It receives the measurements of all sensors, updates its tracks with that information and evolves them to the next measurement instants. Because this is the most important task of the tracking system, we devote the next section to an outline of this track continuation module. After tracks have been updated with the available measurements, the appropriate measurements are associated with tracks, while all other measurements are handed over to the track-initiation modules. Our track initiation system has a distributed architecture (Farina and Studer, 1986), in the sense that each site has its own track-initiation system. The track-initiation system is responsible for aircraft that enter the surveillance region through the area of the corresponding site. Each initiated track is immediately handed over to the track-continuation system. Obviously, a track continuator can work in combination with any track-initiation system, but as a track continuator can only continue a track after it has been initiated, we think that a high-performance track continuator should cooperate with a high-performance track-initiation system. Therefore, we developed a Bayesian track-initiation system (Hogendoorn and Blom, 1988).

For brevity the following modules are not elaborated upon:

- Track-merging module.

Due to split measurements or aircraft, flying in a tight formation, that are occasionally seen apart, tracks may be generated that are essentially the same. In order to reduce the work load of the tracking system, these tracks are combined into a single track by the track-merging module.

- Track-deletion module.

If an aircraft leaves the surveillance area, it can no longer be seen by any of the sensors. Because the border of the surveillance region fluctuates randomly (due to atmospheric conditions, sensor malfunctioning, etc.), such an exit occurs randomly. Therefore, a track-deletion system checks, after each update of a track with new measurements, both the accuracy and the consistency of that track. If one or both are out of bounds, then the track is stopped and all associated past measurements are transferred to the track initiators of the originating sites. This track-deletion module also takes care of deleting any false track that might sneak into the track-continuation system.

- Systematic-error estimator.

Due to the large number of measurements that are available to estimate the systematic errors (azimuth, gain and timing), this can be done by simple but robust methods (Farina and Studer, 1986).

- Coordinate-transformation module.

This module transforms all measurements into a fixed global coordinates system and corrects for all estimated systematic errors, before the measurements are handed over to the track continuator.

3. THE TRACK CONTINUATOR

In this section, we give an outline of the principles that underly the track continuator. Once a track has been initiated, a track continuator has to continue that track as long as it is observed by at least one sensor. During this task a track continuator has to cope with several uncertainties, of which the following three cause the major complications:

1. Non-linear aircraft dynamics during a turn.
2. The association of measurements with ongoing tracks.
3. Sudden starts and stops of manoeuvres.

To develop a high-quality track continuator, we adopted the Bayesian approach. It consists of building causal stochastic models; developing the exact filter solution from the theory of Bayesian estimation for Markov processes and, finally, introducing efficient numerical approximations of the exact solution. By following these three steps, several approximate Bayesian methods were developed for each of the above mentioned subproblems of tracking. The various approximate Bayesian methods show a trade-off between computational load and performance, depending on the particular application (Chong et al., 1982; Pattipati and Sandell, 1983).

To cope with subproblem 1, the well known Extended-Kalman method of linearization along the predicted path is adopted as a good compromise (Jazwinski, 1970).

Of the various approximate methods to cope with subproblem 2, a Multiple-Model Probabilistic Data Association (PDA) method (Gauvrit, 1984; Bar-Shalom and Fortmann, 1988) was judged to be the best compromise to update an aircraft track from new observations (a PDA method efficiently updates a track from all measurements, rather than from one likely measurements).

For the third subproblem, the existing methods were judged to be insufficient for meeting the objectives of the study. The desired results were obtained by applying Markov Jump-Diffusion theory to the modelling of aircraft behaviour. Bayesian estimation is used to identify sudden aircraft manoeuvres. Without going into the mathematical details of these methods, it is quite well possible to explain how they apply to sudden aircraft manoeuvres.

An aircraft trajectory, as seen by ATC, can be subdivided into distinct segments, corresponding to modes of flight, such as constant acceleration, bank angle or flight-path angle. Examples of such segments are a left or a right turn, a climb, a descent and uniform motion. The switching from one mode to another is controlled by the pilot. An appropriate model for the switching between modes is a finite-state (semi-)Markov process. An aircraft is then modelled as having a continuous (diffusive) state and a discrete state. The discrete state models the various modes of flight. The diffusive state of the aircraft consists of the horizontal position, ground speed, course and, for some modes, bank angle, flight-path angle and acceleration. The evolution in time of the discrete state (i.e. switching between modes) and the diffusive state is determined by the physical relations between the state components, the jump-type

changes of the control outputs by the pilot, and disturbances caused by both the pilot and the wind. In this model, a switching from one mode to another mode generally causes a simultaneous random jump in bank angle, flight-path angle and acceleration. The combination of discrete states and diffusive states in a manoeuvring trajectory model causes the associated tracking problem to fall within the class of so called hybrid-state estimation problems. Filtering algorithms for hybrid-state estimation consist in general of a bank of Kalman filters and some algorithm to organize the cooperation between the individual Kalman filters. The better such cooperation is organized, the less Kalman filters are necessary to perform close to the exact Bayesian solution. The study of this type of problems led to a better way of organizing the cooperation between Kalman filters, viz. the Interacting Multiple-Model (IMM) algorithm (Blom, 1984, 1985; Blom and Bar-Shalom, 1988).

The IMM algorithm (Fig. 1) has, for each possible mode m_i , one Kalman filter. The efficient cooperation between the Kalman filters is realized by an interaction between the estimates \hat{x}_i for the different modes at the beginning of each filter cycle. The interaction is determined by the conditional probabilities of switching between modes of flight. For problems like tracking, the IMM interaction is so effective, that IMM performs almost like the exact Bayesian filter (Blom, 1985; Blom and Bar-Shalom, 1988). Moreover, IMM requires a far lower computational power than other, recently developed, high-performance algorithms for tracking manoeuvring aircraft (Bogler, 1987; Bar-Shalom et al., 1988).

The last step is to assemble a complete track-continuation module from the three selected suboptimal Bayesian methods:

- the extended Kalman filter to deal with the non-linear aircraft dynamics during turns;
- PDA to deal with unassociated measurements;
- the IMM algorithm to deal with sudden manoeuvres.

Figure 2 shows the complete track-continuation set-up.

Due to the generality of the Bayesian approach, each of the three approximate methods in figure 2 is efficient for a large family of causal stochastic models. As such, the Bayesian tracking set-up of figure 2 can adequately be parametrized for a large family of track continuation problems. Therefore, it is possible to incorporate the measurements of a large variety of sensors into the set-up of figure 2. The price of this generality is that a large number of parameters has to be set properly. Experience, however, showed that most of these parameters are not very critical.

4. EVALUATION OF THE TRACKING PERFORMANCE

In this section, we give an impression of the performance of a prototype implementation of the Bayesian tracker. This prototype is called "Jump-Diffusion Tracker".

The performance evaluation is based on both Monte Carlo simulated measurements and measurements of live traffic. These data sets are selected, such that they present a wide range of difficulties to a tracker. Some typical Jump-Diffusion Tracker results are given in figures 3-5. The main results of this evaluation are that the Jump-Diffusion Tracker gives

- very accurate state estimates during constant mode of flight;
- very fast response upon and convergence after a change of mode;
- estimates of its own accuracy that are consistent with the actual errors.

Next, the performance of the Jump-Diffusion Tracker is compared against a tracker that consists of PDA combined with an Extended Kalman filter (Blom, 1983). Although this is also a Bayesian tracker, it lacks an adequate solution to the switching nature of manoeuvres. Using the above mentioned data sets, the comparison showed that the Jump-Diffusion tracker responds far better on sudden manoeuvres, while it is, at the same time, far less sensitive to bad measurement conditions. The observed differences are even larger than the differences reported for comparisons between Kalman filtering and IMM filtering in simpler situations of sudden accelerations (Blom, 1985). These results indicate that the Jump-Diffusion tracker realizes an effective cooperation between the IMM, the PDA and the Extended-Kalman filter methods.

For practical applications, it is of course more interesting to make a comparison of the Jump-Diffusion Tracker with operational trackers, viz.

- A logic-based α - β tracker;
- A logic-based extended α - β - γ tracker.

The α - β tracker and the α - β - γ tracker were operational for the main en-route radar system in the Netherlands, respectively before and after 1985. The indication "extended" of the α - β - γ refers to its capability to detect and follow turns.

The result of the comparison is that the Jump-Diffusion Tracker performs best, the α - β - γ tracker scores second, the PDA Extended-Kalman tracker scores third and the α - β tracker scores last. Moreover, the differences between the first and the last trackers are very large. The PDA Extended-Kalman tracker performs significantly better than the α - β tracker, i.e. far less sensitivity to outlier and false measurements, better convergence during a turn and smaller RMS speed errors. The α - β - γ tracker shows significant improvements over the PDA Extended-Kalman tracker, i.e. far smaller RMS state errors during uniform motion and far better convergence after starting or stopping a turn. The Jump-Diffusion Tracker performs significantly better than the α - β - γ tracker, i.e.

- far less sensitivity for outlier and false measurements;
- faster convergence after starting or stopping a manoeuvre;
- far smaller RMS speed errors;
- more stable behaviour during "strange" manoeuvres (accelerated turn, s-turn, expedite turn, non-circular turn, etc.)

Some examples of position and speed comparisons between an α - β - γ tracker and the Jump-Diffusion Tracker are given in figures 6-10 (live-data from the Leerdam Primary Surveillance Radar).

These comparisons show that an α - β - γ tracker provides ATC of far better track information than an α - β tracker and that, on its turn, Jump-Diffusion Tracking provides ATC of far better track information than an α - β - γ tracker.

5. SUMMARY AND CONCLUSIONS

An outline is given of the capabilities of a Bayesian multi-sensor tracking system. This system consists of several modules of which track continuation plays for ATC the most important role. We outlined the underlying principles of the Bayesian track continuator. It is assembled from the most efficient approximate Bayesian methods, such as Extended-Kalman filtering, Probabilistic Data Association and the Interacting-Multiple-Model algorithm. The latter was developed as a part of the tracking study. A prototype of this Bayesian track continuator was implemented (called "Jump-Diffusion Tracker") and evaluated with respect to computational load and performance. Although the computational load of Jump-Diffusion Tracking is rather high, it is possible to run a multi-sensor version in real-time on presently available multi-processor systems (Gerlofs, 1986). Its performance was evaluated and compared with that of other trackers. It showed that the Jump-Diffusion Tracker performs superior to other trackers or, more specifically, it shows better response on sudden manoeuvres and a lower sensitivity for measurement errors. Also, when measurement conditions deteriorate, the performance degrades far slower than the performance of the other trackers.

The overall conclusion of the study is, that an adequate Bayesian approach to the problem of tracking aircraft for ATC resulted in a new tracking method, called Jump-Diffusion Tracking, that can be implemented on presently available hardware. The tracker showed excellent behaviour and is also able to provide advanced ATC system of additional state information, such as mode of flight probabilities and a reliable indication of its own accuracy.

6. REFERENCES

1. Y. Bar-Shalom, K.C. Chang and H.A.P. Blom, Tracking a manoeuvring target using Input Estimation versus the Interacting Multiple Model algorithm, IEEE Tr. on Aerospace and Electronic Systems, Vol. 24, October 1988.
2. Y. Bar-Shalom and T.E. Fortmann, Tracking and data association, Academic Press, 1988.
3. S.S. Blackman, Multiple target tracking with radar applications, Artech Book Company, London, 1986.
4. H.A.P. Blom, Comparison of a Jump-Diffusion tracker with a Kalman tracker. An evaluation with emphasis on Air Traffic Control, Report NLR TR 83063, National Aerospace Laboratory NLR, 1983.
5. H.A.P. Blom, An efficient filter for abruptly changing systems, Proc. 23rd IEEE Conf. on Decision and Control, Dec. 1984, pp. 656-658.
6. H.A.P. Blom, An efficient decision-making-free filter for processes with abrupt changes, Proc. 7th IFAC Symp. Ident. and System Param. Estimation, York (U.K.), 1985, pp. 631-636.
7. P. Bogler, Tracking a manoeuvring target using Input Estimation, IEEE Tr. Aerospace and Electronic Systems, Vol. 23 (1987), pp. 298-310.
8. C.B. Chang and J.A. Tabaczynski, Application of state estimation to target tracking, IEEE Tr. Automatic Control, Vol. 29 (1984), pp. 98-109.
9. C.Y. Chong, S. Mori, E. Tse and R.P. Wishner, Distributed hypothesis formation in distributed sensor networks, Report TR 1015-1, Advanced Decision Systems, Mountain View, CA, 1982.
10. A. Farina and F.A. Studer, Radar data processing, Vol. 1, Introduction and tracking, Research Studies Press/Wiley, 1985.
11. A. Farina and F.A. Studer, Radar data processing, Vol. 2, Advanced topics and applications, Research Studies Press/Wiley, 1986.
12. M. Gausvrit, Bayesian adaptive filtering for tracking with measurements of uncertain origin, Automatica, Vol. 20 (1984), pp. 217-224.
13. J.F. Gerlofs, Technical feasibility of the multi-radar Jump-Diffusion tracker, NLR memorandum IR-86-030 L, National Aerospace laboratory NLR, Amsterdam, 1986.
14. R.A. Hogendoorn and H.A.P. Blom, Bayesian track initiation by time-reversion of trajectory models, NLR MP, 1988.
15. A.H. Jazwinski, Stochastic processes and filtering theory, Academic Press, New York, 1970.
16. K.R. Pattipati and N.R. Sandell, Jr, A unified view of state estimation in switching environments, Proc ACC, June 1983, pp. 458-465.

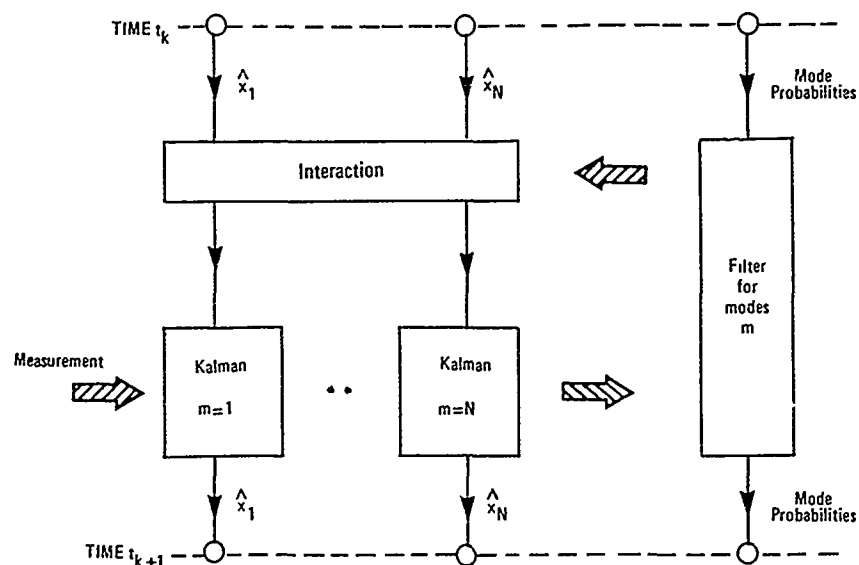


Fig. 1 One cycle of the IMM algorithm (N modes).

\hat{x}_i represents the conditional expectation and covariance given mode i is effective. The mode probabilities represent the conditional probabilities that each of the N modes is effective.

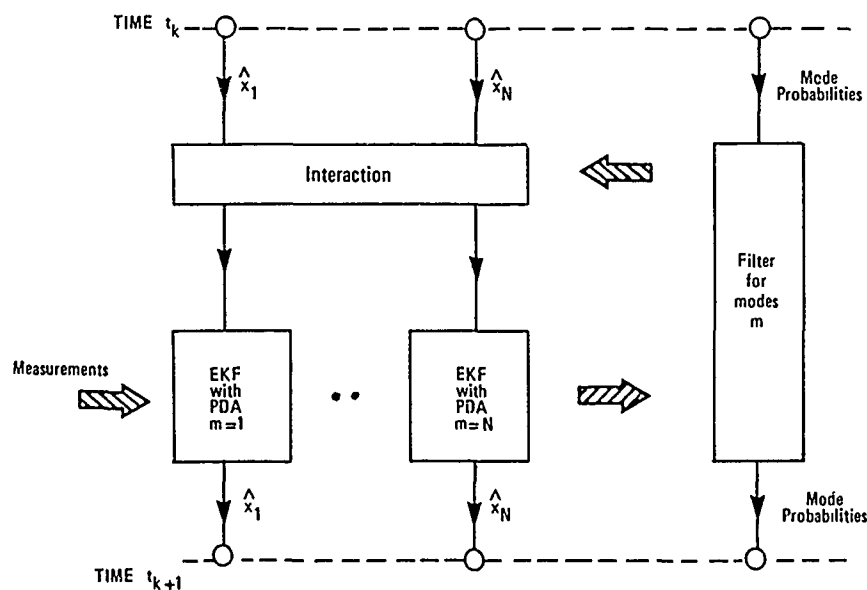
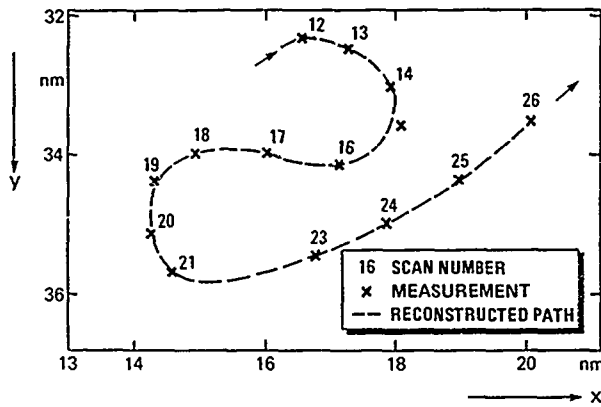
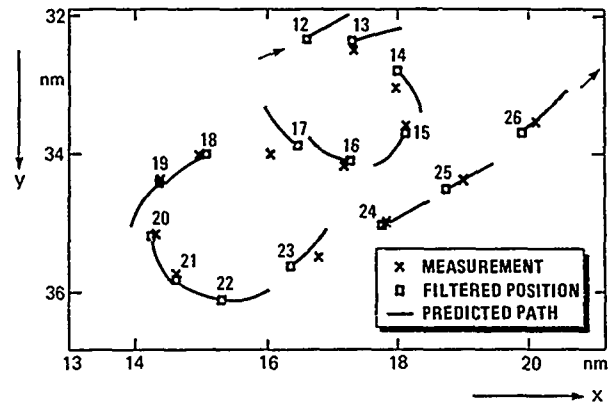


Fig. 2 One cycle of a Bayesian track continuator (N modes).

\hat{x}_i represents the conditional expectation and covariance given mode i is effective. The mode probabilities represent the conditional probabilities that each of the N modes is effective.

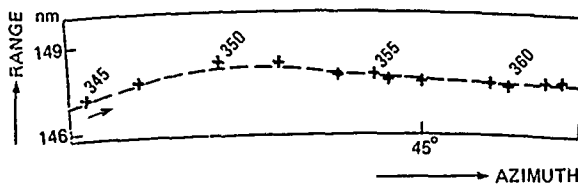


a) Reconstructed trajectory

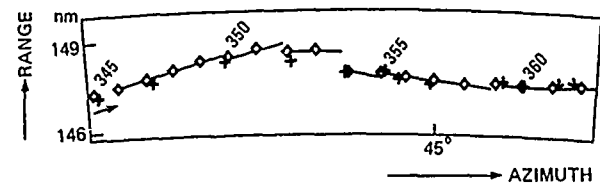


b) The jump-diffusion track

Fig. 3 A "strange" manoeuvre

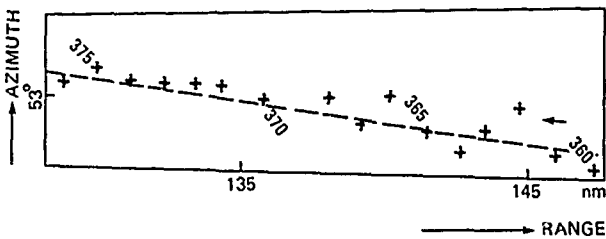


a) Reconstructed trajectory

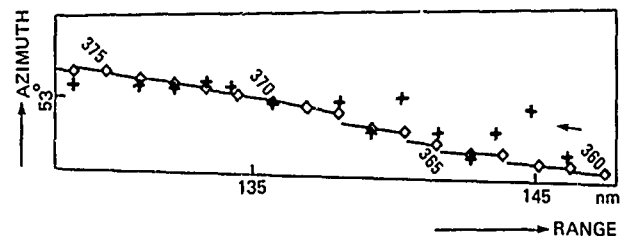


b) The jump-diffusion track

Fig. 4 A tangential flight with a change of course



a) Reconstructed trajectory



b) The jump-diffusion track

Fig. 5 A radial flight

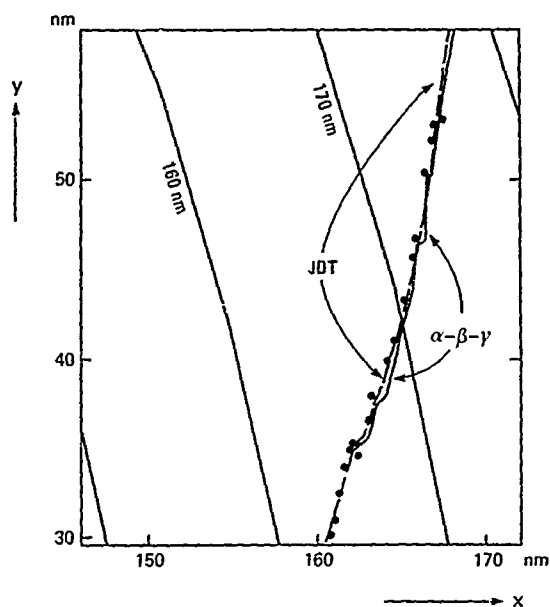


Fig. 6 En route tracking

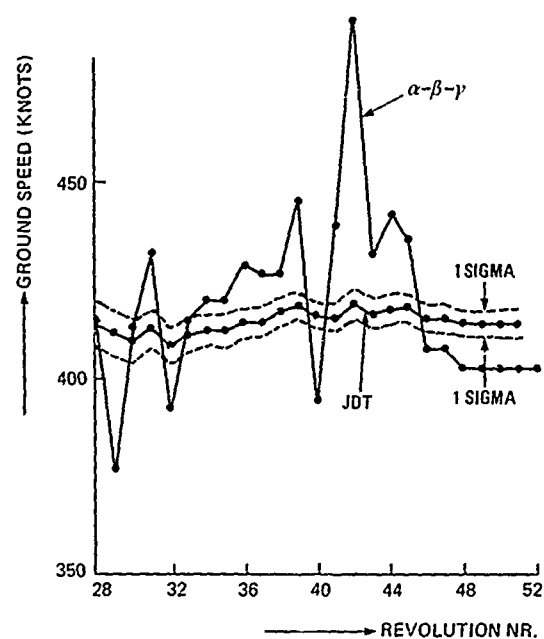
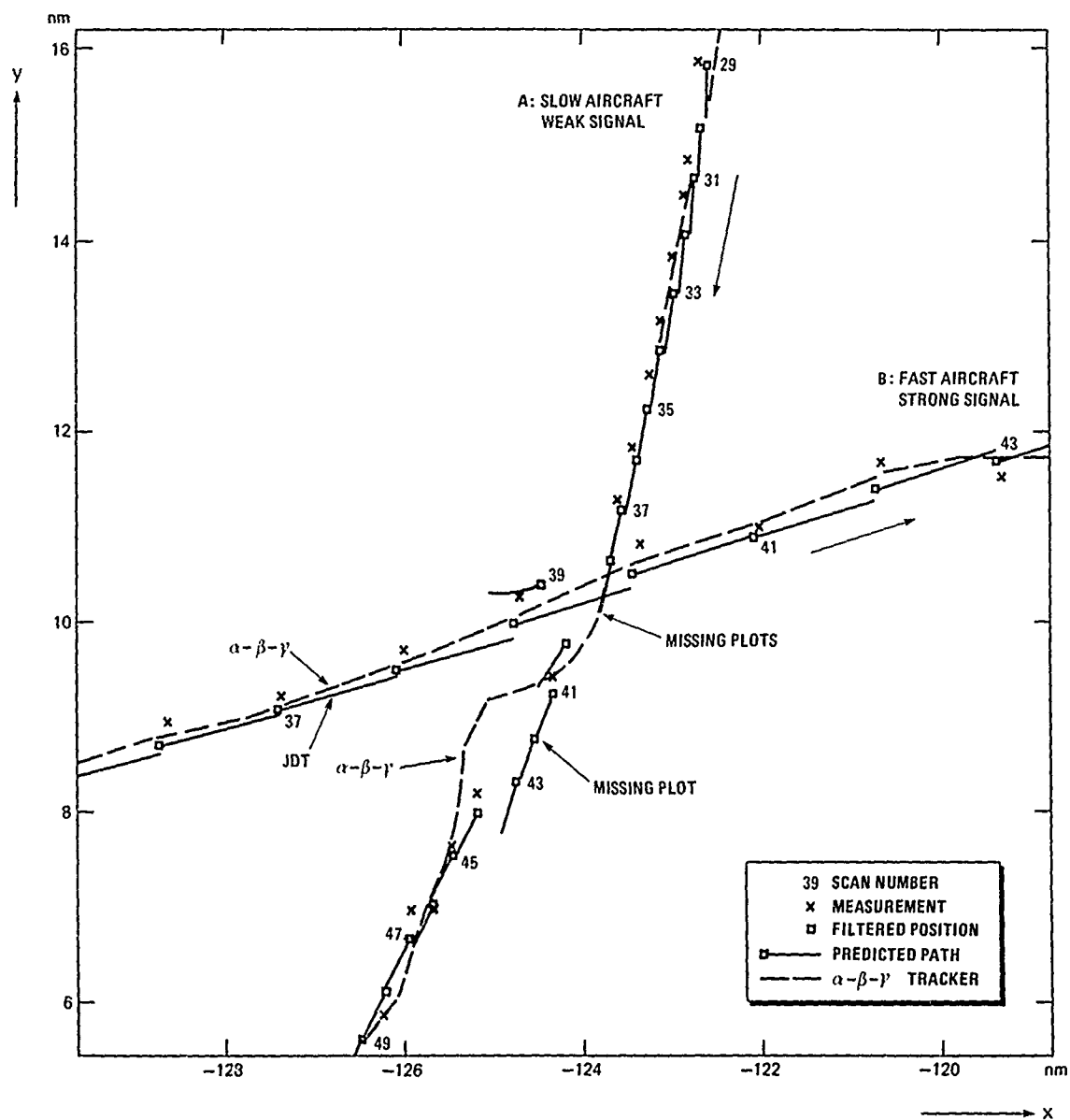


Fig. 7 Ground speed comparison for the track of figure 6

Fig. 8 Crossing tracks (α - β - γ tracker compared to JDT)

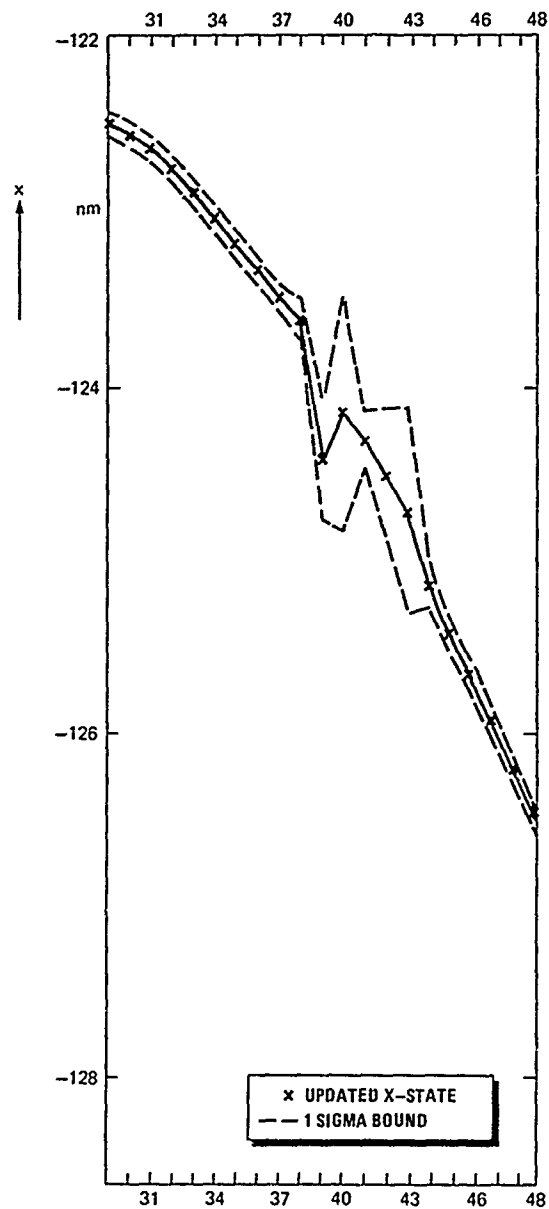


Fig. 9 Updated x-state
(referring to slow aircraft (A) in
figure 8)

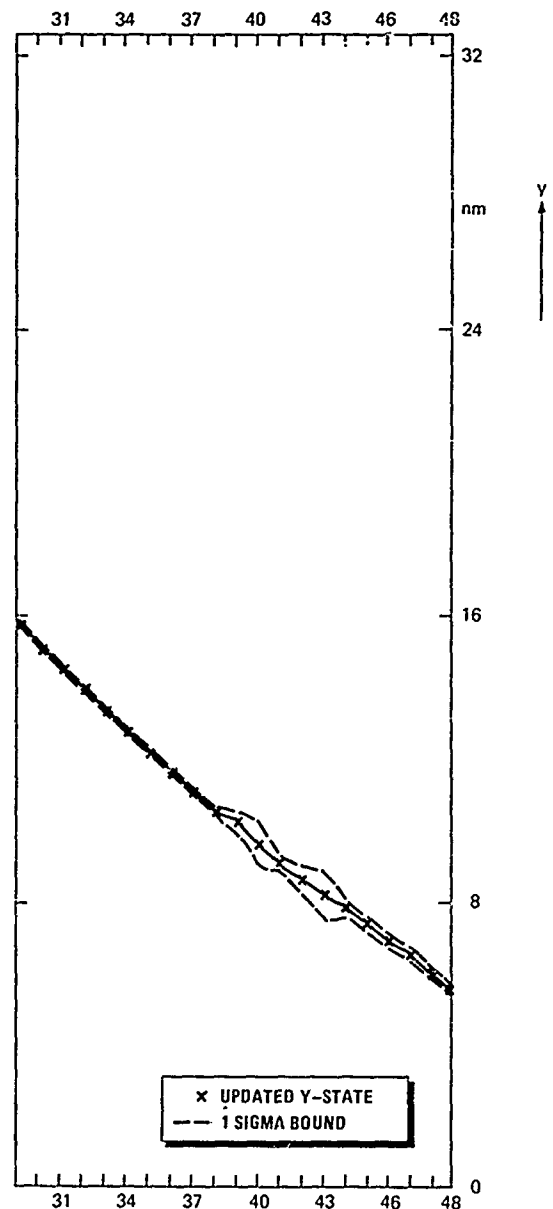


Fig. 10 Updated y-state
(referring to slow aircraft (A) in
figure 8)

→ REVOLUTION NR.

THE USE OF DOWNLINKED MEASUREMENTS TO TRACK CIVIL AIRCRAFT

by

C.C. Lefas

associate professor, Technical University of Crete
19 Arapaki str, 176.76 Kallithea, Athens, Greece

SUMMARY

This paper describes the use of measurements made on board civil aircraft to improve tracking accuracy in air traffic control (ATC) systems. The measurements are transmitted to the ground station via the SSR mode S data link.

First the widely used α - β filter and the first order Kalman filter are reviewed. Next the problem of maneuver handling is described and it is established that significant improvements, in terms of tracking accuracy, are expected when tracking maneuvering aircraft. The shape of maneuvers is examined using recordings made on board civil aircraft during normal scheduled services.

The on board measurements considered are roll angle, heading and true air speed (TAS). Roll angle and the rate of change of Heading are theoretically equivalent, since they are related through aircraft velocity. Maneuver tracking filters using either roll angle or heading are described and compared. It is shown that the filter using heading provides a better performance in the event of missing replies, since changes of heading are eventually detected. Both filters cannot track longitudinally accelerating targets.

Next the use of velocity measurements, derived from TAS and heading, is considered. A filter is described that is capable of estimating the wind speed in the vicinity of the aircraft. The same filter provides satisfactory tracking accuracy during maneuvers and can handle longitudinal accelerations.

Under monoradar coverage, where the data rate and accuracy are fairly constant, the filters reduce to a particularly simple form, that may be regarded as an enhanced α - β filter.

The performance of the filters is evaluated using data recorded during normal scheduled services.

1. INTRODUCTION

The formation of civil aircraft tracks for air traffic control (ATC) purposes is investigated in the present paper. Initially radar measurements were the only measurements available to the ground data processing system and consequently aircraft tracks were formed using noisy positional data only. In this respect a great deal of effort has been concentrated on suboptimal filters with reduced computational requirements and, in the case of straight line tracks, a vast body of knowledge exists e.g. [1-6]. In the case of monoradar coverage, where data rate and accuracy is approximately constant, a simple filter, known as the α - β filter, is being widely used with satisfactory results. In the case of multiradar coverage however, where neither data rate nor data accuracy are constant, trackers based on the first order Kalman filter are used. In either case the tracking accuracy achieved is satisfactory during straight line tracks (i.e. during straight line/constant velocity flight), whereas during maneuvers it is not.

Civil aircraft tracks are adequately modelled as straight line segments connected together with turns. During these turns the straight line model acquired by processing previous measurements is not valid and totally erroneous tracks result if no provision to handle maneuvers is made. At present maneuvers are handled by maneuver detectors, which merely detect maneuvers as statistically significant departures from the straight line/constant velocity model. This is achieved by processing the tracking filter residuals (difference between the predicted and the measured aircraft position). Once a maneuver is detected, smoothing is relaxed, so that the tracker acquires quickly another straight line model from new positional measurements. Consequently any tracker incorporating a maneuver detector is bound to suffer a significant loss of accuracy during and immediately after maneuvers, since it makes no attempt to track them. In this sense the overall performance of the tracker is degraded by its inability to track maneuvering aircraft.

To overcome the maneuver tracking problem a number of adaptive filter trackers has been developed. Instead of using a simple maneuver detector to relax smoothing, these trackers estimate the probability of a maneuver and change the flight model accordingly (for an excellent review of adaptive filter trackers look [7]). All adaptive trackers have large computational requirements, compared to the first order Kalman filter tracker, and perform best in environments where measurements are available at a rate in the order of 10 measurements per second or higher.

The evolutionary development of the secondary surveillance radar (SSR) towards SSR mode S opens new possibilities in radar tracking in ATC systems. A transponder is available on board which is automatically triggered when the aircraft is scanned, transmitting back code and altitude data. Via the same link other measurements made on board, like roll angle or magnetic heading, can be transmitted to the ground. The

importance of such measurements stems from the fact that they are directly related to the state of the aeroplane. Roll angle for example is directly related to the lateral acceleration of the aircraft. Similarly the rate of change of heading is directly related to the angular velocity of maneuvering aircraft. Consequently by processing such measurements on the ground, it is possible to detect and track aircraft maneuvers far more efficiently than processing positional measurements only. The present paper describes ways of incorporating roll angle, heading and TAS measurements in ground based trackers. Several algorithms are described using each of these parameters and are finally compared. The comparison takes place by using data recorded on board civil aircraft during normal scheduled services. These data are combined with radar measurements to provide a realistic data base on which aircraft derived data assisted trackers may be compared and evaluated.

2. BACKGROUND

2.1 The first order Kalman filter tracker

The first order Kalman filter tracker is used to track aircraft moving on a straight line/constant velocity course. Consider an aeroplane flying on a straight line with constant velocity. Two identical filters are used to track it, each operating on each axis of a cartesian coordinate system OXY. The earth is assumed to be flat and measurements are assumed to be uncorrelated between the two axes. Although these assumptions are not strictly true they are made to enable the decoupling of the tracking process between the two axes. Under these assumptions the motion of the aeroplane is described by two equations on each axis as follows:

$$\begin{aligned} x_{k+1} &= x_k + vx_k T + 0.5 vx_k T^2 \\ vx_{k+1} &= vx_k + yx_k T \end{aligned} \quad (1.1)$$

$$x_m = x_{k+1} + \text{noise}$$

In matrix form these equations are written as follows:

$$\begin{aligned} \begin{bmatrix} x_{k+1} \\ vx_{k+1} \end{bmatrix} &= \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_k \\ vx_k \end{bmatrix} + \begin{bmatrix} 0.5T^2 \\ T \end{bmatrix} vx_k \end{aligned} \quad (1.2)$$

$$x_m = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_{k+1} \\ vx_{k+1} \end{bmatrix} + \text{noise} \quad (1.3)$$

Define the transition matrix Φ_k , the noise matrix G_k and the measurements matrix M_k :

$$\begin{aligned} \Phi_k &= \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} & G_k &= \begin{bmatrix} 0.5T^2 \\ T \end{bmatrix} & M_k &= \begin{bmatrix} 1 & 0 \end{bmatrix} \end{aligned}$$

The standard deviation of the plant noise and the measurement noise are assumed to be constant under monoradar coverage and equal to σ_{pn} and σ_x respectively. T and σ_x are not constant under multiradar coverage.

At the end of the k th iteration the best estimates of the position and the velocity, \hat{x}_k and \hat{vx}_k respectively, are available. The Kalman filter tracker for the system described by eqns 1.2 and 1.3 consists of the following five steps:

1. Given \hat{x}_k and \hat{vx}_k calculate the predicted position and velocity
at $t=t_{k+1}$, \tilde{x}_{k+1} and \tilde{vx}_{k+1} .

$$\tilde{x}_{k+1} = \hat{x}_k + \hat{vx}_k T \quad (1.4)$$

$$\tilde{vx}_{k+1}$$

2. given the covariance matrix \hat{P}_k of \hat{x}_k and \hat{v}_k calculate the covariance matrix \tilde{P}_{k+1} of \tilde{x}_{k+1} and \tilde{v}_{k+1}

$$\tilde{P}_{k+1} = \begin{bmatrix} \hat{p}_{11} + 2\hat{p}_{12}T + \hat{p}_{22}T^2 + 0.25T^4\sigma_{pn}^2, & \hat{p}_{12} + \hat{p}_{22}T + 0.5T^3\sigma_{pn}^2 \\ \hat{p}_{12} + \hat{p}_{22}T + 0.5T^3\sigma_{pn}^2, & \hat{p}_{22} + \sigma_{pn}^2T^2 \end{bmatrix} \quad (1.5)$$

3. Compute the Kalman gain matrix (smoothing coefficients).

$$K_{k+1} = \begin{bmatrix} \tilde{p}_{11} \\ \hline \sigma_x^2 + \tilde{p}_{11} \\ \tilde{p}_{12} \\ \hline \sigma_x^2 + \tilde{p}_{11} \end{bmatrix} \quad (1.6)$$

4. Calculate the new best estimates x_{k+1} and v_{k+1} .

$$\hat{x}_{k+1} = \tilde{x}_{k+1} + k_{11}(x_m - \tilde{x}_{k+1}) \quad (1.7)$$

$$\hat{v}_{k+1} = \tilde{v}_{k+1} + k_{21}(x_m - \tilde{x}_{k+1}) \quad (1.8)$$

where k_{ij} are the elements of K_{k+1} and x_m is the $k+1$ positional measurement.

5. Compute the covariance matrix \hat{P}_{k+1} of \hat{x}_{k+1} and \hat{v}_{k+1} .

$$\hat{P}_{k+1} = \frac{1}{\tilde{p}_{11} + \sigma_x^2} \begin{bmatrix} \tilde{p}_{11}\sigma_x^2, & \tilde{p}_{12}\sigma_x^2 \\ \tilde{p}_{12}\sigma_x^2, & (\tilde{p}_{11} - \sigma_x^2)\tilde{p}_{22} - \tilde{p}_{12}^2 \end{bmatrix} \quad (1.9)$$

At this stage \hat{x}_{k+1} and \hat{v}_{k+1} and their covariance matrix \hat{P}_{k+1} are available. Note that \hat{p}_{11} is the variance of \hat{x}_{k+1} , \hat{p}_{22} is the variance of \hat{v}_{k+1} and $\hat{p}_{12} = \hat{p}_{21}$ is the their covariance. (\hat{p}_{ij} are the elements of \hat{P}_{k+1}).

3. SHAPE OF MANEUVERS

Since the second order tracker can estimate only a constant acceleration, it is important to consider a proper model for the aircraft turns. The shape of maneuvers is investigated from roll angle, TAS and heading recordings made on board civil aircraft. These aeroplanes usually maintain the same longitudinal velocity during turns and this is conformed from TAS recordings. Figure 3.1 shows roll angle, TAS, heading and pressure altitude measurements recorded during a typical maneuver. The longitudinal acceleration of the aircraft is nearly zero, and the lateral acceleration is directly related to roll angle.

A particular maneuver model has to be chosen to be used by the maneuver tracking filter. The simplest model is the circle, for which roll angle should be a step function. Unfortunately large asymmetries are found in almost all civil aircraft maneuvers. Figure 3.2 shows roll angle recordings during four typical maneuvers. It can be seen that the transition times from zero to maximum roll and, particularly, from maximum roll back to zero are very long compared to the time during which roll is steady. This a feature commonly found in civil aircraft maneuvers. Therefore smaller maneuvers resemble a circular turn less than large maneuvers. Figure 3.2b shows a typical small maneuver and it can be seen that roll angle is never steady. Figure 3.2a represents a total change of heading of 25°, and figure 3.2b of only 7°. Figure 3.2c shows a quite irregular turn consisting of four subarcs like the one shown in figure 3.2b yielding an overall change of heading of 20°. Figure 3.2d shows

another irregular maneuver yielding a total change of heading of 14° . From the above examples it is seen that no maneuver model fits all civil aircraft maneuvers. Therefore a circular maneuver model is used, treating any deviation as noise. An alternative is to use directly roll angle or change of heading measurements without any processing to estimate the state of a maneuvering aircraft. This possibility yields simple filters capable of tracking irregular maneuvers and is exploited in filters developed later.

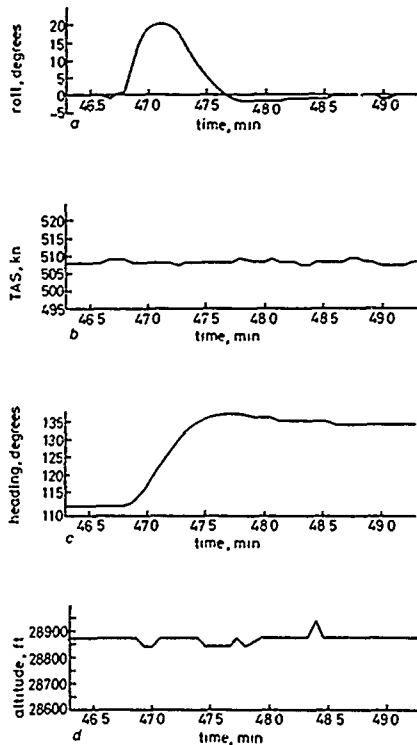


Figure 3.1
Roll angle, true air speed, magnetic heading and pressure altitude plotted against the time during a typical maneuver. The tracked aeroplane is a B747 airliner.

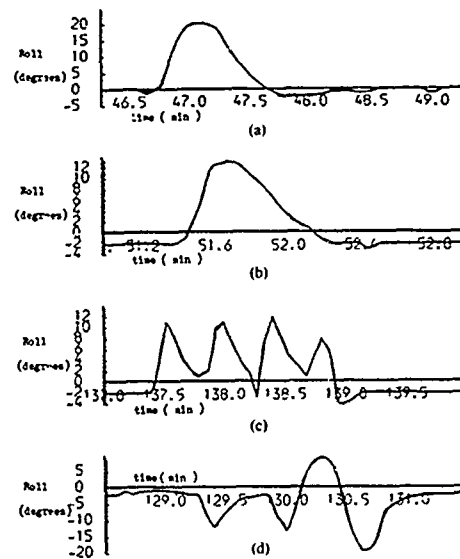


Figure 3.2
Roll angle plotted against time during four typical maneuvers. The aeroplane is a B747 airliner.

4. FILTERS USING ROLL ANGLE

4.1 The extended Kalman filter

Consider an aircraft maneuvering along a circular track. In this case its motion is described by the following equations:

$$\begin{aligned}
 \dot{x} &= vx + \text{noise} \\
 \dot{vx} &= -(a/v)vy + \text{noise} \\
 \dot{y} &= vy + \text{noise} \\
 \dot{vy} &= (a/v)vx + \text{noise} \\
 \dot{a} &= 0 + \text{noise}
 \end{aligned} \tag{4.1}$$

$$\text{where } v = \sqrt{vx^2 + vy^2}$$

vx and vy are given as functions of time by:

$$vx = v \cos(\varphi_0 + (a/v)t)$$

$$vy = v \sin(\varphi_0 + (a/v)t)$$

where φ_0 is the angle between the velocity vector and the X axis at time $t=0$. Since x, y and a are measurable, the measurement equation becomes:

$$\begin{bmatrix} x_m \\ y_m \\ a_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ vx \\ y \\ vy \\ a \end{bmatrix} + \text{noise} \tag{4.2}$$

a_m is derived from roll angle measurements according to:

$$a_m = g \tan(\text{roll}) \tag{4.3}$$

x_m and y_m are obtained by resolving radar range and bearing measurements:

$$x_m = R_m \sin(\theta_m) \tag{4.4}$$

$$y_m = R_m \cos(\theta_m) \tag{4.5}$$

The covariance matrix R_{k+1} of the measurements (x_m , y_m and a_m) is given by:

$$R_{k+1} = \begin{bmatrix} \sigma_x & p_{xy} & 0 \\ p_{xy} & \sigma_y & 0 \\ 0 & 0 & \sigma_a \end{bmatrix} \tag{4.6}$$

where

$$\sigma_x = \sigma_R \sin(\theta_m) + R \sigma_\theta \cos(\theta_m) \tag{4.7}$$

$$\sigma_y = \sigma_R \cos(\theta_m) + R \sigma_\theta \sin(\theta_m) \tag{4.8}$$

$$p_{xy} = 0.5(\sigma_R - R \sigma_\theta) \sin(2\theta_m) \tag{4.9}$$

$$\sigma_a = \sigma_{\text{roll}} (1 + \tan^2(\text{roll})) \tag{4.10}$$

where σ , σ , p , σ , R , θ , σ , σ are as defined in the list of principal symbols.

Equations 4.1 and 4.2 describe a mildly nonlinear dynamic system. The extended Kalman filter is an appropriate filter to use with this system.

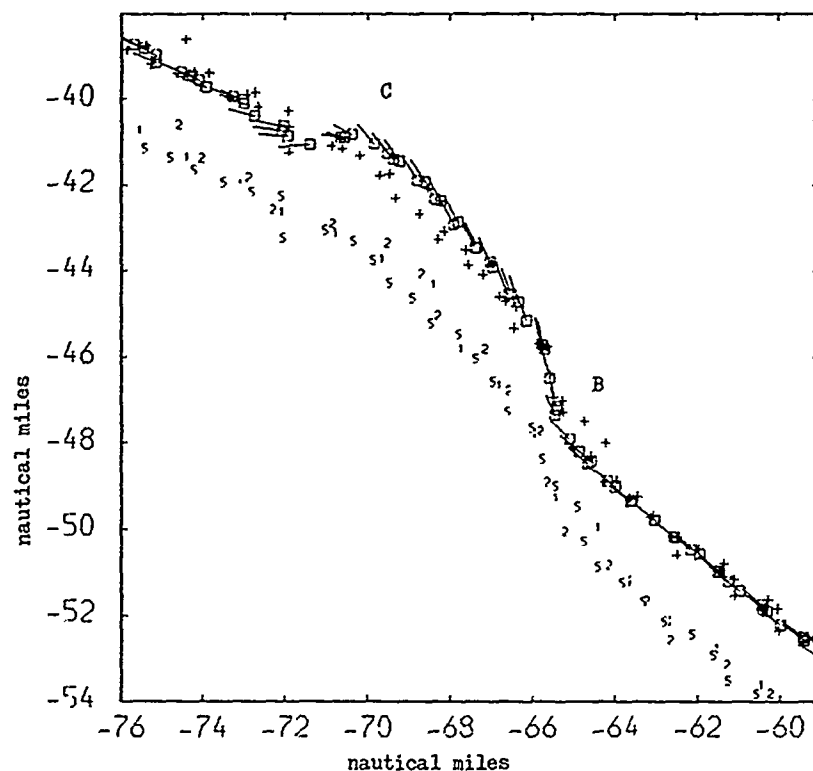


Figure 4.1

+ denote measurements, $\hat{\alpha}$ denote filter estimates. The number of the radar taking the measurements is shown displaced under the actual measurement.

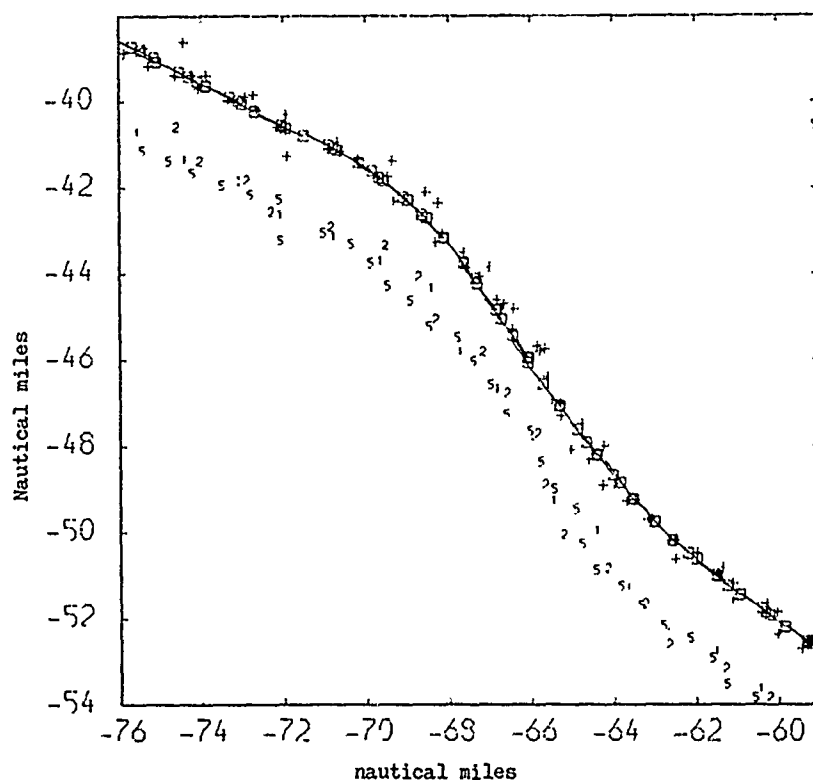


Figure 4.2

Typical maneuver tracked by the extended Kalman filter using roll angle.
+ denote measurements, \square denote filter estimates. The number of the radar taking the measurements is shown displaced under the actual measurement.

Figure 4.1 shows a typical maneuver tracked by the extended Kalman filter using roll angle measurements. Figure 4.2 shows the same maneuver tracked by a first order Kalman filter tracker with a maneuver detector. The extended Kalman filter tracks the maneuvering aircraft satisfactorily whereas the classical first order Kalman filter tracker suffers a serious loss of accuracy during the maneuver until a new straight line track is established. It can be seen from equations 4.1 and 4.2 that the extended Kalman filter requires the multiplication and inversion of 5X5 matrices, which constitutes a serious computational requirement compared to the first order Kalman filter tracker. The computation requirements of the extended Kalman filter would be significantly reduced if the tracking process could be split and performed independently on the two axes of the coordinate system, but this is not possible under the formulation of equation 4.1. This is so because the acceleration term appears on both axes and is an element of the state vector of the system. Roll angle measurements made onboard civil aircraft and transmitted to the ground station via the mode S data link are of good quality, so that the acceleration term in equations 4.1 can be obviated. In this case the roll angle estimate is set equal to the current acceleration measurement. This makes the separation of the tracking filter in two suboptimal tracking filters possible, each one operating on one axis of the coordinate system. This leads to a simple and efficient tracker, the acceleration bias filter (ABF) described in the next section.

4.2 The acceleration Bias Filter (ABF)

A simpler alternative to the extended Kalman filter exists since roll angle measurements available on board civil aircraft are of sufficiently good quality to obviate the use of the acceleration term in equations 4.1. In this case the lateral acceleration is calculated from the last roll angle measurement using equation 4.3. The standard deviation of the new lateral acceleration measurement is calculated according to equation 4.10. Since the lateral acceleration is calculated from the last roll angle measurement only, it is uncorrelated to any other measurement or estimate (position and velocity on each axis). In addition no particular maneuver model has to be used, at least as far as the computation of lateral acceleration is concerned.

The above assumption lead to a simple maneuver tracking filter. The target dynamics are still described by the first four equations 4.1. In this case however the correlation between the X and Y axes can be neglected, as is done by the first order Kalman filter tracker during straight line/constant velocity flight. In addition lateral acceleration is regarded as a noisy input to the system.

The new maneuver tracking filter, called the acceleration bias filter (ABF) for reasons that will be described later, consists of the five steps as does the first order Kalman filter tracker.

1. Predictions are calculated by integrating equations 4.1 from $t=t_k$ to $t=t_{k+1}$. After some manipulation prediction equations become:

On X axis:

$$\hat{x}_{k+1} = \hat{x}_k + \hat{v}_x T \cos(0.5 \hat{a}_k T / \hat{v}_k) - \hat{v}_y T \sin(0.5 \hat{a}_k T / \hat{v}_k) \quad (4.11)$$

$$\hat{v}_{x,k+1} = \hat{v}_x \cos(\hat{a}_k T / \hat{v}_k) - \hat{v}_y T \sin(\hat{a}_k T / \hat{v}_k) \quad (4.12)$$

On Y axis:

$$\hat{y}_{k+1} = \hat{y}_k + \hat{v}_y T \cos(0.5 \hat{a}_k T / \hat{v}_k) + \hat{v}_x T \sin(0.5 \hat{a}_k T / \hat{v}_k) \quad (4.13)$$

$$\hat{v}_{y,k+1} = \hat{v}_y \cos(\hat{a}_k T / \hat{v}_k) + \hat{v}_x T \sin(\hat{a}_k T / \hat{v}_k) \quad (4.14)$$

where \hat{a}_k is put equal to the last lateral acceleration measurement. Note that on each axis a separate filter is iterated.

2. Calculate the prediction covariance matrix:

For the X axis the prediction covariance matrix becomes:

$$\hat{P}_{k+1} = \begin{bmatrix} \hat{x}_{p11} & \hat{x}_{p12} \\ \hat{x}_{p12} & \hat{x}_{p22} \end{bmatrix} \quad (4.15)$$

where $\hat{x}_{p_{ij}}$ are given in Appendix A.

Similarly for the Y axis the prediction covariance matrix becomes:

$$\hat{P}_{k+1} = \begin{bmatrix} \hat{y}_{p11} & \hat{y}_{p12} \\ \hat{y}_{p12} & \hat{y}_{p22} \end{bmatrix} \quad (4.16)$$

where $\hat{y}_{p_{ij}}$ are given in Appendix A.

At this stage the only measurement left to be processed is the k+1 positional measurement x_m . Since the covariance between the two axes is neglected, smoothing takes place independently on each axis. Since the positional measurement is the only one left to be processed the rest of the equations of the ABF are identical to the equations of the first order Kalman filter.

3. Calculate the Kalman gain matrix.

The Kalman gain matrix (smoothing coefficients) are calculated by the formulas of the first order Kalman filter (equations 1.6).

4. Calculate the new best estimates \hat{x}_{k+1} and \hat{v}_{k+1}

The new best estimates are calculated as in the first order Kalman filter by equations 1.7 and 1.8.

5. Calculate the new covariance matrix \hat{P}_{k+1}

The new covariance matrix is calculated as in the first order Kalman filter by equation 1.9.

Comparing the new tracker with the first order Kalman filter it is readily seen that they differ only in the prediction and prediction covariance equations. Actually prediction and prediction covariance equations are performed independently on each axis. The resulting equations may be regarded as the equations of an augmented Kalman filter where its prediction equations are biased by a non zero lateral acceleration measurement (hence the name ABF).

Comparing further the first order Kalman filter and the ABF equations, it is readily seen that the ABF reduces to the first order Kalman filter for $\hat{a}_k = 0$. The only difference is that an additional term remains in the prediction \hat{x}_k covariance equations, reflecting the fact that for the ABF the straight line/constant velocity flight is an event estimated with a certain probability (for $\hat{a}_k = 0$) whereas for the first order Kalman filter the straight line/constant velocity flight is an a-priori assumption. The operation of a non-zero \hat{a}_k measurement may therefore be regarded as biasing the prediction and prediction \hat{x}_k covariance equations of a first order Kalman filter tracker to allow it to adapt to the change of the behaviour of the target. In addition there is no particular assumption made about the shape of the maneuver, since the acceleration estimate is always put equal to the current acceleration measurement. Consequently the ABF is capable of tracking maneuvers of irregular shape.

Figure 4.3 shows an irregular maneuver tracked by ABF. Figure 4.1 shows the same part of flight tracked by a first order Kalman filter tracker with a maneuver detector. The ABF tracks the maneuver satisfactorily whereas the first order Kalman filter suffers a great loss of accuracy.

The ABF is a simple filter relying on the quality of the data linked roll angle measurements. In a practical implementation first order Kalman filters are used to track straight line/constant velocity flight, switching to the ABF as soon as a non-zero lateral acceleration measurement is received. Alternatively the ABF can be used throughout the entire flight since it is capable of tracking both maneuvering and non-maneuvering aircraft. The penalty in this case is the computational overhead of the ABF as it is seen from appendix A.

The only problem with the ABF is that it relies heavily on the received roll angle measurements. In the event of a data link disruption the ABF yields totally erroneous tracks. Consequently a false roll angle measurement rejection scheme must be employed before the received roll angle measurements are fed to the tracker.

4.3 False measurement rejection

Civil aircraft maneuver with a maximum lateral acceleration of 1g. taking into account that lateral acceleration and roll angle are related through equation 4.3, the maximum acceptable roll angle measurement is 45°. Consequently a simple false roll angle measurement rejection scheme is to accept all roll angle measurements within the $\pm 45^\circ$ window and reject all others.

To assess the efficiency of this scheme consider a false roll angle measurement of exactly 45° received during an actually straight line flight. This measurement is accepted as valid and will cause an error in the prediction equations. This error is less than $0.5\hat{a}_k T^2$. Assuming a typical sampling interval of 5s the error is less than 0.08nm. This \hat{x}_k error is acceptable and will not cause any severe transient errors in the behaviour of the filter. In the case of a false measurement the missing roll angle measurement is replaced by the last valid roll angle measurement and σ is increased by 50% for each missing reply. The value of 50% increase has been reached by trial and error to give good results for 5s sampling intervals.

4.4 Necessary range and resolution for the roll angle measurements

As is described earlier, the maximum lateral acceleration to which a civil aeroplane may be subjected is $1g$. Therefore the necessary range of roll angle measurements is $\pm 45^\circ$. A 1° resolution has been used in the present data, but this is too coarse since roll angle measurements have a standard deviation less than 1° . On the other hand increasing the roll angle measurement resolution increases the data link capacity taken to transmit roll angle. Consequently a very fine resolution for roll angle is also undesirable and 0.5° is a reasonable compromise.

The maximum data rate is once per antenna revolution. This is marginally sufficient, particularly with low speed aircraft. Consider for example an aeroplane flying at 200Knots executing a 30° turn. It takes only 9.5s to complete the turn and therefore, if a larger sampling interval is used, there is a certain probability that no measurement is received during the maneuver. If this happens then the ABF has no means to adapt to the maneuver and a large overshoot and loss of accuracy will occur. Consequently roll has to be transmitted every scan.

Even with the maximum data rate there is a possibility that slow turns are missed by the ABF. The same thing applies in the event of missing replies. This is so because roll angle returns to zero after the maneuver is completed, so that its detection is not possible if no roll angle measurement is received during the maneuver. This is true for any filter using roll angle and to treat this problem heading has to be used instead of roll angle. Changes of heading are eventually detected even if no measurements are received during the actual maneuver. Also the change of heading is equivalent to roll angle, given the longitudinal velocity of the aeroplane. The use of heading is examined in the next chapter.

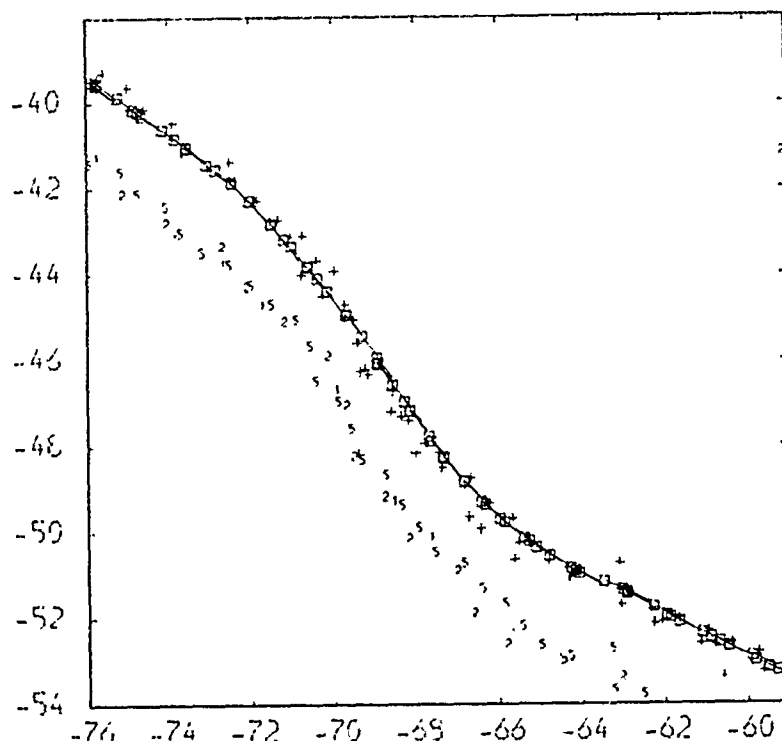


Figure 4.3

Typical maneuver tracked by the acceleration bias filter (ABF).
 + denote measurements, D denote filter estimates. The number of the radar taking the measurements is shown displaced under the actual measurement.

5. FILTERS USING HEADING

5.1 The Extended Kalman filter

A circular motion of the aeroplane may be described using its angular velocity instead of its lateral acceleration. In this case the system state equations become:

$$\begin{aligned}\dot{x} &= vx + \text{noise} \\ \dot{y} &= vy + \text{noise} \\ \dot{\omega} &= 0 + \text{noise}\end{aligned}\tag{5.1}$$

where $v = \sqrt{vx^2 + vy^2}$

vx and vy are given as functions of time by:

$$vx = v \cos(\phi_0 + \omega t)$$

$$vy = v \sin(\phi_0 + \omega t)$$

where ϕ_0 is the angle between the velocity vector and the X axis at time $t=0$. Since x, y and ω are measurable, the measurement equation becomes:

$$\begin{bmatrix} x_m \\ y_m \\ \omega_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ vx \\ y \\ vy \\ \omega \end{bmatrix} + \text{noise}\tag{5.2}$$

ω_m is derived by differentiating heading measurements

x_m and y_m are obtained by resolving radar range and bearing measurements:

$$x_m = R_m \sin(\theta_m)\tag{5.3}$$

$$y_m = R_m \cos(\theta_m)\tag{5.4}$$

Equations 5.1 and 5.2 describe a mildly nonlinear dynamic system. The extended Kalman filter is an appropriate filter to use with this system. Figure 5.1 shows a typical maneuver tracked by the extended Kalman filter using heading measurements. Figure 4.1 shows the same maneuver tracked by a first order Kalman filter tracker with a maneuver detector. The extended Kalman filter tracks the maneuvering aircraft satisfactorily whereas the classical first order Kalman filter tracker suffers a serious loss of accuracy during the maneuver until a new straight line track is established. It can be seen from equations 5.1 and 5.2 that the extended Kalman filter requires the multiplication and inversion of 5X5 matrices, which constitutes a serious computational requirement compared to the first order Kalman filter tracker. The computation requirements of the extended Kalman filter would be significantly reduced if the tracking process could be split and performed independently on the two axes of the coordinate system, but this is not possible under the formulation of equation 5.1. This is so because the angular velocity term appears on both axes and is an element of the state vector of the system.

It can also be seen that the only use of the angular velocity term in the prediction equations of the extended Kalman filter is the calculation of the term $\omega_k T/\dot{\phi}_k$. This term represents the angle by which the velocity vector has turned during the sampling interval. This angle however is directly measurable as the difference between successive heading measurements. Since heading is directly measured on board and transmitted to the ground, the use of the angular velocity term can be obviated. In this case the turn of the velocity vector is put equal to the difference of the two most recent heading measurements. This leads to a simpler filter which is described below.

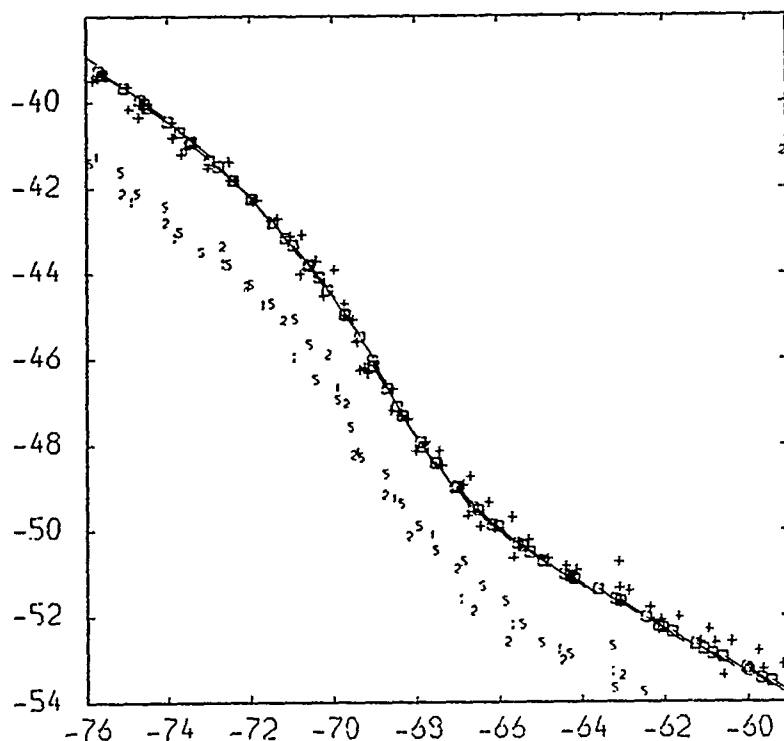


Figure 5.1

Typical maneuver tracked by the extended Kalman filter using Heading. + denote measurements, x denote filter estimates. The number of the radar taking the measurements is shown displaced under the actual measurement.

5.2 The Heading Bias Filter (HBF)

A simple filter can be constructed for tracking maneuvering targets, since heading is directly measured on board. As in the case of the ABF the new filter using heading (called the heading bias filter (HBF)), consists of five steps. The only difference is that HBF uses equations 5.1 to formulate the motion of the aeroplane.

Predictions from $t=t_k$ to $t=t_{k+1}$ are made by integrating equations 5.1. It is seen that the angular velocity estimate $\hat{\omega}_k$ is used merely to calculate an estimate of the change of the direction of flight during the sampling interval, represented by the term $\hat{\omega}_k T$. This quantity however is directly derived from the received heading measurements h_k according to:

$$\delta\varphi = -(h_{k+1} - h_k) \quad (5.5)$$

where h_k is the heading measurements at $t=t_k$ (the negative sign is due to the way heading h_k is measured).

Assuming that $\delta\varphi$ is normally smaller than 20° , the prediction equations are further simplified to:

On X axis:

$$\tilde{x}_{k+1} = \hat{x}_k + \hat{v}_x T \cos(0.5\delta\varphi) - \hat{v}_y T \sin(0.5\delta\varphi) \quad (5.6)$$

$$\tilde{v}_{x_{k+1}} = \hat{v}_x \cos(\delta\varphi) - \hat{v}_y \sin(\delta\varphi) \quad (5.7)$$

On Y axis:

$$\tilde{y}_{k+1} = \hat{y}_k + \hat{v}_y T \cos(0.5\delta\varphi) + \hat{v}_x T \sin(0.5\delta\varphi) \quad (5.8)$$

$$\tilde{v}_{y_{k+1}} = \hat{v}_y \cos(\delta\varphi) + \hat{v}_x \sin(\delta\varphi) \quad (5.9)$$

Since $\delta\phi$ is calculated from heading measurements, the angular velocity term is no longer required. The filter equations are further simplified by neglecting the correlation between the axes. Since this simplification is done during straight line flight, it is reasonable to make it during maneuver tracking too. In this case covariance equations are iterated separately on each axis. On X axis, for example, prediction covariance equations are calculated by considering \hat{x}_{k+1} and \hat{v}_x_{k+1} as

functions of \hat{x}_k , \hat{v}_x_k , \hat{v}_y_k and $\delta\phi$. The prediction covariance equations are given in appendix B.

Smoothing and the calculation of the new covariance matrix take place separately on each axis. Since the positional measurement is the only measurement left to be processed, the rest of the equations are identical to the ones of the first order Kalman filter. It can also be seen that for $\delta\phi=0$ the HBF reduces to a first order Kalman filter, as it should since for $\delta\phi=0$ the aeroplane flies on a straight line. There is only an additional term in the prediction covariance equations reflecting the fact that $\delta\phi=0$ is still an estimate and not an assumption as it is in the first order Kalman filter. HBF therefore may be regarded as an augmented first order Kalman filter using heading measurements to bias the prediction and prediction covariance equations.

The HBF does not assume any particular maneuver model. In this sense it is capable of tracking maneuvers of irregular shape, as civil aircraft maneuvers are in practice. Figure 5.2 shows the same maneuver as the one shown in figure 4.1 tracked by HBF. No overshoot or any other loss of accuracy is seen during the maneuver.

Comparing HBF with ABF it is seen that the HBF eventually detects maneuvers, even if no replies are received during the maneuver. Figure 5.3 shows a typical case where only one reply was received during a maneuver. The target is a HS748 propeller powered aeroplane, flying at 10,000 ft with a speed of 200 knots and executing a turn of 30° . Only one roll angle measurement of 2.86° is received during the maneuver, whereas the total change of heading is easily detected from later measurements.

5.3 False heading measurement rejection

Since the difference of successive heading measurements is actually used by HBF it is reasonable to screen heading measurements that result in unrealistically large changes of heading. Civil aircraft do not maneuver with lateral acceleration larger than $1g$. Angular velocity, ground speed and lateral acceleration are related through:

$$\omega = a/v$$

from which the maximum acceptable change of heading is derived:

$$h_{k+1} - h_k = \hat{\omega}_k T = \hat{a}_k T / \hat{v}_k$$

For $\hat{a}_k = 1g$ the maximum acceptable change of heading measurement is:

$$\delta\phi_{\max} = 1g(T/\hat{v}_k) \quad (5.7)$$

where T is the time elapsed from time the last valid heading measurement is received.

Any received heading measurement resulting in a $\delta\phi$ larger than the maximum acceptable is rejected and the current heading measurement is put equal to the last valid heading measurement. A more sophisticated false heading measurement rejection scheme is not required since HBF is not sensitive to small measurement errors. Note that a data link error in the least significant bits, resulting in an erroneous (but accepted) single heading measurement, results in an $\delta\phi$ error in two successive measurements which almost cancel each other.

5.4 Necessary resolution of the heading measurements

The range of heading measurements is 0° - 360° . A 1° resolution has been used in the present data, but this is too coarse since heading measurements have a standard deviation less than 1° . On the other hand increasing the heading measurement resolution increases the data link capacity taken to transmit it. Consequently a very fine resolution is also undesirable. 0.7° is a reasonable compromise occupying 9 data bits in the data link.

The maximum data rate is once per antenna revolution. As it is outlined in section 4.4 this is marginally sufficient, particularly with low speed aircraft. However since HBF is relatively unsensitive to missing replies one measurement per antenna revolution is satisfactory for the operation of the HBF.

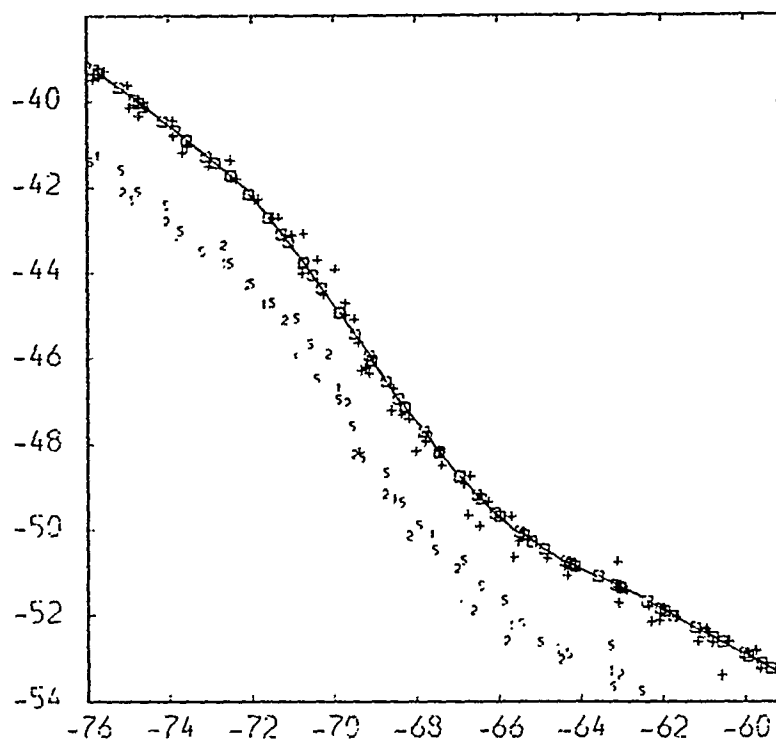


Figure 5.2

Typical maneuver tracked by the heading bias filter (HBF).
 + denote measurements, x denote filter estimates. The number of the radar taking the measurements is shown displaced under the actual measurement.

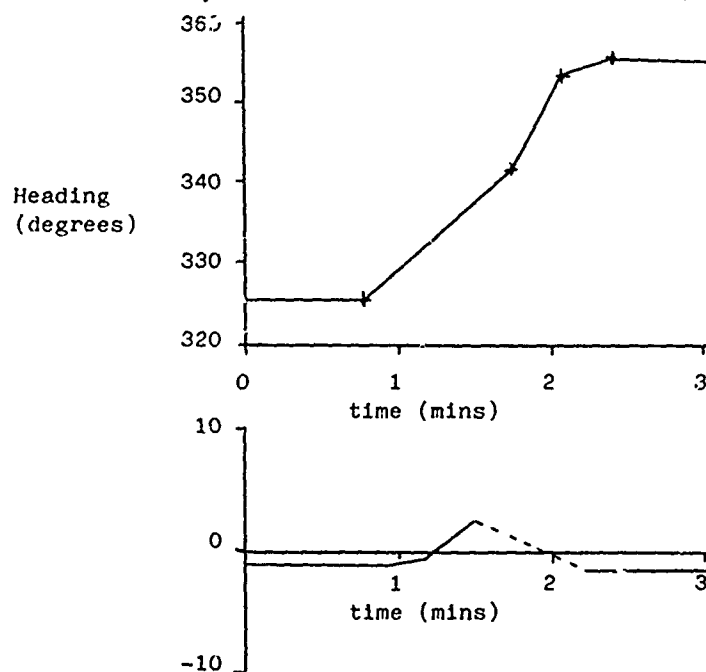


Figure 5.3

Roll angle and heading recorded during a small maneuver. The aeroplane is a HS748 propeller powered airliner and the ground speed is approximately 200 Knots.

6. FILTERS USING COMBINED AIRSPEED AND HEADING MEASUREMENTS

6.1 The velocity bias filter (VBF)

Downlinked TAS and heading measurements are resolved to provide aircraft velocity measurements in the X and Y axes:

$$v_{x_m} = TAS \sin(h)$$

$$v_{y_m} = TAS \cos(h)$$

The covariance matrix P_{vm} of v_{x_m} and v_{y_m} is calculated by considering V_{xm} and V_{ym}

as random variables which are functions of the random variables TAS and h. TAS and h are independent and P_{vm} becomes:

$$P_{vm} = \begin{bmatrix} \sigma_v^2 \sin^2(h) + TAS^2 \sigma_h^2 \cos^2(h), & (\sigma_v^2 - TAS^2 \sigma_h^2) \sin(2h) \\ (\sigma_v^2 - TAS^2 \sigma_h^2) \sin(2h) & , \sigma_v^2 \cos^2(h) + TAS^2 \sigma_h^2 \sin^2(h) \end{bmatrix} \quad (6.1)$$

As was stated earlier the covariance (off diagonal) elements in (6.1) is ignored to decouple tracking in the two axes to reduce the computational load.

The velocity measurements v_{x_m} and v_{y_m} calculated are an unbiased noisy measure of the velocity of the airplane relative to its surrounding atmosphere. As a measure of the aircraft ground speed, however, they are biased by the wind which is assumed to be constant for small periods of time. To incorporate the velocity measurements in the tracking filter, the aircraft motion is modelled as follows:

$$\begin{bmatrix} x_{k+1} \\ r_{k+1} \\ b_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & T & T \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_k \\ r_k \\ b_k \end{bmatrix} + \begin{bmatrix} \frac{T^2}{2} & 0 \\ T & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \delta x_k \\ w_{g_k} \end{bmatrix} \quad (6.2)$$

$$\begin{bmatrix} x_m \\ v_{x_m} \\ b_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{k+1} \\ r_{k+1} \\ b_{k+1} \end{bmatrix} + \text{noise} \quad (6.3)$$

The velocity of the airplane relative to its surrounding atmosphere is used instead of the target ground speed as a system state variable.

Since TAS and heading are measured on board velocity need not be estimated and the second term in (6.2) is omitted (r_k is always put equal to v_{x_m}). This results in the following motion equations:

$$\begin{bmatrix} x_{k+1} \\ b_{k+1} \end{bmatrix} = \begin{bmatrix} 1 & T \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_k \\ b_k \end{bmatrix} + \begin{bmatrix} \frac{T^2}{2} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_{x_k} \\ w_{g_k} \end{bmatrix} + \begin{bmatrix} T \\ 0 \end{bmatrix} v_{x_m} \quad (6.4)$$

$$x_m = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_{k+1} \\ b_{k+1} \end{bmatrix} + \text{noise} \quad (6.5)$$

Note that the only assumption is that \hat{b}_k is constant. No particular assumption is made about v_x and consequently a filter using equation (6.4) will be able to track maneuvering m targets and estimate the wind at the same time. This filter, called the velocity bias filter (VBS) is described by the following simple equations:

At the beginning of the $k+1$ iteration, \hat{x}_k , v_x and their covariance matrix \hat{P}_k are known.

Predictions.

$$\tilde{x}_{k+1} = \hat{x}_k + v_x T + \hat{b}_k T \quad (6.6)$$

$$\tilde{b}_{k+1} = \hat{b}_k$$

Prediction Covariance Matrix.

$$\tilde{P}_{k+1} = \begin{bmatrix} \hat{p}_{11} + 2\hat{p}_{12}T + \hat{p}_{22}T^2 + 0.25T^4\sigma_{pn}^2 + \sigma_{vx}^2T^2, & \hat{p}_{12} + \hat{p}_{22}T \\ \hat{p}_{12} + \hat{p}_{22}T, & \hat{p}_{22} + \sigma_{pn}^2T^2 \end{bmatrix} \quad (6.7)$$

where \hat{p}_{ij} are elements of \hat{P}_k .

Smoothing coefficients.

$$K_{k+1} = \begin{bmatrix} \frac{\hat{p}_{11}}{\sigma_x^2 + \hat{p}_{11}} \\ \frac{\hat{p}_{12}}{\sigma_x^2 + \hat{p}_{12}} \end{bmatrix} \quad (6.8)$$

Smoothing

$$\hat{x}_{k+1} = \tilde{x}_{k+1} + k_{11}(x_m - \tilde{x}_{k+1}) \quad (6.7)$$

$$\hat{v}_{x,k+1} = \tilde{v}_{x,k+1} + k_{21}(x_m - \tilde{x}_{k+1}) \quad (6.9)$$

where k_{ij} are the elements of K_{k+1} and x_m is the $k+1$ positional measurement.

New estimate covariance matrix

$$\hat{P}_{k+1} = \frac{1}{\tilde{p}_{11} + \sigma_x^2} \begin{bmatrix} \tilde{p}_{11}\sigma_x^2, & \tilde{p}_{12}\sigma_x^2 \\ \tilde{p}_{12}\sigma_x^2, & (\tilde{p}_{11} - \sigma_x^2)\tilde{p}_{22} - \tilde{p}_{12}^2 \end{bmatrix} \quad (6.10)$$

Where \tilde{p}_{ij} are elements of \tilde{P}_{k+1} .

Equations 6.6 to 6.10 resemble strongly the first-order Kalman filter equations with minor differences in the prediction and prediction covariance equations only. The VBF however estimates the wind as \hat{b}_k instead of the aircraft ground speed and tracks maneuvering targets.

Maneuver tracking can also be achieved by using heading measurements only. The advantage obtained using TAS and heading is that slightly simpler filter equations result and that the wind speed is estimated. Also VBF copes with longitudinal accelerations as well as with lateral accelerations, whereas by using heading, only lateral accelerations are treated. This is a significant advantage when tracking targets other than airliners, which accelerate in the longitudinal axis, e.g. helicopters, VSTOL aircraft etc.

The computational load of VBF is similar to that of the first-order Kalman filter. The additional performance is achieved at the penalty of transmitting two additional airborne measurements. Figure (6.1) shows a typical maneuver tracked by VBF. The target is a boeing 747 airliner during normal scheduled flight. Tracking accuracy is preserved during the maneuver despite its irregular shape. This performance is typical of all flights used to test the tracking accuracy of VBF.

VBF estimates the wind in the vicinity of the airplane as a bias in the velocity measurements. If, for any reason, a bias source other than the wind exists, then tracking accuracy is not lost but the additional bias is incorporated into b_k . Figure (6.2) shows a typical case that has occurred during the flight tracked in Fig.(6.1). The estimated wind speed and direction are shown together with the wind speed and direction measurements made by the on board INS. Although tracking accuracy is not lost, as is seen in Fig.(6.1) a constant difference in the VBF-INS wind estimates is clearly seen. Table 1 shows wind estimates made by VBF and INS during four typical flights. The agreement is very good in the two flights, but there is a disagreement in the other two either in the wind speed or the wind direction. In all flights tracking accuracy is very good as is shown in Fig.(6.1).

The ability of VBF to absorb any TAS or heading bias provides a stable operation in the event of a system failure where the data linked parameters are partially or fully lost.

If TAS is lost permanently, then TAS is given an arbitrary nonzero value e.g. 500 knots. In this case tracking accuracy is preserved, even during maneuvers, but wind speed estimate accuracy is lost. If both TAS and heading are lost (e.g., due to a transponder failure) then TAS and heading are given arbitrary values but maneuver tracking accuracy is lost.

The ability of VBF to absorb any bias in the wind speed estimate can also be used to check the TAS and heading measuring equipment. The wind estimate obtained from the tracking of a particular aircraft is compared to the average wind estimate of other aircraft flying in the vicinity. Excessive differences, not justified by the noise in the wind estimates, indicate a sensor error in the tracked airplane.

6.2 False velocity measurement rejection

A source of awkward errors in the airborne parameters is the data linking process which can result in wildly erroneous measurements. Since velocity measurements are used unaltered by VBF, large data linking errors must be removed before they are fed to the filter. TAS and headings are treated separately and a suitable procedure for processing the heading measurements is described in section 5. A fading memory averager is used to compute the velocity average (AVTAS) that is used by VBF.

Where l is a constant $0.1 < l < 0.3$. TAS is first compared to AVTAS, and if it is declared as valid and is used further. A value for $l=0.2$ and a rejection window have been used successfully with the present data. In any case, the values of l and the rejection window are not critical.

6.3 Necessary range and resolution of airspeed measurements

The range of TAS is 0-660 knots for subsonic airplanes. A 1.3 knots resolution is satisfactory, in view of the present data, and therefore the transmission of TAS occupies 9 data link bits.

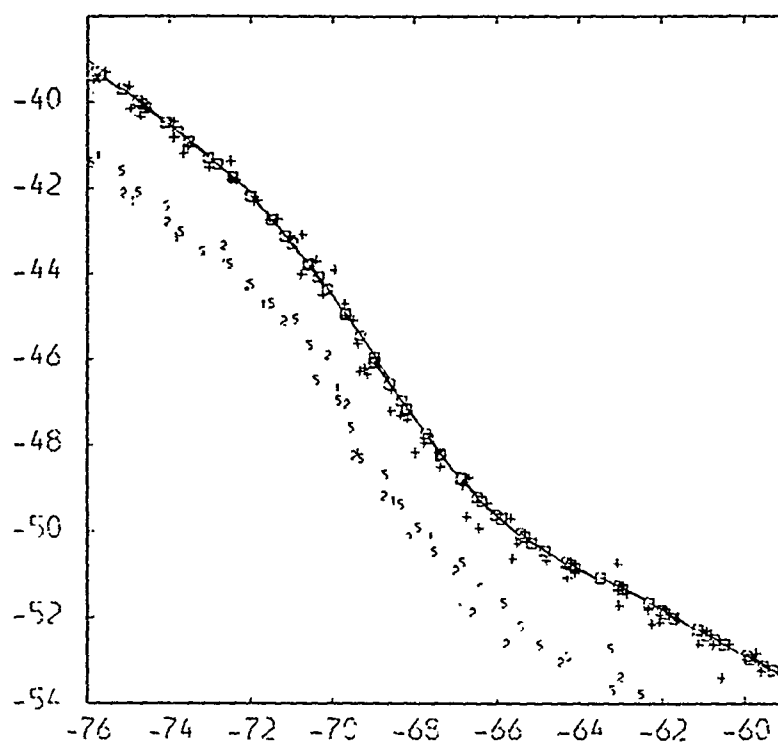


Figure 6.1

Typical maneuver tracked by the velocity bias filter (VBF).
 + denote measurements, □ denote filter estimates. The number of the radar taking the measurements is shown displaced under the actual measurement.

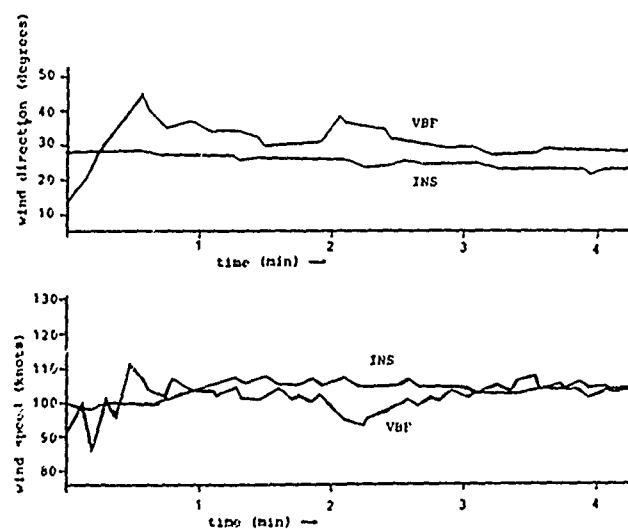


Figure 6.2

Wind speed and wind direction estimates produced by VBF and the on board INS plotted against time. The flight is the one shown in figure 6.1

7. Discussion

Roll angle and heading are the two most important downlinked measurements to aid the tracking of maneuvering civil aircraft. Both result in simple filters using equivalent target motion models (ABF and HBF) which differ only in the way they handle missing data events. HBF provides superior performance since changes of heading accumulate and are eventually detected. This does not apply to roll angle, so that ABF suffers a serious (and unacceptable) loss of accuracy in the event of missing replies during maneuvers.

VBF is another filter formulation that provides longitudinal acceleration maneuver tracking in addition to lateral maneuver tracking, provided by HBF. VBF uses true air speed measurements, in addition to heading measurements. VBF provides also estimates of the wind. The wind however is not estimated as such, but as the average difference of measured airspeed and estimated ground speed. Consequently any systematic error in heading or true airspeed measurements will show up in the wind speed estimates.

An overall comparison of tracking using heading and using S.S.R. obtained positional data only is shown in figures 7.1 and 7.2. Figure 7.1 shows the track obtained by a first order tracker with a maneuver detector. The situation is multiradar coverage with three radars covering the area simultaneously. Apart from the typical behaviour on maneuvers, false triggering of the maneuver detector by noise occurs at several points. Between maneuvers the track is acceptably smooth, since it is a straight line flight. The track obtained by HBF is shown in figure 7.2. No significant loss of accuracy is observed in any part of the flight.

The final conclusion is that HBF provides the safest operation combined with a low use of the data link capacity. VBF provides in addition longitudinal acceleration tracking at the cost of a higher data link load. With civil aircraft however longitudinal accelerations are not large, so that HBF provides an overall satisfactory performance.

Nomenclature

$\hat{\cdot}$	denotes an estimate
\sim	denotes a prediction
x	denotes the aircraft position on X axis at $t=t_k$
y	denotes the aircraft position on Y axis at $t=t_k$
v_x	denotes the aircraft velocity on X axis at $t=t_k$
v_y	denotes the aircraft velocity on Y axis at $t=t_k$
a	denotes the aircraft lateral acceleration at $t=t_k$
ω	denotes the aircraft angular velocity at $t=t_k$
r	denotes the relative velocity of the aircraft with respect to its surrounding atmosphere at time $t=t_k$
v_x	denotes the plant noise (random accelerations) at $t=t_k$
T_k	denotes the sampling interval
R	Radar range measurement
θ	Radar bearing measurement
x^m	position measurement on X axis
y^m	position measurement on Y axis
a^m	lateral acceleration measurement
v_x^m	velocity measurement on X axis
σ_x	standard deviation of x measurement
σ_y	standard deviation of y^m measurement
σ_R	standard deviation of R^m measurement
σ_θ	standard deviation of θ^m measurement
σ_{v_x}	standard deviation of v_x^m (plant noise)
σ_{h^k}	standard deviation of h^k (magnetic heading) measurement

References

- [1] Singer A.R. and Behnke K.W. (1971): "Real time tracking filter evaluation and selection for tactical applications", IEEE transactions vol AES-7 (Jan 1971), 100-110
- [2] Wold M. al (1972): "ARTSIII augmented tracking study", FAA rep FAA-RD-73-27, 1972
- [3] Friedland B. (1973): "Optimum steady state position and velocity estimation using noisy sampled position data", IEEE transactions, vol AES-9, No 6, (Nov 1973), 906-911
- [4] Thomas H.W. "Manoeuvre handling in a multiradar environment" IEE pt F, 126,6,469
- [5] Lefferts R.E. (1981): "Adaptive correlation regions for alpha-beta tracking filters", IEEE transactions, vol AES-17, no 6, (Nov 1981), 783-747
- [6] Kendrick J.D., Maybeck P.S., Reid J.G. (1981): "Estimation of aircraft target motion using orientation measurements" IEEE transactions, vol AES-17, no 2, 254-260
- [7] Farina A. Pardini S. (1980): "Survey of data processing techniques in air traffic control and surveillance systems", IEE Pt F, vol 127, no 3, 190-204
- [8] Lefas C.C. (1985): "Algorithms for improved, heading assisted, maneuver tracking" IEEE transactions, vol AES-21, no 3, (May 1985), 351-359.

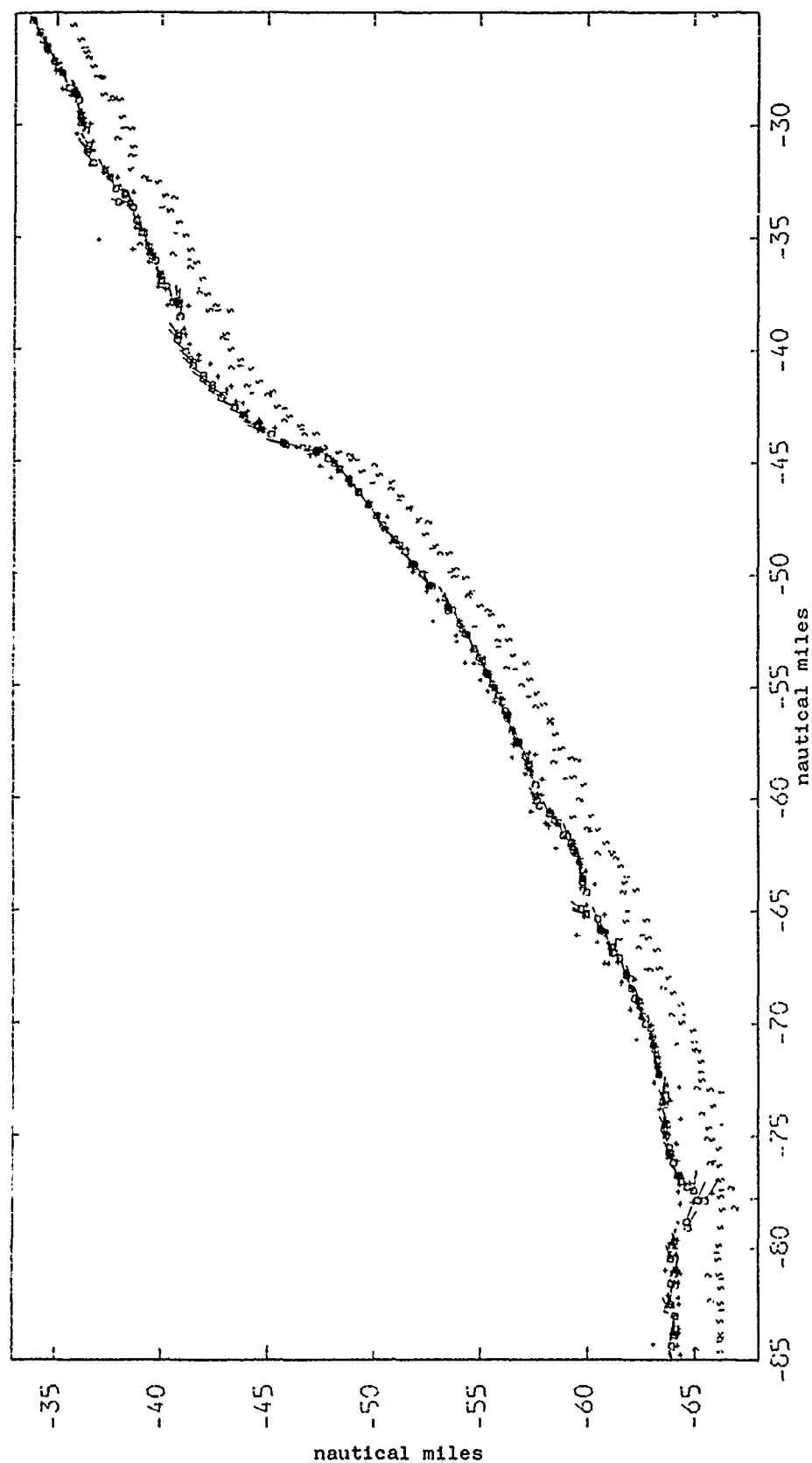


Figure 7.1

B747 flight tracked by a first order Kalman filter and a maneuver detector.
 + denote measurements, O denote filter estimates. The number of the radar taking the
 measurements is shown displaced under the actual measurement.

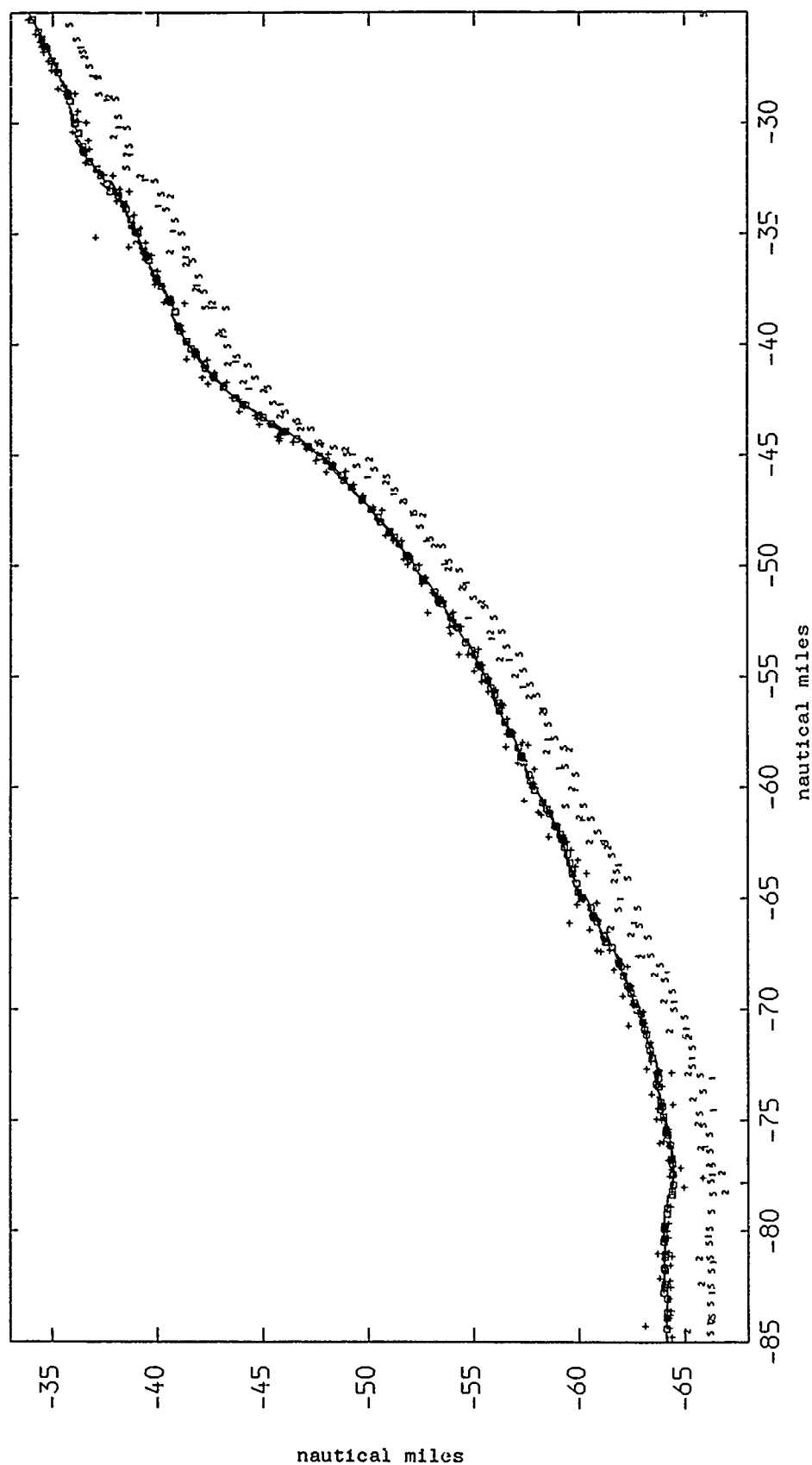


Figure 7.2

B747 flight tracked by the heading bias filter (HBF).
 + denote measurements, o denote filter estimates. The number of the radar taking the measurements is shown displaced under the actual measurement.

APPENDIX A

Prediction covariance equations of the acceleration bias filter (ABF).For the ABF operating on the X axis:

$$\tilde{P}_{k+1} = \begin{bmatrix} \tilde{x}_{p11} & \tilde{x}_{p12} \\ \tilde{x}_{p12} & \tilde{x}_{p22} \end{bmatrix}$$

$$\begin{aligned} \tilde{x}_{p11} = & \hat{x}_{p11} + 2\hat{x}_{p12}T + \hat{x}_{p22}T^2 + \hat{a}T^2(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)\hat{x}_{p12} + \hat{a}T^3(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)\hat{x}_{p22} \\ & + 0.25\hat{a}^2T^4(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)^2\hat{x}_{p22} + 0.25\hat{a}^2T^4(\hat{v}_{x_k}/\hat{v}^{1.5})^4\hat{y}_{p22} + \sigma_{pn}^2T^4 \\ & + 0.25\sigma_a^4(\hat{v}_{y_k}/\hat{v} + 0.33\hat{a}T\hat{v}_{x_k}/\hat{v}^2)^2 \end{aligned}$$

$$\begin{aligned} \tilde{x}_{p12} = & \hat{x}_{p12} + \hat{x}_{p22}T + \hat{a}T(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)\hat{x}_{p12} + 1.5\hat{a}T^2(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)\hat{x}_{p22} \\ & + 0.5\hat{a}^2T^3(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)^2\hat{x}_{p22} + 0.5\hat{a}^2T^3(\hat{v}_{x_k}/\hat{v}^{1.5})^4\hat{y}_{p22} + 0.5\sigma_{pn}^2T^3 \\ & + 0.5\sigma_a^2T^3((\hat{v}_{y_k}/\hat{v})^2 + (\hat{a}T\hat{v}_{x_k}/\hat{v}^2)^2/6 + 5\hat{a}T\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3/6) \end{aligned}$$

$$\begin{aligned} \tilde{x}_{p22} = & \hat{x}_{p22} + 2\hat{a}T(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)\hat{x}_{p22} + \hat{a}^2T^2(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)^2\hat{x}_{p22} + \sigma_{pn}^2T^2 \\ & + \hat{a}^2T^2(\hat{v}_{x_k}/\hat{v}^{1.5})^4\hat{y}_{p22} + \sigma_a^2T^2(\hat{v}_{y_k}/\hat{v} + 0.5\hat{a}T\hat{v}_{x_k}/\hat{v})^2 \end{aligned}$$

where \hat{x}_{p11} and \hat{y}_{p11} are elements of \hat{P}_k of the ABF operating on the X axis and the Y axis respectively.

For the ABF operating on the Y axis:

$$\tilde{P}_{k+1} = \begin{bmatrix} \tilde{y}_{p11} & \tilde{y}_{p12} \\ \tilde{y}_{p12} & \tilde{y}_{p22} \end{bmatrix}$$

$$\begin{aligned} \tilde{y}_{p11} = & \hat{y}_{p11} + 2\hat{y}_{p12}T + \hat{y}_{p22}T^2 - \hat{a}T^2(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)\hat{y}_{p12} - \hat{a}T^3(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)\hat{y}_{p22} \\ & + 0.25\hat{a}^2T^4(\hat{v}_{x_k}\hat{v}_{y_k}/\hat{v}^3)^2\hat{y}_{p22} + 0.25\hat{a}^2T^4(\hat{v}_{y_k}/\hat{v}^{1.5})^4\hat{x}_{p22} + \sigma_{pn}^2T^4 \\ & + 0.25\sigma_a^4(\hat{v}_{x_k}/\hat{v} - 0.33\hat{a}T\hat{v}_{y_k}/\hat{v}^2)^2 \end{aligned}$$

L'APPORT DES TECHNIQUES SATELLITAIRES A LA SURVEILLANCE DE LA NAVIGATION AERIENNE

par

Olivier Carel,
Ingénieur en Chef de l'Aviation Civile
Chef du Département Radiocommunication et Radioguidage du
Service Technique de la Navigation Aérienne
Membre français du Comité Spécial FANS de l'OACI
246 rue Lecourbe
75015 PARIS , FRANCE

RESUME

La mise en oeuvre des satellites pour les communications, navigation et surveillance de l'aviation a été étudiée et a commencé à être planifiée par l'Organisation de l'Aviation Civile Internationale qui a créé le comité spécial Future Air Navigation Système (FANS) à cet effet. Ce comité vient de rendre son rapport final. La note présente ses travaux et analyse les conséquences de l'introduction des satellites dans le cas particulier de la surveillance du trafic. L'élément le plus important sera la "surveillance dépendante automatique" (ADS) qui consiste en une retransmission automatique de l'avion vers le sol de divers paramètres mesurés à bord, principalement sa position telle qu'elle est fournie par les moyens de navigation de l'appareil. Ce système permettra un contrôle bien plus efficace dans les zones sans infrastructure sol. Dans les zones continentales à fort trafic, les satellites ne se substituent pas au radar secondaire, cependant les nouvelles techniques permettront plus de souplesse dans la conception de l'infrastructure.

SUMMARY

The International Civil Aviation Organisation asked a special committee FANS (Future Air Navigation Systems) to study satellite system implementation for communication navigation and surveillance applications. This committee issued recently its final report. The paper presents FANS work and analyses the consequences of satellite system implementation upon the surveillance of air traffic. The most important element will be automatic dependent surveillance (ADS) which implies the automatic air to ground return transmission of various airborne measured parameters, i.e. mainly aircraft position as supplied by the aircraft navigation equipments. This concept is to allow a much more efficient air traffic control in every area lacking a ground infrastructure. In continents areas with heavy air traffic, satellites will not substitute the secondary surveillance radar. The new techniques however will allow a flexible design of the ground infrastructure.

1 - INTRODUCTION

L'apport des satellites a été étudié récemment par l'Organisation de l'Aviation Civile Internationale qui a confié cette réflexion à un groupe de travail dont les travaux viennent de s'achever. Ce travail va être rappelé dans une première partie. Les satellites pourront jouer un rôle dans le système CNS (communication navigation surveillance) de l'aviation civile future. La présente communication restreint sa réflexion au problème de la surveillance. Elle examinera surtout deux cas : le premier cas est celui de la surveillance dépendante, c'est à dire celle où le mobile informe le centre chargé de le suivre de sa position actuelle, le second cas concerne la surveillance indépendante coopérative, c'est à dire la détermination par le centre de la position du mobile, en se servant de mesures effectuées sur des émissions de ce mobile. Nous concluons en essayant de prévoir la façon dont ces techniques nouvelles arriveront, ou non, à s'introduire dans les opérations aériennes.

2 - LE TRAVAIL EFFECTUE A L'OACI.

L'Organisation de l'Aviation Civile Internationale a créé en 1984 un comité spécial qu'elle a chargé d'établir une description des moyens futurs de la navigation aérienne. Ce comité s'appelle FANS (pour "future air navigation systems"). Il est composé de seize membres officiels (Allemagne fédérale, Australie, Brésil, Canada, Danemark, Espagne, Etats Unis, France, Grande Bretagne, Islande, Italie, Japon, Pays Bas, Tanzanie, URSS, IATA (association internationale du transport aérien), IFALPA (fédération internationale des associations, des pilotes de ligne) IATCA (fédération internationale des associations de contrôleurs de la circulation aérienne). De nombreux observateurs ont participé au débat, certains de façon fondamentale (Agence pour la sécurité de l'aviation civile en Afrique et à Madagascar, Eurocontrol, Agence Spatiale

européenne, INMARSAT, Portugal, etc...). Le président de FANS a été M. Jan Smit des Pays Bas qui vient de prendre sa retraite et qui a ainsi achevé sa carrière aéronautique par un franc succès. Le comité FANS s'est réuni quatre fois en réunion officielle à Montréal. Les comptes rendus des réunions 2 et 3 sont des documents vendus par l'OACI. La quatrième et dernière réunion s'est tenue du 2 au 20 mai 1988. Son rapport va bientôt être édité officiellement. Ce rapport va être, selon toute probabilité, proposé à la prochaine Assemblée Générale de l'OACI qui se tiendra à Montréal à l'automne 1989. Le plan proposé par le FANS, s'il est approuvé par cette assemblée générale, prendra un statut officiel et international. L'auteur de cette note a représenté la France au comité FANS. L'activité de ce comité a en particulier été consacrée à l'introduction des techniques spatiales dans la navigation aérienne, ou, pour être plus précis, dans le système de communication de navigation et de surveillance de la navigation aérienne, ce que l'on trouve parfois contracté dans les initiales "CNS". On trouvera en annexe 1 à cette note les tableaux établis par FANS pour décrire l'ensemble de ces systèmes. Ces tableaux comprennent 3 lignes, la dernière étant consacrée à la surveillance. Les trois colonnes correspondent à la période actuelle, et à deux mystérieuses phases A et B que le comité n'a pas voulu appeler par des dates trop précises. La colonne A correspond à des systèmes dont la mise en oeuvre est déjà planifiée (ce qui est le cas du GPS/Navstar, par exemple), elle vise en gros la période 1990/2005. La phase B correspond au système futur que souhaite FANS et qui sera mis en oeuvre quelque part entre 2000 et 2015. On voit que le comité FANS n'est pas, à tort ou à raison, révolutionnaire. Les communications vocales VHF, par exemple, sont considérées comme éternelles. Mais FANS et l'OACI doivent se tenir à des systèmes acceptables par tous les pays, or, à travers le monde, la dispersion des niveaux de développements dans le domaine aéronautique est considérable. On notera dans ces tableaux quelques termes relevant du français (certains espaces aériens sont devenus "espaces aériens sélectionnés" par contagion de l'anglais "selected air spaces"), mais l'édition que nous reproduisons n'est pas encore l'édition finale. On remarquera aussi de nombreux acronymes dont certains correspondent à des concepts assez nouveaux qu'il vaut la peine de considérer en détail.

3 LES PERFORMANCES DE NAVIGATION REQUISES, RNPC (Required Navigation Performance Capability).

Les réglementations actuelles sur l'emport de moyens de navigation sont désuètes, elles obligent par exemple tous les avions à être équipés de récepteurs VOR, même les avions équipés de centrales à inertie dont les pilotes ne consultent pas le VOR. La réglementation applicable dans la zone contrôlée de l'Atlantique nord montre une nouvelle voie : pour accéder à cette zone, on demande aux avions de savoir tenir leur route à mieux que 5,2 milles nautiques dans 95% des cas, mais on laisse à l'opérateur le choix des moyens pour y parvenir, l'Oméga, l'inertie etc... Ce concept sous le nom de RNPC devrait être étendu à tous les espaces contrôlés. Les autorités responsables d'une certaine zone devront déclarer quelle classe de RNPC est nécessaire pour fréquenter cette zone. Les autorités de certification vérifieront que l'avion remplit bien les conditions de cette classe dans l'espace considéré. Les services du contrôle établiront leurs procédures sans avoir à connaître le type d'équipement de chaque avion. Cette nouvelle réglementation se mettra en place lentement. Un groupe d'experts de l'OACI est chargé de se pencher sur le sujet, ce groupe partira des quelques textes déjà établis par le comité FANS.

Le concept de RNPC simplifiera la vie de tout le monde, mais une des conséquences pour la surveillance est qu'on établira les séparations entre avions suivant ces seules normes. On ne séparera pas tel et tel avion, de 5 nautiques parce que l'un se sert du Loran-C et l'autre du VOR et telle autre paire de 3 nautiques parce que ces avions utilisent le GPS. Il y aura une norme et une seule.

4 - LE GNSS (Global Navigation Satellite System).

En ce qui concerne la navigation (et on verra plus loin que la navigation et la surveillance pourront être fortement associées), le comité est certain que la navigation par satellite fournira une solution universelle, facile d'emploi, sûre pour que la position présente d'un mobile soit connue avec précision dans le mobile lui-même. Le comité FANS sait bien (cf les travaux du comité SC-159 du RTCA et du groupe 19 d'Eurocae tous deux sur l'utilisation de GPS dans l'aviation civile) que le seul système bien étudié est le GPS américain et que celui-ci pose des problèmes assez alarmants de continuité de service (possibilité pour un mobile de se retrouver sans signal GPS au milieu d'une opération délicate, et d'intégrité (possibilité pour qu'un mobile utilise des signaux GPS hors normes sans qu'on puisse en être prévenu ou sans qu'on sache le détecter par des moyens internes au mobile). Le comité FANS a donc appelé GNSS un système futur supposé à l'abri des difficultés de continuité de service et d'intégrité sans que l'on puisse dire de quoi sera composé le GNSS. Une hypothèse serait que le GNSS soit formé de l'ensemble des satellites américains (GPS) et soviétiques (GLONASS), ce qui ferait tant de satellites que la panne définitive ou la dérive pernicieuse de l'un d'eux ne pourrait entraîner aucune conséquence grave. Une autre hypothèse serait que le GNSS soit composé des éléments du système GPS tel qu'il est actuellement planifié par le Département de la défense des Etats-Unis, augmenté de moyens de surveillance au sol des signaux GPS et de moyens de diffuser des renseignements sur l'état de système par exemple à partir de satellites en orbite géostationnaire (cf article de Geneviève Eydaleine dans le bulletin de l'OACI de mars

1988). Ces moyens auxiliaires de surveillance de GPS pourraient être mis en place par les autorités civiles. Les notions de continuité du service et d'intégrité ont été étudiées très finement par les spécialistes de l'atterrissage tout temps. (cf annexe 10 de l'OACI, supplément C à la 1ère partie, section 2-8). Mais ces notions ne s'appliquent peut être pas très bien à des approches guidées par des satellites. En effet, toute panne dramatique d'un moyen d'atterrissage actuel, survenant au moment le plus délicat de l'atterrissage, ne mettrait en danger que le seul avion en fin d'approche, alors qu'une panne équivalente d'un satellite GPS peut compromettre la sécurité de tous les avions en approche sur un quart de la surface de la terre. La probabilité de pouvoir terminer son approche est la même dans le cas d'une aide locale (ILS ou MLS) ou dans le cas d'un guidage par satellite et pour chaque passager d'un avion donné c'est probablement ce qui compte. Il est cependant déplaisant de voir que la probabilité d'échec de nombreuses approches vont être couplées et que la panne unique d'un sous ensemble sur un satellite risque de compromettre tant d'approches de sorte que chaque panne pourrait bien entraîner un authentique accident. Le risque est difficile à évaluer, mais si dans la couverture d'un satellite se trouvent quelques milliers d'avions en l'air, que ceux-ci volent en moyenne deux heures et qu'il y a peut être quinze à trente secondes de vraiment sensibles, encore qu'une panne ne causera d'accident que dans une fraction de ces remises de gaz aventurées à très basses altitudes, on arrive au taux d'un accident toutes les dix pannes de satellites, ce taux serait inférieur si les moyens d'atterrissage au sol restaient très répandues (les moyens d'atterrissage au sol seront toujours nécessaires aux approches de précision). La fiabilité de la surveillance de la circulation aérienne par l'usage détourné d'un "GNSS", c'est à dire l'ADS, n'a guère été étudié. On en reparlera plus loin.

5 - SURVEILLANCE DEPENDANTE OU INDEPENDANTE, COOPERATIVE OU NON COOPERATIVE.

Les concepts de surveillance dépendante ou indépendante, coopérative ou non coopérative ont beaucoup été utilisés dans les travaux du comité FANS.

On dit qu'un système de surveillance de la circulation aérienne est "coopératif" quand les aéronefs sont munis d'un équipement radio de bord qui participe au système. Ainsi, les IFF, les radars secondaires qui utilisent des répondeurs dans les avions sont des systèmes coopératifs. Les radars primaires qui utilisent des réflexions sur les surfaces conductrices d'un mobile sont des systèmes "non coopératifs". Le cas de la goniométrie, c'est à dire du relèvement par des moyens au sol de la source d'émissions, peut relever de l'une ou de l'autre classe, mais en ce qui concerne l'aviation civile, la goniométrie des émissions ou la mesure de distance basée sur le temps de transmission d'échanges de données codées relèvent évidemment de la surveillance coopérative.

La surveillance coopérative peut elle-même se partager entre surveillance indépendante ou dépendante.

On dit qu'un système de surveillance coopérative constitue une "surveillance indépendante" lorsque l'estimation de la position du mobile par le sol est faite à partir de mesures faites du sol. Le radar secondaire qui se base pour ses mesures d'azimut comme pour ses mesures de distance sur des mesures faites au sol relève de la surveillance indépendante.

On dit qu'un système de surveillance met en oeuvre une "surveillance dépendante" lorsque l'estimation de la position du mobile se fait seulement à partir de données mesurées dans l'avion et transmises au sol. C'est le cas aujourd'hui de la surveillance de l'altitude par le radar secondaire, puisque l'altitude pression est mesurée dans l'avion, codée puis transmise au sol en utilisant le mode C du radar secondaire. On trouvera dans les textes FANS deux applications particulières si fréquentes qu'on les désigne par leurs initiales, il s'agit de l'ADS (Automatic Dependant Surveillance) et la CIS (Cooperative Independent Surveillance soit la surveillance indépendante coopérative).

Ce sont ces deux techniques qui, si elles sont mis en oeuvre par l'intermédiaire de satellites, peuvent très profondément modifier la façon d'estimer la position des aéronefs en vol dans certains espaces aériens.

6 - LA SURVEILLANCE DEPENDANTE AUTOMATIQUE (ADS), PRINCIPE DE BASE.

Il existe de nombreux espaces aériens où le trafic est trop faible pour justifier l'implantation d'un réseau important de moyens au sol : il s'agit de nombreuses zones désertes (arctiques, antarctiques, déserts, etc...) et de la plupart des océans. Il existe quelques zones océaniques où le trafic aérien n'est pas du tout négligeable, c'est le cas de la bande de l'Atlantique Nord sur laquelle se concentrent les vols transatlantiques (Oceanic Track Système, OTS) et d'une zone analogue dans le Pacifique Nord, entre les Etats Unis et les pays industrialisés d'Extrême Orient. Dans ce cas, le trafic justifierait des investissements mais pas assez pour entretenir des moyens de surface en haute mer. Dans toutes ces zones sans moyens au sol, donc sans radar secondaire, la seule possibilité de surveillance moderne sera l'ADS, c'est à dire la transmission automatique de données mesurées dans l'avion vers le service sol. Le système sera automatique, c'est à dire sans intervention de l'équipage. Ceci impliquera

donc un protocole de dialogue pour cette application entre les systèmes informatisés des services de contrôle aérien et les systèmes informatisés, à bord des avions (le cas des avions anciens et des aéronefs pas trop équipés de l'aviation générale, impliquera peut être quelques interventions humaines dans le système mais cela reste à voir).

Le message ADS sera demandé par le centre de contrôle. Celui-ci précisera à chaque avion quelles sont les données qui l'intéressent et le moment où il aura besoin de ces données, par exemple : une fois tout de suite, ou autre exemple, toutes les cinq minutes, à partir de tel instant. Le message ADS sera assemblé dans l'avion et adressé au moment indiqué. Le message le plus simple contiendrait par exemple les données suivantes (cf rapport FANS 4, point 3 appendice B, tableau 1a).

ADS DE BASE (POSSIBILITES OBLIGATOIRES DE L'EQUIPEMENT EMBARQUE)				
	Eléments à communiquer			
Elements de données	Dans chaque rapport	Sur demande	Résolution	Bits
latitude/longitude	X		0,0125 minute d'arc	42
Altitude	X		2,4 m (8 pieds)	16
Temps	X		0,125 seconde	15
Indice de qualité	X			7
Champ d'activation				
Capacité ADS		x1	8 x 6 bits	16
Identification		X		48
1) le champ d'activation/capacité indique ce que l'équipement de l'avion peut transmettre, ou va transmettre.				

Les messages plus longs pourraient comprendre en plus des données ci-dessus, les coordonnées du prochain point de cheminement, ou le vecteur vitesse de l'avion, ou des renseignements sur la météorologie locale comme l'estimation du vent fournie par les centrales à inertie. Les données de base données ci-dessus ne sont pas encore figées par l'OACI. Bien des discussions sont encore nécessaires avant que ces chiffres figurent dans l'Annexe 10. Un groupe d'experts de l'OACI vient d'être chargé de cette tâche de mise au point. Deux sujets ont déjà fait couler beaucoup d'encre, ce sont l'horodatage (faut-il ou non donner dans le message l'heure à laquelle il a été établi?) et l'indice de qualité (en anglais "figure of merit") qui devrait indiquer la confiance que le contrôle peut accorder aux renseignements envoyés : si les données viennent d'une centrale à inertie, il serait intéressant de savoir si celle-ci a pu être recalée, ou non, récemment. On peut se demander s'il est bien utile de répéter ce renseignement à chaque message.

On trouvera en seconde annexe un texte extrait du rapport FANS-4 et qui prêche de façon assez convaincante en faveur de l'ADS.

7 - LES MOYENS DE COMMUNICATION DE L'ADS.

Quels seront les moyens physiques de transmission de l'ADS? Les premières applications, les plus évidentes, se trouvent dans les zones océaniques où le trafic aérien est le plus important. Dans ce cas, le moyen de communication le plus sûr va être le système de communication mobile aéronautique par satellite (AMSS Aeronautical Mobile Satellite Système) pour lequel divers prestataires de service sont prêts à fournir des moyens (la SITA par exemple, en union avec les services officiels des télécommunications de France, du Canada et d'Australie; mais il y a des organisations concurrentes). L'agence internationale Inmarsat va lancer prochainement des satellites comportant des répéteurs dans la bande aéronautique, soit 1545 à 1555 MHz vers les avions et 1646,5 à 1656,5 MHz vers les satellites. Ces moyens serviront à passer à la fois le téléphone des passagers et les communications techniques des compagnies aériennes et des services de contrôle de la circulation aérienne, qu'il s'agisse de voix ou de données. Un passager qui parle aura besoin de 10 mille bits par seconde pour transmettre son discours avec la fidélité sonore à laquelle le téléphone public nous a habitués. A côté de ces 10 000 bits/s, le débit de données de l'ADS ne représente rien, disons cinq bits par seconde, par avion. Une conséquence de cette disproportion est que ce sera le passager qui paiera le plus clair du coût de ces nouvelles communications. Une conséquence de cette conséquence est que l'AMSS ne se répandra vite que si les passagers révèlent un fort besoin de téléphoner pendant les vols. Bien sûr les quelques bits pourraient être transmis par bien d'autres techniques, par exemple, par le système mis en oeuvre sous le nom d'ACARS en Amérique du Nord, et d'AIRCOM ailleurs, système qui permet de transmettre des bits sur un canal VHF. Ce système n'a pas d'application ATC (Air Traffic Control) pour le

moment (mais il y a déjà une exception au moins au Canada où l'ACARS sert à transmettre à certains avions le détail du plan de vol que l'ATC impose avec le décollage). Il est possible que d'autres moyens de communiquer des données des avions vers le sol, qui n'emploient pas de satellite, soient offertes un jour à l'aviation civile. Ils pourraient utiliser soit une partie de la bande AMSS citée plus haut, soit une partie de la capacité du futur téléphone "cellulaire" qui permettra un jour prochain en Europe de téléphoner d'un avion comme on téléphone d'une voiture.

La nature du moyen de communication n'est pas très importante pour le transfert de données codées. On peut imaginer que ce soit la tâche de systèmes automatisés de trouver pour chaque message le support le plus adapté à l'instant et au lieu considéré. Cette possibilité d'utiliser n'importe quel moyen de transmission de données, là où un radar secondaire n'est pas disponible est attrayante : elle permettra d'offrir un contrôle de qualité presque partout (bien entendu, un bon contrôle exige bien d'autres éléments que des moyens de surveillance).

8 - LA SECURITE DE L'ADS.

La sécurité de l'ADS n'a guère été étudiée. Et il conviendra que cette étude soit entreprise (encore que les moyens les plus anciens de l'aviation n'ont jamais fait l'objet d'études de sécurité très poussées avant leur introduction).

En ce qui concerne le radar secondaire, la logique est souvent celle de la double couverture : chaque espace aérien est observé par deux radars qui fonctionnent tout à fait indépendamment l'un de l'autre. On n'utilise opérationnellement qu'un seul radar en un endroit donné, mais le radar viendrait-il à tomber en panne qu'on pourrait aussitôt utiliser l'autre. D'autre part, chaque avion a un double transpondeur. Si jamais il perdait l'usage de ses deux transpondeurs, cela poserait un problème de contrôle mais on peut négliger la probabilité que deux avions voisins perdent tous leurs transpondeurs au même instant.

En ce qui concerne l'ADS, la chaîne est bien plus longue. Il y aura des avions luxueusement équipés et d'autres équipés de façon sommaire. On pourra dans chaque cas, effectuer une étude de performance et une étude des pannes possibles. Les performances de l'ADS dépendront par exemple des éléments suivants :

- Des avions voisins, dont le contrôleur surveille l'espacement, peuvent utiliser des moyens de navigation identiques ou des moyens différents. Leurs erreurs de navigation peuvent être indépendantes ou elles peuvent être couplées, ce qui sera le cas s'ils utilisent le même système de radionavigation. Comme nous l'avons indiqué plus haut, les avions évoluant dans un même espace auront tous prouvé qu'ils suivaient les normes RNPC locales, et le plus simple serait de s'en tenir là. Cependant le cas de sources d'erreurs communes à plusieurs avions (par exemple erreur due à une horloge de satellite qui dérive au voisinage des tolérances fixées) doit être considéré et étudié.

- L'analyse des pannes de l'ADS devra aussi être faite. L'ADS exige le fonctionnement simultané du système de radionavigation qui peut exiger 4 ou 5 satellites en vue de la zone contrôlée considérée, des récepteurs de bord de ce système, des systèmes embarqués de gestion des transmissions de données, des émetteurs-récepteurs de bord, des centres d'émission-réception au sol (et entre émetteurs et récepteurs, il y a toujours une place pour une source de brouillage du spectre radioélectrique), des moyens de transmission des messages entre la station terrienne de communication par satellite et le centre de contrôle de la circulation aérienne, etc...

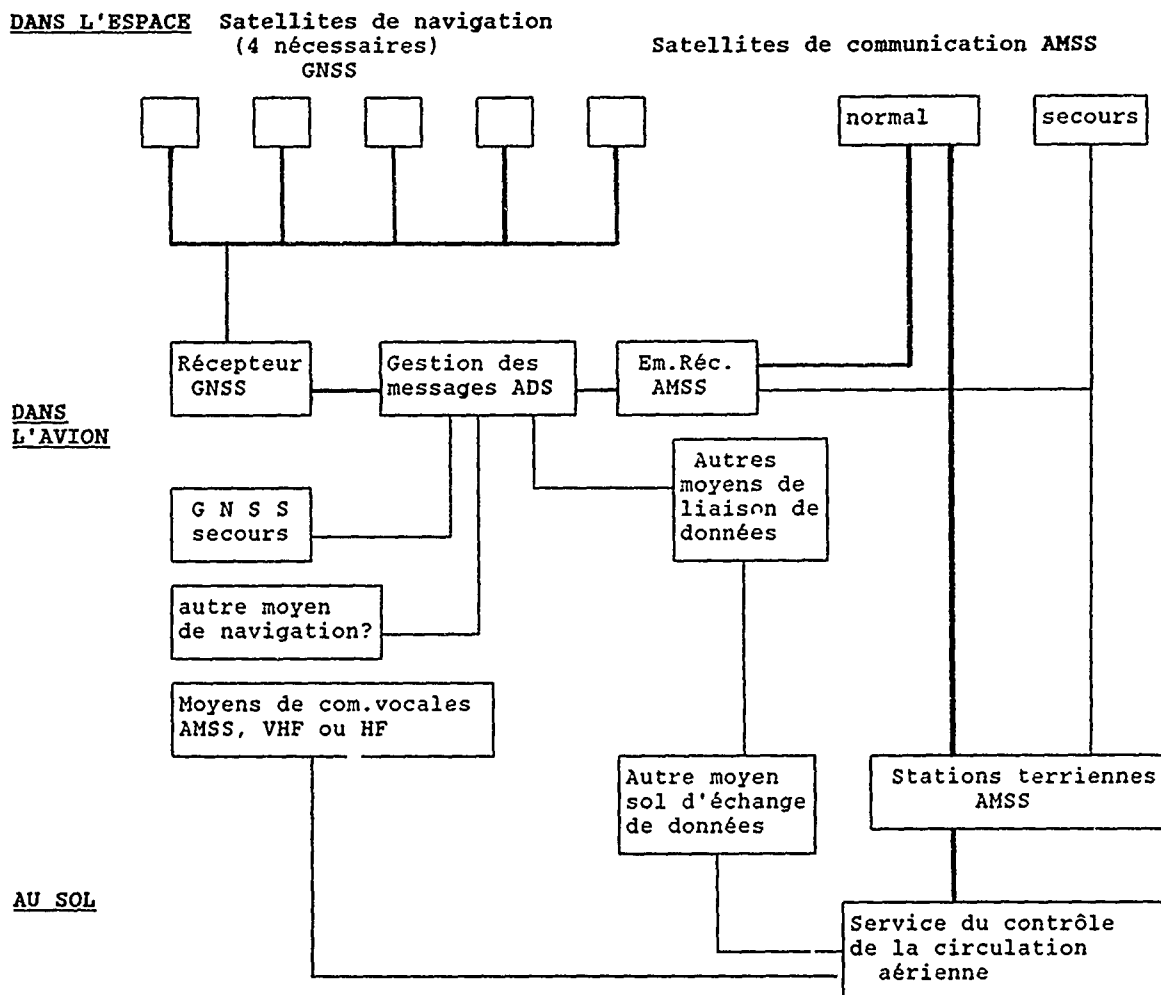
La figure 1 est une tentative de représentation de cette situation. On voit qu'il peut exister des moyens de secours. Le système de navigation par satellite aura sa propre sécurité grâce à un nombre de satellites supérieur au minimum nécessaire à un calcul de position. Si le système de satellite ne présente aucune redondance, il faut impérativement disposer d'un autre moyen. (Cependant les trous du système GPS, seront probablement assez brefs, de l'ordre d'une dizaine de minutes, on pourra dans de nombreux cas utiliser l'estime pour survivre à ces moments difficiles). Le système de communication par satellite comptera normalement un satellite de secours. Donc si au moment du décollage, il y a deux satellites AMSS disponibles, le système devrait être sûr. Mais si un de ces satellites meurt, et cela arrivera forcément, faut-il laisser les avions décoller pour des vols transocéaniques? A des heures de pointe, cela posera problème, et il faudra trouver d'autres cheminements, ou alors revenir aux procédures en vigueur aujourd'hui avec leurs espacements latéraux et longitudinaux considérables.

L'ADS peut être assez raisonnablement envisagée au dessus des continents où existent d'autres moyens CNS et elle pourra faire une certaine concurrence au radar secondaire, dans les zones où le trafic n'est pas trop serré.

FIGURE 1

Le réseau des informations ADS

Chaîne normale de transmission : ————
 Cheminements de secours : ————



L'ADS n'est guère applicable dans les zones terminales qui demandent des renseignements très précis et très rapides sur les mouvements des avions. Mais ailleurs, sera-t-il toujours indispensable de maintenir une double couverture du radar secondaire lorsque la plupart des avions pourront transmettre leur position de façon assez fiable? Et dans certains espaces à trafic assez faible, le radar secondaire sera-t-il toujours justifié?

9 - LA SURVEILLANCE COOPERATIVE INDEPENDANTE PAR SATELLITE (CIS/S)

A long terme, certains membres du FANS font confiance à la CIS/S, surveillance indépendante coopérative par satellite, c'est à dire à une estimation par les services au sol de la position des avions, basée sur des mesures indépendantes de la navigation de l'avion, et faite en coopération avec l'avion c'est à dire en utilisant ses émissions. L'idée générale, qui remonte au projet Aérosat et à la fin des années 60, est d'évaluer la distance entre l'avion et divers satellites en mesurant le temps qui s'écoule entre les interrogations de l'avion émises par les services au sol et la réception au sol des réponses envoyées par l'avion. Tout échange aller-retour de données permet une mesure de distance. L'existence de communications de données sol-satellite - avion - satellite - sol fournirait donc une mesure de distance gratuite, ou tout au moins peu coûteuse.

Ce principe de localisation fonctionne certainement et les systèmes Geostar et Locstar vont bientôt offrir de tels services sur le marché (Geostar aux Etats-Unis, et Locstar en Europe). Le format de Geostar n'est cependant pas un simple et banal échange de message codé. Pour obtenir la précision recherchée (qui est de quelques mètres, c'est à dire d'une qualité analogue de celle du service de précision de GPS), il a fallu utiliser des techniques de compression d'impulsion, le message lui-même ne peut alors

transporter que relativement peu d'information utile (784 bits au plus par message, 250 bits en général). Le format Geostar est bien adapté à un certain type de clientèle comme les mobiles terrestres, mais il ne convient pas spécialement à l'aviation qui a besoin de mesurer les positions très fréquemment pendant les vols. Un usage aéronautique de Géostar par l'aviation saturerait probablement une bonne part du système (500 000 transactions sont possibles par heure par "faisceau" Géostar dans les premières applications, mais 60 millions pour un système absolument complet, en 2010 il y aurait 60 000 avions volant simultanément sur le continent américain). Les échanges de données de l'AMSS vont être optimisés pour économiser le spectre radioélectrique, l'énergie émise, le nombre de bits par seconde. C'est exactement le contraire de ce qui convient à une bonne mesure de la distance. Dans un canal de 2,5 kHz de largeur, avec un débit de quelques centaines à quelques milliers de bits par seconde, il faudrait un temps considérable pour obtenir une mesure de distance utilisable, soit à quelques hectomètres près. La totalité de la bande AMSS n'est elle-même que de 10 MHz. Ces considérations un peu vagues (mais le format AMSS n'est pas encore figé) et plutôt pessimistes sur les applications à court terme des communications AMSS à la localisation des avions, ne doivent pas aller jusqu'à déclarer la CIS infaisable. Pour obtenir des mesures de distance de précision intéressante, il faudra que le système AMSS soit surabondant pour les communications, afin que l'on puisse utiliser pour la CIS/S du spectre et du temps. Avec les bilans de liaison très serrés que l'on vise actuellement, il n'en est pas question, mais si un jour les satellites ont des antennes assez grandes pour assurer une densité de puissance confortable dans l'atmosphère terrestre, on pourra inventer des formats de messages convenant à l'AMSS. D'autres progrès peuvent jouer, si l'avion par exemple possède une horloge de bord précise à une fraction de microseconde près (1 us correspond à 300 mètres), il n'est plus nécessaire d'avoir un échange aller-retour pour mesurer une distance, un trajet aller suffira (à la réflexion cette idée est un peu douteuse, car si l'horloge de bord est mise à l'heure avec les signaux GPS, la CIS obtenue ne sera plus si indépendante que ça de la navigation).

CONCLUSIONS.

Les satellites grâce à leur altitude élevée permettent de couvrir d'énormes espaces avec peu de moyens. Malgré le coût des techniques spatiales, satellites et lanceurs, les satellites permettront d'obtenir des services de qualité uniforme à un coût acceptable sur une grande partie du globe. Ces progrès concerneront la navigation grâce à Navstar-GPS et peut être grâce à Glonass, la contrepartie soviétique du GPS. On sait que GPS commencera sa vie opérationnelle bientôt (couverture à trois dimensions mondiale en 1992). Les communications air-sol par satellite (AMSS) vont se mettre en place bientôt, Inmarsat devant mettre sur orbite en 1988 son premier satellite de seconde génération comportant donc des transpondeurs dans la bande aéronautique. Le premier appel téléphonique depuis un vol régulier a eu lieu le 18 octobre 1987 (cf Aeronautical Satellite News décembre 1987) grâce à un satellite expérimental japonais. Les normes des signaux AMSS sont étudiées dans divers formes. Le document mis au point par les compagnies aériennes (norme ARINC 741) est déjà d'une bonne épaisseur.

Les conséquences sur la surveillance du trafic aérien, de ce démarrage très prochain des services spatiaux à l'aviation seront assez mesurées au début. La mise en place de l'ADS (Automatic Dependant Surveillance) va certainement apporter d'immenses progrès au contrôle du trafic aérien au-dessus des océans et ceci avant la fin du siècle. Mais l'ADS ne saura pas pas concurrencer la précision et la rapidité du système de surveillance par radar secondaire dans les zones terminales chargées. L'ADS pourra peut être permettre d'économiser certaines stations radar de rentabilité marginale, elle permettra aussi d'obtenir des renseignements plus précis, plus tôt sur les avions qui viennent des zones océaniques.

La surveillance indépendante coopérative ne semble pas avoir d'application précise d'ici quelques temps. En effet le format nécessaire à une bonne surveillance n'est pas le même que celui qui convient à des communications économiques, or la stratégie de tous les intéressés vise aujourd'hui à lancer ce nouveau commerce des communications aéronautiques.

Références :

- (1) Annexe 10 "Télécommunications aéronautiques, volume 1, OACI Montréal.
- (2) Rapports des réunions FANS 2 (1985), 3 (1986) et 4 (1988), OACI Montréal
- (3) La navigation par satellite, prochaine étape de l'aviation civile, G.Eydaleine, bulletin de l'OACI, mars 1988.
- (4) Les services de radiorepérage par satellite, ITA, commission africaine de l'aviation civile, Brazzaville mai 1987.
- (5) Project Paper 741, Aviation Satellite Communication Système (Satcom), juillet 1988, ARINC, Annapolis, Maryland.

ANNEXE 1EXTRAIT DU RAPPORT SUR LE POINT 2 DE L'ORDRE DU JOUR DE FANS/4

Tableau I-A . Evolution du CNS - Espace aérien en route océanique/continental à faible densité de circulation (Note 5)

fonction	Période actuelle	PHASE A	PHASE B	Evolution future possible
Navigation	OMEGA/LORAN-C NDB VOR/DME Alt.barométrique INS/IRS	Période actuelle (note 4) RNAV/RNPC GNSS	RNAV/RNPC GNSS Alt. barométrique- Altimétrie GNSS Alt. (Note 3) INS/ IRS	
Communication	Signaux vocaux VHF Signaux vocaux HF	Période actuelle + Données/signaux vocaux SMAS (note 1)	Signaux vocaux/ Données/Signaux vocaux SMAS - HF au dessus des pôles seulement (Note 6)	Signaux vocaux/ données Bande L de terre
Surveillance	Radar primaire/ SSR (continents) Comptes rendus de position vo - caux.	Radar primaire/SSR (Note 2) -Comptes- rendus de position vocaux ADS	ADS	CIS par satellite (espaces aériens sélectionnés) (Note 5)

LEGENDE

SMAS	- Service mobile aéronautique par satellite
RNAV/RNPC	- Navigation de surface/ qualité de navigation requise
GNSS	- Système mondial de satellites de navigation
ADS	- Surveillance dépendante automatique
CIS	- Surveillance indépendante coopérative
INS	- Système de navigation par inertie
IRS	- Système à référence inertielle

Note 1 - Les services vocaux ne sont peut-être pas disponibles dans certaines régions ou à bord de tous les aéronefs.

Note 2 - Le radar primaire est moins nécessaire

Note 3 - Là où l'altimétrie barométrique n'est pas utilisable

Note 4 - Les NDB seront progressivement retirés.

Note 5 - Comprend les basses couches, les régions off-shore et les régions reculées

Note 6 - Jusqu'à ce que les communications par satellite soient disponibles.

Tableau I-B .Evolution du CNS - Espace aérien continental à forte densité de circulation.

fonction	Période actuelle	PHASE A	PHASE B	Evolution future possible
Navigation	OMEGA/LORAN-C NDB VOR/DME Alt.barométrique INS/IRS	Période actuelle (note 4) RNAV/RNPC GNSS	RNAC/RNPC GNSS Alt. barométrique- Altimétrie GNSS Alt. (Note 3) INS/ IRS	
Communication	Signaux vocaux VHF Signaux vocaux HF	Signaux vocaux/données VHF Signaux vocaux/données SMAS (Note 1) Liaison de données SSR - Mode S	Signaux vocaux/ Données/Signaux vocaux SMAS - Liaison de données SSR Modes S	Signaux vocaux/ données Bande L de terre
Surveillance	Radar primaire/ SSR modes A/C -	Radar primaire/ (Note 2) - SSR Modes A/C ou SSR Modes S	SSR Modes A/C ou SSR Modes S ADS	CIS par satellite (espaces aériens sélectionnés) (Note 5)

LEGENDE

SMAS	- Service mobile aéronautique par satellite
RNAV/RNPC	- Navigation de surface/ qualité de navigation requise
GNSS	- Système mondial de satellites de navigation
ADS	- Surveillance dépendante automatique
CIS	- Surveillance indépendante coopérative
INS	- Système de navigation par inertie
IRS	- Système à référence inertielle

Note 1 - Les services vocaux ne sont peut-être pas disponibles dans certaines régions ou à bord de tous les aéronefs.

Note 2 - Le radar primaire est moins nécessaire

Note 3 - Là où l'altimétrie barométrique n'est pas utilisable

Note 4 - Les NDB seront progressivement retirés.

Note 5 - Comprend les basses couches, les régions off-shore et les régions reculées.

Tableau I-C .Evolution du CNS - Espace aérien océanique à forte densité de circulation.

fonction	Période actuelle	PHASE A	PHASE B	Evolution future possible
Navigation	MNPS OMEGA/LORAN-C Alt.barométrique INS/IRS	Période actuelle + RNAV/RNPC GNSS	RNAC/RNPC GNSS Alt. barométrique- Altimétrie GNSS Alt. (Note 3) INS/ IRS	
Communication	Signaux vocaux HF	Signaux vocaux VHF Données / Signaux vocaux SMAS (Note 1)	Données/Signaux vocaux SMAS -	
Surveillance	Comptes rendus de position vocaux	Comptes rendus de position vocaux A D S	ADS	CIS par satellite (espaces aériens sélectionnés) (Note 5)

Note 1 - Les services vocaux ne sont peut-être pas disponibles dans certaines régions ou à bord de tous les aéronefs.

Note 3 - Là où l'altimétrie barométrique n'est pas utilisable

Tableau I-D .Evolution du CNS - Régions terminales à forte densité de circulation.

fonction	Période actuelle	PHASE A	PHASE B	Evolution future possible
Navigation	NDB VOR/DME ILS Alt.barométrique INS/IRS	Période actuelle (Note 4) + RNAV/RNPC GNSS MLS	RNAC/RNPC GNSS MLS NDB (Note 4) VOR/DME (Note 5) Alt. barométrique INS/ IRS	
Communication	Signaux vocaux HF	Signaux vocaux / données VHF Liaisons de données SSR Mode S	Données/Signaux vocaux VHF -	Signaux vocaux/ données- Bande-L de Terre
Surveillance	Radar primaire	Radar primaire (Note 2) SSR Modes A/C ou SSR Modes S	SSR Modes A/C ou Modes S ADS (Note 2)	SSR

Note 1 - Les services vocaux ne sont peut-être pas disponibles dans certaines régions ou à bord de tous les aéronefs.

Note 4 - Les NDB seront progressivement retirés.

Note 5 - Comprend les basses couches, les régions off-shore et les régions reculées.

LEGENDE

SMAS	- Service mobile aéronautique par satellite
RNAV/RNPC	- Navigation de surface/ qualité de navigation requise
GNSS	- Système mondial de satellites de navigation
ADS	- Surveillance dépendante automatique
CIS	- Surveillance indépendante coopérative
INS	- Système de navigation par inertie
IRS	- Système à référence inertielle

Tableau II -A Evolution de l'ATM - Espace aérien en route océanique / continental à faible densité de circulation.

FONCTION	PERIODE ACTUELLE	PHASE A	PHASE B
		additions :	additions :
Caractéristique/particularités de base	<ul style="list-style-type: none"> - comptes rendus de position vocaux - traitement des plans de vol - contrôle aux procédures - système comprenant principalement des routes fixes - importantes séparations longitudinales et latérale - signaux vocaux HF et VHF 	<p>A D S</p> <ul style="list-style-type: none"> - Résolution tactique de conflit - transmission de données - routes optimales 	<ul style="list-style-type: none"> - plus grande précision de la surveillance - plus grande capacité de planifier la circulation
Fonctions dans le système ATC automatique	<ul style="list-style-type: none"> - traitement automatique des données de plan de vol 	<ul style="list-style-type: none"> - corrélation automatique données de plan de vol - données ADS 	<ul style="list-style-type: none"> - prédiction de trajectoire - moyens améliorés de recherche et de résolution des conflits (pour les routes optimales aussi).
Fonctions à bord des aéronefs	<ul style="list-style-type: none"> - moyens RNAV 	<ul style="list-style-type: none"> - Fonction ADS - moyens de transmission de données - communications vocales par satellite - moyens RNAV complets (RNPC) - moyens de navigation par satellite. 	<ul style="list-style-type: none"> - Moyens améliorés de navigation par satellite

ANNEXE 2EXTRAIT DU RAPPORT FANS/4

PERSPECTIVE ATC - UN SYSTEME D'AUTOMATISATION ATC POSSIBLE
ET EXIGENCES FONCTIONNELLES ADS.

1. Généralités.

1.1 Afin d'illustrer la contribution que l'ADS, conjointement avec d'autres outils ATC, pourrait apporter à l'amélioration du système ATS, considérons, l'exemple suivant. Dans cet exemple, le système ATC automatisé comprendrait le suivi de la position des aéronefs, le traitement des messages de données air-sol, le traitement des données de vol, ainsi que des dispositifs appropriés d'entrée-sortie, y compris des affichages de situation et des affichages sous forme de tableaux. Le système comprend aussi l'équipement informatique nécessaire. Les possibilités fonctionnelles censées être disponibles pour appuyer la mise en oeuvre initiale et / ou finale de l'ADS sont les suivantes :

- a) communications directes, fiables et efficaces, entre le pilote et le contrôleur ou entre le système de bord et le système ATC, sur liaison de données, par satellite et/ou par d'autres moyens appropriés pour l'ADS et les communications ATC connexes ;
- b) cadence théorique de mise à jour des comptes rendus de position d'aéronef de 5 minutes, avec possibilité de faire varier la cadence en fonction des besoins et, selon la demande, en fonction des meilleures informations concernant la position de l'aéronef, ses intentions concernant la trajectoire de vol, le cap et l'état opérationnel du système de navigation de bord (avertissement du contrôleur si l'état n'est pas satisfaisant) ;
- c) affichage de situation de la position de l'aéronef complété de données comme l'identification, l'altitude et la vitesse de l'aéronef, méthode de compte rendu de la surveillance (voix ou ADS) ;
- d) au moins une fois par minute, extrapolation de la position affichée de l'aéronef entre les mises à jour de la position (sur la base du dernier compte rendu de position, des renseignements supplémentaires les plus récents et des renseignements concernant le plan de vol) ;
- e) affichage de la position de l'aéronef avec un minimum de délai après la transmission du compte rendu ;
- f) alerte automatique variable en cas de non-réception des comptes rendus de position ;
- g) possibilité pour le contrôleur de demander et d'obtenir sur liaison de données la position d'un aéronef, indépendamment du compte rendu de position automatique ;
- h) système tridimensionnel, automatique et manuel, (c'est à dire à l'initiative du contrôleur), de recherche de conflits et d'alerte, fondé sur la projection sur trajectoire des informations de position ADS et des intentions de navigation ;
- i) système tridimensionnel d'alerte automatique déclenchée par un seuil d'écart, avec paramètres adaptables à l'échelle du système ;
- j) possibilité de réautorisation et de validation automatiques du plan de vol sur liaison de données (information relative aux points de cheminement, envoyée par l'aéronef sur demande du sol).

2. L'ADS, les services ATC automatisés et le contrôleur.

2.1 Les possibilités fonctionnelles ADS exposées ci-dessus indiquent les possibilités d'une ADS initiale en ce qui concerne la présentation et la poursuite des aéronefs, le traitement des données et les fonctions connexes ; alerte à l'intention du contrôleur et fonctions déclenchées par lui.

2.2 Les possibilités du contrôle ATC automatisé (et les possibilités connexes supposées du système de communication et du système de bord) et l'interface contrôleur pour les communications directes pilote-contrôleur comprennent à la fois les affichages de situation et les affichages du traitement de message. Il serait évidemment avantageux de permettre au contrôleur d'assurer la plupart des communications en utilisant l'affichage de situation et les données déjà présentées sur cet affichage (par exemple en utilisant l'information figurant dans les blocs de données). Cependant, pour les messages plus longs, comprenant par exemple la réception et le traitement de demandes de changement de route, l'affichage du message serait nécessaire.

2.3 Pour les communications sur liaison de données utilisant l'affichage des messages, on pourrait utiliser des zones distinctes pour le message reçu, le message envoyé et la formulation des messages, ainsi qu'une zone réservée à l'affichage des données de vol.

2.4 Les messages reçus et transmis comprendraient l'identification de l'aéronef, la priorité, le contenu du message, un numéro de message et une indication précisant, sur le message reçu, si le contrôleur en a accusé réception ou non, etc...

2.5 Lors de la réception d'un message par le système ATC, le contrôleur serait alerté par un indicateur approprié de bloc de données correspondant à l'aéronef considéré sur l'affichage de trafic. Au même moment, le message serait présenté dans la zone d'affichage de message reçu de telle façon qu'il soit visible sans aucune intervention supplémentaire du contrôleur. Lorsque le contrôleur aurait accusé réception du message, le bloc de données repasserait au mode normal, la teneur ou la présentation du message serait modifiées pour refléter le nouveau statut du message, et le système modifierait la liste des messages selon les besoins. Un indicateur différent serait présenté pour souligner la réception d'un message hautement prioritaire.

2.6 Pour transmettre les messages que l'on ne peut obtenir à l'aide du bloc de données d'aéronef, on disposerait d'une liste relativement courte de messages (transmis couramment) "prêts à l'emploi" à sélectionner par numéro ou par menu ; il existerait aussi un type de message à format libre. Les types de messages "prêts à l'emploi" ne nécessiteraient que l'identification d'aéronefs et éventuellement quelques autres éléments de données, par exemple un vecteur de cap. Après la formulation de ces messages, dans la zone de formulation de messages, le contrôleur les transmettrait au moyen d'une intervention simple. La zone de formulation de messages serait alors dégagée et le message apparaîtrait au bas de la zone "message envoyé" de l'affichage, avec l'heure d'envoi.

2.7 Les messages dont il aurait été accusé réception seraient effacés de l'affichage, aussi automatiquement que possible, et seraient alors mis en mémoire.

2.8 Une amélioration que l'on pourrait envisager consisterait à apparier les messages sur l'affichage, pour représenter une transaction avec un aéronef. Par exemple, après l'envoi d'un message de réponse comme suite à un message de demande, on pourrait transférer le message de demande de la zone "message reçu" à la zone "message", où il serait apparié avec le message de réponse. On pourrait automatiser cette fonction et réduire ainsi le travail d'entrée/sortie.

2.9 L'emploi de formats de messages "prêts à l'emploi" pour les messages reçus permettrait un traitement plus automatisé des messages de données et serait avantageux pour le traitement des messages sur liaison de données utilisant l'affichage de situation.

3. Jonction entre le contrôleur et les aéronefs dotés uniquement d'un équipement HF.

3.1 Pour permettre l'application de procédures analogues dans le cas d'aéronefs HF seulement, le système devrait permettre de reconnaître les messages destinés à des aéronefs équipés pour les communications vocales HF seulement ; ces messages seraient présentés sur affichage ou sur support en papier, transmis à l'aéronef par communication vocales HF. Dans la direction aéronef-sol, le message vocal serait introduit dans un système de traitement qui lui donnerait le format du message ADS standard (ou du message de communication connexe) et qui l'enverrait ensuite au système ATC.

4. Communications vocales directes pilote-contrôleur.

4.1 Les communications vocales par satellite pourraient être déclenchées par le pilote ou par le contrôleur. Dans le deuxième cas, il serait nécessaire d'envoyer un message de demande de canal vocal, soit en faisant une désignation appropriée dans le bloc de données d'aéronef, soit en mettant l'identification de l'aéronef dans un message de liaison de données préalablement mis en format. Le contrôleur serait alors informé par le système de communications qu'un canal vocal a été établi et que le contrôleur peut émettre.

PART VII

Meteorological Forecasts

DEVELOPMENTS TO ENHANCE METEOROLOGICAL FORECASTING FOR AIR TRAFFIC SERVICES

by

M.E. Cox

European Organisation for the Safety of Air Navigation
EUROCONTROL
Engineering Directorate

rue de la Loi, 72, B - 1040 Brussels (Belgium)

and

D. A. Forrester

The Meteorological Office,
London Road, Bracknell,
Berkshire, RG12 2SZ, U.K.

SUMMARY

In the future, the quality of the meteorological data available for use both in ground-based systems and on aircraft will become even more important as ATC strives to handle increasing volumes of traffic in the most efficient manner. This paper, which deals primarily with European work, commences with an indication of the effect of errors in meteorological data on the precision of predictions of aircraft trajectories and then discusses the variability of wind and temperature, showing the influence of location, altitude and season, in the European area. An outline of present-day forecasting methods follows: the data used and accuracies achieved are included. Potential sources of improvements are then discussed with the emphasis being placed on the use of aircraft-derived data: details are given of the accuracy of such data, possible methods of recovery and their application within the Meteorological Services. A further short section describes the impact of turbulence on both the safety of air traffic and the accuracy of flight profile predictions: possible methods of providing aircraft with the means for the automatic reporting of turbulence are included. This is followed by a short description of some experimental work either performed or being planned in the European area, aimed at improving the quality of the meteorological data made available for ATS purposes as a result of using data recovered from aircraft through both satellite and ground-based (Mode S SSR) systems. The final section of the paper outlines some future work and other factors that could also influence the extent to which improvements in forecasting might be made.

1. INTRODUCTION

During the early 1970's, before the fuel crisis occurred, some thought was being given within the EUROCONTROL Organisation to the question of developing a system of Air Traffic Control (ATC) for Western Europe capable of handling the high volume of air traffic expected during the 1980's and 90's. Apart from similar or improved standards of safety, two other system features considered essential were: first, the system should permit aircraft to be operated close to their optimum profiles and, second, that in the event of system failure perfectly safe operations would continue for a period of many minutes. Initial proposals made by Martin and Benoît in 1972 for en-route control were based on the exploitation of trajectory prediction techniques by the ground system. The predictions would enable each flight to be planned on a more 'strategic' basis and thereby considerably reduce the need for tactical interventions by the controller. By 1973 these ideas had been further developed and a system concept, using such techniques, was outlined at EUROCONTROL. Studies of the accuracies achievable for predictions over extended periods of time quickly underlined the need for high quality upper-air meteorological data for all predictions apart from those based solely on radar data, which can be made only for aircraft already in flight and are generally valid for only a few minutes ahead. The requirement for high-quality upper-air meteorological data comprises two components: the first, wind-vector data, is a key element in predicting along-track progress throughout all phases of flight and, indeed, their quality is likely to be the factor limiting the precision of any prediction over an extended period of time; the second, temperature data, is of most importance during the climb phase. As a result of collaboration with meteorological authorities it was soon established that the existing methods used to provide forecast data would be incapable of meeting the possible future demands for short-term forecast data having the precision desired - a limitation that arises from the relatively small number of upper-air measuring stations and the frequency of soundings made (2-4) per day. Accordingly a programme of studies was started to examine the feasibility of using upper-air measurements made on board aircraft and relayed to the ground by means of a digital data link.

Today, a large number of aircraft are being equipped with Flight Management Computer Systems (FMCS's) capable of making profile predictions in order to follow optimum flight trajectories and, although the majority of these systems operate on 3-D profiles, by the turn of the century, many aircraft will have a 4-D capability. The carriage of FMCS's could perhaps reduce the need for ground-based predictions but, wherever the predictions are made, there will remain a requirement for good wind-vector and temperature data to be available for use by Air Traffic Services (ATS). This paper discusses the significance of meteorological data on prediction accuracies but its main purpose is to provide an overview of the work underway in Europe to obtain the improvements in quality desired, in particular, through the use of aircraft-derived data.

2. THE IMPACT OF METEOROLOGICAL ERRORS ON TRAJECTORY PREDICTION ACCURACY

2.1. General

The application of trajectory prediction techniques to ATC embraces a range of possibilities : techniques have been developed both to meet different objectives in terms of the phase(s) of flight to be covered and the period of validity required, and to exploit different levels of data availability. Simple predictions can be made employing either readily available data, e.g. by extrapolation, for controller assistance or system estimates. Considerable use is also made today of more precise short-term predictions, using radar data and covering time periods from a few seconds to a few minutes ahead, for controller displays and Short-Term Conflict Alert (STCA) systems,

For the longer-term predictions possibly covering more than one phase of flight and valid for a period of up to 30 or more minutes ahead, as required for conflict 'probing' or in strategic systems of control, data requirements are increased considerably, as discussed by Benoit et al in 1975. Moreover, the need for good meteorological data becomes paramount: first, any error in the along-track component of the wind vector translates into an error in the estimate of ground speed and thereby impairs any prediction of along-track progress throughout all phases of flight; second, errors in air temperature data impair the precision of both climb/descent predictions and true air speed (TAS) calculations. As will be shown later, in Western Europe air temperature variability is of less significance than wind variability. Nevertheless, apart from enabling a high degree of precision to be achieved in climb/descent predictions, good temperature data are also important to the meteorological services in assisting in the accurate forecasting of cloud, fog, and icing conditions and thus have a further bearing on the safety of aircraft operations.

2.2. The significance of wind vector and temperature errors

The difference between predicted and actual trajectories may be expressed in terms of ground distance or time in the case of both altitude and along-track progress. Figure 1 illustrates the effect of constant head and tail winds on the climb profile of a very modern medium-range airliner. Any estimate of an aircraft's ground speed will be directly modified by the along-track component of a wind-vector error. Actual prediction errors will depend on how well the atmosphere is modelled in both the horizontal and vertical plane, the latter being relevant only to vertical manoeuvres.

The influence of temperature errors on prediction accuracy varies considerably both with aircraft power plant and with the mean temperature difference from the International Standard Atmosphere (ISA) and tends to be greatest at the upper operating altitudes. Figure 2 illustrates the effect as computed for constant temperature differences of between $\pm 20^{\circ}\text{C}$ from ISA on the climb profile of a very modern medium-range airliner. It will be noted that, whereas with negative temperature differences or positive differences up to $+10^{\circ}\text{C}$ from ISA, there is little influence on climb performance below FL 290. With greater positive differences from ISA the influence of a temperature error will be more pronounced.

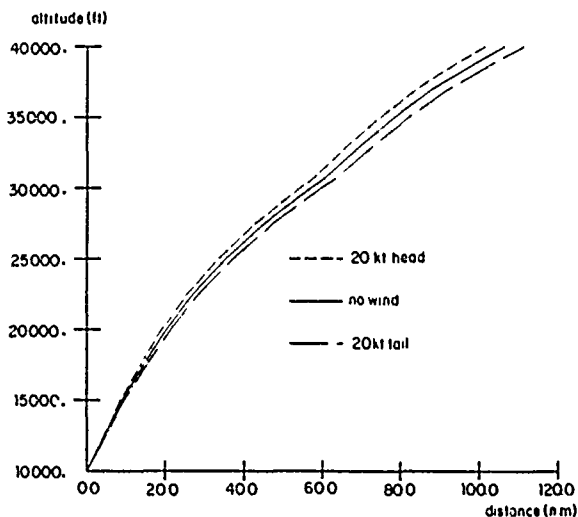


Fig.1 - The effect of wind on a typical climb profile of a modern medium-range jet (82T; profile 300 kt IAS, 0.80 Mach)

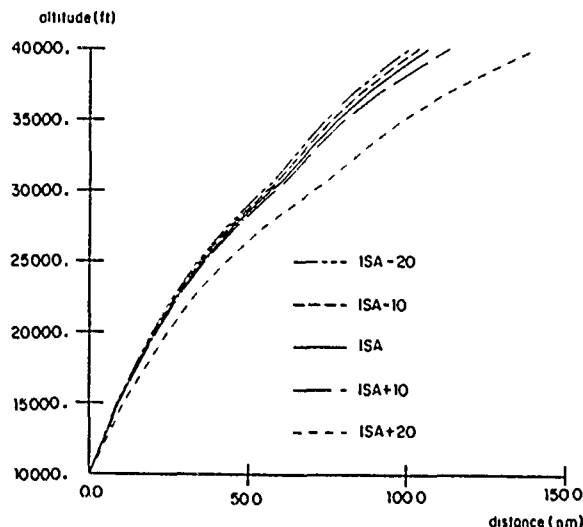


Fig.2 - The effect of temperature on a typical climb profile of a modern medium-range jet (82T; profile 300 kt IAS, 0.80 Mach)

Calculations of TAS from Mach or Indicated Air Speed (IAS) are temperature dependent, but for normal aircraft operations, the effect of a temperature error is small : for example, with an aircraft operating at FL 290, and Mach 0.8, a 3°C error produces approximately a 3-knot or 0.65% error in TAS.

2.3. Wind and temperature variability

2.3.1. Wind variability

In mid-latitudes the wind field is highly variable. On the basis of daily observations, Tucker (1960) has shown that the standard vector deviation (SVD) reaches a peak of 65 knots at FL 300 in the North Atlantic in January (the highest anywhere in the world) and 45 knots in July. Over Western Europe at FL 300 the SVD is 50 knots in January but still 40 knots in July; at FL 390 it is about 40 knots in January and also about 40 knots in July; at FL 180 it is 35 knots in January and 25 knots in July; at FL 100 it is 30 knots in January and 20 knots in July.

Variability (σ_t) on time scales (t) of a few hours is governed by a power law

$$\sigma_t \propto \text{SVD} \times t^p$$

Using pilot balloons, Jaspersen (1982) has shown that p can take the value $1/3$ or $1/2$ depending on the synoptic situation. Using a large source of aircraft flight data recordings, Gage and Nastrom (1986) have obtained power spectra which are in theoretical agreement with the $1/3$ power law. A similar equation can be used to describe spatial variability.

2.3.2. Temperature variability

By reference to daily observations, Goldie, Moore and Austin (1958) have shown that the standard deviation of temperature reaches a peak of 8°C at FL 180 and FL 100 over Newfoundland and 7°C at FL 390 over the North Atlantic in January, and 6°C at FL 390 over Scotland in July. Over Western Europe at FL 300 the variability is small ($3-4^\circ\text{C}$) in both January and July; at FL 390 it is large ($6-7^\circ\text{C}$ in January, $5-6^\circ\text{C}$ in July); at FL 180 and FL 100 it is large ($5-6^\circ\text{C}$) in January but small ($3-4^\circ\text{C}$) in July.

3. PRESENT-DAY FORECASTS

Currently (summer 1988) a global numerical model is run operationally at the World Area Forecast Centre in Bracknell to produce wind and temperature forecast information for distribution to aviation users worldwide.

Data from many sources are assimilated into this model every 6 hours. The main sources of upper-air data are radiosonde ascents (temperatures, humidities and winds usually at 00 and 12 GMT), pilot balloon ascents (winds usually at 06 and 18 GMT), satellites (temperature profiles and cloud movement winds), and aircraft (mainly AIREPs over the oceans). Surface reports come from both land stations and ships. Human intervention plays an important role in the quality checking of this data prior to the running of the forecast model.

The model, which is based on the primitive equations solved using finite difference techniques, has a grid resolution of 1.5° in latitude by 1.875° in longitude (about 150 km in mid-latitudes), has 15 levels in the vertical and is run on a Cyber 205 supercomputer. Forecasts are produced for up to 6 days ahead twice a day from 00 and 12 GMT starting conditions. There is also a limited area fine-mesh model covering roughly $80^\circ\text{W}-40^\circ\text{E}$, $30^\circ\text{N}-80^\circ\text{N}$ with a resolution of about 75 km in mid-latitudes.

The World Area Forecast System grid-code data are disseminated on a 2.5° by 5.0° grid, but proposals have been made to reduce this to 1.5° by 2.0° .

With the recent acquisition of a new ETA 10 supercomputer improvements to the numerical models will soon be implemented. It is anticipated that the horizontal resolution will be increased (the new grid probably becoming 0.833° by 1.25°), and that extra levels will be inserted.

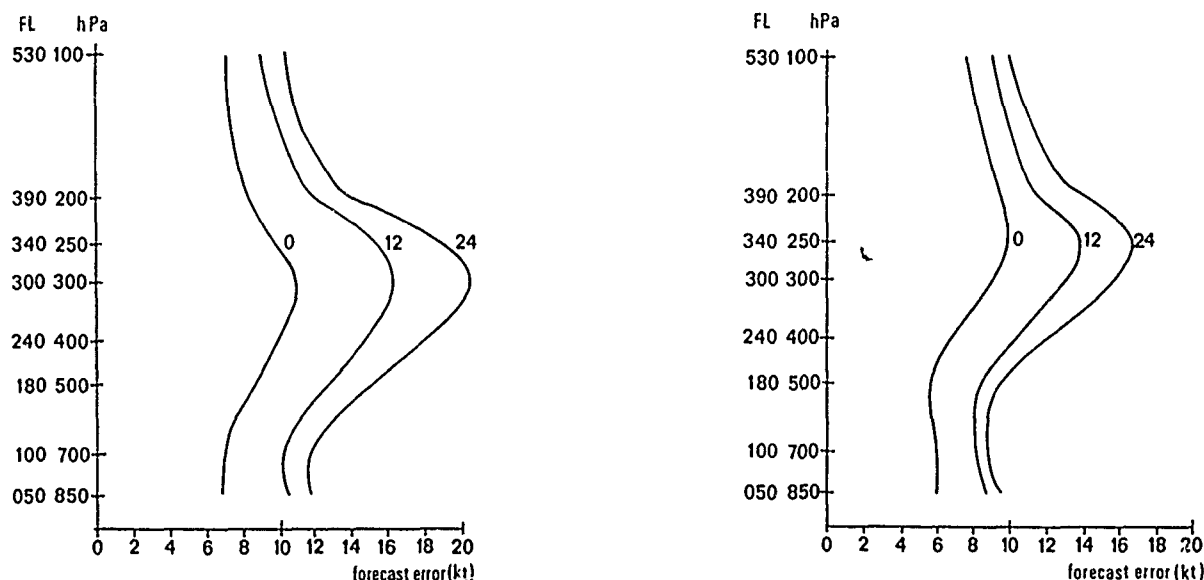


Fig.3 - RMS vector wind errors for typical winter (left) and summer months

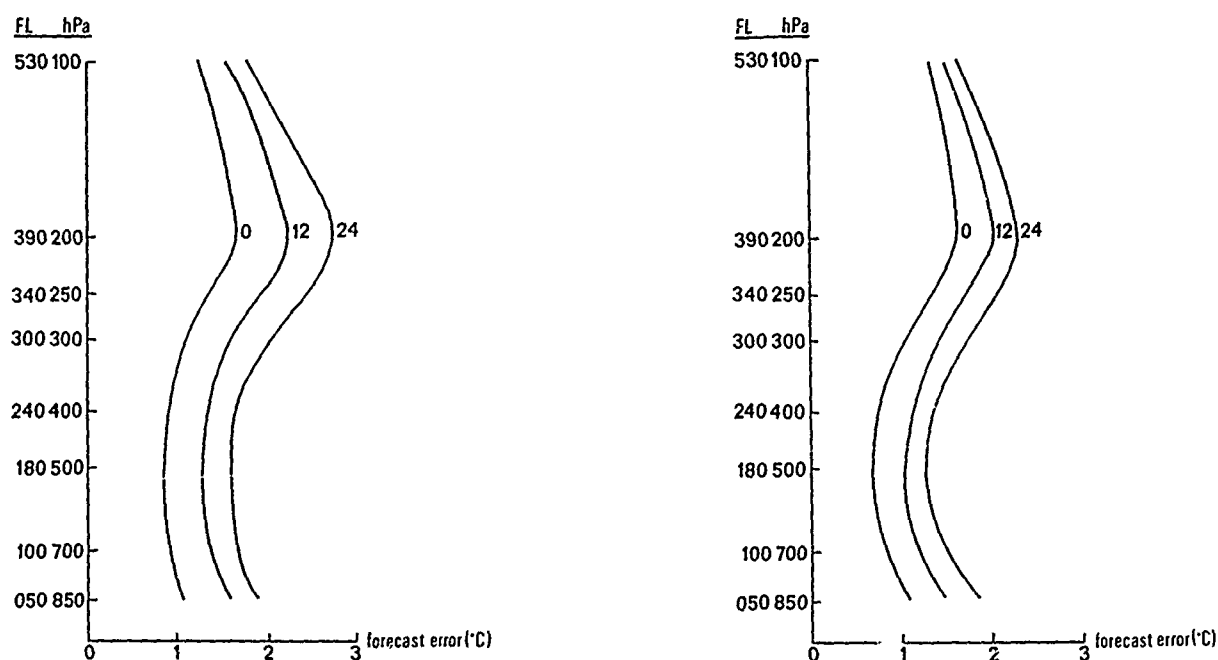


Fig.4 - RMS temperature errors for typical winter (left) and summer months

The accuracy of the wind and temperature forecasts can be seen from Figures 3 and 4 where plots of monthly RMS vector wind errors and RMS temperature errors are displayed against flight level for a typical winter and summer month. The errors are based on the global model forecasts and on comparison with radiosondes over Western Europe. The curves for 0, 12 and 24-hour forecasts clearly show a peak in wind error at about FL 300 in winter and FL 340 in summer (near jet stream level) and a peak in temperature error at about FL 390 (near tropopause level). The mean wind speed error is generally small (less than 3 knots in the 24-hour forecast), but is consistently negative, indicating that wind strengths are slightly under-forecast. The mean temperature error is less than 1°C. The fine-mesh model generally has slightly smaller RMS errors.

The relatively large RMS vector wind error in the analyses (or 0-hour forecasts) is partly due to the inability of the model to represent local intensifications on its relatively coarse grid. It is also partly due to the need to allow mutual adjustment between the analysed variables so that the resulting fields satisfy the dynamic constraints of the forecast model. Hence, it is not always possible to fit the observations within their expected observational errors.

4. POTENTIAL SOURCES OF IMPROVEMENT

4.1. NEXRAD/TDWR

The NEXt Generation Weather RADar (NEXRAD), is currently under development in the United States. It will be a 10cm scanning doppler radar, measuring line-of-sight velocities, and is designed to monitor severe weather - thunderstorms and tornadoes. It may also provide some information on winds in clear air, but probably only at very low altitudes. A prototype is to be set up at Norman, Oklahoma, in autumn 1988, and 196 systems are to be installed nationwide by 1995. The proposals cover installation at certain sites in Europe, possibly including 3 in central, south and eastern England. The NEXRAD will be most useful for monitoring outside the terminal areas, and consideration is being given to implementing a separate system of doppler radars at major airports to monitor the terminal areas, particularly for windshear. This latter system is referred to as the Terminal Doppler Weather Radar (TDWR).

4.2. Profiler

The wind profiler is a vertically pointing "clear-air" doppler radar (operating on VHF or UHF frequencies) capable, unattended, of almost continuous measurements of wind above the site. The vertical resolution depends on the operating mode, and is hence a function of altitude, but is about 100 metres at low levels degrading to about 1km above FL 300. Following trials in Colorado, 30 profilers are planned to be in operation throughout the Midwest of the United States during 1989-1992. An experimental profiler may be set up at Bracknell in 1989. COST 74 is a 5-year project recently set up to consider a European-wide network of wind profilers.

4.3. LIDAR (Light Detection And Ranging)

Ground-based and airborne LIDARs have been developed to measure low-level windshear, but have not had the power to operate at high altitudes, where the air is much cleaner. However, Curran and Readings (1988) claim that advances in laser technology could make feasible by the mid-1990's space-based lidars capable of accurate measurements of upper-air winds (amongst other parameters), but these would not be able to penetrate optically thick layers (i.e. thick clouds).

4.4. SODAR (Sound Detection And Ranging)

The doppler acoustic sounder or SODAR has shown promise in the detection of certain types of low-level windshear (in particular the presence of low-level wind maxima), but is unlikely to be able to penetrate to altitudes much above the boundary layer.

4.5. Aircraft-derived meteorological data

Today, an increasingly large proportion of commercial airliners are equipped both with Air Data Computers (ADC's), capable of computing the static air temperature (SAT) to within $\pm 1^\circ\text{C}$, and Area Navigation (RNAV) systems or FMCS's which can provide good estimates of the wind speed and direction pertaining to the air mass through which they are flying. The accuracy of the wind information is not usually specified - it depends on a number of factors including the sensors used, their basic accuracy, and the extent to which different data are combined, e.g. an Inertial Navigation System (INS) may use inputs from precision ground-based radio systems such as DME to improve positional accuracy when operating in continental airspace. The ultimate accuracy of winds from high precision aids lies in the accuracy achievable in measuring true airspeed (TAS), about 4 knots RMS using a conventional pitot-static system, although doppler laser devices are capable of higher accuracy. When first set up, an INS produces winds probably to an accuracy of about 6 knots RMS vector error; however, owing to drift, the wind component error could build up to 10 knots or more after several hours flying. Harlow (1982) has reported good agreement between the winds derived from DME/DME RNAV and those derived from INS.

The introduction of GPS (Global Positioning System), a very precise system of navigation, should result in a significant improvement in the accuracy and reliability of wind information over the oceans. However, the limitation of the pitot-static measurements will remain the obstacle to obtaining near-perfect measurements of wind velocity.

Under good conditions, Omega is capable of quite high accuracy, but it is subject to unpredictable ionospheric disturbances, which can seriously degrade its performance.

By using the principles of renavigation to correct for INS drift and Schuler oscillation using Doppler, Decca, Loran or Omega, research aircraft such as the UK Meteorological Office C-130 Hercules can measure horizontal wind components to an absolute accuracy of better than 1 knot and a resolution of almost 0.1 knot in straight and level flight in relatively undisturbed conditions over the sea. This involves, however, the use of wind vanes to measure the angles of attack and sideslip and an accurate pitot-static device, all of which are mounted on a long nose boom.

In comparison, the accuracy of 1 minute (1000 ft) radiosonde winds, derived in the UK using the Cossor 535D radar, is about 3 knots (RMS vector error) at a slant range of 90 km (Nash and Schmidlin, 1987). Using Omega or Loran results in poorer accuracy. The accuracy of radiosonde temperatures is about 0.5°C .

Bisiaux et al (1983) showed that very erroneous wind data were obtained from INS during aircraft manoeuvres, but that this phenomenon was highly correlated with roll angle. Since rolls occupy only a small percentage of flight time, albeit mostly in the terminal area, it is essential to ignore INS winds if the roll angle exceeds a predetermined threshold. Otherwise, INS winds have been found to agree well with nearby radiosonde winds. Bisiaux also found very large errors in static air temperature recorded on flight data cassettes. However, when recalculated from total air temperature and mach number, good agreement was obtained with radiosonde temperatures.

In using automatically acquired aircraft-derived data it is important to ensure that the accuracy of estimates is maintained by the correct labelling of all reports with altitude, location and time. Whether these are added in the aircraft or on the ground will depend on the data link systems employed.

5. THE TRANSFER OF AIRCRAFT-DERIVED DATA

5.1. Radiotelephony (R/T)

It is current practice for pilots on certain flights, particularly transoceanic ones, to make routine reports by R/T regarding the meteorological conditions observed at intervals along their flight path. In addition, on all international flights, they are required to report any incidence of meteorological phenomena likely either to affect the safety or have a marked effect on the efficiency of other aircraft operations. Although these aircraft reports, known as AIREPS or PIREPS, are very useful, they have a number of limitations which preclude an extension of their use to achieve the measure of improvement required in forecasting. The major limitations are :

- they impose workload on the pilot and are thus unsuitable for the high reporting rates that would be required during climb-outs and other operations in continental airspace;
- on receipt at an ATC or communications centre, further manual effort is necessary to convert the AIREPS into a form suitable for onward transfer and subsequent use in the meteorological centre, with possible consequences on both accuracy and the timeliness of their availability for applications;
- because they are made most frequently in remote areas their transfer is invariably by HF radio, with its widely varying performance.

Whereas the last limitation could be overcome by a more reliable communications channel, viz. satellite-based, the continuing use of R/T would not diminish pilot workload. By means of a digital data link, which can be supported by a satellite in remote areas, meteorological data can be transferred automatically and readily introduced into the forecasting system, as will now be discussed.

5.2. Digital data links

5.2.1. Mode S

This is a development of secondary surveillance radar (SSR) in which a unique address is used for each aircraft: it is capable of supporting a two-way air/ground data link within the line-of-sight coverage. Mode S is compatible with existing SSR but new ground systems and avionics (transponders plus some interfacing/processing facilities) are necessary to support the data link. Although the system currently uses a rotating antenna, transactions are possible every six seconds, which would permit meteorological data to be transferred at approximately 400 ft. intervals during a climb/descent of up to 4000 ft/min. Further technical details of this type of application were discussed by Cox (1986). The implementation of Mode S in Europe is lagging behind the USA but a number of ground stations plus sufficient aircraft to provide reports should be in operation during the late 1990's.

5.2.2. ACARS (Aircraft Communications Addressing and Reporting System)

This is a digital data link developed by the airlines primarily for Airline Operational Communications (AOC). Although VHF ACARS has a range of only about 200 miles, this system could provide meteorological data close to land areas equipped with ground installations. Several major airlines, e.g. British Airways, are taking delivery of new aircraft such as B-747-400's and B-767's fitted with ACARS, and also plan to retrofit many of their older aircraft. Many US airlines already submit reports in this way, but this information is not available in Europe. If ACARS moves to a satellite-based system, then this opens up the potential for near global coverage from a large number of aircraft.

5.2.3. Satellite systems

Satellite communications systems have been proposed by the International Civil Aviation Organization (ICAO) Future Air Navigation Systems (FANS) Committee (1988) as a means of transferring meteorological reports from aircraft; this application would be an extension of satellite use for automatic dependent surveillance (ADS), which relies on aircraft transmitting their position and altitude at specific intervals of time. A limited number of fully operational aircraft may be in service in the early 1990's and some aircraft may carry experimental equipment during this period. The growth in installations will follow the introduction of ADS, which should become very significant by the turn of the century. In the meantime reports will be available from purpose-built systems known as ASDAR. This Aircraft to Satellite Data Relay was developed for the Global Weather Experiment in 1979, and fitted to 17 wide-bodied aircraft. Wind and temperature data were sampled every 7.5 minutes during flight, and this information was transmitted via geostationary satellite every hour. A new, improved ASDAR system, capable of giving more detailed climb and descent profiles, as well as cruise data, is under development and 13 units are expected to come into operation during 1989. This system is designed primarily to obtain meteorological information from data-sparse areas of the world to help improve numerical forecasts worldwide.

6. TURBULENCE

Turbulence, both in clear air and in cloud, takes its toll in terms of discomfort and injury to, and occasionally death of, airline passengers and crew, increased flying costs due to diversions, changes of flight level or reductions in airspeed and stress damage to, or even the complete loss of, an aircraft. Unforeseen speed and/or altitude changes may also invalidate trajectory predictions made over extended periods of time.

Meteorological forecasts and airborne doppler weather radar usually provide adequate warning of convective cloud turbulence. On the other hand, although forecasting of clear air turbulence (CAT) has improved somewhat in recent years (Forrester, 1986), there is still no airborne instrument capable of the remote detection of CAT in operation. (Stearns, 1981, describes an experimental instrument.) Moreover, the submission of AIREPs which contain turbulence reports as well as winds and temperatures, is practised only over the oceans and not over land areas. There is, therefore, a need for automated measurements of turbulence transmitted to the ground in a timely fashion.

One measure of turbulence is the vertical (normal) acceleration increment experienced at the centre of gravity of an aircraft. This appears in the definitions of light, moderate and severe. A better measure, which describes the atmosphere itself rather than the effect of the atmosphere on the aircraft, is the derived equivalent gust velocity. Sherman (1985) shows how this quantity is related to the vertical acceleration, the airspeed and the weight of the aircraft. The provision of a processor unit with the Mode S transponder should be adequate to handle the computations necessary on board the aircraft and thereby make the automatic reporting of turbulence feasible in continental airspace. Development in avionics architecture should enable satellite-based systems to report turbulence in a similar manner.

7. EXPERIMENTAL WORK

7.1. MODE S

7.1.1. Outline

Following studies to develop techniques by which large quantities of asynoptic data could be introduced into Bracknell's forecasting model (Forrester, 1979), two Tristars of British Airways were equipped with experimental Mode S transponders and processing facilities which enabled them to transfer, for ground use, meteorological and other aircraft-derived data via the UK CAA's experimental Mode S ground station in S. England. All data recovered from the aircraft were transferred to the EUROCONTROL Experimental Centre, where meteorological messages (CODARS) were prepared automatically and transmitted to Bracknell via a terminal in the WMO network located in Paris. Recordings from Digital Flight Data Recorders (DFDR's) on the aircraft were obtained from BA for each flight to permit comparisons with data received via the link.

During trials which lasted approximately 12 months, some 200 normal commercial flights were monitored within the radar's coverage and data transferred to Bracknell.

7.1.2. Tests performed

Within EUROCONTROL, comparisons were made of the data received in the Comm-B messages and the on-board (DFDR) recordings to investigate the frequency of errors and their possible causes.

At Bracknell, the meteorological data were validated and used to continue the studies into the use of such aircraft derived information for improving the quality of forecast data. Validation was performed by comparing the received data with appropriate radiosonde ascents and other data available within the Centre. Methods of handling were confirmed but, on account of the small number of flights available daily, the CODAR messages were not introduced into background data banks.

For the latter stages of the experiment, wind/temperature profiles were constructed at Bracknell and transferred to London (Heathrow) Airport for use by forecasters. A functional diagram of the experimental set-up is given in Figure 5. The value of wind/temperature profiles transferred to London (Heathrow) was judged subjectively by the forecasters at the airport.

7.1.3. Results

Of the 200 flights monitored, valid data from some 35 were checked against DFDR data. Discrepancies were found in between 0.1% - 0.2% of the meteorological data received but it is believed that some of the errors could be attributed to the method of comparison.

Bracknell found the temperature structure to be very well represented; unlike the comparisons made earlier with data from other types of aircraft, however, the temperatures were generally 2 - 3° too warm. A specialist investigation into the possible cause of the bias revealed firm reasons for only 0.7°C of this figure.

The forecasters at London (Heathrow) were very enthusiastic in their support for visual plots and tabulations of the upper-air winds and temperatures made available to them, virtually in real time.

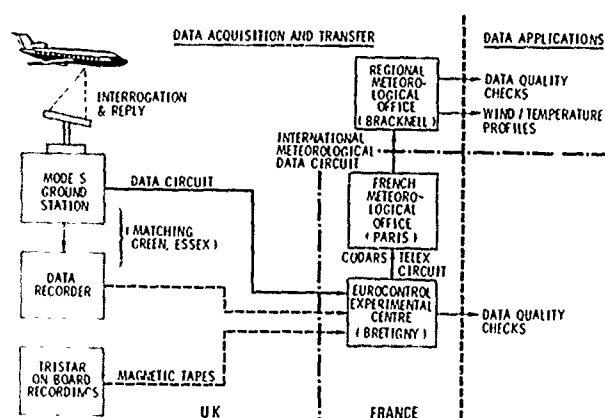


Fig.5 - The experimental facilities used in recovering and evaluating aircraft-derived meteorological data reports.

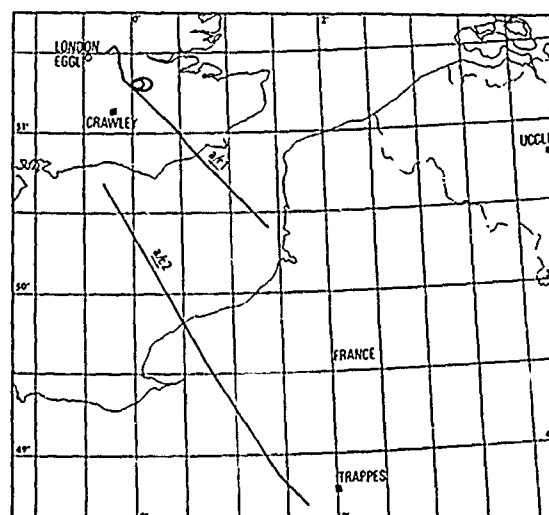


Fig.6 - The disposition of Crawley, Trappes and Uccle and the tracks of two Tristar aircraft used in data comparisons

On some occasions the two Tristars were observed in fairly close proximity at a time near to radiosonde ascents. In Figure 6 the approximate tracks of the aircraft (A/C) on one such occasion are shown together with the location of the sites from which radiosonde launches were made, i.e. Crawley, Uccle and Trappes (A/C 1 was descending to London from where A/C 2 was departing). A comparison of the aircraft and radiosonde temperature measurements is made in Figure 7; aircraft positions and the appropriate timing of events are also given. Figures 8 and 9 show respectively the wind speed and wind direction data obtained from the two aircraft together with their altitudes. The presence of a jet-stream can be clearly seen from A/C 2 measurements - the approximate forecast data indicated this activity to be 300 nm to the north of the Paris (Trappes) area. The 20kt variation occurring in the wind speed measurements emanating from A/C 1 between 1040 - 1046 GMT, i.e. 23 - 30 min. of elapsed time, coincided with the aircraft rolling $\pm 25^\circ$ in a holding pattern. Table I shows comparisons made by Bracknell of the wind-vector data and radiosonde observations at specific pressure levels.

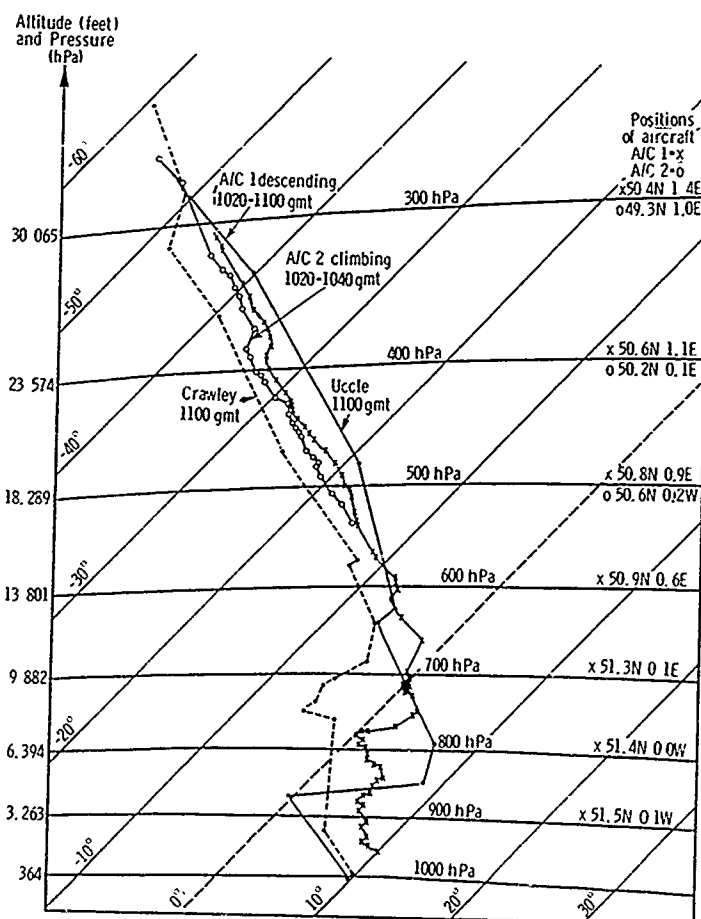


Fig.7 - A simplified tephigram comparison of radio ascents from Crawley and Uccle with aircraft temperature measurements relayed via the Mode S data link

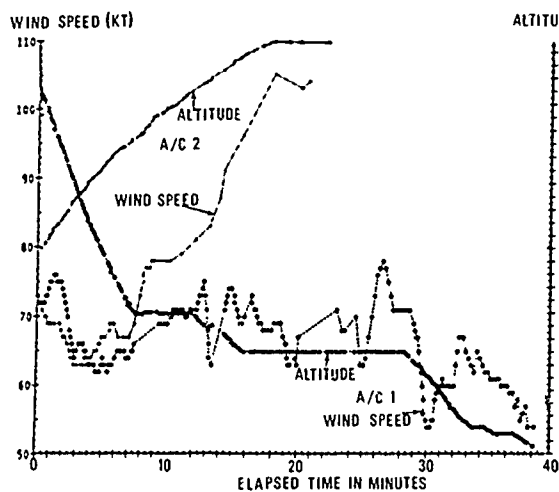


Fig.8 - Wind speed and altitude data relayed from the two aircraft observed in Fig.6

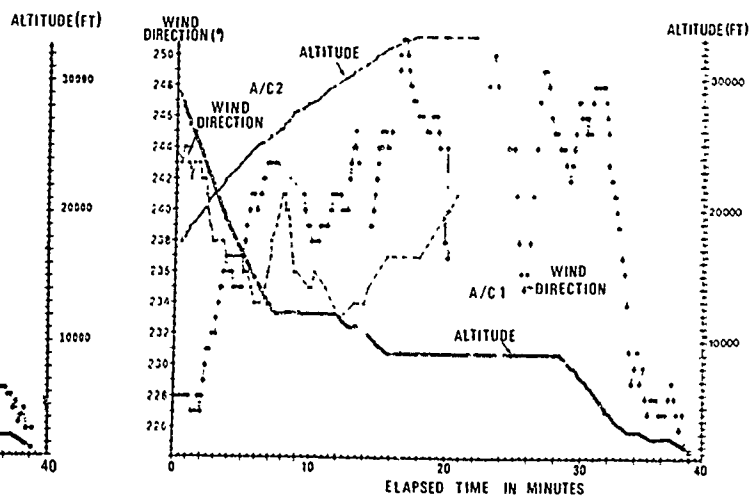


Fig.9 - Wind direction and altitude data relayed from the two aircraft observed in Fig.6

TABLE 1 **WIND-VECTOR DATA OBTAINED FROM RADIOSONDE ASCENTS**
AND AIRCRAFT AT SPECIFIC PRESSURE LEVELS

		WIND DIRECTION / SPEED (kt) FROM DIFFERENT SOURCES				
		RADIOSONDE ASCENTS			A I R C R A F T	
Pressure hPa	Altitude approx. (ft)	CRAWLEY 1100 GMT	UCCLE 1100 GMT	TRAPPES 1100 GMT	a/c 1 (descending 1020-1100 GMT)	a/c 2 (climbing) 1020-1040 GMT
250	34000	235/63	225/91	230/96	- -	- -
300	30000	240/60	220/88	230/95	- -	234/91
400	24000	235/73	225/81	230/78	230/74	234/69
500	18000	235/73	225/67	235/58	240/65	243/69
700	10000	240/67	240/62	240/47	240/73	- -
850	5000	240/59	240/53	245/48	240/60	- -

7.2. Radar trackers

A further application of aircraft-derived data lies in improving the performance of radar trackers, which are used on the ground to provide estimates of aircraft position, speed vector and future position. This application, which is discussed briefly by Cox (1986), also appears to offer possibilities for providing an alternative source of wind-vector data for aircraft not equipped with INS or other suitable advanced RNAV systems, which might be very useful in covering areas, routes and flight levels not used frequently by better-equipped aircraft.

Essentially the technique employs positional data to provide a precise ground track which, when combined with other data readily available via the link, e.g. magnetic heading and true airspeed (TAS), permits the computation of wind-vector estimates.

Preliminary experimental work has yielded promising results, particularly during level flight and under conditions of high wind, but more work is necessary to develop the techniques. Specimen results from a Heading Bias Filter radar tracker are compared with INS-derived wind vectors in Figures 10 and 11.

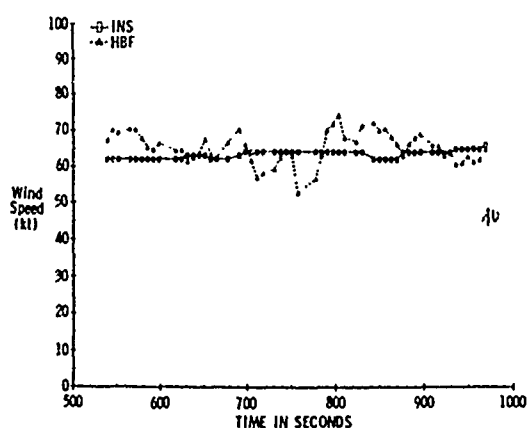


Fig.10 - A comparison of wind speed data obtained from a Heading Bias Filter radar tracker with aircraft-derived (INS) data.

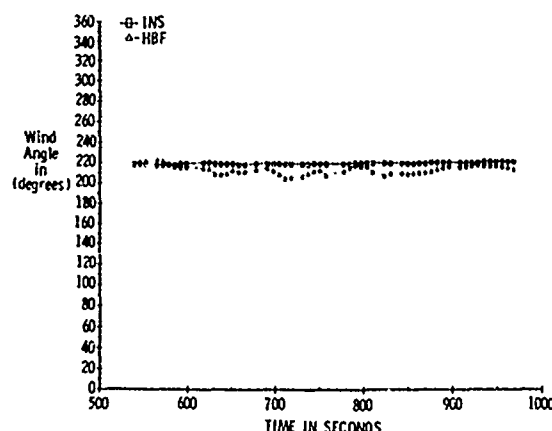


Fig.11 - A comparison of wind angle data obtained from a Heading Bias Filter radar tracker with aircraft-derived (INS) data.

7.3. PRODAT

Since 1985 the United Kingdom CAA, the Spanish DGAC and EUROCONTROL have been working with the European Space Agency (ESA) in a series of experiments known as PRODAT, aimed at exploiting satellites for aeronautical purposes, as summarised by Cooke and Cox in 1988. One aspect of this work includes the transfer of meteorological data from a number of aircraft equipped with experimental satellite terminals. Within the UK these data are being transferred to Bracknell for assessment (similar to that performed with the Tristar data); EUROCONTROL will be studying the value of the data on trajectory predictions over very extended periods of flight, which, to date, has not been practicable.

It is intended to conclude the PRODAT experiment during 1990.

8. FUTURE WORK

8.1. Use of current meteorological forecasts

Although much use is made of 12, 18 and 24-hour forecasts of winds and temperatures from the World Area Forecast Centres in Bracknell and Washington in terms of pre-flight planning (grid-code data) and in-flight management (charts), little general use is made of this information by air traffic control in Europe. This may be partially remedied within a few years when a degree of automation is implemented at London Air Traffic Control Centre which will require as one input a recent forecast of upper-air wind to allow the allocation of time slots for aircraft landing in the London area. It will be interesting to see how well this model performs using conventional forecasts, the most recent available being the 6-hour forecast ready for transmission about 3 hours after start time. Thompson (1987) has constructed a statistical model to simulate the 0 and 12-hour forecast wind errors over the UK in the Bracknell limited-area model. This technique could be applied to the simulation of the likely errors in the timing of aircraft arrivals.

8.2. Use of Mode S data in forecasting models

Work has recently begun at Bracknell towards constructing a 4-dimensional wind model designed to be available for use by Air Traffic Services in the 1990's. The model will be based on bivariate optimal interpolation (Gandin, 1963), a statistical method of using current (and recent) observations together with a suitable background field to obtain the best estimate of the current field (the analysis) at any desired point.

The model need not be restricted to using a regular lattice of grid-points, as is employed in large-scale numerical models, but could be based on an irregular set of waypoints. The observations need not be at the same points as the analysis. The horizontal "resolution" of such a grid, i.e. the mean spacing between analysis points on any particular route, will be determined by theoretical studies of aircraft arrival times, and will probably lie in the range of 10 to 25 km. Because of the stratified nature of the atmosphere, which can result in vertical wind shears in excess of 60 knots over 1000 ft (Crossley, 1962), the vertical resolution of the model will be 1000 or 2000 ft, substantially better than in large scale models.

Optimal interpolation requires a knowledge of the covariances of the errors in the observations and in the background field. This information will be obtained from a study of flight data recorded on research and civil aircraft together with archived forecast fields.

The principal source of data for this model will be Mode S but conventional meteorological data, e.g. 6-hourly balloon soundings, and possible future profiler data will also be incorporated. It should be borne in mind that winds computed from balloon tracks are layer means taken over at least one minute of flight time (about 1000 ft), whereas aircraft measured winds, whether during climb/descent or cruise, are more nearly "spot" values.

The background field will be derived from a forecast from a previous time based on either the (new) limited area model (50 km grid length) or the mesoscale model (15 km grid length).

When regular Mode S data become available, it is visualised that analyses will be carried out at frequent intervals, perhaps each hour, but only during daytime unless night-time flying becomes more popular.

Methods will be studied for producing a short period forecast (one to three hours ahead) - sometimes referred to as a nowcast. Rather than simply using persistence, i.e. no change until the next analysis becomes available, it may be possible to use the large scale flow to advect the small scale features.

Trials are planned to test the usefulness of Mode S wind and temperature data in other models. Being available only over land in Western Europe where an adequate network of radiosonde stations exists, Mode S data will probably have only a very small impact in large-scale numerical models. However, it should prove to be a useful supplement to other sources of data as input to models such as the UK Mesoscale Model, which is used to forecast surface weather elements such as temperature, wind, precipitation, cloud and fog. At a later stage it is hoped to undertake some limited trials on the automatic reporting of turbulence by means of the link.

Further action must be taken to standardise through ICAO the formats to be used in recovering aircraft-derived meteorological data with, ideally, identical formats being agreed for all air/ground links. A method of identifying the aircraft providing the data or, at worst, indicating the quality of the on-board systems, must also be agreed. Further work will be necessary to determine the most effective collection strategy for use in acquiring aircraft-derived data, taking account of link loading and data transfer costs.

8.3. Satellite-based data links

Any real-time source of reliable observations from data-sparse areas of the world, e.g. much of the southern hemisphere, would be beneficial to global numerical modelling. PRODAT or similar satellite-based systems being developed for aeronautical use in accordance with international standards, e.g. for automatic dependent surveillance, should readily complement the ASDAR system. Measures in the near-term may be necessary in Europe and, indeed, worldwide, to ensure the availability of appropriate ground communications facilities for the transfer of the aircraft reports between earth stations and the user communities.

8.4. Significant weather charts

Recent research at Bracknell and Washington has been aimed at automating the production of high (and ultimately also medium) level significant weather forecasts. Within a few years this information will be available in grid-code format for dissemination to users along with the grid-code wind and temperature forecasts.

8.5. Terminal airfield forecasts

Improvements in statistical forecasting may lead ultimately to the automated production of both short (9 hour) and long (18 hour) TAF's, as well as the 2-hour TREND, which is part of the METAR.

9. CONCLUSIONS

If the rapidly growing volume of air traffic in W. Europe is to be handled in an effective and efficient manner, it is expected that an increased level of automation in ATC will be necessary. For such a measure, good-quality meteorological data will be essential. Steps have been taken during recent years which are helping to improve the quality of data made available to Air Traffic Services, including an upgrading of the computer systems at the World Area Forecast Centre, Bracknell, UK, and moves have been made to facilitate a greater use of meteorological data automatically reported from aircraft. Short-term plans should result in the availability of a limited number of aircraft with satellite terminals for this purpose which will be particularly advantageous in respect of operations in remote or oceanic areas. During the 1990's, the introduction of ADS should greatly expand this capability; moreover, within this time frame, it is expected that the implementation of Mode S in W. Europe will likewise bring similar benefits in continental airspace.

Much work remains, however, if the potential for improvement, as seen today, is to be converted into an effective and efficient reality.

10. DISCLAIMER

The views expressed in this article are those of the authors and do not necessarily reflect the policies of the Organisations to which they belong.

11. REFERENCES

- Bisiaux M. Cox M.E. Forrester D.A. and Storey J.T.
 "Possible Improvements in Meteorology for Aircraft Navigation"
 Journal of Navigation, Vol. 36, pp 54-63 (1983)
- Cooke G.A. and Cox M.E.
 "Collaborative Experiments Involving the Use of a Satellite-Based Data Link for Air Traffic Services"
 Inst. of Electrical Engineers Conf., Pub. 294, London (1988)
- Cox M.E.
 "Possible Contributions from the SSR Mode S Data Link to the Conduct of Efficient Aircraft Operations", Paper 25, AGARD CP No. 410 (1986)
- Crossley A.F.
 "Extremes of Wind Shear"
 Meteorological Office Scientific Paper No. 17 (1962)
- Curran R.J. and Readings C.
 "Lidar Systems"
 World Climate Research Programme Report No. 5, Annex C published by ICSU/WMO (1988)
- Forrester D.A.
 "Data Link Application Study - The Application of Aircraft-Derived Meteorological Data", 1979 (unpublished, copy held in EUROCONTROL Library, Brussels)
- Forrester D.A.
 "Automated clear air turbulence forecasting"
 Meteorological Magazine, Vol. 115, pp 269-277 (1986)
- Gage K.S. and Nastrom G.D.
 "Theoretical Interpretation of Atmospheric Wavenumber Spectra of Wind and Temperature Observed by Commercial Aircraft During GASP". Journal of the Atmospheric Sciences, Vol. 43, pp 729-740 (1986)
- Gandin L.S.
 "Objective Analysis of Meteorological Fields"
 Leningrad, Gidromet (1963)
 Translated from Russian
 Israel Programme for Scientific Translations (1965)
- Harlow R.A.
 "Flight Measurements of Area Navigation System Performance using Various Combinations of Ground Aids and Airborne Sensors"
 Royal Aircraft Establishment, Tech. Report No. 81154, Farnborough, U.K., (1982)
- Goldie N. Moore J.G. and Austin E.E.
 "Upper Air Temperature Over the World"
 Geophysical Memoirs No. 101, Meteorological Office (1958)
- Jasperson W.H.
 "Mesoscale Time and Space Wind Variability"
 Journal of Applied Meteorology, Vol. 21, pp 831-839 (1982)
- Martin R. and Benoît A.
 "Accurate Aircraft Trajectory Predictions Applied to Future En-Route Air Traffic Control" 19th IATA Technical Conference, Dublin, EUROCONTROL Doc. 722031, Brussels, Belgium (1972).
- Nash J. and Schmidlin F.J.
 "WMO International Radiosonde Comparison"
 WMO Instruments and Observing Methods Report No. 30 (1987)
- Sherman D.J.
 "The Australian Implementation of AMDAR/ACARS and The Use of Derived Equivalent Gust Velocity as a Turbulence Indicator"
 Aeronautical Research Laboratories, Melbourne, Structures Report 418 (1985)
- Stearns L.P. Kuhn P.M. Kurkowski R.L. and Caracena F.
 "Clear Air Turbulence: An Airborne Alert System"
 Science, Vol. 213, pp 1007-1008 (1981)
- Thompson J.D.
 "Forecast Wind Error Modelling for the Fine Mesh Numerical Model"
 Meteorological Office, SITN 51 (1987) (unpublished, copy held in National Meteorological Library, Bracknell)
- Tucker G.B.
 "Upper Winds over the World, Part III"
 Geophysical Memoirs No. 105, Meteorological Office (1960)
- FANS - "Special Committee on Future Air Navigation Systems",
 Report of 4th Meeting
 ICAO, Montreal, Doc. 9524, FANS/4 (1988)

PART VIII

**Aircraft Operation in Air Traffic
Handling Simulation**

INTEGRATION OF AIRCRAFT CAPABILITY IN AIR TRAFFIC HANDLING SIMULATIONS

by

André Benoît and Sip Swierstra

EUROCONTROL
European Organisation for the Safety of Air Navigation
Engineering Directorate
72, rue de la Loi, B-1040 Brussels (Belgium)

and

Yves Delnatte

Direction des Opérations
Belgian World Airlines
SABENA
Brussels - National Airport
B - 1930 Zaventem

SUMMARY

The incorporation of airline/aircrew/aircraft specific procedures and performances into simulations and air traffic handling operations is a prerequisite for the next generation of management and control techniques. This matter is analysed in the light of the shortcomings inherent in the present situation, in order to meet operators' demands in terms of capacity and efficiency.

A practical approach is then proposed which includes the operators (aircrew/aircraft/avionics) in the overall ground/air/ground control loop at development, assessment, validation and real-time simulation levels.

As an illustration of the potential offered, this approach is used to assess a ground/air coordinated 4-D guidance technique, and the results are summarised.

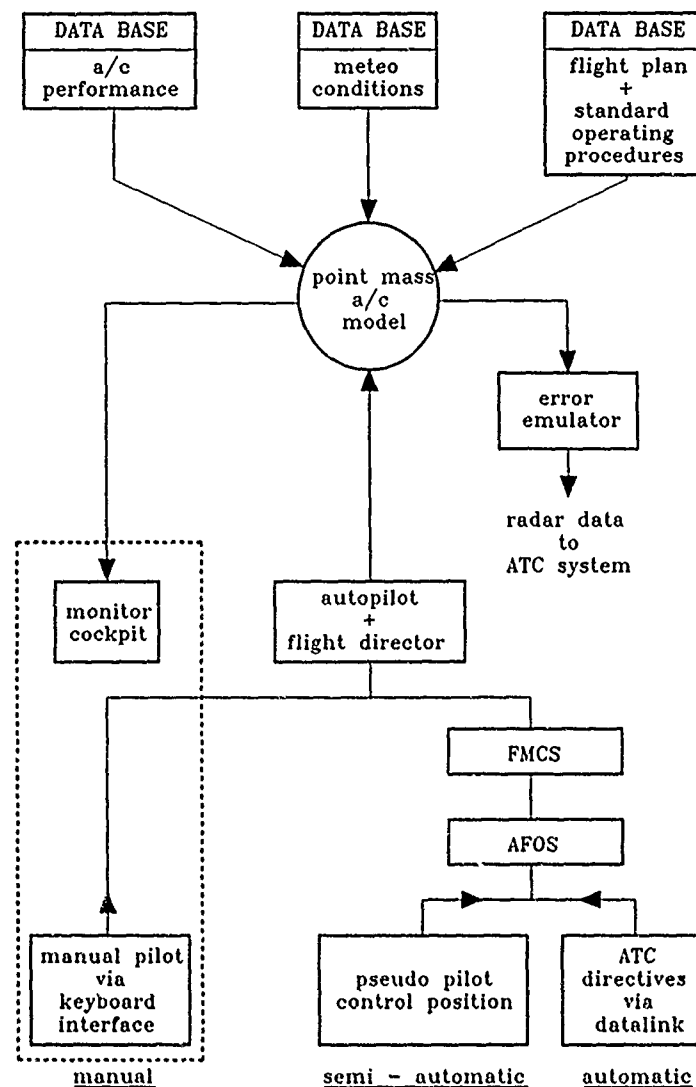
REQUIREMENTS

In order to assess the performance of the guidance system (Ref.1) necessary to ensure the stability of the on-line management of inbound traffic in extended areas including and surrounding a main terminal (Ref.2), use was made of full-scale flight simulators operated by airline crews. Indeed, the usual ATC simulation facilities include fairly simple aircraft models that are inadequate to reproduce both aircraft motion and pilot response in a realistic manner. As a matter of historical interest, it is worth noting that a connection was established between a Concorde flight simulator located in Toulouse and the EUROCONTROL Experimental Centre to investigate the impact of the introduction of supersonic civil transport on traffic and on ground-based control.

In current aircraft operation the pilot tends to use the automatic control facilities available on board, essentially the autopilot modes and, where installed, the flight management computer. With this in mind, it was decided to develop a computerised flight simulator such that the following requirements would be met :

- (i) realism of aircraft model in dynamic operation such that a pilot operating the simulator recognises the corresponding aircraft response ;
- (ii) modular structure including the following :
 - a fixed operator/flight simulator interface ;
 - an aircraft/airline individual performance data base ;
 - a specific data base for the navigational aids for the geographical area ;
 - a navigation data base for the geographical area of interest ;
- (iii) possible use in various modes of operation covering :
 - manual operation by professional pilots, in particular to assess the simulator itself (computer/pilot interface included), to introduce pilot reaction into the overall ground/air control loop and to conduct detailed and accurate parametric studies - also as a means of familiarisation with aircraft autopilot modes of operation ;
 - semi-automatic operation for use in air traffic control simulation facilities. In this mode of operation each operator or pseudo-pilot is in charge of some 10 different aircraft, each responding in a most realistic manner.

- automatic operation mode, in which the ground-based control directives are sent direct to the airborne FMCS by datalink and automatically implemented in the aircraft ;
 - automatic mode in "fast-time" operation to generate realistic flight profiles for reference purposes and performance evaluations such as fuel burn, vertical speed, etc.
- (iv) production of a low-cost module, suitable for direct integration into a large-scale ATC simulation environment and use in a wide range of applications.



ACCESS SYSTEM ELEMENTS

Figure 1

2. ACCESS FLIGHT SIMULATOR FACILITY

The requirements stated above call for a very flexible tool with user-friendly interfaces, both from the man-machine point of view and with respect to integration with other systems. The flight simulation facility discussed below is a further extension of the ACCESS (Aircraft Control Console for Experiments and Simulations) flight simulator. A description of the initial version was presented at the 15th Congress of the International Council of the Aeronautical Sciences, London, U.K., 7-12 September 1986*. In its present state of development ACCESS includes modes of operation to support single and multi-aircraft ATC simulations in combined en-route and TMA environments assuming different levels of system sophistication. Simulation scenarios may include anything from single-engine propeller aircraft with standard on-board instrumentation up to advanced jet transport equipped with FMCS and Mode-S transponder with digital ground/air/ground datalink capability. In addition, integration of ACCESS into existing ATC simulation facilities has proved straightforward.

3. STRUCTURE AND RANGE OF OPERATION

The various system elements and their interrelationships are depicted in Figure 1.

In the basic "manual" operating mode, ACCESS is controlled by an experienced pilot who can operate the flight simulator by means of a standard computer terminal. The aircraft status is presented on the terminal screen and the pilot has access to all autopilot, flight director and auto-throttle functions through the keyboard. The flight profile is computed using a point-mass model supported by several data bases. The resulting 4-D aircraft positions are modulated with systematic and random radar errors before transmission to the ATC system. For large-scale ATC simulations, "semi-automatic" and "automatic" operating modes are provided.

In the semi-automatic mode a "pseudo-pilot" controls several aircraft simultaneously. Typically he/she would receive ATC directives via an R/T channel and communicate them to ACCESS via a special-purpose interface. The Automatic Flight Operating System (AFOS), together with the FMCS functions, will translate the encoded ATC instructions to yield elementary autopilot flight director selections, hence providing the same operational flexibility in the two automatic modes as is available in the manual mode.

The automatic mode can be used when the ATC system includes an advanced guidance and control module, as is the case for instance with the implementation of the Zone of Convergence (ZOC) concept as described in Ref.2. The ATC directives generated may be transmitted via a ground/air datalink to the AFOS/FMCS modules in which they are decoded and subsequently implemented.

As suggested in Figure 1, all three modes of operation are in principle available simultaneously for a given aircraft. This allows the organisation of complex ATC simulations with a minimum manpower requirement.

4. MONITOR COCKPIT

The monitor cockpit modules allow the presentation of the status of any simulated aircraft on the screen of a standard character-oriented computer terminal.

A typical display is presented in Figure 2, which shows the cockpit of flight SAB999B, a B-737 currently intercepting the localiser of runway 25L at Brussels National Airport. The top line represents the datalink communication area. The display shows that the last instruction received pertained to a directive to reduce speed to 170 kt IAS. The columns below present from left to right the selected "speed bug" values and the flight mode annunciators for roll, pitch and auto-throttle. On the lower part of the screen the active Horizontal Situation Indicator (HSI) with VOR/DME information is displayed with, to its right, a summary of the current aircraft configuration.

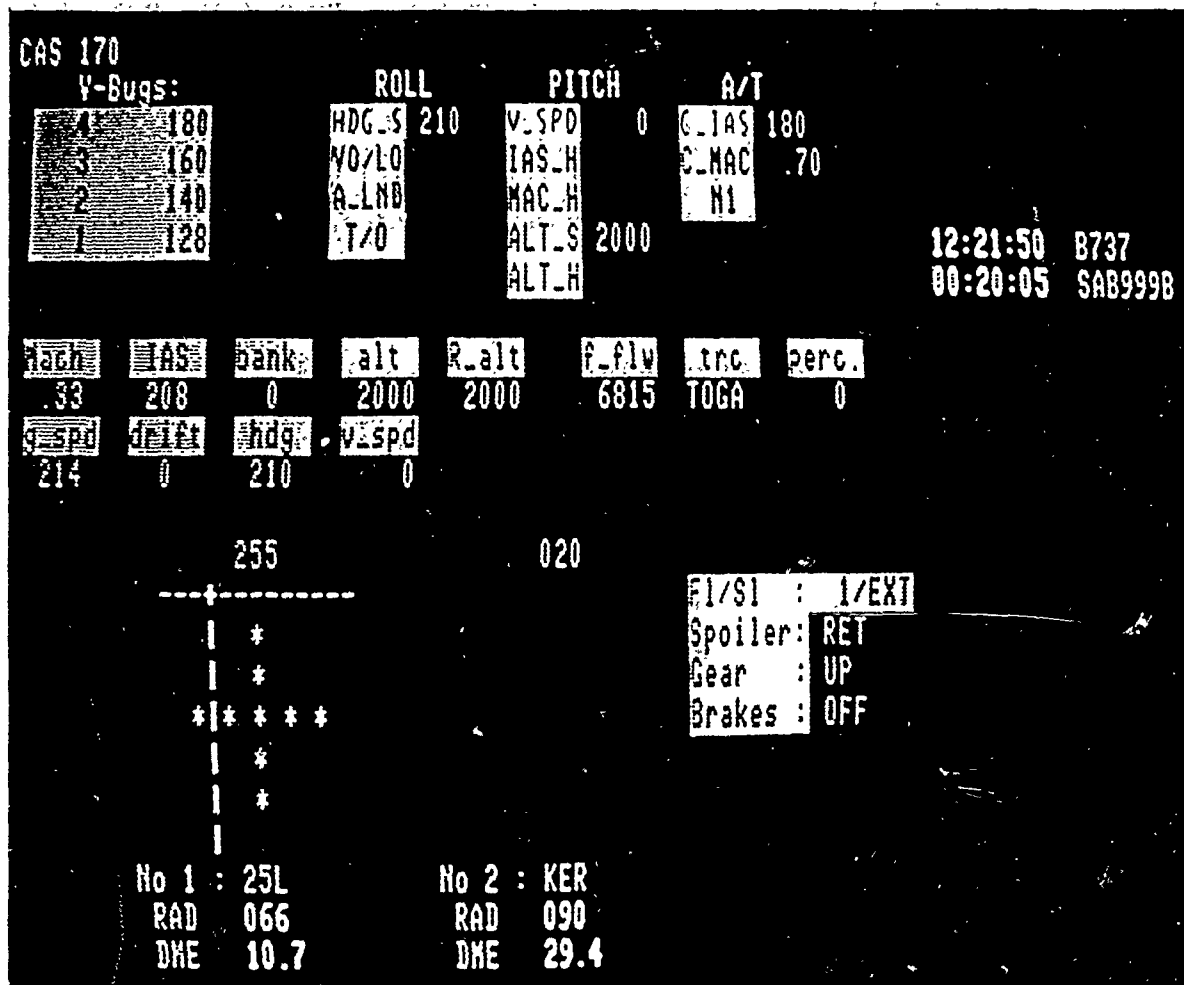
Tests with professional airline pilots have confirmed that after only a very short training time the ACCESS simulator can indeed be flown according to standard company operating procedures and that the pilot actions required are compatible with those executed whilst navigating the real aircraft.

5. PSEUDO-PILOT CONTROL POSITION

Air traffic control simulations including a TMA environment are particularly complex for two reasons. On the one hand they require an accurate approximation of aircraft behaviour in turns and configuration changes, and on the other, the man-machine interface operated by the pseudo-pilot must allow the implementation of any ATC directive sufficiently rapidly to ensure an adequate real-time response from the aircraft concerned.

To that effect, a special interface has been developed which is based on an IBM-compatible personal computer using a digitizing tablet as the sole input device. An example of the tablet menu layout is presented in Figure 3.

* Also EUROCONTROL Doc. 862017, June 1986



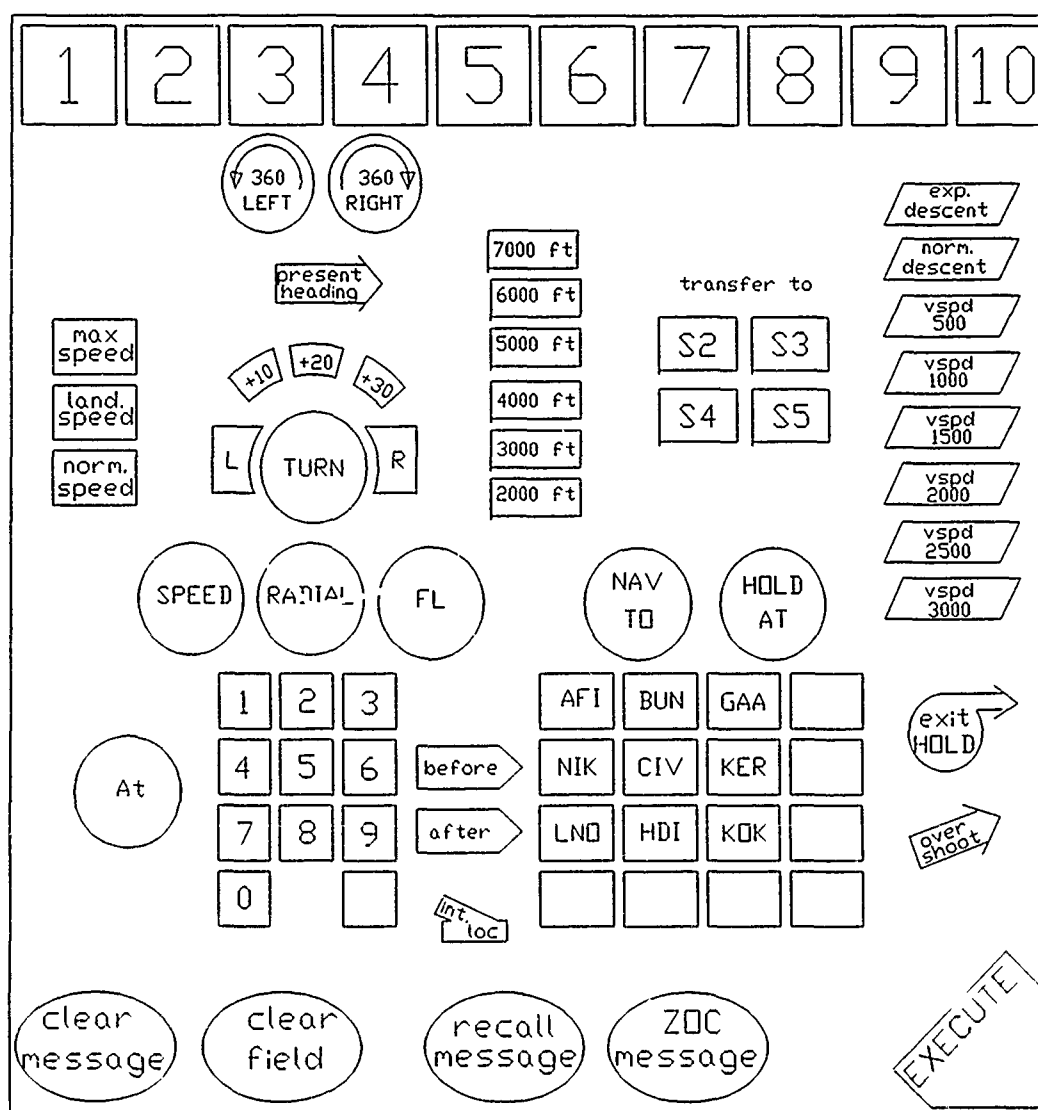
View of a typical cockpit display

Figure 2

The boxes marked 1 - 10 at the top allow the selection of the aircraft for which a directive has been received. The "ovals" in the lower part of the tablet menu are for special editing and housekeeping functions. The other fields are used to compile the various commands and are defined in such a way that the commands can be entered in the same form as they are spoken by the controller on the R/T channel. Heading, speed and altitude clearances may be entered using the appropriate "circle" fields and the numeric keypad, or the specific "short cut" boxes if possible.

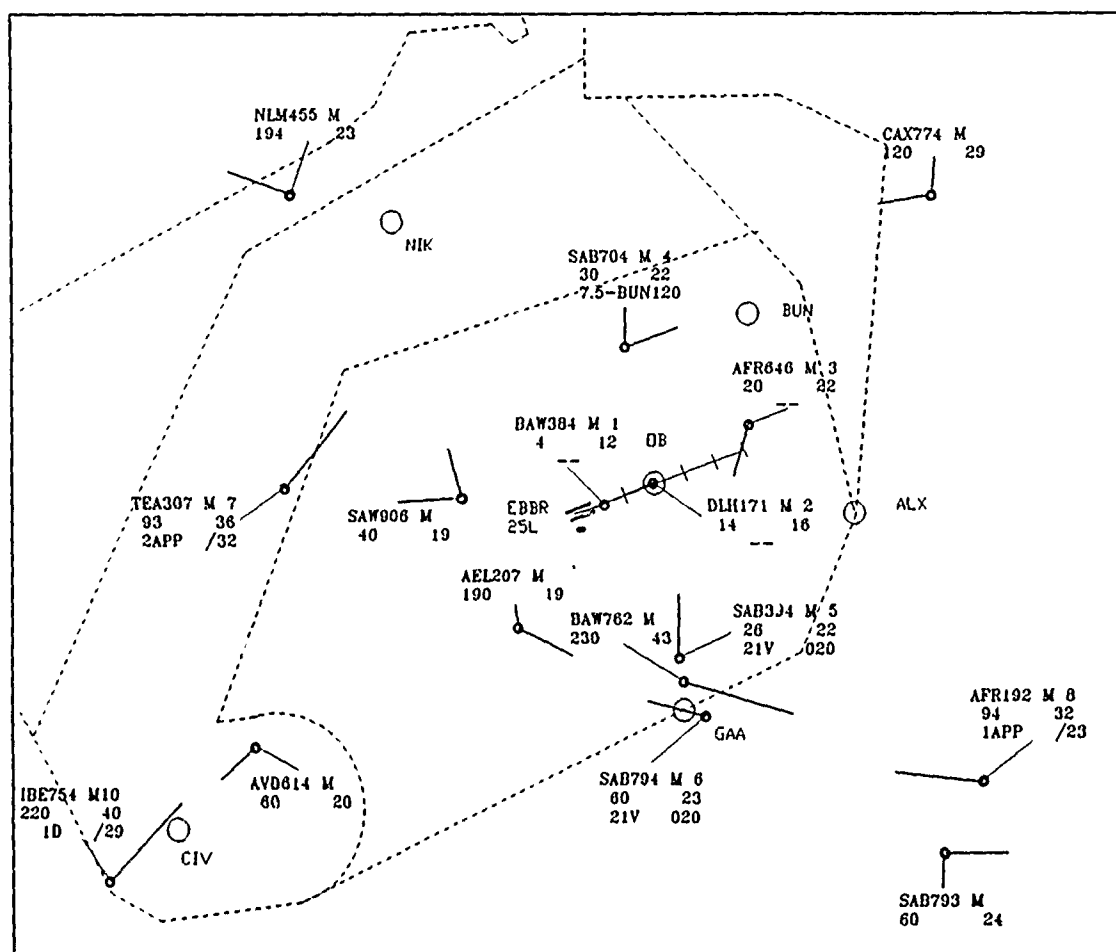
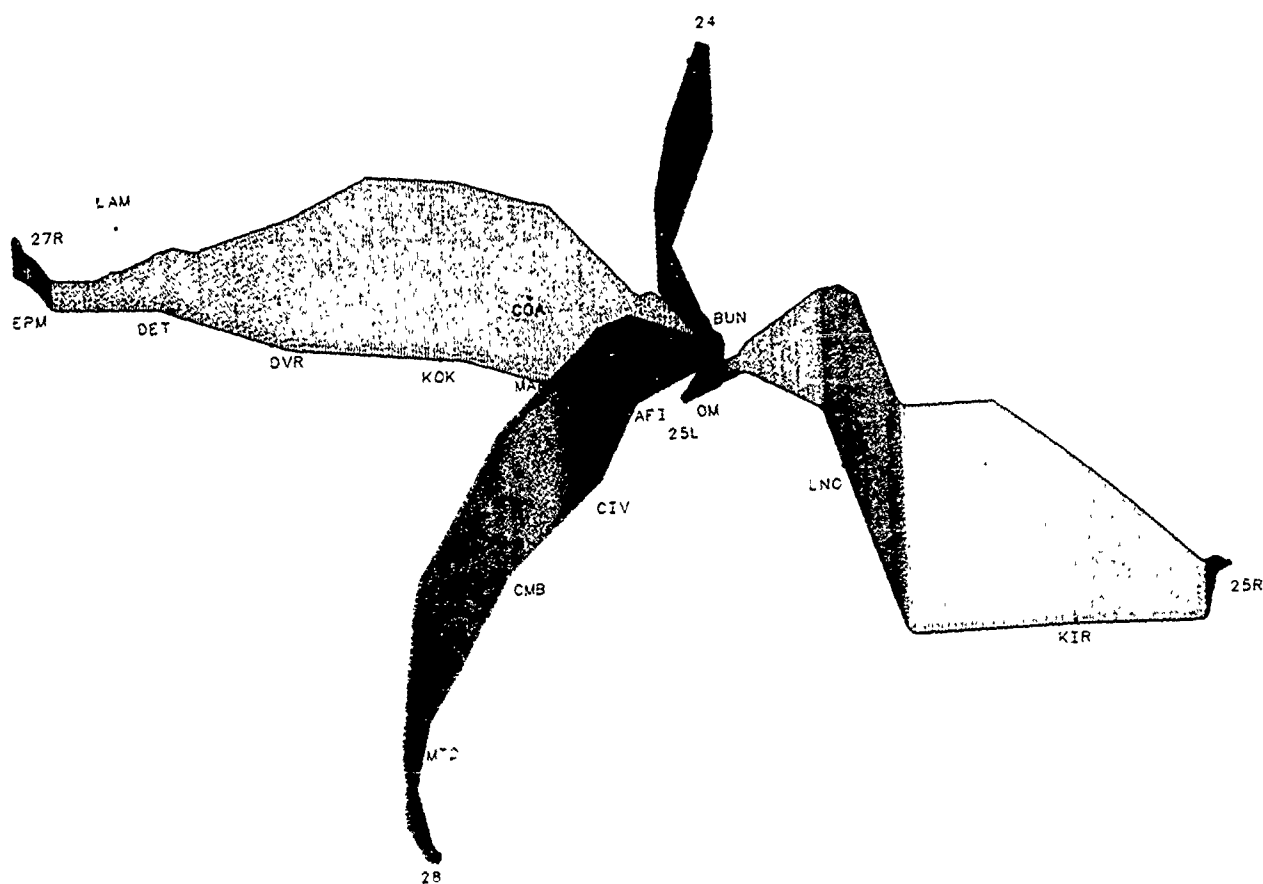
6. AIRCRAFT PERFORMANCE

The flight profiles are computed using a point-mass model with, for most common aircraft types, a possible choice between two aircraft performance models (Ref.3). For parametric studies the "table" approach may be selected, which provides detailed thrust, drag and thrust-specific fuel flow data in table form. Using this performance model, accurate estimates of fuel burn can be obtained, at the cost, however, of computation overheads. For ATC simulations accurate modelling of aircraft behaviour is of prime concern and the polynomial aircraft performance approximation based on EROCOA/PARZOC techniques yields the optimum in terms of flight profile realism, simplicity of the performance model and the required computation resources. The navigational accuracy along flight plan routes is a function of the assumed level of on-board instrumentation, regardless of the performance model selected for the definition of the vertical profile. This results, inter alia, when aircraft are assumed to be equipped with an Inertial Navigation System (INS), in the effect that they will follow the planned route centre line more closely than others which are not.



Pseudo-pilot position for ATC simulations

Figure 3



Radar screen :
Real-time ZOC simulation using ACCESS in automatic mode

Figure 5

7. APPLICATIONS

In this section we present two typical applications. Figure 4 shows in 3-D perspective a study of the various inbound procedures to Brussels National Airport. Such tests represent a typical application of the manual operating mode using the aircraft performance data in table form to optimise the default arrival procedures under given meteorological conditions.

In contrast, Figure 5 presents the contents of a radar screen covering the Brussels TMA. It pertains to certain evaluation trials of the ZOC concept utilising the ACCESS facility in automatic mode. For inbound aircraft the guidance and control module (CINTIA) of the ZOC system generates advisories which are displayed to the controller in the third line of the standard radar label. Whenever an ATC directive is required it can be sent direct to the aircraft concerned through the emulated ground/air datalink. In such a simulation environment outbound and overflying aircraft tend to follow predefined default flight profiles and human intervention is required only for conflict avoidance action, which can be entered via the pseudo-pilot control position.

8. IMPLEMENTATION

The ACCESS flight simulation facility, in combination with the pseudo-pilot interface, was successfully used during the large-scale real-time simulation of the ZOC concept at the EUROCONTROL Experimental Centre in Brétigny-sur-Orge, France, in June 1989. Its use on a processing unit with 0.9 mips capacity meant that at least 50 aircraft could be simulated simultaneously in real time, whilst 8 pseudo-pilot positions could be supported.

For manual operation, a single aircraft ACCESS implementation version is also available for an IBM-compatible personal computer. This provides, in addition to the cockpit display, a "navigation mode" display compatible with the equivalent FMCS mode.

9. CONCLUSIONS

The ACCESS flight simulation facility offers a consistent source of flight profiles for applications ranging from the evaluation of specific flight operating procedures in terms of economy, safety, noise, etc., to the assessment of advanced ATC systems, such as the ZOC concept, requiring large-scale ATC simulation facilities.

Specific aircraft performance has been validated against full-scale airline flight simulators and provides very realistic aircraft behaviour, in particular in a TMA environment. In manual mode the man-machine interface presents a realistic workload to the pilot/operator, whereas the automatic mode offers optimum flexibility in large-scale simulation scenarios while requiring minimum human resources.

10. REFERENCES

1. "The Control of Inbound Flights - Basic principles"
A. Benoît and S. Swierstra
AGARDograph AG-301, Paper 23.
Also EUROCONTROL Report 892011-E, December 1989
2. "Air Traffic Management and Aircraft Guidance in a Zone of Convergence"
A. Benoît and S. Swierstra
AGARDograph AG-301, Paper 29.
Also EUROCONTROL Report 892009-E, December 1989
3. "Generation of Aircraft Trajectories for on-line Operation"
A. Benoît and S. Swierstra
AGARDograph AG-301, Paper 17.
Also EUROCONTROL Report 892008-E, December 1989

SIMULATION OF AUTOMATED APPROACH PROCEDURES CONSIDERING DYNAMIC FLIGHT OPERATIONS

by

Prof. Dr.-Ing. Manfred Fricke and Dr.-Ing. Andreas Hörmann

Technical University of Berlin, Institute of Aeronautics and Astronautics
D-1000 Berlin 10, Marchstr. 14, Germany

SUMMARY

During peak hours almost all major commercial airports operate close to their capacity limits. Moreover, the traffic demand often exceeds the offered capacities leading to more or less stringent restrictions in slot allocation.

Purpose of the fast-time air traffic simulations performed at the Technical University of Berlin, was to analyze and assess the performance and the practicability of automated time-based approach concepts, currently developed to optimize the terminal area air traffic process with respect to safety, capacity and economy.

The developed program system TASIMD (Terminal Area SIMulation considering the aircraft Dynamics) simulates flight operations of arriving aircraft within a terminal area during a specified time interval. TASIMD models all major elements of a TMA scenario related to the control and operations of automated approach procedures on the ground and in the air (e.g. surveillance, control procedures, aircraft dynamics, flight guidance).

The aircraft fly along 4D-trajectories, described by a horizontal profile, an altitude profile and a speed profile to integrate the time element, considering influences on the path following accuracy in space and time. Sources of error impact are: entry fix time deviation, navigation, wind, airspeed error and profile management algorithm error. Errors are modeled in Monte-Carlo technique.

Two types of automated approach procedures were developed and analyzed: a variable path speed control concept (VPSC) and a fixed path speed control concept (FPSC). Both concepts presume a shared air/ground responsibility for profile control.

Being a typical representative of an airport with capacity problems the terminal scenario of Frankfurt/FRG has been taken as data base for the developed simplified model TMA. The layout of the different scenarios (e.g. configuration with navigation systems) was chosen on the basis of requirements for future terminal navigation previously derived from results of a simplified macroscopic Monte-Carlo simulation. TASIMD is written in FORTRAN and kept as general as possible to allow similar investigations for almost any future terminal scenario.

Generally, the analysis indicated the practicability of applying automated terminal procedures based on a shared air/ground responsibility. In order to adapt such concepts to a real environment, however, many details as e.g. emergency procedures or procedures for aircraft with less sophisticated equipment, have to be considered. The analysis of such questions which would require real time simulations in cooperation with pilots and controllers, however, goes beyond the scope of TASIMD.

1. INTRODUCTION

A steady growing traffic volume with an increasing inhomogeneity of the traffic structure, due to the Regionals previously being almost unknown in Europe, leads to more and more regular delays at major airports, being the bottlenecks of the air traffic system. The capacity problem is intensified by an often used hub-and-spoke service concept of the airlines. To guarantee safe and regular flight operations more or less stringent restrictions in slot allocation are required.

Due to institutional and environmental factors the possibilities for an expansion of airport capacities are rather limited. Therefore, new technologies in the fields of air traffic control and flight guidance are currently under development to handle the already high and still increasing traffic volume in the most safe and economic way, optimizing the usage of the available airspace and runway capacity.

One aspect in the context of developing a future integrated flow management concept with respect to the terminal area problem is the impact of navigation on the path following accuracy in space and time.

An increase in flight path accuracy would allow to reduce the so called "safety buffer" of 20 sec or more (Ashford, Wright, 1979; Thomas, Dec. 1982) leading to a direct increase in terminal capacity. The "safety buffer" is applied today for sequencing the arriving traffic flow. It is added to the actually required minimum separation to compensate for inaccuracies in flying along the commanded paths or profiles, e.g. caused by wind, navigation or human reaction. Figure 1 (Hörmann, Feb. 1985) shows the effect of a buffer reduction which depends on the traffic structure, i.e. the mix of heavy, medium and light class aircraft. Two traffic samples are considered: homogeneous traffic and a typical traffic mix of Frankfurt/FRG (30% heavy, 60% medium, 10% light).

Due to the occurring aerodynamical problems the future scenario the simulation model is based on, does not assume reduced separation standards, though such a reduction, e.g. of half a mile, would yield a much higher increase in landing capacity than just reducing the "waste" of airspace by an additional safety margin, unnecessary in the future. Furtheron, a future terminal scenario will include some kind of position shift algorithm to optimize the sequence of the landing aircraft with respect to the separation required.

To analyze the operational practicability and efficiency of future (automated) approach procedures regarding safety and economy and to compare different concepts with each other a program called TASIMD (Terminal Area SIMulation considering the Aircraft Dynamics: Fricke, Hörmann, Dec. 1983/II; Hörmann, Feb. 1985) has been developed.

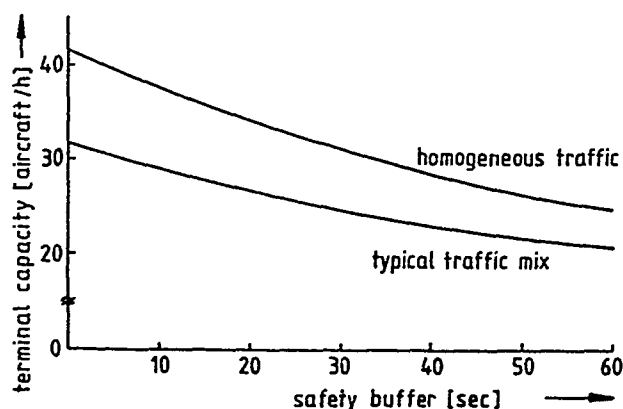


Figure 1: influence of a safety buffer on the landing capacity

TASIMD simulates flight operations of landing aircraft within a terminal area scenario (between the entry fixes, a gate, approx. the outer marker, and the threshold of the runway) considering various operational and environmental error influences. The aircraft model used reflects the dynamic reaction of the aircraft to control inputs while proceeding along flight profiles determined according to specified 4 D-approach procedure concepts.

Two different automated approach control procedures were analyzed: a variable path speed control concept (VPSC) and a fixed path speed control concept (FPSC). Both concepts are based on a shared air/ground responsibility to match the time goal specified by the air traffic control. The VPSC concept, primarily applying path control within a maneuvering area by heading changes, is comparable to an automated radar vectoring. It offers advantages with respect to the controllability of flight times. The FPSC concept uses fixed routes of different length for rough flight time corrections. In addition speed control is applied proceeding along these routes to exactly match the specified times. The FPSC concept offers advantages regarding the monitoring of flight operations by the air traffic controller.

Being a typical representative of an airport with capacity problems the terminal scenario of Frankfurt/FRG has been taken as data base for the developed simplified model TMA. The configurations of the radio navigation systems used as example to perform the analysis were chosen on the basis of accuracy requirements for future terminal area navigation systems derived from Monte-Carlo simulation with a simplified statistical model to generate flight paths. TASIMD, however, allows to simulate satellite navigation, too. TASIMD is written in FORTRAN and kept as general as possible to allow similar investigations for any future terminal scenario, if the applied automated air traffic management is comparable to the implemented concepts.

2. MODELS DEVELOPED TO ANALYZE FUTURE TERMINAL AREA SCENARIOS

2.1 The Future TMA Scenario

To analyze and compare the operational performance of different concepts of automated approach control procedures a simplified but realistic model of a future terminal area environment is required.

There are two ways to define such a model. Either an absolutely new ATC scenario with a fundamental change of all ATC control services or future procedures for terminal area control which fit into the current system could be projected. Due to reasons of safety and acceptance, especially considering operational problems during the transition phase, the evolutionary strategy was chosen to develop the model scenario.

Therefore, two main boundary conditions had to be considered:

- The future terminal area is limited to the geometry of today's terminal area. Due to noise abatement the (geometric) layout of future (approach) procedures is further limited to the arrival routes and the maneuvering areas used for radar vectoring today.
- The proposed 4D-procedures should fit into today's control process, i.e. they should be applicable during the transition phase, too.

Due to the given task of analyzing the general performance of different approach procedures, the simulation was restricted to considering only landing traffic, this being the main limiting factor of the terminal area capacity.

Projecting a concept based on the current airspace structure and organisation, leaving a rather small potential for flight profile corrections, the major control actions have to take place outside the terminal area. The terminal control then guarantees the operation of the airport's runway system with maximum utilisation of the available capacity (if required). Proposing a "terminal control" starting at a further distance, requiring a complete redefinition of the existing ATC sector structure, would probably yield a more effective control. However, considering the transitional problems this is a rather idealized approach, at least for the near future.

Presuming an integrated flow management concept some, kind of smoothening function for the arriving traffic flow outside the terminal area, limiting the possible deviation at the entry fixes, should exist.

To eliminate the remaining time error compared to the planned arrival at the TMA entry fix and to compensate for the additional errors accumulating during the flight, procedures for approach control are required. Flight times may be corrected by path modifications (path control) and/or speed modifications (speed control).

Due to the need of integrating the projected control procedures into the current terminal scenario the trajectory specification was chosen in accordance with the currently applied radar vectoring technique. This approach led to the profile parameters: x , y (waypoints, the heading is determined by the FMS), altitude and airspeed. With respect to FMS-equipped aircraft the control concept introduces a shared air/ground responsibility to make use of the highly sophisticated avionic capabilities of future aircraft in contrast to today's ATC philosophy of operating a system with only ground responsibility. If an aircraft is not equipped with a FMS the required calculations could be performed on the ground and the controller could then transmit the respective heading, speed and altitude commands to the aircraft.

2.2 Automated Approach Control Concepts

Two types of automated approach procedures have been developed and analyzed: a variable path speed control concept (VPSC) and a fixed path speed control concept (FPSC). To achieve comparable results the fan geometries of both types use some common waypoints, e.g. the entry fixes, the fan entry points and the gates. The altitude and the speed profiles have been chosen according to the flying practise.

- The Variable Path Speed Control Concept (VPSC)

This type of procedure is based on path control performed in a maneuvering area between the extended centerline and the fan entry point. Figure 2a shows the layout of a simulated example scenario according to the VPSC concept (EP: entry point, CP: centerline point, the other characters indicate north, east, south and west, resp.). Though the necessary path variations to achieve the assigned gate times are determined on-board, this kind of procedure corresponds most to the radar vectoring technique applied today. The speed profiles remain fixed except for the fan-in and the fan-out segments, where speed control may be applied to achieve additional system controllability. The role of the ground ATC is reduced to assigning gate times considering the specific aircraft performance and to a monitoring function. If the on-board monitored time error exceeds a certain value the system performs an update procedure by a heading change. The assigned gate times automatically imply the landing sequence and the corresponding landing times (according to the aircraft performance on the final). Figure 2b shows as example trajectories of flights approaching from northeast and northwest to Frankfurt's runway 25 R/L simulated with TASIMD between the entry fixes and the gate.

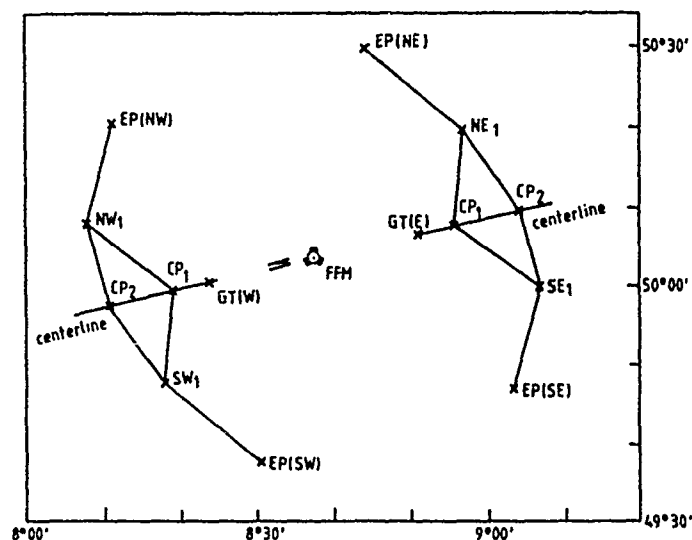


Figure 2a: layout of the model scenario (VPSC concept)

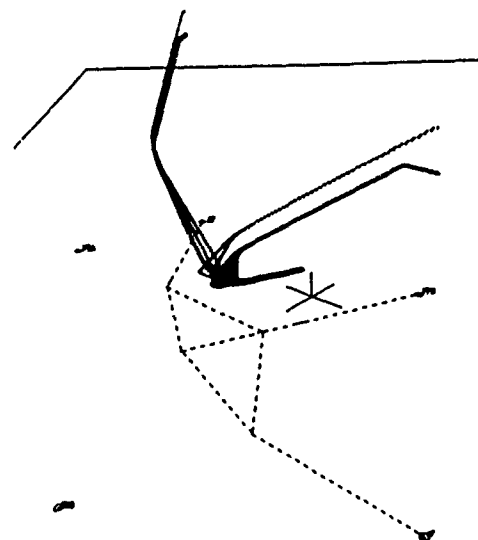


Figure 2b: trajectories of simulated flights using a VPSC type fan system

- The Fixed Path Speed Control Concept (FPSC)

Though this type of procedure is mainly based on speed control (on-board) it uses path control (ground) to compensate for the rather limited controllability of speed control. For the purpose of rough corrections three alternate routes (shortened, nominal, extended) with a flying time difference of about 20 seconds compared with the middle one are available. These routes are assigned by the ATC together with the gate times according to the time deviations determined at the entry fixes. Besides these activities the ATC again has only a monitoring function for safety purposes. The speed control updates are performed by the FMS on each straight flight segment by determining the most favourable point on the assigned route to start the speed reduction. Speed changes within the terminal area are limited to reductions. Figure 3a shows the layout of the example scenario according to the FPSC concept. Figure 3b corresponds with Figure 2b giving an impression of the resulting trajectories.

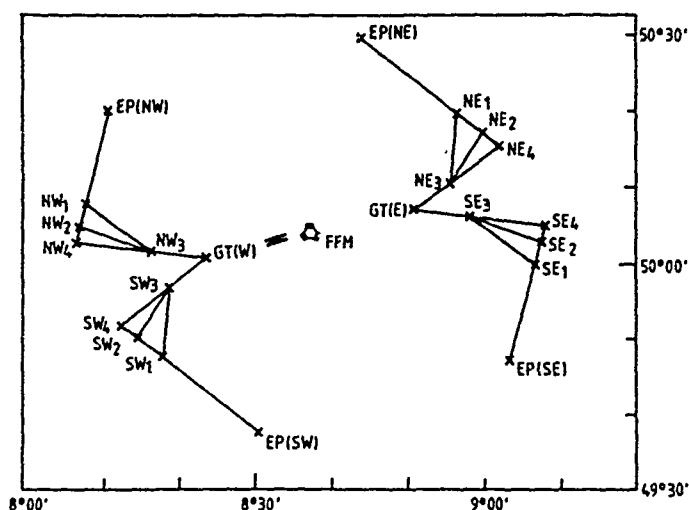


Figure 3a: layout of the model scenario (FPSC concept)

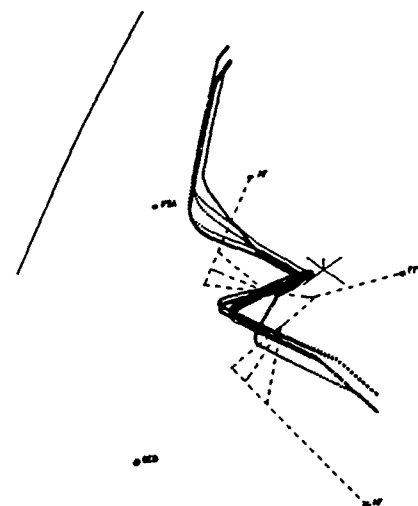


Figure 3b: trajectories of simulated flights using a FPSC type fan system

2.3 Determination of 4D-Trajectories

Flying from the entry fix to the gate and on until touch-down the on-board 4D-device (4D: x, y, z and as fourth dimension time) determines the parameters of the trajectories according to the anticipated time target. Such 4D-trajectories may be described by a horizontal profile, an altitude profile and a speed profile (to integrate the time element).

The horizontal profile is defined by the x, y-coordinates of waypoints (longitude and latitude). The vertical profile is defined by altitudes assigned to the different waypoints or by an initial and a final altitude (e.g. at the outer marker) if a continuous descent approach (CDA) should be performed for the purpose of fuel conservation. The speed profile is defined by assigned indicated airspeeds at the different waypoints instead of using ground speed, which would presume all aircraft to be entirely equipped with FMS. If an aircraft is not FMS equipped the respective parameters may be commanded by the controller.

Figure 4 shows the interaction of the different profiles on the aircraft's way from the entry fix to the gate. Though the example is plotted for a flight within a fan system according to the FPSC concept it is principally the same for a VPSC fan type structure, just the intercept onto the final would be performed somewhat earlier.

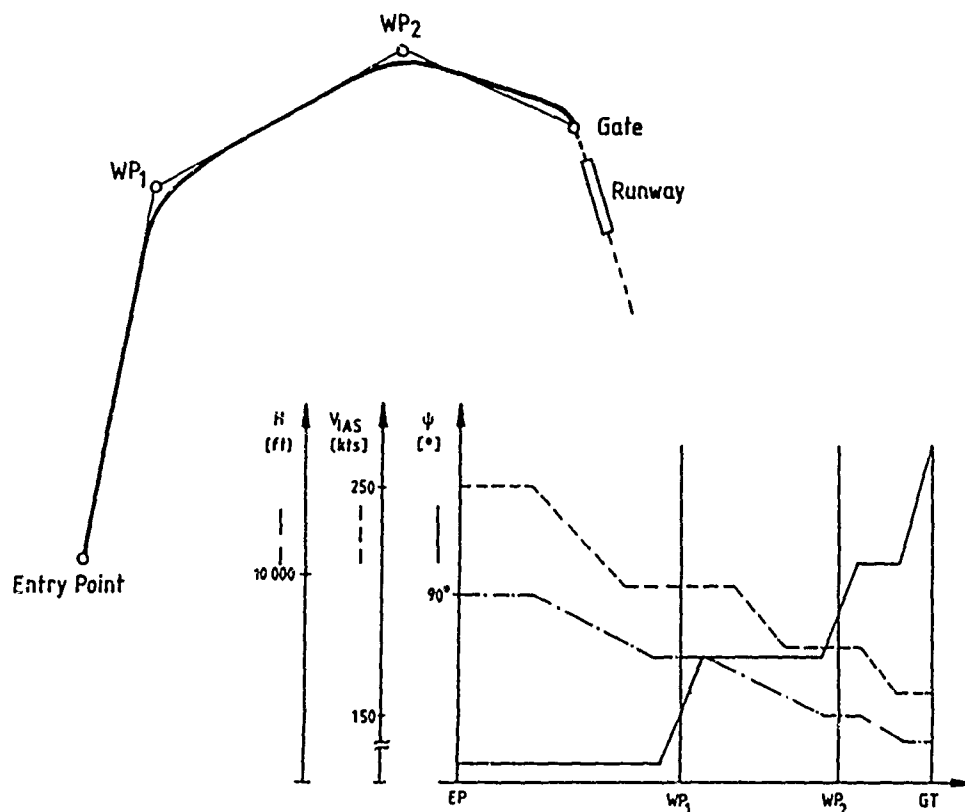


Figure 4: definition of a 4D-trajectory by profiles

2.4 The Aircraft Model

The simulated aircraft should navigate from an entry point into the TMA to the threshold with the boundary condition to match a prespecified time target, i.e. the aircraft modeled have to be capable of flying 4D-profiles. Thus the model algorithms plan 4D-trajectories (x, y, z, t), determine the respective control inputs for the aircraft to follow these predetermined paths and model the dynamic aircraft reaction to these control inputs.

Figure 5 shows the basic structure of the aircraft model integrated into the dynamic simulation model. The inner loop (dynamic aircraft reaction, flight path determination and feedback control system) characterized as aircraft is completed by a 4D-module (4D-device of the navigation computer) which determines the different profiles (azimuth, altitude, speed) according to the gate time goal. For the developed control concepts a point close to the outer marker is considered as gate. The ATC assigns those target times considering the aircraft performance, the delay fan geometry and the forecasted winds aloft. To compensate for the time errors accumulating during the aircraft's flight along the 4D-trajectories due to the various error sources (wind, navigation, airspeed, FMS) an update device as shown in the outer loop is required.

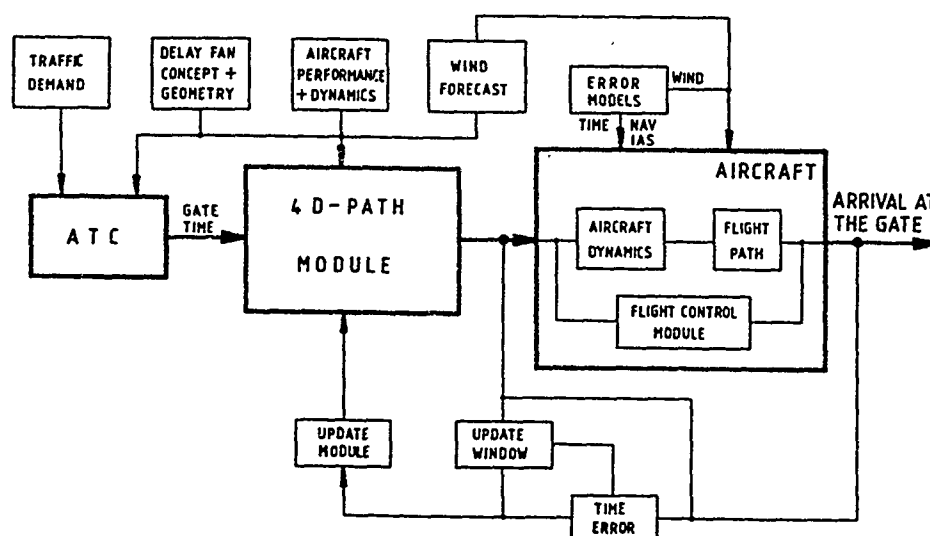


Figure 5: basic structure of the TASIMD model to simulate 4D-flight operations

2.4.1 Aircraft Dynamics and Flight Control

To simulate for example two hours of high density terminal area air traffic operations with up to twenty aircraft in the air at the same time the evaluation of the complete system of differential equations describing the aircraft motion would exceed reasonable computing time limits. Such a system would lead for each aircraft to a 7th order transmission function with respect to the longitudinal motion (aircraft dynamics: 4, engine dynamics: 1, control dynamics: 2) and to a 6th order transmission function with respect to the yawing motion (aircraft dynamics: 4, control dynamics: 2).

However, purpose of the simulation is to analyze flight guidance procedures, not to develop flight control algorithms. An aircraft model designed for such purposes may be significantly simplified by just modeling the dynamic reaction instead of modeling the aircraft dynamics themselves. As the analysis showed, the complete dynamic reaction of the aircraft including control functions may be approximated with sufficient accuracy by two 2nd order time response elements and one 3rd order time response element (Alles, Sundermeyer, 1978). This aircraft model considers three control channels: the airspeed, the path angle and the bank angle. The time constants of the approximated solutions are determined on the basis of the complete transmission functions by a compensation of poles and zeros or by numerical optimization, depending on the data available.

To have the aircraft follow the predetermined 4D-profiles the introduction of a dynamic system requires the design of a corresponding flight management system (autopilot function). Though the control device itself works automatically, the update mechanism influences the speed regulation (speed control, FPSC) and/or the track regulation (path control, VPSC) by modifying the predetermined profiles. According to the developed aircraft model the control device commands three signals: air speed, path angle and bank angle. The aircraft reacts to those signals comparable to an aircraft equipped with control wheel steering (CWS).

As example of the designed path control algorithms, each comprising an open loop and a closed loop control device, Figure 6 shows the input bank angle control signal and the resulting aircraft heading of a typical flight from the entry fix to the outer marker (FPSC concept with three turns).

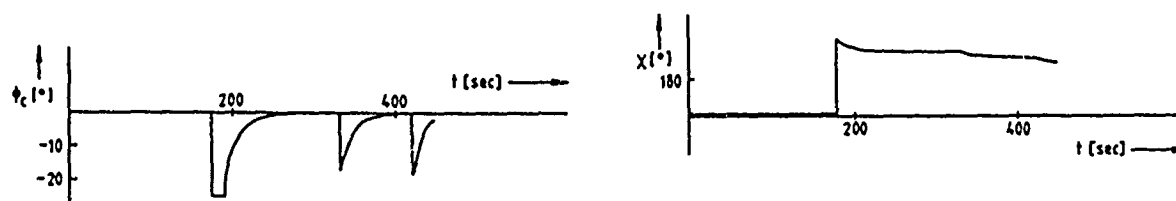


Figure 6: horizontal control of a simulated 4D-flight (example)

Turns are initiated if an aircraft reaches the switch radii determined by the 4D-module or automatically if the aircraft deviates from the desired track and/or heading. According to the definition of the course angle the first turn from a north eastern to a north western direction includes a change of the angle value by 360° ($0^\circ = 360^\circ$). The steep ascending flank results from initiating the turn with the steering device. To avoid overshoots when capturing a new heading, the return to a zero bank angle is much slower (regulator). The remaining intermediate bank angle changes to compensate for cross-track deviations are usually very small and therefore not noticeable within the scale of this diagram. Due to ending the simulation at the time the aircraft crosses the "outer marker line" there remains a non-zero bank angle caused by the operational and environmental influences considered.

To simulate air traffic operations within the TMA, the described simplified dynamic aircraft model has to be completed by a system of equations to determine the aircraft's movement through the airspace.

2.4.2 Aircraft Performance

To simulate flight operations within a terminal area the large variety of different aircraft types has to be reduced to (a few) representative performance classes. Due to modeling TMA traffic, the main criteria to classify the aircraft types are: landing speed and landing weight. Table 1 shows the chosen classification, differentiating between ten performance classes. Listed are the reference aircraft with wake vortex classes plus mean landing speeds and corresponding example aircraft types.

aircraft class	weight class	mean landing spd. [Kts]	reference aircraft	further aircraft types
1	LIGHT	90	Nord 262	DHC 6, DO 28
2	MEDIUM	98	SHD 3	Merlin IV, DHC 7
3	MEDIUM	110	HS 748	F 27
4	MEDIUM	115	B 115	F 28, S 210, YAK-42, VFW 614, BAE 146, TU-104
5	MEDIUM	125	B 727	TU-134, DC 9, B 737, B 720, TU-154
6	HEAVY	125	B 707	DC 8, VC 10, IL-62, A 320, B 757
7	HEAVY	130	A 300	Galaxy, IL-86, B 767, A 310
8	MEDIUM	135	CV 980	CV 990
9	HEAVY	135	B 747	DC 10, L1011
10	HEAVY	167	Concorde	TU-144

Table 1: classification of aircraft types

The actual landing speeds related to specific gross weights are determined by interpolation with a quadratic function. The landing weights are generated on the basis of a fifty percent payload with a normal distributed deviation.

2.5 Models to Simulate Operational and Environmental Influences

The considered influences on the flights within the terminal area are:

- entry fix time deviation
- navigation (position accuracy)
- wind
- airspeed error and
- FMS algorithm error.

All error values, except for the initial time error and the wind error direction, are assumed to be normal distributed with a mean of zero. The specific error values are generated on the basis of a compiler integrated random number generator source supplying uniformly distributed numbers between zero and one which may be converted into normal distributed variables according to (White, 1975).

2.5.1 Entry Time Related Inaccuracies

The entry fix time deviation describes the initial condition of the aircraft with respect to flight plan time deviations at the terminal (system) entry. Due to the mentioned limitation of the terminal geometry and the required en-route control functions of a future integrated flow management concept the maximum occurring values are limited to ± 30 sec.

On a digital computer random numbers according to this distribution may be obtained by drawing new normal distributed random numbers if the resulting actual time error value exceeds the specified boundary value.

2.5.2 Navigation

Simulating flight operations with the TMA both, the navigation system location and the position of the aircraft, are known exactly. In contrast, in reality the actual position of the aircraft navigating along the predetermined 4D-trajectory may be determined with limited accuracy only. If the navigational error would be modeled like this, i.e. the aircraft proceeding along their paths determine their position every time step of the integration, a dynamic aircraft model would work like a digital filter with respect to the normal distributed navigational error. To avoid this effect the truly positional error of the aircraft was shifted into the waypoints.

The system determines the correct waypoint coordinates, the deviation due to the navigation and commands the perturbed values. The precisely working track control device then leads the aircraft to these wrongly located waypoints. Waypoints determined by the update device are shifted according to the respective navigational error, too.

Tolerance areas of waypoints defined by radio navigation systems are modeled according to the resulting geometry as intersections of straight lines (theta-system(s), radio bearing) and/or circles (rho-system(s), distance), VOR and NDB overhead as defined by ICAO (ICAO, 1979).

The different equations to determine waypoint coordinates perturbed by navigation inaccuracies in position measurement have been explicitly derived in (Fricke, Hörmann, Dec. 1983). Most important in the context of analyzing terminal area flight operations are the rho/theta-navigation and the rho/rho-navigation. Figure 7a shows the geometrical relationship for determining the position by rho/theta-navigation with one convolut station. Figure 7b is an example of the resulting two-dimensional error distribution using the developed algorithm to model rho/theta nav-errors. The respective algorithms corresponding to the other navigation methods are listed in (Fricke, Hörmann, Dec. 1983/1). Table 2 shows typical accuracies of representative navigation systems.

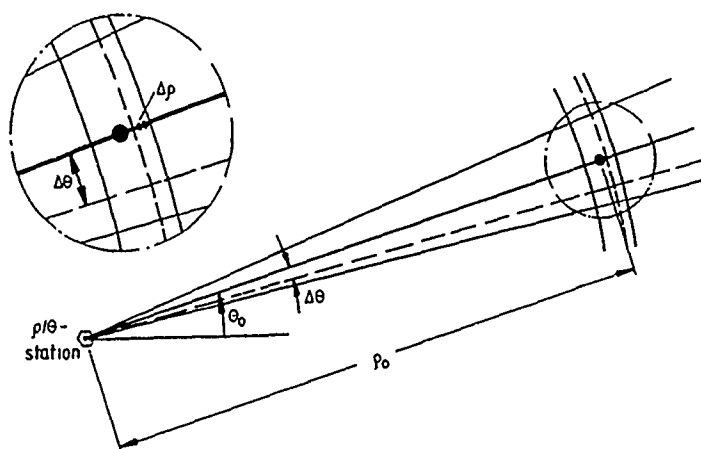


Figure 7a: rho/theta-navigation (geometrical relationship)

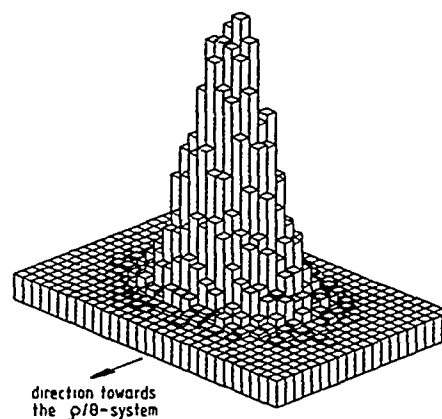


Figure 7b: position error distribution using rho/theta-navigation (example)

system alternative	accuracy (2 sigma) a(zimuth), d(istance), p(osition)	remarks
VOR	4.53 ° (a)	ICAO minimum requirements enhanced system
VOR overhead	1.72 ° (a)	
NDB overhead	acc. to ICAO PANS-OPS	function of altitude
DME	926 m or 3 % of dist. (d)	ICAO minimum requirements enhanced system
DME	259 m (d)	
DME/P	30 - 50 m (d)	industry data
DAS	0.2 ° (a) / 30 m (d)	industry data
GPS	100 - 200 m (p)	industry data
INS	0.2 km/h (p)	function of flight time

Table 2: typical navigation system accuracies

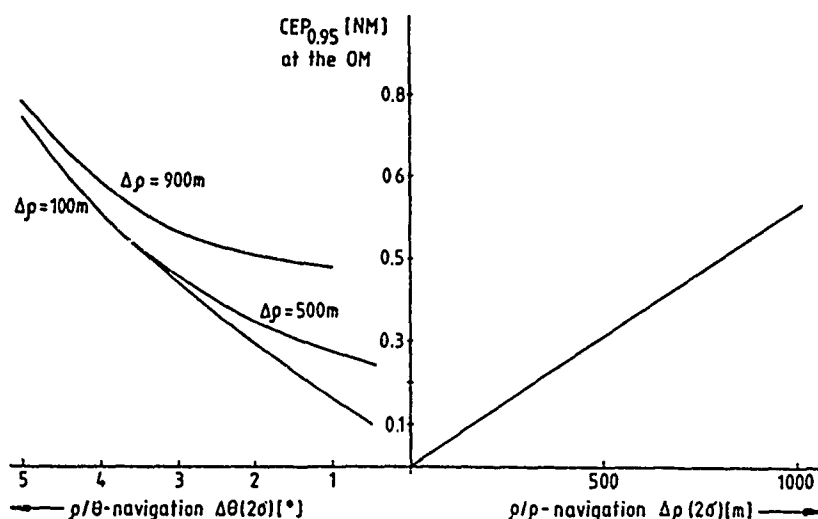


Figure 8: radio navigation accuracies and corresponding CEP_{0.95}-values

If navigational aspects are to be investigated in more general terms without the reference to a specific ground station location and performance, waypoint tolerance areas may be defined by CEP 0.95-values (circular error probability (Schroepl, 1979)). Using this abstract definition of tolerance areas around waypoints the TASIMD navigation model also allows the modeling of satellite navigation (with respect to the resulting accuracy). Figure 8 illustrates the relation between CEP_{0.95}-values and radio navigation accuracies.

2.5.3 Wind

Most problems in simulating a realistic environment usually occur in modeling the wind influence. Interesting with respect to modeling 4D-trajectories is the error of the predicted wind compared with the actual wind conditions, i.e. the difference between the wind considered for profile determination and the actual wind during the flight. If high precision navigation systems are to be used, the wind error shows to be the prime error source.

The TASIMD wind model consists of a "mean wind"-model, considered by the 4D-FMS in determining the profile parameters, and a "wind error"-model. Due to designing a wind model to be applied for a simulation of TMA operations the model may be simplified with respect to wind changes in the horizontal plane and with respect to special weather conditions, e.g. gusts, or wind shear situations.

What remains is a (mean) terminal wind varying in speed and direction over altitude. This relationship is described by a two segmented model. Starting from the ground an "EKMAN spiral" leads to a change in wind velocity and direction. This spiral ends in approx. 1400 m with a change of 45° in direction. From there on only the velocity varies according to an exponential relationship. The parameters describing the model were determined on the basis of data supplied by the German National Weather Services (Deutscher Wetterdienst, 1961-1971).

Wind error vectors are generated with a normal distributed speed and a direction uniformly distributed between 0° and 360° deg. The fact that the occurring wind errors will not be uncorrelated is considered by limiting the error values for successive aircraft, successive meaning aircraft succeeding on the same delay fan within 1 or 2 minutes. Primarily important with respect to the flight time management is the along-track component, i.e. the wind (error) vector component in the direction of the trajectory. The cross-track component leading to a deviation from the desired track will be automatically corrected by the path control algorithm.

2.5.4 Air Speed

The airspeed error is an operational error considering that the aircraft do not fly exactly the assigned speeds. The airspeed error is generated according to a normal distribution. The deviation of the speed variation is defined by a percentage of the proper IAS and a minimum value. The speed error may be higher if there is a large share of non-equipped aircraft and the control mainly bases on manually issued commands (delay times in executing commands, wrong values, etc.).

2.5.5 Flight Management System

The FMS error considers the limitation of the on-board equipment in exactly predicting profiles. Therefore, this error is of mathematical and numerical nature (calculation time, interpolation). The FMS error decreases as an aircraft approaches the gate with a shorter remaining distance to fly (and trajectory to predict). On the last segment between the outer marker and the threshold profile corrections to adapt flight times are very limited. Typical values as measured by the DFVLR are approx. 2 sec at the entry into the terminal area decreasing to 0.5 sec. Due to the integration of such an FMS into the aircraft model, there is no separate consideration of this error source.

3. THE DEVELOPED SIMULATION SOFTWARE: TASIMD

Due to the completely different control concepts of the considered approach procedures and the corresponding differences with respect to data storage and organisation two versions of TASIMD were developed: one to simulate a VPSC fan system and one to simulate a FPSC fan system. From the user's point of view, however, both versions look alike. Simulations were run on a Control Data Cyber 175, requiring approx. 600 sec to simulate two hours of high density air traffic using the VPSC concept and approx. 260 sec using the FPSC concept.

The program structure was tailored to allow similar investigations for any future scenario under various aspects. Thus, almost any future TMA scenario may be defined by geographic coordinates and control parameters to choose the respective program modules, if air traffic management procedures comparable to the implemented ones are to be used.

Neglecting a short program section of processing data to control the program run and the simulation analysis itself, the general structure of TASIMD (Figure 9) may be differentiated into four main sub-blocks as listed below.

a) definition of the TMA geometry and configuration

Within this sub-block the geographic layout of the terminal area is defined by waypoints and configured with navigation systems. All geographic points are defined by longitude and latitude. The coordinates are transformed into the geodetic simulation coordinate system by a stereographic projection. The control concept to be simulated is selected by the respective TASIMD version.

b) determination of the ATC reference planning data

The division of the air traffic into a ground section (ATC) and an air section (pilot, aircraft) is reflected in the structure of TASIMD. Following the definition of the geometry and the strategy of the approach control procedure the sub-block "ATC planning" calculates the reference times later on assigned as target times to the arriving aircraft. These reference times are determined by a simulation without error influences.

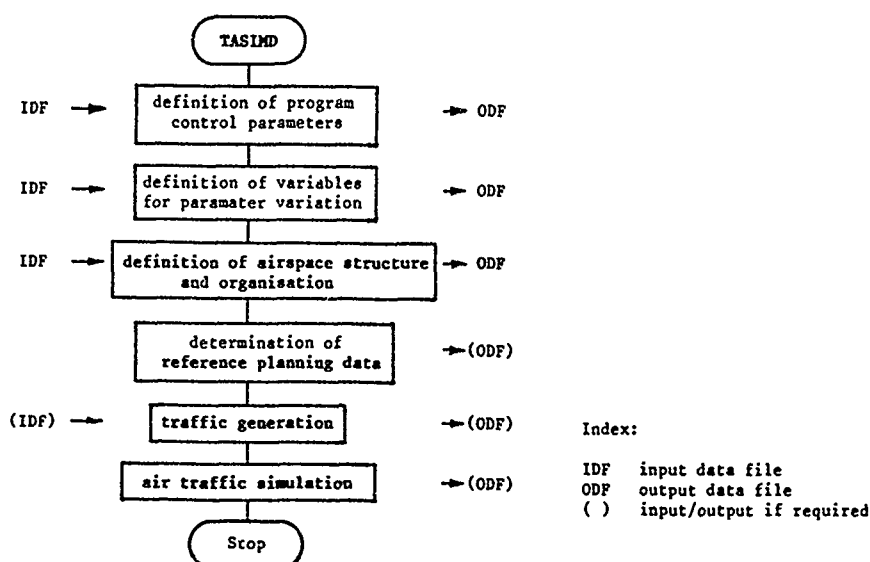


Figure 9: general structure of the TASIMD program

In the case of a VPSC delay fan the program determines the flying times for eleven equidistant centerline points between the earliest and the latest centerline intercept point. This procedure allows for an easy path control updating with minimum CP-time requirements by interpolating between two predetermined times.

In the case of a FPSC delay fan the program determines the flying times via the three alternate routes. The nominal time is used for the time assignment. The differences between the alternate routes are needed to perform rough flight time corrections.

Table 3 gives an impression of the flight time controllability for the example of a delay fan (VPSC, FPSC) layed out to handle southeastern traffic destined to runway 25 R/L at Frankfurt/FRG (see Figure 2 and Figure 3).

delay fan	path control [sec]		speed control [sec]	
	min.	max.	min.	max.
VPSC	-44.7	59.3	-16.3	16.3
FPSC	shortend	-18.1	-	-21.4
	nominal	-	-	-23.9
	extended	-	18.1	-26.6

Table 3: time controllability (example: southeast delay fan)

Due to the applied path control the VPSC fan type shows higher controllability than the FPSC fan type, though both fans use comparable geometries with similar maneuvering areas. A positive sign means deceleration potential, a negative sign acceleration potential.

c) generation of air traffic and coordination

TASIMD allows the use of two types of traffic samples: artificially generated traffic or specified traffic demand lists, e.g. based on recordings of real traffic during peak hours. If the aircraft should be generated, the aircraft mix (number, distribution over the different types or classes) and the traffic structure (distribution of the traffic demand over the available delay fans) have to be specified.

The scheduler calculates the required separation according to the wake vortex classes and determines the resulting generation time at the entry fixes, considering a safety buffer value if desired.

d) simulation of dynamic flight operations

This sub-block initializes the different flights at the entry fixes, simulates those flights through the terminal area, monitors the separation and determines parameters required for the result assessment.

A specific point is reached if an aircraft crosses a line running through this point, perpendicular to the trajectory direction. If necessary the delivery time error is determined by interpolation.

Each simulation run supplies a short summary of the air traffic handled within the analyzed time interval to facilitate identifying flights deserving further inspection. Besides the lineprinter output all aircraft and air traffic related parameters are recorded on tape for each integration time step. Except for some statistics the result analysis is performed off-line using several evaluation programs with mostly graphic output.

4. ASSESSMENT OF AUTOMATED APPROACH PROCEDURES

Characteristic criteria to assess the quality of air traffic within a terminal area are: safety, economy and capacity. Parameters may be defined to evaluate the system performance with respect to one or two of those qualitative goals. However, a TMA is a very complex system to assess with a lot of contrary interdependencies of the different influences and, of course, a lot of different interests. The only commonly accepted goal is safety. Figure 10 shows the main interest groups with the primary influence parameters, typical assessment parameters and the qualitative goals including major interdependencies.

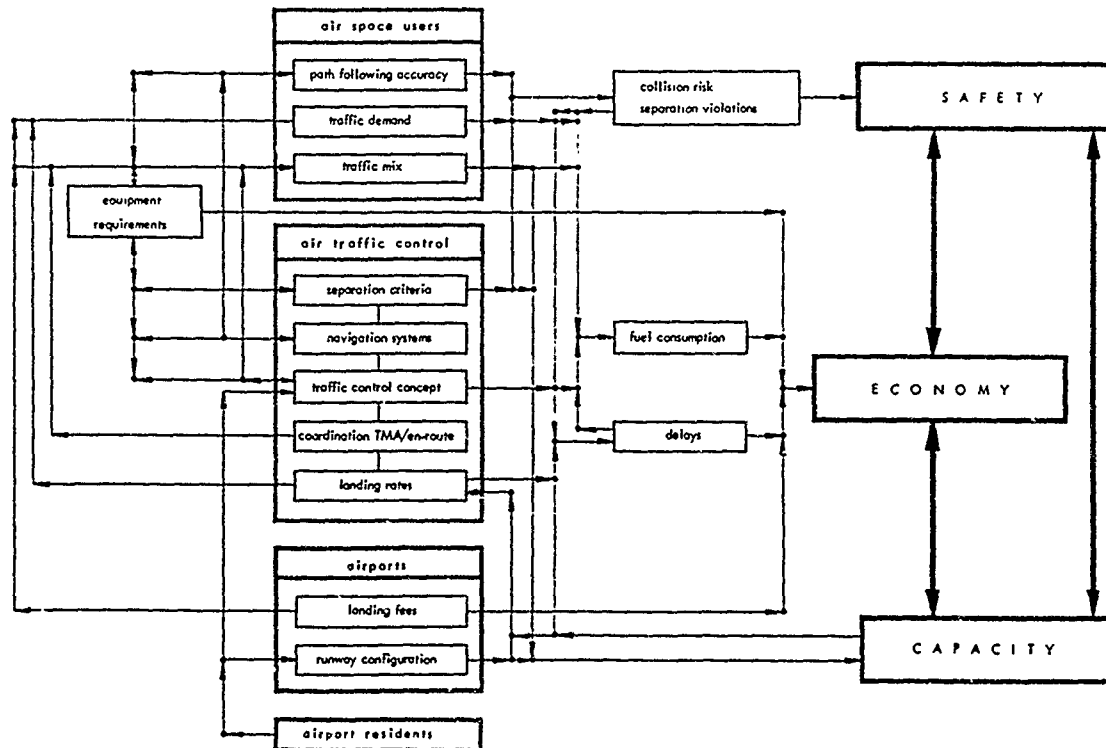


Figure 10: characteristics of a terminal area scenario

The given task is to assess and compare different automated approach concepts with respect to safety and practicability. Within this context the evaluation may be reduced to safety related aspects.

However, as the analysis of terminal control concepts showed the safety related parameters imply almost every other criterion, e.g. capacity is a function of the separation minima applied (Hörmann, Feb. 1985). Regarding economy the cost assessment is rather difficult and of minor sensitivity: applying automated procedures the required electronic equipment is in general the same and the variation of operating costs is mainly influenced by a potential delay due to a lack of capacity.

The criteria chosen for the analysis performed to assess the simulation results are:

- the achievable delivery accuracy and
- the occurring separation violations.

The achievable delivery accuracy is related to safety and capacity. Within the analysis the simulated scenarios are configured with navigation systems according to accuracy requirements for a 10 sec and a 5 sec time error target determined by means of a statistical Monte-Carlo simulation. Thus, the delivery accuracy is rather used to analyze the consistency of the results derived from different simulation models than to assess the performance of the control procedures. Prime assessment criterion are the occurring separation violations, a parameter requiring a continuous model to be evaluated.

Separation violations are related to safety and suitable to assess the general practicability of concepts operating on the basis of a shared air/ground responsibility for profile control, i.e. to match time targets and to assure separation.

5. SIMULATION ANALYSIS

The simulation analysis of the two proposed approach concepts performed with TASIMD started with a sensitivity analysis to get an impression of the impact and the sensible range of the different influences considered. Together with the accuracy requirements for future terminal area navigation the results led to the definition of two example scenarios with different configurations of navigation systems. To evaluate the approach concepts a VPSC type fan system and a FPSC type fan system were embedded into those scenarios.

5.1 Sensitivity Analysis of Important Influence Parameters

5.1.1 Entry Time Deviation

Due to the available limited airspace within a terminal area, the controllability of an approach control (without holdings) is in the order of one to a few minutes, depending on the time (distance) the aircraft are under terminal control. Thus a rather precise delivery of the aircraft at the entry fixes by the en-route control is required.

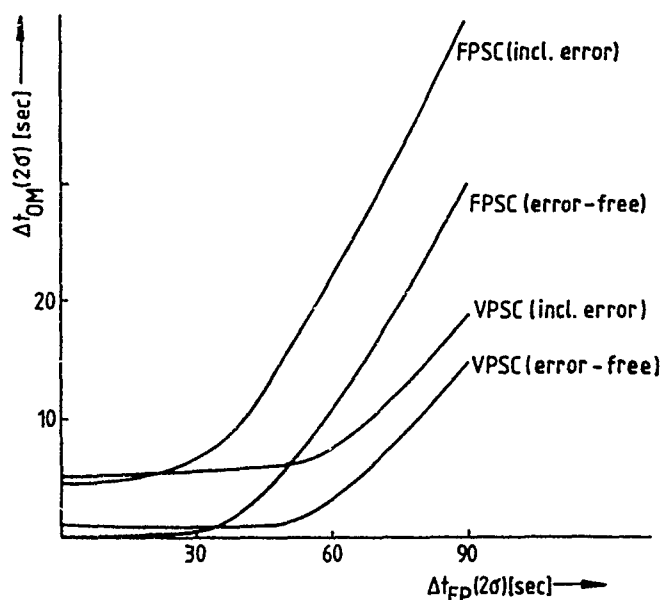


Figure 11: impact of the delivery accuracy achieved by the en-route control

Figure 11 shows the resulting delivery accuracy at a gate (outer marker) as function of the achieved delivery accuracy at the entry fixes. The results of the different control concepts are marked with VPSC and FPSC. Considered are two cases: one with VOR/DME-navigation and the error influences described in section 2.5 and the other with the entry time deviation being the only error source.

The simulation results clearly show the time flexibility of the designed control procedures (VPSC: approx. 60 sec, FPSC: approx. 40 sec). As soon as the entry fix accuracy reaches these values the gate accuracy dramatically declines. Considering other error sources the time controllability is only partly used to correct the entry time deviation leading to an earlier decline of accuracy.

5.1.2 Navigation

Aircraft capable of approaching the runway via one of the designed delay fans have to be (at least) equipped with area navigation (RNAV). The increasing number of aircraft having a flight management system (FMS) on board will certainly use inertial navigation (INS) even within the TMA, others will use satellite navigation which should be available in a future scenario. However, analyzing a time horizon covering not only the system of the future, but at the same time the transition, the application of radio navigation is presumed.

There are two alternatives for radio system based 4D-RNAV procedures: rho/theta-navigation and rho/rho-navigation. Theta/theta-navigation leads to waypoint accuracies not sufficient to fly 4D. As the single-aircraft-analysis by Monte-Carlo simulation (Fricke, Hörmann, Dec. 1983/1) indicated, the application of rho/rho-navigation yields superior accuracies depending to a large degree on favourable geometries. To avoid the generation of such secondary (geometrical) influences on the results due to the actual configuration selected, the simulated aircraft navigates using the rho/theta-method.

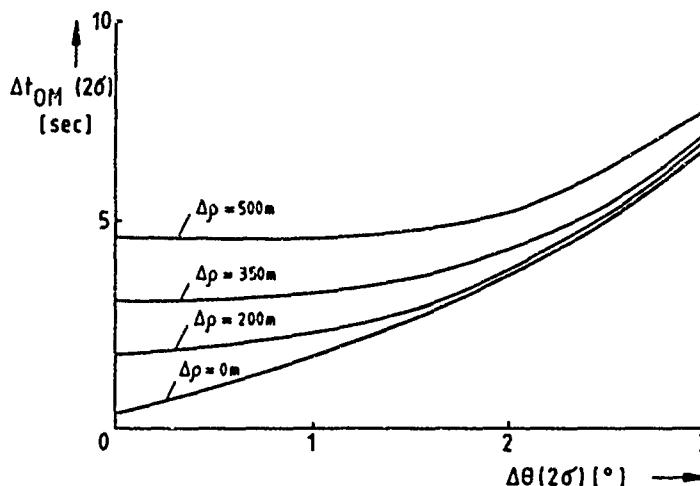


Figure 12: delivery accuracy at the outer marker using rho/theta-navigation (FPSC concept)

Figure 12 shows the resulting delivery accuracy at the outer marker with no other error source considered than navigation (rho/theta-station located in the center of the TMA). The different curves, valid for a constant distance measuring error, are drawn as function of the azimuthal error.

As the azimuthal error increases all graphs asymptotically approach the curve determined with an error-free DME. The results using systems with low theta-errors are dominated by the DME influence.

Despite the variation of capacity by influencing the delivery accuracy, the navigation impact on operating costs is almost neglectable (Hörmann, Feb. 1985).

5.1.3 Wind

The achievable delivery accuracy of 4D-procedures basing on precise navigation predominantly depends on the quality of the predicted wind vectors along the determined trajectory (Fricke, Hörmann, Sep. 1984).

Figure 13 shows the resulting delivery accuracies with increasing magnitude of the wind error vector generated according to the developed wind model (section 2.5.3). Analyzed are two scenarios for each control concept: one with all modeled error influences and the other considering only the wind influence.

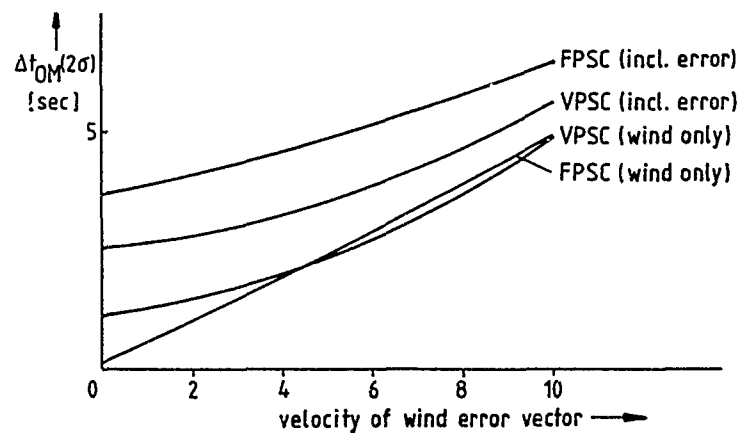


Figure 13: impact of the wind error on the delivery accuracy

Figure 13 illustrates the dominant impact of the wind error. Differences in the results between the two control concepts are due to the general layout of the fans and the time control procedure applied, for path control with heading changes are slightly more sensitive to errors in wind prediction.

5.1.4 Traffic Samples

The maximum available capacity of a certain scenario may be determined on the basis of the required safety buffer in spacing the aircraft. This safety buffer corresponds with the achievable delivery accuracy influenced by various operational and environmental error sources. However, the structure of the traffic sample determines to which degree the available terminal area capacity is used. For the simplified model TMA with simulating only approaching traffic, TMA capacity signifies landing capacity.

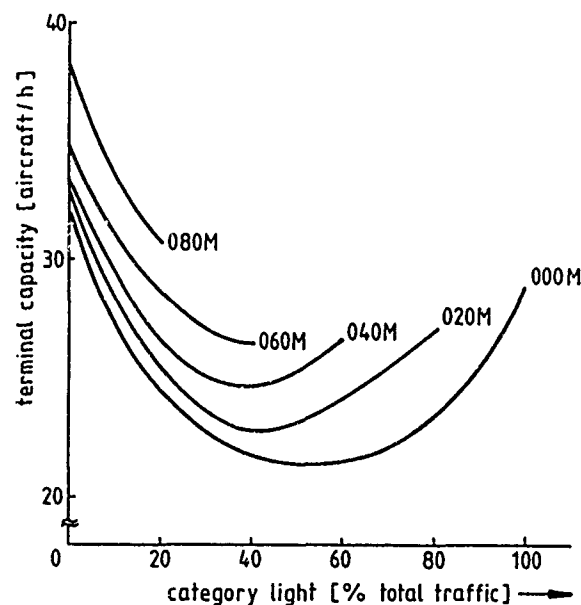


Figure 14: achievable maximum landing capacity as function of the aircraft mix

There are three parameters related to the traffic structure influencing the system throughput: the mix of aircraft types, the geographical distribution of the arriving traffic flows and the distribution of traffic demand over time with the traffic mix being the most important parameter regarding capacity.

Despite some attempts to optimize the landing sequence, in general the first-come-first-served (FCFS) strategy is applied for spacing the aircraft. The influence of the traffic mix is twofold: according to the weight classes of succeeding aircraft different separation distances are required, at the same time the spacing has to consider the different landing speeds of the aircraft.

Figure 14 shows the variation of the landing capacity with an increasing share of LIGHT aircraft. The different curves are determined with a constant share of the weight category MEDIUM, marked as "% M". The remaining difference between the sum of "% L" and "% M" are HEAVY aircraft.

The worst combination with respect to the required minimum separation is a preceeding HEAVY with a succeeding LIGHT. The lowest capacity values occur for very inhomogenous traffic samples, maximizing the combinations HEAVY/LIGHT and MEDIUM/LIGHT.

5.2 Analysis of Example Scenarios

5.2.1 Definition of the Example Scenarios

The operational practicability of the designed approach procedure concepts (section 2.2) was analyzed on the basis of two example configurations. The general TMA layout comprised two delay fans (VPSC or FPSC) north and south of runway 25 R/L of the Frankfurt airport. Aircraft arriving west of Frankfurt were assumed to be directed towards one of the two entry fixes east of the airport.

Due to the task of analyzing different control concepts and not the impact of different traffic samples, the simulation runs were performed with a homogenous traffic sample consisting of only MEDIUM category aircraft.

The traffic was generated with maximum density, i.e. minimum separation. It was assumed that 50 % of the traffic arrive from either direction (north or south). Thus, the results present some kind of worst case analysis. Simulations with 100 % via one delay fan showed consistant results. Each program run simulated two hours of TMA traffic flow.

The error influences considered were (see section 2.5):

- entry fix time deviation: limited to ± 30 sec
- wind error vector: velocity 10 Kts (normal distributed)
direction $0^\circ - 360^\circ$ (uniform distributed)
- airspeed error: 2 % of the IAS (normal distributed)
or 2 Kts, whichever is greater
- navigation (Table 4): central enhanced VOR/DME station
central DAS station

configuration	system accuracies	
	theta-error [deg] (2 sigma)	rho-error [m] (2 sigma)
enhanced VOR/DME	1.72	259
DAS	0.20	30

Table 4: navigation accuracies of the example configurations

The two configurations were chosen on the basis of the requirements for future terminal navigation derived from a statistical Monte-Carlo simulation (Fricke, Hörmann, Dec. 1983/1). The VOR/DME-configuration represents a solution to achieve a 10 sec time error goal, the DAS-configuration yields a delivery accuracy below 5 sec.

5.2.2 Delivery Accuracy

Both simulations, the simulation of realistic dynamic TMA operations with TASIMD and the Monte-Carlo flight path combination of straight segments and curves, led to consistent results. Assuming the precise navigation based on DAS or enhanced VOR/DME the simulations again highlighted the dominant wind error impact. A careful modelling of the FMS is required in order to provide an adequate time and trajectory planning for the individual aircraft flying under varying wind conditions. Differences in the results are due to the very simplified FMS algorithms designed for a first order analysis of the general practicability of computerized approach procedures. Table 5 lists the received delivery time error values determined on the basis of a two hour traffic sample.

delay fan	navigation	delivery accuracy [sec] (2 sigma)
VPSC	DAS	4.18
	enhanced VOR/DME	9.46
FPSC	DAS	6.90
	enhanced VOR/DME	9.83

Table 5: resulting delivery time error

5.2.3 Practicability of the Proposed Approach Procedures

To analyze the practicability of the proposed automated TMA procedures based on a shared ground/air responsibility special attention was given to the occurring separation violations.

The review of the occurring separation violations showed that there are three typical types of events:

- Potential violations of longitudinal separation at the entry fixes due to the assumed entry fix time error distribution. In such a case the proposed TMA procedures provide for an initial vertical separation of 1000 ft (9000 ft resp. 10000 ft at the entry fix for the two aircraft concerned).
- Violations of separation during maneuvers if the aircraft fly along the same delay fan. If all aircraft fly the same profile (continuous descent approach) the vertical separation of 1000 ft will be guaranteed. However, separation violations according to existing regulations will occur if the flights are subjected to errors and/or if the aircraft fly their own non-fixed altitude profile (2D + time navigation). The separation of 3 NM usually is reestablished without intervention because these violations last only for the period of the turn of one aircraft due to the fan geometry.
- Final longitudinal separation violations occurring at the outer marker (gate). To avoid these violations, the final spacing (scheduling) has to consider a buffer value to compensate for the estimated delivery time error besides the minimum separation.

For a more detailed review of the occurring events, the violations were classified according to their severity in steps of 0.1 NM within the interesting interval between 2.0 NM and 3.0 NM. In this context it has to be discussed whether a separation which remains for example above 2.8 NM is a real violation and a severe problem for the safety of the system. Or another point: what about the temporary separation reductions due to the fan geometry?

Figure 15 shows the statistics of the separation violations occurring during maneuvers using the FPSC concept for both example configurations: the very precise navigation with a central DAS-station and the navigation with an enhanced VOR/DME-station. The quantization chosen in Figure 15 comprises a large number of separation violations that are close to their respective upper class boundaries. In so far the graph gives a somewhat pessimistic impression of the minimum distances between aircraft during maneuvers. The simulation with the less accurate VOR/DME-navigation yields a lower total number of separation violations than in the case of DAS, but a higher percentage of more severe events. This can be attributed to the fact that an increased error in navigation in turn increases the total variability of the simulated TMA operations, either by identically compensating the influences of other error sources (wind, aircraft speed, FMS algorithm) or by increasing the total number and/or severity of separation violations.

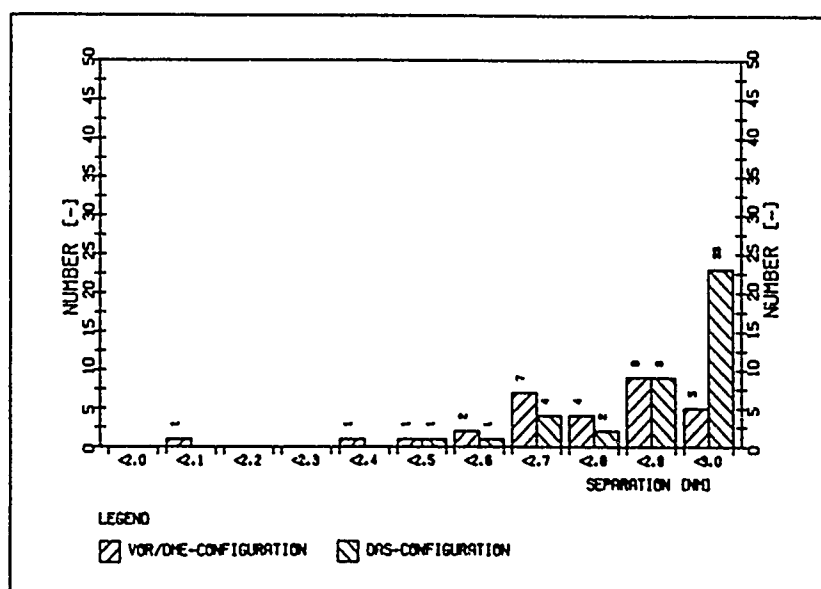


Figure 15: separation violations during maneuvers (FPSC concept, 2 hours simulated)

The remaining separation violations at the outer marker may be reduced by the introduction of a planning buffer. Table 6 shows this effect for different buffer values assuming DAS-navigation. This buffer reduces of course the system throughput (Figure 1). However, a value of 10 sec, which leads to almost no separation violation, still lies considerably below the safety buffers presently practiced by experienced controllers.

buffer value [sec]	separation [NM]											
	2.0			2.4			2.7			3.0		
0	0	0	0	0	1	0	1	4	2	9	23	
5	0	0	0	0	0	0	0	0	1	3	5	
10	0	0	0	0	0	0	0	0	0	0	2	
15	0	0	0	0	0	0	0	0	0	0	0	

Table 6: separation violations at the gate with different values of the safety buffer (FPSC concept, DAS-navigation)

With respect to the practical execution of flight operations the VPSC concept allows an easy update with usually small heading changes. In most cases fixed updates at the fan entry point and the centerline point are sufficient, no intermediate update becomes necessary. Though the simulated aircraft have speed control capability this function was neither needed nor applied. However, the continuous monitoring of the time error requires rather sophisticated airborne computing capabilities. A replacement of the ahead simulation by algorithms on an analytical basis within the path generating function would reduce the necessary computing time but at the same time increase the FMS error.

Though showing a comparable performance, there are some specific differences in the results of the different control concepts. The number of occurring violations within a VPSC type fan system (Figure 16) is significantly higher than within a FPSC type fan system with a dominant majority of less severe events. At the same time there exists a stronger influence of navigation accuracy on the number and severity of separation violations due to the intercept procedure onto the final from two different directions (north and south, Figure 2a/b). As for the FPSC concept the number of violations (not only at the gate) may be significantly reduced by the introduction of a buffer value.

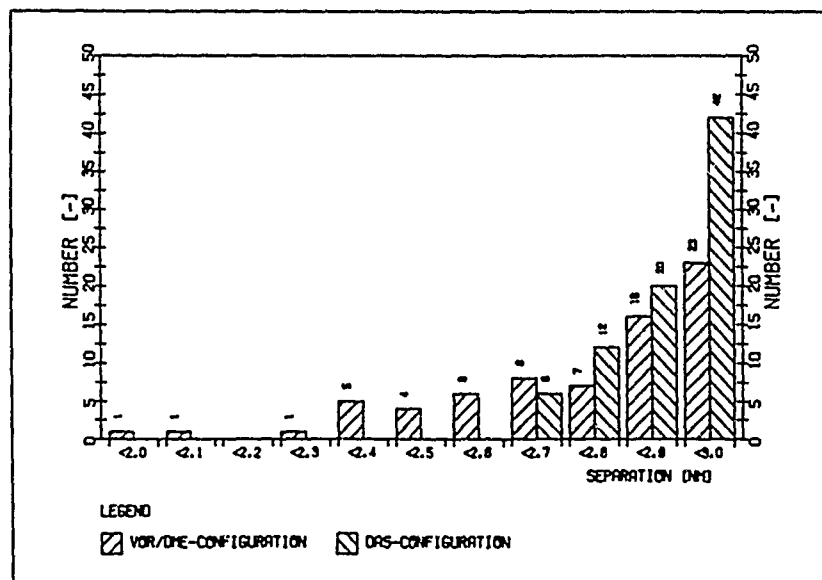


Figure 16: separation violations during maneuvers (VPSC concept, 2 hours simulated)

Looking at the overall system performance both control concepts prove the general practicability of automated terminal RNAV procedures in dynamic flight operations without intervention by ATC. For practical use, however, the developed concepts have to be refined in order to handle also traffic situations which do not comply with the assumptions made for this study.

6. CONCLUSIONS

Purpose of the performed simulations was to analyze the operational practicability of automated approach procedures in a "real" air traffic control environment of the future. Assessment criteria were the achievable delivery time error and, primarily, the occurring separation violations. The simulation model developed for the analysis (TASIMD) allows the simulation of dynamic operations of approaching aircraft in the entire terminal area. The TMA Frankfurt/FRG was taken as data base for the layout of the model of a future terminal area scenario comprising automated traffic flow control procedures.

The results of the navigational impact with respect to the delivery accuracy are in general consistent with accuracy requirements derived from single-aircraft-analysis with a statistical model (Fricke, Hörmann, Sep. 1984). To achieve a delivery time error of approx. 10 sec (2 sigma) enhanced versions of used navigation systems used today, (VOR, DME) are sufficient. Due to the strong geometrical dependencies of DME/DME navigation, the simulated aircraft navigate using VOR/DME stations. Only high precision navigation systems may yield lower delivery time error targets. Reducing the share of the navigational error the wind error becomes the dominant error source. Thus, the benefits of a high precision navigation may only be used in combination with a definite reduction of the wind error. The same applies to navigation based on other than radio systems.

To get an impression of the overall performance of such procedures the activities of the ATC were limited to a monitoring function except at the entry fixes (target time assignment, vertical separation if required). In contrast to reality the ATC does not intervene into the running system if separation standards are violated. Furthermore, the received results depend on the set up separation standards. It was not intended to change the currently defined standards though traffic of 4D-equipped aircraft using a high performance navigation system may allow for reduced separation minima under consideration of the wake vortex problem and the runway occupancy times. Simulating 2 hours of traffic with maximum density the performed simulation runs represent some kind of worst case analysis.

Even within a scenario using high precision nav aids separation violations occur. The negative influence of less precise navigation primarily results in increasing the severity of the occurring separation violations, though the total number may be less. The VPSC fan type generally yields more violations due to the path variation. However, most of the additional events are within a 0.1 NM limit of the defined 3.0 NM separation standard. The effect of less precise navigation remains the same, though there generally exists a stronger influence of navigation due to the application of path control.

The received number and severity of the separation violations may be considerably decreased by the introduction of a buffer to compensate for the expected delivery time error. Approximations for these gate time error deviations were determined earlier by Monte-Carlo simulation (Fricke, Hörmann, Dec. 1983). The required buffer values yielding acceptable results still lie much below the today applied values.

Looking at the overall system performance both delay fan types prove the practicability of automated terminal RNAV-procedures in dynamic flight operations on the basis of a shared air/ground responsibility. The VPSC fan type offers a higher controllability, the FPSC fan type requires less complex update algorithms. Future approach control concepts have to combine the advantages of both control types.

In order to adapt such concepts to a real environment, however, many details as e.g. emergencies or aircraft with less sophisticated equipment, have to be considered. The analysis of such operational problems, however, requires the performance of real time simulations in cooperation with pilots and controllers.

7. ABBREVIATIONS

ATC	Air Traffic Control
CDA	Continuous Descent Approach
CEP _{0,95}	Circular Error Probability, 95 % error radius (Schroepl, 1979)
CHA	Charlie, navaid within TMA Frankfurt/FRG
CP	Centerline Point
CWS	Control Wheel Steering
DAS	DME based Azimuth System
DME	Distance Measuring Equipment
DME/P	Precision DME
EP	Entry Point, arrival fix
FCFS	First-Come-First-Served
FFM	Frankfurt, navaid within TMA Frankfurt/FRG
FMS	Flight Management System
FPSC	Fixed Path Speed Control
GED	Gedern, navaid within TMA Frankfurt/FRG
GT	Gate
IAS	Indicated AirSpeed
ICAO	International Civil Aviation Organization
INS	Inertial Navigation System
NDB	Non Directional Beacon
OM	Outer Marker
RNAV	aRea NAVigation
TMA	Terminal Maneuvering Area
VOR	VHF Omni Directional Beacon
VPSC	Variable Path Speed Control
WP	WayPoint

REPORT DOCUMENTATION PAGE						
1. Recipient's Reference	2. Originator's Reference AGARD-AG-301 Volume 2	3. Further Reference ISBN 92-835-0562-X	4. Security Classification of Document UNCLASSIFIED			
5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France					
6. Title	AIRCRAFT TRAJECTORIES — Computation — Prediction — Control VOLUME 2					
7. Presented at						
8. Author(s)/Editor(s) Various Edited by André Benoît		9. Date May 1990				
10. Author's/Editor's Address Various		11. Pages 482				
12. Distribution Statement		This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.				
13. Keywords/Descriptors						
<table border="0"> <tr> <td>Aircraft trajectories: — Computation — Prediction — Control Air traffic handling Air traffic control Air traffic management Aircraft dynamics Bayesian tracking</td> <td>Computer/controller/pilot dialog Dynamic flight operations Ground-based 4-D guidance of aircraft Integration of control phases Man/computer interface Meteorological forecasts Radar tracking Satellite techniques</td> <td>Simulation (ATH, ATM, ATC) Surveillance Terminal area arrival paths Time-based flight operations Time-based terminal flow-control ZOC 4-D Control of flight 4-D Guidance of aircraft</td> </tr> </table>				Aircraft trajectories: — Computation — Prediction — Control Air traffic handling Air traffic control Air traffic management Aircraft dynamics Bayesian tracking	Computer/controller/pilot dialog Dynamic flight operations Ground-based 4-D guidance of aircraft Integration of control phases Man/computer interface Meteorological forecasts Radar tracking Satellite techniques	Simulation (ATH, ATM, ATC) Surveillance Terminal area arrival paths Time-based flight operations Time-based terminal flow-control ZOC 4-D Control of flight 4-D Guidance of aircraft
Aircraft trajectories: — Computation — Prediction — Control Air traffic handling Air traffic control Air traffic management Aircraft dynamics Bayesian tracking	Computer/controller/pilot dialog Dynamic flight operations Ground-based 4-D guidance of aircraft Integration of control phases Man/computer interface Meteorological forecasts Radar tracking Satellite techniques	Simulation (ATH, ATM, ATC) Surveillance Terminal area arrival paths Time-based flight operations Time-based terminal flow-control ZOC 4-D Control of flight 4-D Guidance of aircraft				
14. Abstract						
<p>This volume — part of a set of three — is composed of a preface and 28 papers covering : respectively,</p> <ul style="list-style-type: none"> — AIR TRAFFIC HANDLING, Integration of control phases; A future European ATC concept; On-line prediction of aircraft trajectories; Air traffic management; — GUIDANCE OF AIRCRAFT IN A TIME BASED CONSTRAINED ENVIRONMENT; Context — objective — plans; General discussion; Guidance and control principles and concepts; Conduct of Air Traffic Control in a Zone of Convergence; Ground-based 4-D guidance of aircraft in moving atmosphere; The Computer/Controller/Pilot dialogs; — SURVEILLANCE; Radar tracking; Satellite techniques; — METEOROLOGICAL FORECASTS; Impact of forecasts quality on trajectory prediction; Flight operations within a terminal area; — AIRCRAFT OPERATION IN AIR TRAFFIC HANDLING SIMULATION; Realistic operation and motion of aircraft; Flight operations within a terminal area. 						

<p>AGARDograph No.301 Volume 2 Advisory Group for Aerospace Research and Development, NATO AIRCRAFT TRAJECTORIES: COMPUTATION — PREDICTION — CONTROL. VOLUME 2 Edited by André Benoit Published May 1990 482 pages</p> <p>This volume — part of a set of three — is composed of a preface and 28 papers covering respectively,</p> <p>— AIR TRAFFIC HANDLING: Integration of control phases; A future European ATC concept; On-line prediction of aircraft trajectories; Air traffic management.</p> <p>P.T.O.</p>	<p>AGARD-AG-301 Vol.2</p> <p>Aircraft trajectories: — Computation — Prediction — Control Air traffic handling Air traffic control Air traffic management Aircraft dynamics Bayesian tracking Computer/controller/pilot dialog Dynamic flight operations Ground-based 4-D guidance of aircraft Integration of control phases Man/computer interface Meteorological forecasts Radar tracking</p>	<p>AGARDograph No.301 Volume 2 Advisory Group for Aerospace Research and Development, NATO AIRCRAFT TRAJECTORIES: COMPUTATION — PREDICTION — CONTROL. VOLUME 2 Edited by André Benoit Published May 1990 482 pages</p> <p>This volume — part of a set of three — is composed of a preface and 28 papers covering respectively,</p> <p>— AIR TRAFFIC HANDLING: Integration of control phases; A future European ATC concept; On-line prediction of aircraft trajectories; Air traffic management.</p> <p>P.T.O.</p>	<p>AGARD-AG-301 Vol.2</p> <p>Aircraft trajectories: — Computation — Prediction — Control Air traffic handling Air traffic control Air traffic management Aircraft dynamics Bayesian tracking Computer/controller/pilot dialog Dynamic flight operations Ground-based 4-D guidance of aircraft Integration of control phases Man/computer interface Meteorological forecasts Radar tracking</p>
<p>AGARDograph No.301 Volume 2 Advisory Group for Aerospace Research and Development, NATO AIRCRAFT TRAJECTORIES: COMPUTATION — PREDICTION — CONTROL. VOLUME 2 Edited by André Benoit Published May 1990 482 pages</p> <p>This volume — part of a set of three — is composed of a preface and 28 papers covering respectively,</p> <p>— AIR TRAFFIC HANDLING: Integration of control phases; A future European ATC concept; On-line prediction of aircraft trajectories; Air traffic management</p> <p>P.T.O.</p>	<p>AGARD-AG-301 Vol.2</p> <p>Aircraft trajectories: — Computation — Prediction — Control Air traffic handling Air traffic control Air traffic management Aircraft dynamics Bayesian tracking Computer/controller/pilot dialog Dynamic flight operations Ground-based 4-D guidance of aircraft Integration of control phases Man/computer interface Meteorological forecasts Radar tracking</p>	<p>AGARDograph No.301 Volume 2 Advisory Group for Aerospace Research and Development, NATO AIRCRAFT TRAJECTORIES: COMPUTATION — PREDICTION — CONTROL. VOLUME 2 Edited by André Benoit Published May 1990 482 pages</p> <p>This volume — part of a set of three — is composed of a preface and 28 papers covering respectively,</p> <p>— AIR TRAFFIC HANDLING: Integration of control phases; A future European ATC concept; On-line prediction of aircraft trajectories; Air traffic management.</p> <p>P.T.O.</p>	<p>AGARD-AG-301 Vol.2</p> <p>Aircraft trajectories: — Computation — Prediction — Control Air traffic handling Air traffic control Air traffic management Aircraft dynamics Bayesian tracking Computer/controller/pilot dialog Dynamic flight operations Ground-based 4-D guidance of aircraft Integration of control phases Man/computer interface Meteorological forecasts Radar tracking</p>

<p>— GUIDANCE OF AIRCRAFT IN A TIME BASED CONSTRAINED ENVIRONMENT: Context — objective — plans; General discussion; Guidance and control principles and concepts; Conduct of Air Traffic Control in a Zone of Convergence; Ground-based 4-D guidance of aircraft in moving atmosphere; The Computer/Controller/Pilot dialogs.</p> <p>— SURVEILLANCE: Radar tracking; Satellite techniques.</p> <p>— METEOROLOGICAL FORECASTS: Impact of forecasts quality on trajectory prediction; Flight operations within a terminal area.</p> <p>— AIRCRAFT OPERATION IN AIR TRAFFIC HANDLING SIMULATION: Realistic operation and motion of aircraft; Flight operations within a terminal area.</p> <p>ISBN 92-835-0562-X</p>	<p>Satellite techniques Simulation (ATH, ATM, ATC) Surveillance Terminal area arrival paths Time-based flight operations Time-based terminal flow-control ZOC 4-D Control of flight 4-D Guidance of aircraft</p>	<p>— GUIDANCE OF AIRCRAFT IN A TIME BASED CONSTRAINED ENVIRONMENT: Context — objective — plans; General discussion; Guidance and control principles and concepts; Conduct of Air Traffic Control in a Zone of Convergence; Ground-based 4-D guidance of aircraft in moving atmosphere; The Computer/Controller/Pilot dialogs.</p> <p>— SURVEILLANCE: Radar tracking; Satellite techniques.</p> <p>— METEOROLOGICAL FORECASTS: Impact of forecasts quality on trajectory prediction; Flight operations within a terminal area.</p> <p>— AIRCRAFT OPERATION IN AIR TRAFFIC HANDLING SIMULATION: Realistic operation and motion of aircraft; Flight operations within a terminal area.</p> <p>ISBN 92-835-0562-X</p>	<p>Satellite techniques Simulation (ATH, ATM, ATC) Surveillance Terminal area arrival paths Time-based flight operations Time-based terminal flow-control ZOC 4-D Control of flight 4-D Guidance of aircraft</p>
<p>— GUIDANCE OF AIRCRAFT IN A TIME BASED CONSTRAINED ENVIRONMENT: Context — objective — plans; General discussion; Guidance and control principles and concepts; Conduct of Air Traffic Control in a Zone of Convergence; Ground-based 4-D guidance of aircraft in moving atmosphere; The Computer/Controller/Pilot dialogs.</p> <p>— SURVEILLANCE: Radar tracking; Satellite techniques.</p> <p>— METEOROLOGICAL FORECASTS: Impact of forecasts quality on trajectory prediction; Flight operations within a terminal area.</p> <p>— AIRCRAFT OPERATION IN AIR TRAFFIC HANDLING SIMULATION: Realistic operation and motion of aircraft; Flight operations within a terminal area.</p> <p>ISBN 92-835-0562-X</p>	<p>Satellite techniques Simulation (ATH, ATM, ATC) Surveillance Terminal area arrival paths Time-based flight operations Time-based terminal flow-control ZOC 4-D Control of flight 4-D Guidance of aircraft</p>	<p>— GUIDANCE OF AIRCRAFT IN A TIME BASED CONSTRAINED ENVIRONMENT: Context — objective — plans; General discussion; Guidance and control principles and concepts; Conduct of Air Traffic Control in a Zone of Convergence; Ground-based 4-D guidance of aircraft in moving atmosphere; The Computer/Controller/Pilot dialogs.</p> <p>— SURVEILLANCE: Radar tracking; Satellite techniques.</p> <p>— METEOROLOGICAL FORECASTS: Impact of forecasts quality on trajectory prediction; Flight operations within a terminal area.</p> <p>— AIRCRAFT OPERATION IN AIR TRAFFIC HANDLING SIMULATION: Realistic operation and motion of aircraft; Flight operations within a terminal area.</p> <p>ISBN 92-835-0562-X</p>	<p>Satellite techniques Simulation (ATH, ATM, ATC) Surveillance Terminal area arrival paths Time-based flight operations Time-based terminal flow-control ZOC 4-D Control of flight 4-D Guidance of aircraft</p>