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FOREWORD

In the evolution of Air Traffic Control certain important phases can be identified. Until recently, these phases were usually characterized by the advent of a particular technical or technological development.

A first phase which roughly covered the period 1930–1950 was characterized by manual operation, visual surveillance, time separation of aircraft, the use of radio for communication and low frequency aids for navigation. A second phase which extended, say, from the late 1950's until about 1970 was essentially characterized by the introduction and extensive use of two techniques: radar, both primary and secondary, for surveillance and VOR/DME for navigation. Then, from the late 1960's onwards, the introduction of the computer in to ATC opens a new era: flight plans and radar data processing, synthetic data displays and digital communications. In some systems, automation is already providing systematic back-up for the controller and this phase of automation is only just starting.

In the early 1970's, a new and completely different phase started in parallel and is continuing. It is a phase not related to any particular technological developments but one born of concern, concern shown by both the users of the airspace and the authorities responsible for the ATC services for economy and concern expressed by the community regarding the conservation of natural resources, in general, and the impact which further development of aviation can have on ecology, in particular.

In this era, demands and constraints issued from various sources are no longer simple and may even contain some degree of contradiction. Consequently, present overall requirements for aviation operation have reached a high level of complexity. As a result, the management and control of air traffic as expressed in terms of modern control theory, have become a large multicriteria system. In this system, safety remains the basic constraint whilst expedition will progressively result from a wider economic criterion which will also ensure the maximum use of available capacity. This is to be reflected at each stage of the planning, management or actual control of the air traffic and related services. In particular, a prerequisite to any subsequent investigation, consists in clearly defining the "control variables" to be associated with each hierarchical control/management loop, each loop being characterised by a particular "look ahead" period of time, ranging from, say, twenty years for major orientations to some thirty seconds for pilot actions following collision avoidance directives or commands.

Further, in the NATO environment, there are strong recommendations for considering air traffic control as a joint civil/military system, the emphasis being placed on the compatibility, the coordination and complementary aspects of both civil and military components. A valuable effort is presently being made in Europe towards such objectives and it is probably therefore appropriate to openly debate the various views on the challenges which result from such requirements.

In the past, the civil air traffic systems have largely benefited from the results of military research and development programs in the fields of surveillance, navigation, communications and automation. Today, military effort is greater than ever: it is expected that several programs or technological developments which have been initiated will have an appreciable impact on the future orientation of air traffic systems. These include a wide range of subjects such as the global positioning system, the automatic distribution of information, the integration of various functions, the use of digital communications between the air and the ground.

In conclusion, from whatever angle we look at air traffic today, one leading directive appears, printed in capital letters: ECONOMY. On the civil side, it characterizes the new procedures and practices, and is demonstrated by a general policy on fuel conservation. Similarly, civil/military cooperation should be enhanced and the possible future applications of present military developments duly investigated to this end. Thus, it appeared timely and appropriate to initiate this symposium as part of the programme of activities of the Guidance and Control Panel of AGARD.

Dr A.BENOIT
Programme Chairman

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** Not presented at the meeting.

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SESSION V: FLIGHT MANAGEMENT IN TERMINAL AREA

SESSION VI: SUBSYSTEM TECHNOLOGY

SESSION VII: ADVANCED SYSTEMS

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AIR TRAFFIC IN NATO EUROPE
ITS CHARACTERISTICS AND ITS NEEDS

by

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SUMMARY

This paper reviews the needs and characteristics of air traffic in NATO Europe, and its aim is to focus the attention of all participants to the 29 Symposium of AGARD on to the subject of Air Traffic Management, and, in particular, Civil-Military Systems and Technologies. The paper defines the terms air traffic management, air traffic control, airspace control and NATO Europe. It describes the divergent requirements and particular problems of airspace users and concludes that efficient use of the airspace can only be achieved through co-operation between the civil and military authorities. Finally, it lists some areas where research and development would be fruitful.

INTRODUCTION

1. The first duty of the speaker of a Keynote address is to ensure that he understands the subject of the meeting and the second is to ensure that his audience does too. Air Traffic Management is our theme and we need to have an agreed definition of that phrase and its relationship to other commonly used - and sometimes misused - associated phrases.

DEFINITION OF TERMS

2. Air traffic management (ATM) entails the arrangements made by air traffic services (ATS) agencies to allow each category of airspace user - military and civil - to achieve their desired aims as safely and expeditiously and economically as possible with minimum disruption to other airspace users. Efficient air traffic management will only stem from a thorough understanding of the characteristics and needs of all the airspace users so that reasoned judgements can be made where questions of priority arise.

3. This leads to the subject of the paper - Air Traffic in NATO Europe; its characteristics and its needs. Again, it would be helpful to begin with definitions. The definition of air traffic management is broad enough to embrace such features as airspace design and legislation, various services which provide a range of information on request to pilots and others responsible for the operation of aircraft, as well as the actual control of particular air traffic in specially designated airspace. This last activity - true air traffic control can be defined as -

> A service provided for the purpose of:
>
> a. preventing collision
>   (1) between aircraft
>   (2) between aircraft and obstructions
>
> b. expediting and maintaining an orderly flow of air traffic.

This service is specifically provided for traffic which requires the safest possible separation service whilst retaining an expeditious and orderly flow. Air traffic control can be based on the perceived, real-time, picture of the traffic or can be operated "blind" in a procedural fashion - and it is perhaps unnecessary to point out that the latter method of control is not as efficient as the former by a large margin; possibly having only 25% of the efficiency in terms of traffic capacity.

4. Next, it is necessary to define the term Europe from an air traffic management viewpoint as three Europes can be recognised in this context. First, there is a EUROCONTROL Europe consisting of seven states having full membership and both civil and military elements. Then there is NATO Europe, which is represented at this Symposium with 13 European states. And finally there is ICAO Europe which embraces all of Europe but has no formal military content. In passing, you will note that the Europe of the European Community (EC) has been excluded since it is understood that the organisation has no mandate for engaging itself in matters of air traffic management and the Council of Ministers have not included air traffic management in their own priority programme on air transport.

5. It would be beneficial for the Symposium to carry out its deliberations against the backdrop of NATO Europe in the knowledge that the other two international aviation bodies mentioned (ICAO and EUROCONTROL) have close and continuous ties with NATO through the Committee of European Airspace Co-ordination (CEAC) where both can join in the deliberations of that committee on a wide range of subjects of common concern. But it should also be recognised that only NATO can manage those air traffic matters which touch upon the security of NATO and its member states acting in concert. This aspect will be mentioned later.

CHARACTERISTICS OF AIRSPACE USERS

6. The aim of those engaged in providing an air traffic service, whether they are controllers, engineers, R & D scientists, administrators or financiers, is to help or benefit those who are concerned with using the airspace who are called the customers. The customers are an extremely varied lot from balloonists through helicopters to Concorde and from trainers through Harriers to interceptors.

7. It is usual in attempting to study the characteristics of the airspace population to divide them initially into military and civil elements. First, however, it is worth recognising that most airspace users - with the exception of balloons, gliders, and pedalplanes - have one particular characteristic in common; they all depend on petrol or paraffin for power, and they all - military and civil - have good reasons for wishing to conserve it as far as possible. It is emphasised that the fuel problem is a common problem to all powered airspace users and that its emergence this decade should not affect the military-civil balance in air traffic management. However it does present an additional challenge to air traffic managers who need to develop techniques which might assist in fuel conservation without degrading safety.

8. Turning to the characteristics and needs of the military operator it is found that, in general, only a small proportion of military traffic will wish to participate in an air traffic control service, although most military activities will benefit from advisory services of various types. Military transports and some transit aircraft may find it appropriate to operate in the airways system and in other regulated airspace under control, but the vast majority of military activities (over 80%) are best carried out clear of air traffic control in open airspace where training, exercises and operations can be conducted unimpeded by non-military considerations. Military activities vary between ground level and Flight levels up to 660 and between the hover and Mach 3.0 and some individual vehicles operate over a substantial part of these ranges, moving from one end to the other in a matter of seconds. Of course, the military operators recognise that unrestrained activities of this nature are not practicable in the limited airspace of NATO Europe and constraints in the form of airspace limitations and co-ordination with civil authorities are accepted in peacetime. This does represent some sacrifice on the part of the military but it is a sacrifice matched by their civil counterparts.

NEEDS OF AIRSPACE USERS

9. Civil air traffic can be placed into two main categories for our considerations, General Aviation and Public Transport. General Aviation (GA) includes recreational and training flying and some commercial activities such as air taxis, crop spraying, pipeline and power cable inspections and oil industry support. By and large, GA occupies the same open airspace as the large proportion of the military, does not want air traffic control, but requires some element of the air traffic service; in particular it, and the military, do not want a collision. Here is a fruitful area of study - the provision of a cheap and totally dependable device which will help pilots avoid each other to say, 500 ft with a closing speed of 1000 Kts!

10. Public Transport aircraft, whether scheduled services or tour operators, together with sophisticated business aircraft, are the main users of the airways system, controlled airspace and the related air traffic control service. It is this traffic and the delays experienced which reach the headlines each Summer. The season is of course the important factor since it is the increasing urge by us all to take off for the Summer sun in the Mediterranean which has produced the problem. Each Summer over recent years the annual traffic peak goes higher and the weekly peaks between Friday and Monday are a small reflection of the overall trend. One particular and exacerbating feature of the European situation is the way in which the holiday traffic criss-crosses over Europe as it travels between the North and the South. There are two other features which should be highlighted.

11. The first is the uneven traffic capacity of national European ATS organisations. Some Flight Information Regions (FIRs) are equipped with modern radars, navigation beacons, communications and automatic data processing devices, all with redundancy provided and sufficient highly trained staff to ensure that an adequate service can be maintained on a 24 hrs basis. Others have elderly radars, few beacons, inadequate communications, no automatic data processing and insufficient staff. Traffic flow within an FIR of the second type has to be slowed down to a rate which is considered safe and this dictates the rate through other FIRs. Flow control techniques can even-out the flow and minimise disruptions, but such techniques cannot deal with fundamental problems of air traffic system capacity in some areas of Europe. Efficient air traffic flow along the airways of Europe can only be achieved by a harmonisation - both in performance and quantity - of the equipment and manpower deployed to meet the requirements of the customers. One reason why this is not occurring at present may be because, in some cases, income received from ATS is not reinvested in ATS.

12. Another feature affecting the flow of airways traffic is airport capacity. Most airports in Europe are restrained to operate at less than two-thirds capacity because of night curfews. Further restraints may occur because of environmental routeings, runway configuration and sheer physical constraints in terms of available concrete on the ground or in the shape of terminal buildings. These problems are sometimes exacerbated by the concentrated traffic demands at some airfields particularly at holiday destinations. It is doubtful that many, if any, new civil airports will be built in Europe in the next decade. Quieter aircraft may prove to offer a sufficient environmental improvement to allow existing airports to continue operating much as they do today. But a higher proportion of large, wake-vortex-making, aircraft operating to Cat III standards at some airports will pose further challenges to the safe handling of aircraft at the limited number of airports available.

13. So far these comments have been applicable to a peacetime environment, but it is necessary to briefly consider air traffic management in times of tension less than war. The latter has been excluded since the factors affecting ATM in a war in NATO Europe could be so varied as to only confuse debate. They will undoubtedly confuse us all in war and we shall just have to do our best with what we have got.

14. The most likely activities to which air traffic management will have to respond in a time of tension in NATO Europe would be the redeployment of military aviation units, the reinforcement of NATO Europe from North America via the North Atlantic and escalating defence operations; all this whilst continuing to handle civil traffic in an ICAO-like manner for as long as possible. This is a time when Airspace Control becomes of paramount importance. Airspace Control is defined as:

> A service provided in the combat zone to increase operational effectiveness, by promoting the safe, efficient, and flexible use of airspace. Control is provided in order to permit greater flexibility of operations, while authority to approve, disapprove, or deny combat operations is vested only in the Operational Commander. In this context the word service means the action of serving, helping or benefiting all those who are concerned with the use of airspace.

However, harmonisation between airspace control and air traffic management will be vital. These activities require the development of a NATO-wide joint military-civil flow control system from North America to the Eastern Mediterranean.

CONCLUSIONS

15. The wide range of aspects discussed are regarded as some fundamental ATM issues affecting NATO and its civil opposite numbers in Europe. It will be noted that no radical changes have been suggested to the way in which the dense air traffic in the confined European airspace will be managed in the foreseeable future. In particular, it is stressed that the characteristic needs of air traffic in the open FIR and on the airways system are so different that segregation is necessary. That does not mean that the form of segregation should remain unaltered for 24 hrs a day or 365 days a year; airspace sharing by time is entirely possible and is currently operated successfully by a number of administrations. But it does mean that the airways system will remain. Unhappily, the current airways system performs unevenly and its efficiency needs to be improved, not only for happy peacetime activities such as holiday making, but also to permit NATO to respond to possible challenges and confrontation.

16. Finally, we, and in particular the air traffic managers, must not forget that the key to the operation is the air traffic controller. Within NATO Europe we have a complex mixture of military and civilian controllers with varied capabilities and motivations. We have to recognise that the working environment of controllers is a major factor in the efficiency of the overall system and only with the full support of air traffic controllers and a recognition of the contribution which they can make can we hope to improve the efficiency of the European air traffic system.

17. So what do I hope will emerge from the work of research and development? Here is a little list (it is not exhaustive!)

a. A cheap, but effective and pilot-proof, method of on-board collision avoidance for aircraft operating outside controlled airspace under IFR as well as VFR.

b. In the long term, cost-effective and reliable primary and secondary radar systems, communications and ADP support which will be compatible with each other and attractive enough for each member state to purchase and link to their neighbours.

c. In the meantime, the establishment of an efficient strategic and tactical air traffic flow facility to deal with exceptional peak demands in peace and times of tension.

d. Improved ATS and AD interfaces and associated advances in the use of secondary radar and IFF systems for reliable separation and segregation in peace and in times of tension.

e. Systems to improve - or at least sustain - civil airport capacity and handling in an era of increasing numbers of large transport aircraft mixed with the smaller variety.

f. And, last but not least, more illumination on the needs of the human being in managing and operating a system in which the factors are fast-changing and the penalty for a mistake could be a disaster.

HELICOPTER AIR TRAFFIC MANAGEMENT SYSTEMS WITH CIVIL/MILITARY INTEROPERABILITY

By

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SUMMARY

Evolutionary system engineering can be an attractive and effective mechanism for providing new or improved operational capabilities. It avoids the technical, economic and political burdens always inherent in the process of introducing new equipments and systems. It prevents the proliferation of new systems and promotes interoperability among the various users of the system. These arguments are especially appropriate to Air Traffic Management (ATM) and Landing systems because of the basic need for a large and diverse user community - both civil and military - to operate compatibly over wide geographical areas. In order to achieve significant near-term improvement in the Army's ATM capability, we have developed and are now testing several configurations of Very Lightweight Air Traffic Management Equipment (VLATME) based upon totally compatible use of today's common civil/military system ATCRBS (Air Traffic Control Radar Beacon System). Concurrently with the VLATME development, our helicopter instrument landing technology work over the past few years has revealed that the key to solving this problem lies in the ability to perform deceleration of the aircraft on instruments, along the approach path, so as to bring the aircraft to a hover a few feet above the intended landing point. The decelerated instrument approach means that helicopter spacings will have to be much smaller than those encountered in fixed wing practice if reasonable flow rates are to be realized. Because of the potential garbling problem in conventional ATCRBS with closely spaced aircraft we have developed and successfully test flown a system which integrates the ground and airborne equipments of a scanning beam microwave landing system with the airborne transponder while preserving interoperability. Currently the NATO wide environment is extensively dependent upon the radar beacon system which can be modernized and adapted in an evolutionary way to create system derivatives with operational guidance and control capabilities well beyond those possible with many existing equipments.

INTRODUCTION

The theme for this symposium, presented in the call for papers stated that Air Traffic Control (ATC) is to be considered as a joint civil/military system, that emphasis is being placed on the complementary aspects of the civil and military components, and that transition to future concepts of operation - including evolutionary implementation schemes - should be proposed and discussed.

The principal thrust of this paper is to show that evolutionary system engineering schemes can be employed to solve new or different Air Traffic Management (ATM) problems in ways that are totally compatible and interoperable with contemporary civil/military systems and technologies. It is written from the perspective developed during more than a decade of helicopter ATC and Landing R&D within the U.S. Army Avionics Research and Development Activity, Fort Monmouth, N.J.

Military use of the helicopter has increased rapidly. Aeronautical and turbine-power technology has created a highly versatile vehicle for military tactical missions such as troop support, resupply, anti-tank attack and medical evacuation. Tactical commanders are freed from past constraints of terrain and water boundaries, opening up new vistas of force mobility and flexibility. Consequently, modern Army Aviation has become an integral part of many tactical operational environments, such as NATO.

As helicopter tactical missions increase, so do the needs for prudent management of the low-altitude tactical airspace. Guidance and control are essential for directing the helicopter against enemy forces and for assuring its safe recovery under varying conditions of weather and visibility. Recognizing such Army Aviation needs, our R&D programs have been investigating evolutionary solutions with emphasis on minimizing the proliferation of new equipments aboard Army helicopters. We are also stressing a common civil/military theme in these programs because of the operational and economic benefits realizable through true civil/military compatibility. We have achieved very promising R&D results from evolutionary designs, avoiding dependence on risky, unproven technology. Interoperability among Army and other tactical forces is also assured by this approach. Helicopter mission performance is not sacrificed, yet optimum tactical interoperability and commonality with civil airspace users appears feasible. This approach should allow peacetime flight procedures for safety and efficiency with the ability to switch over rapidly to a battlefield mode of operation.

HELICOPTER INSTRUMENT LANDING

It is essential that equipments for tactical Air Traffic Management and command and control take full advantage of the unique flight properties of helicopters, thereby enhancing the value of these aircraft to a military commander. In our research and development to meet these goals, we have found that direct application of fixed-wing air navigation and traffic control aids to helicopters is not always practical. For example, the standard VHF/UHF Instrument Landing System (ILS) used by both civil and military aviation, cannot tolerate reflections. It requires acres of extremely flat terrain and it cannot be used without several days of sophisticated flight testing and adjustment. ILS cannot be used tactically, so we have pioneered the development of extremely lightweight, highly portable, microwave landing systems that completely overcome the ILS deficiencies. They are independent of terrain for beam formation, they are compatible with the small, often cluttered area needed by the landing helicopter, and they are able to provide flyable guidance down to the extremely short aircraft to ground equipment distances typically encountered in a helicopter instrument approach to a stable hover - distances as low as 50 feet (15 meters).

Figure 1 shows the Army's Tactical Landing System (TLS), a full military specification equipment developed in the early 1970's using experience gained from earlier flight research with a similar but more versatile exploratory system called A-SCAN. A-SCAN was used to examine various facets of the helicopter landing problem such as steep and shallow approach angles, course width sensitivities and siting configurations and, later, to determine what cockpit displays and piloting techniques were needed. TLS consists of the AN/TRQ-33 ground equipment and the AN/ARQ-31 airborne equipment. It is a Ku-band, pulse modulated scanning beam system providing glideslope angles from 3° to 12°, azimuth and elevation guidance with an accuracy of about 0.1 degree and precision Distance Measuring Equipment (DME), with an accuracy of about 50 feet (15 meters). The TLS is similar to the U.S. Navy AN/SPN-41 Carrier Landing system and the U.S. Marine Corps MRAALS (Marine Remote Area Approach and Landing System) now nomenclatured AN/TPN-30. The TLS glideslope and localizer guidance exists in a form which is fully compatible with the angle subsystems of the Navy and Marine Corps equipments. The Navy system does not incorporate a DME, the Marine Corps system uses a precision version of standard L-band DME, and TLS contains a Ku-band DME which is an integral part of the Ku-band pulse signal format of the angle subsystems.

The TLS was purposely designed as a split site system so as to meet the requirement for serving both fixed wing aircraft and helicopters. Figure 2 shows a derivative of TLS - we have come to call it the "Minibox" - which was designed to determine how small the ground landing equipment could become if it were required to serve only the steeper glideslope angles of helicopters. Typically, a modulated scanning beam microwave landing system can provide flyable glideslope guidance down to an elevation angle which is slightly less than the 3db beamwidth of the elevation beam. We have found that the nominal minimum glideslope angle for helicopters is 6° and that the glideslope course width for this approach angle should be about ± 2° for good flyability. This means that the glideslope beamwidth of a helicopter - only ground equipment can be as large as 4°. The minibox employs a 4° glideslope beam and a 6° localizer beam. It also includes the TLS Ku-band precision DME. It is 30 inches (76 cm) high, without its small tripod mounting base, and weights 58 pounds (26.4 kg) without its 24 volt battery source.

Flight research with TLS and the minibox has revealed that the key to solving the helicopter instrument landing problem lies in the ability to perform deceleration of the aircraft on instruments, along the approach path, so as to bring the aircraft to a hover a few feet above the intended landing point. We have achieved this capability for experimental conditions. Our work in this area has most recently been reported in Reference 1. The deceleration maneuver is initiated at some constant approach velocity such as 60 knots and proceeds at approximately a 0.05g rate. The typical deceleration curve is shown in Figure 3. If the deceleration curve is intercepted at 60 knots, Figure 3 shows that the pilot requires about 3125 feet (950 meters) to stop the aircraft with the reasonable deceleration of 0.05g. The important point is that the same 3125 feet is needed to stop for either shallow or steep approach angles. Figure 4 shows that as the glideslope angle increases, so also must the Height Above Touchdown (HAT) at which the pilot must have visual contact with his landing point if he has no capability to decelerate on instruments. Otherwise, there will not be sufficient distance for the pilot to stop the aircraft with the comfortable deceleration of 0.05g. The implication for helicopter operations into confined sites is clear; deceleration on instruments is essential if we are to realize low decision heights, such as the 100 feet (30 meters) of Category II Operations, in confined sites. Figure 5 shows the four cue flight director used in our decelerated landing experiments. The four cues are lateral cyclic (roll), fore-aft cyclic (speed), collective (power) and pedal for aligning the aircraft with the localizer course below 45 knots.

Microwave landing is now a joint civil/military effort by virtue of the international program which led to ICAO's adopting, in April 1978, Time Reference Scanning Beams (TRSB) as the new world standard. Narrow microwave scanning beams eliminate the problems posed by standard ILS use for helicopters. Reflections are vastly reduced by using narrow scanning beams. With the addition of precision DME, the equivalence of CAT II and III landing performance is now available at the steeper glide angles desired by helicopter flight characteristics. Guidance performance tailored to the environment of the exact site and the flight properties of the helicopter can be assured in much less than an hour of set-up time. The range, portability, descent angles, cockpit instrumentation, and coverage have all been engineered to optimize tactical use by helicopters. Tests prove that microwave landing technology is far more useful to Army Aviation than ILS and a modular system design is possible that will allow civil/military commonality.

HELICOPTER TERMINAL AREA AIR TRAFFIC CONTROL

The steep, decelerated instrument approach has brought with it the realization that average helicopter speeds in the terminal area will be quite slow, and resultant helicopter spacings will have to be much smaller than those encountered in fixed wing practice if reasonable flow rates are to be realized. Current civil air traffic control procedures require a nominal 3 mile (5.5km) separation between successive aircraft performing conventional 3° approaches on the ILS system. These separation standards are based on approach speeds of say, 90 to 150 knots. They are not appropriate for helicopters whose terminal area and approach speeds are typically 60 to 80 knots prior to a deceleration to hover during the last half mile (900 meters) or so of the approach. Some of our work in this helicopter terminal area control problem (Reference 2) shows that helicopter spacings of the order of 2000 to 3000 feet (600 to 900 meters) represent a practical goal, resulting in landing rates of from 1 to almost 1½ aircraft per minute for the deceleration profile discussed above. Use of the standard Air Traffic Control Radar Beacon System (ATCRBS) transponder to control aircraft so closely spaced presents a significant problem. With this range of small separations, up to four or six helicopters placed on the same radial (i.e., localizer of the landing system) will have their 20.3 microsecond transponder replies overlapping each other in time at the ground interrogator site. We have found that we can "crossband" our microwave landing systems with the radar beacon system to eliminate this "code garbling" problem while still providing a compatible and fully interoperable terminal area capability.

Figure 6 shows the one "crossbanded" system we have built and test flown. It integrates a collocated version of TLS with the AN/TPX-42, a standard ground interrogator, processor, display set used by both the Federal Aviation Administration and the Department of Defense. The ground landing system equipment transmits pulse modulated, localizer and glideslope scanning beams and DME replies at Ku-band in its normal way. The ground landing system equipment synchronizes the ground portion of the secondary radar system (the AN/TPX-42) by sending it the localizer beam's instantaneous pointing angle pulse code modulation signals. These localizer angle pulse signals also serve as the ground equipment's time reference for measuring aircraft range. Aboard the aircraft, detected video pulses from the localizer scanning beam are used to trigger a standard, unmodified L-band transponder which then replies with its normal message to an omnidirectional receiving antenna at the ground station. The ground station derives aircraft azimuth by knowing the pointing angle of the localizer antenna, it derives aircraft range by measuring the two-way travel time of the Ku-band localizer pulse up-link and the L-band transponder reply down-link (thus the term "crossbanding"), and it derives aircraft identity and/or altitude from the coded transponder message. Thus, the "crossbanded" system develops a ground ATC display by extracting a dual function from the landing system, i.e., it provides landing guidance and also interrogates, through a suitable interface, the aircraft transponder. The integration of the landing system and the transponder offers several advantages over conventional ATCRBS operation especially attractive in the military use of helicopters (see Figure 7). The localizer antenna in this system rotates at 4 revolutions per second or 16 times faster than a typical secondary radar interrogator. We have incorporated means for causing scan countdown such that the first aircraft on localizer course will reply to scan number one, the second aircraft on localizer course will reply to scan number two and so on, until scan number 5, after which the cycle repeats itself. This technique avoids any code garbling problems of our six closely spaced helicopters mentioned earlier, and results in the localizer beam interrogating each aircraft in a 120° approach sector every fifth scan or once each 1.25 seconds. Of course, each aircraft in the approach sector still receives localizer landing guidance at the rate of 4 beam scans per second. In the back 240° of azimuth coverage, aircraft are interrogated by the localizer beam only once every five seconds. Thus we have solved the serious "synchronous garbling" problem that often plagues the use of the radar beacon system by incorporating this novel "crossbanding" technique into our Air Traffic Management system.

Additional studies have been completed (Reference 3) which show that "crossbanded" operation with a Time Reference Scanning Beam (TRSB) landing system can be achieved. In crossbanding with the unmodulated beams of a TRSB system, azimuth, elevation and distance information derived by the airborne landing system equipment would be sent to the ground site using the transponder as a data link.

With either pulse modulated scanning beams or TRSB, crossbanding represents evolutionary systems engineering to solve a new problem - that of very closely spaced helicopters - while maintaining interoperability with contemporary civil/military systems.

RADAR BEACON SYSTEM

The L-band radar beacon system, known variously as "Secondary Surveillance Radar" (SSR), "IFF" or ATCRBS, probably offers greater opportunities for evolutionary system engineering than any other. Radar beaconry is used commonly by civil/military aircraft. It is designed and used as a fully interoperable military tactical system and its radio signals and pulse message formats are sufficiently flexible to allow engineering of helicopter derivatives such as extremely lightweight interrogators and lightweight passive sites that provide the commander a scope display of the aircraft under his responsibility. This display, with air-ground communication, can provide command and control of the helicopter on its missions. Radar beaconry, with its extreme return signal power advantage over primary radar, enhances very low altitude operations, covering airspace typically used by tactical helicopters.

Military aircraft carry the standard beacon (or transponder) for IFF and radar tracking purposes, providing three dimensional data and discrete identity to the interrogating ground units of civil and military aviation. Each military force can track its own aircraft and the aircraft of other forces. Civil traffic control can track civil and military aircraft and military air traffic management can track civil and military aircraft. By retaining the standardized airborne equipments that can reply to dozens of radars simultaneously and the radio signal standards of extensive civil/military agreements, Over 4,000 discrete reply messages assigned to six different modes are utilized. The beacon system appears in thousands of aircraft and has evolved into a sophisticated pulse multiplex system. Hundreds of secondary radars in the NATO environment can interoperate with Army NATO helicopters. Army aviation can benefit greatly from minaturized versions of these secondary radars. Under a program named VLATME (Very Lightweight Air Traffic Management Equipment), we have developed small, low power units using a modular concept (Reference 4). The modules can then be assembled into various configurations to suit the operational requirement. What we call Configuration A, is shown in Figure 8. This unit was evolved using some of the technology from the Army Stinger IFF interrogator program. This A unit weighs 12 pounds, it can be hand held or tripod mounted, it covers an azimuth sector of 45° with an accuracy of about 5°, and its maximum range is about 10 Nmi (18km). It provides range and azimuth (relative to equipment boresight by monopulse techniques) for either of two aircraft whose identity codes are preselected by the operator. The antenna used for both the B and C configurations of VLATME is a 30 inch (76 cm) linear broadside array. It is shown mounted on an extremely lightweight mast in Figure 9 to the left of an 18 foot (5.5m) ATCRBS antenna. Sum and difference patterns provide an effective interrogation beamwidth of about 5°. Both B and C configurations provide 360° of azimuth coverage to a maximum range of 30 Nmi (55km) and are capable of displaying all 4096 aircraft identity codes and mode C altitude. They differ principally in the number of targets processed and displayed. For example, the B configuration can display 10 aircraft on either a hand held LED (Light Emitting Diode) electronic flight strip device (Figure 10) or on a 5 inch cathode ray tube in PPI (Plan Position Indicator) format (Figure 11). It was envisioned that a system with the performance and capacity of the B unit would be quite useful at austere sites in conjunction with man-portable ATC communications equipments being procured by the Army. The C configuration uses a plasma display, shown in Figure 12 with a local aviation chart mounted on the back side of the transparent panel. The C configuration offers full alpha-numerics for up to 50 targets and is appropriate for use with Army ATC systems and shelters such as the AN/TSC-61 Flight Control Central. In their present forms, the B and C configurations weigh almost 100 pounds (45kg) and 200 pounds (91kg) respectively, and projections are that these weights could be cut in half in the next development phase.

Army users have conducted evaluations of the several configurations of VLATME in both the US and Europe with favorable results. Additional testing in Europe is being conducted at this time. Results show what we really expected to find - that radar beacon does provide for guidance and control of helicopters on a fully interoperable basis with the systems and aircraft of other military services and NATO without modifying any aircraft in any way.

In connection with the VLATME program we are developing a lightweight, electronically scanned antenna/interrogator (Reference 5). The E-SCAN antenna (Figure 13) is a circular phased array utilizing synthetic beam sharpening and monopulse processing. It is easier to conceal physically than a mechanically rotating antenna, and its versatility in being able to provide 360° scan, sector scan or combinations thereof at a low, variable Pulse Repetition Frequency decreases its susceptibility to electronic countermeasures. Its unusually large vertical aperture (for the ATM application) was chosen with the thought of providing better coverage for low flying helicopters. Using a few rapidly emplaced VLATME units, it is possible to envision aircraft being radar vectored along a specific route structure composed of way points connected by straight line segments. We would postulate a typical VLATME unit spacing on the order of 5 to 10 Nmi (9 to 18 km). They are low power units, purposely not capable of the 200 mile interrogation ranges of the FAA secondary radars used with high altitude jet transports. With helicopters, we do not expect to have line of sight for great distances. The operational benefits of VLATME seem quite clear. Technically, the equipment performs well because, while it incorporates advanced RF and digital electronics technology, it is based on a thoroughly debugged and refined system. Economic justification comes from the observation that for a very small expenditure, the user receives the benefits of the billions of dollars already invested in radar beaconry.

PASSIVE RADAR BEACON

We have followed closely work in the collision avoidance field over the past several years. We noted that a passive BCAS (Beacon Collision Avoidance System) equipped aircraft utilized the interrogations to (by two or more SSR's) and the responses from surrounding aircraft to determine the range, bearing, identity and altitude of these other aircraft in its immediate vicinity (Reference 7). The technique appeared attractive for developing a ground display of ATC information, given that line of sight for the necessary signals existed. Such a system would aid significantly in concealing the ground control point.

Further, it was totally compatible with the ATCRBS signal format, so that whatever Collision Avoidance System might ultimately be selected for standardization (recently summarized in Reference 8), there was little to prevent implementation of the technique for "listening-in" to the existing radar beacon signals. Study showed that only one SSR interrogator is required to derive the other aircraft information if the distance and bearing from the SSR to the receiving site are known. This is shown in Figures 14 and 15. Figure 14 illustrates the time difference between the direct path of the SSR interrogator signal from the secondary radar to the passive radar site (C), and the indirect path from the secondary radar to aircraft to passive radar (A + B). The earlier arrival of the interrogation signal (C) starts a receiver that detects and times the delay of the transponder signal (B). With (C) as zero, the arrival time of signal (B) is known as the "time of arrival" or "TOA." Each TOA for each of many aircraft can be measured to a few hundredths of a microsecond, and each TOA is an ellipse. Shown in Figure 15 is the time (T_2) between successive passages or 360 degrees of rotation of the scanning secondary radar beam. T_1 is the time it takes for the beam to scan the angle from the aircraft transponder's azimuth to the azimuth of the passive radar site. Time thus represents a given angle of scan in degrees so that the ratio of T_1/T_2 represents the differential azimuth between the transponder and the passive radar. All azimuthal data is relative to the line between the active and passive site and is encoded as right or left.* The computer calculates 360 x T_1/T_2 to obtain a quantitative measurement to tenths of a degree of the transponder's angular position, DAZ. All transponder replies received at the passive site are measured with the two horizontal position coordinates of Figure 16. TOA and DAZ (Time of Arrival and Differential Azimuth) produce the intersecting passive coordinates. The computer, with a fixed input of the positions of the SSR and passive site, then performs a coordinate conversion to produce a PPI display of range and bearing to each of the aircraft relative to the passive site. Decoded aircraft messages provide the altitude or third positional dimension of each aircraft. The mathematics of the computer corrects for any elliptical distortions, producing a true rho-theta plan position display. Each aircraft can be discretely identified by separate SSR codes selected from the source of 4,096 codes. Consequently, each aircraft can be uniquely identified, tracked, and guided in three demensions to perform its assigned tactical mission. An active SSR interrogator can provide services to several passive radar sites so that several low-cost guidance and control sites (say, at each helicopter landing site) can be provided without enemy detection of the site. Figure 17 shows four control sites are established with but one active SSR interrogator.

Figure 18 illustrates another example of the flexibility of passive radar using the same single-site equipments as shown before, but now in a configuration utilizing replies to two interrogators. These interrogators can be small units with only an antenna and a transmitter. They may even be small, expendable units. The computer, display, and other command and control elements would be placed at the passive radar location. This configuration improves accuracy because aircraft position can be determined solely by intersections of the TOA ellipses; the DAZ measurement is not needed. Each of the ellipses can produce line of position data to about 0.05-microsecond accuracy, or the equivalent of about 20 meters. When needed, two crossing TOA measurements improve the tracking and control data. Dual TOA is superior to angular configurations such as in active interrogator radar or a single-site passive radar. Thus we see that radar beaconry offers us the active, independent, small secondary radar, the single (or multiple) passive radar site and, where presicion guidance and control is required, the multiple active with one (or more) passive site configuration - all fully compatible with the existing system. A significant advantage in combining active and passive units is the reduced load on the single, two-way radio channel of ATCRBS - a countermeasures feature. Also, the passive site has no radar radiations and its location is secret. The enemy may hear intermittent voice communications but he does not know such communication is based on all-weather, three-dimensional guidance data from the passive units.

Figure 19 presents a sampling of preliminary performance data for passive radar. Note that the maximum secondary radar to passive radar distance was 26 Nmi (48km), which was the FAA long range interrogator near JFK airport in New York. The second column of Figure 19 gives the distance of the test aircraft from the passive radar site. The notation "Rear of Passive Site" means that, with respect to the passive site, the aircraft was in the hemisphere toward the secondary radar interrogator. It is in this rearward area where, for the one active site and one passive site configuration, the intersection of DAZ with the TOA ellipse occurs at a shallow angle, giving rise to somewhat greater errors. The data is quite satisfying except perhaps for last angle error of + 3.7°. Indications are that this error is likely due to a software (not system) problem.

CONCLUSION

A great deal of R&D has been accomplished which places the helicopter at the threshold of becoming all-weather capable and of being more fully integrated into the airspace and systems of the other services and NATO. For perhaps 200 pounds (about 90kg) of ground equipment and an associated airborne landing equipment, the equivalent of Category III terminal area operations could be a reality. The technology is here to support it in ways that could be compatible and interoperable with contemporary civil/military systems.

The L-band beacon-derived VLATME equipments and the passive radar experiments have demonstrated the feasibility of both the passive and active modes. A commander can be provided a display of his aircraft using small, portable units based on either or both modes. Standardized modular units could be deployed in the high accuracy configuration for precision guidance and control of missions well forward. Similarly, configurations with moderate accuracies would be used in the phase of flight between rear and forward areas for the outbound and return flight. At one end of the flight the active/passive beacon equipments guide the helicopter pilot by command and control into the small "window" for his tactical mission and, at the other end of the flight, the beacon equipments guide the pilot into the "window" of his landing area. Accuracies of the several active/passive configurations can vary by a factor of 10 to 20 times, including the effects of siting geometry, and are used adaptively to satisfy mission needs. Thus, the Air Traffic Management (ATM) function and the tactical command and control functions for Army Aviation would be supported by one basic system concept. No longer is Air Traffic Management a liability as some have considered it, but it becomes a part of a tactical command and control concept. ATM and command and control are integrated to meet many of the total needs of the tactical mission. Tactically, command and control and ATM/Landing must be interoperable in any case. Integrated design minimizes on-board equipments and provides common ground units for guidance of such functions as forward tactical missions and rear resupply. Fortunately, modern digital technology, microcomputing, and electronic display techniques provide the commander of the operation displays which are suited for weapon delivery as well as traffic management. Coordinate conversion using microprocessors and digital keyboards afford way-points and destination points to be shown in the commander's display so that he can readily command and control his aircraft.

Today's electronic advances have created derivatives of proven helicopter guidance and control techniques for major advances equalling or surpassing some of the promises of futuristic systems. Entirely new systems must first go through the grueling testing, modifications, and engineering that every system must endure successfully before it can be fielded. Only then can new systems be compared to modern, evolutionary versions of existing systems. One should not confuse the application of advanced electronic techniques with basic system concepts. Advanced techniques applied to existing systems greatly enhance their tactical use, portability, and interoperability. Such a design avoids the high costs and long delays of unproven, futuristic systems to meet the same needs.

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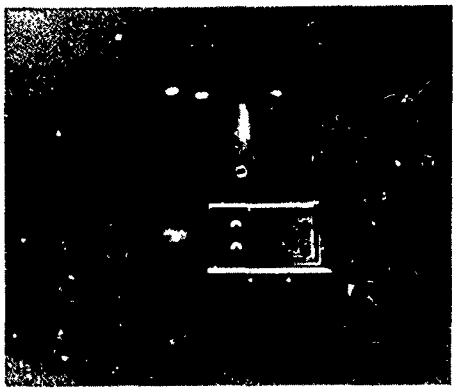


LOCALIZER,TRANSMITTER GROUP
OT-64(XE-1)/TRQ-33

GLIDESLOPE TRANSMITTER GROUP
OT-65(XE-1)/TRQ-33

AIRBORNE INSTRUMENT LANDING SET
AN/ARQ-31(XE-1)

FIGURE 1:
TACTICAL LANDING SYSTEM (TLS)

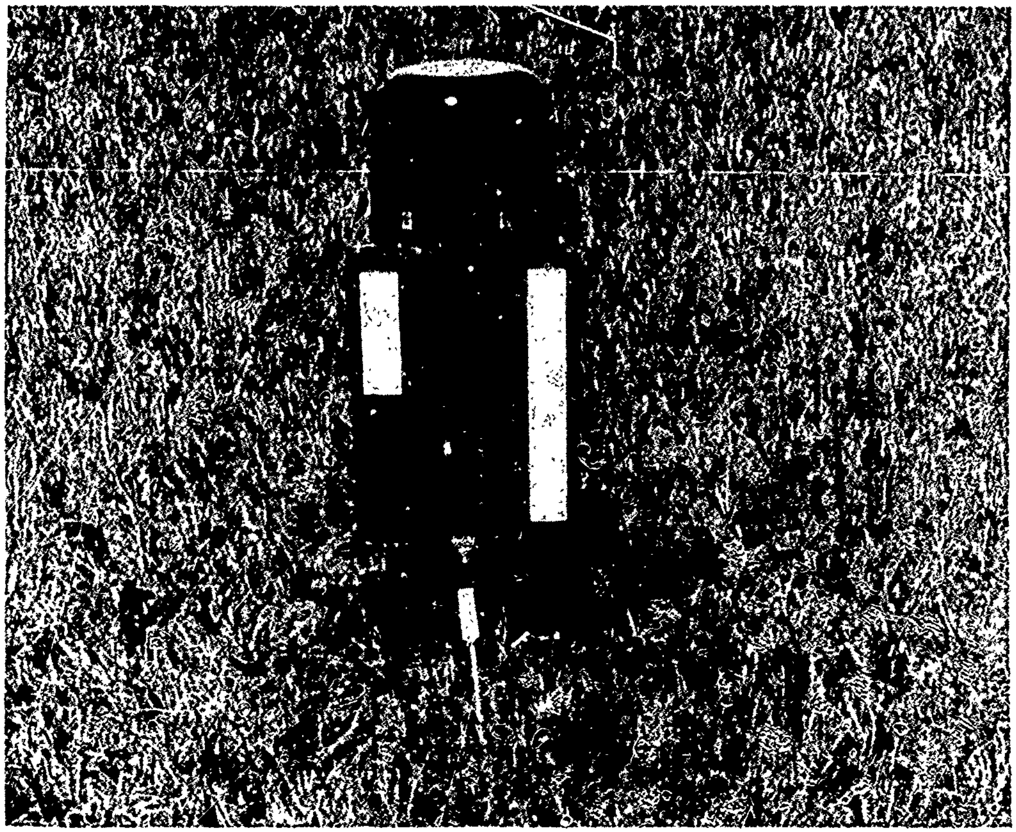
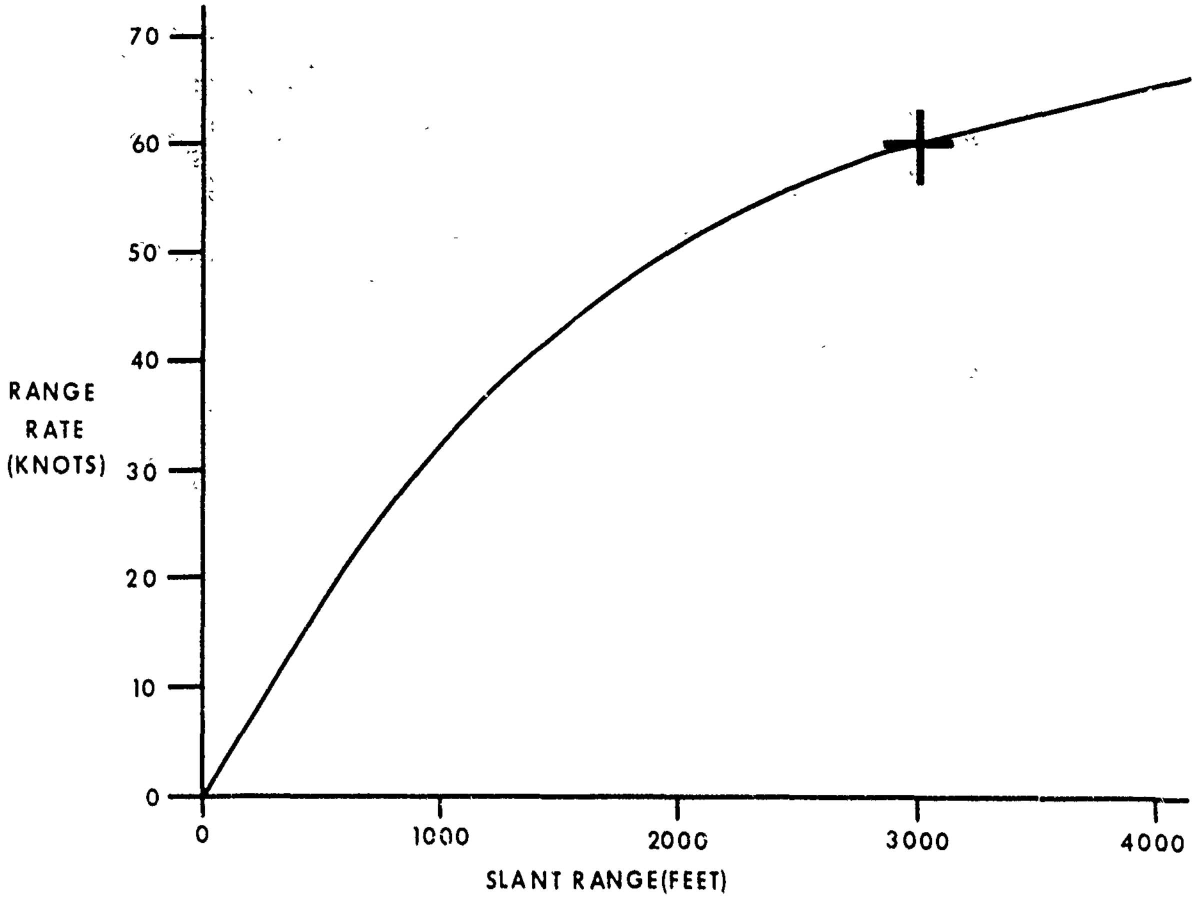
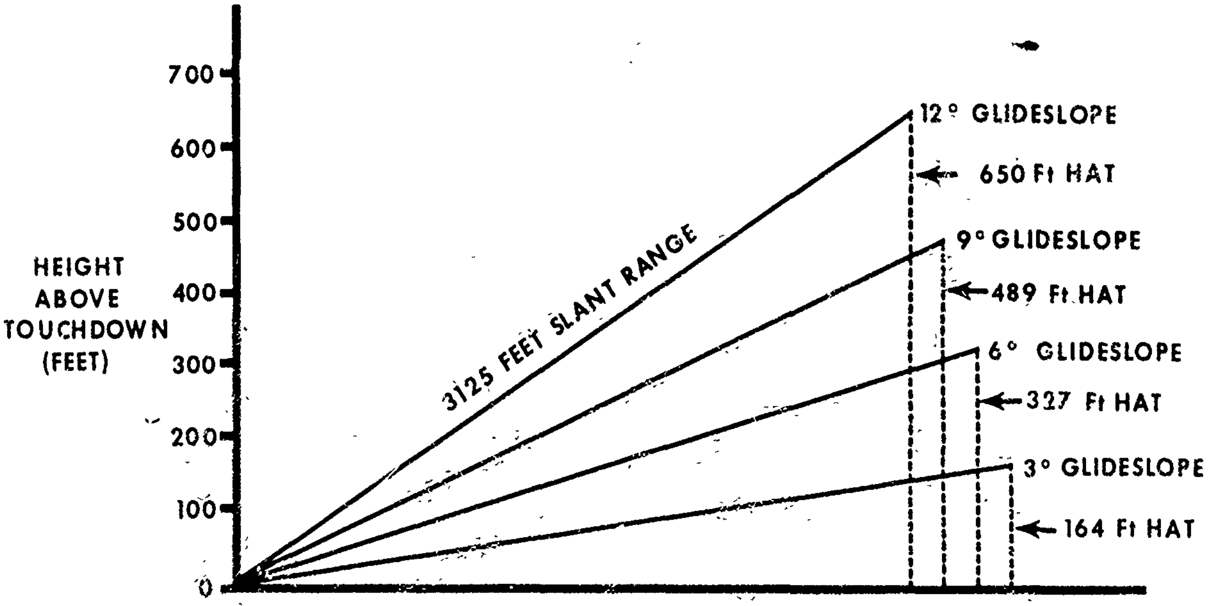


FIGURE 2: TLS DERIVATIVE "MINIBOX"



HELICOPTER DECELERATION CURVE

FIGURE 3



HEIGHT ABOVE TOUCHDOWN WHEN 3125 FEET OF SLANT RANGE IS AVAILABLE FOR DECELERATION

FIGURE 4

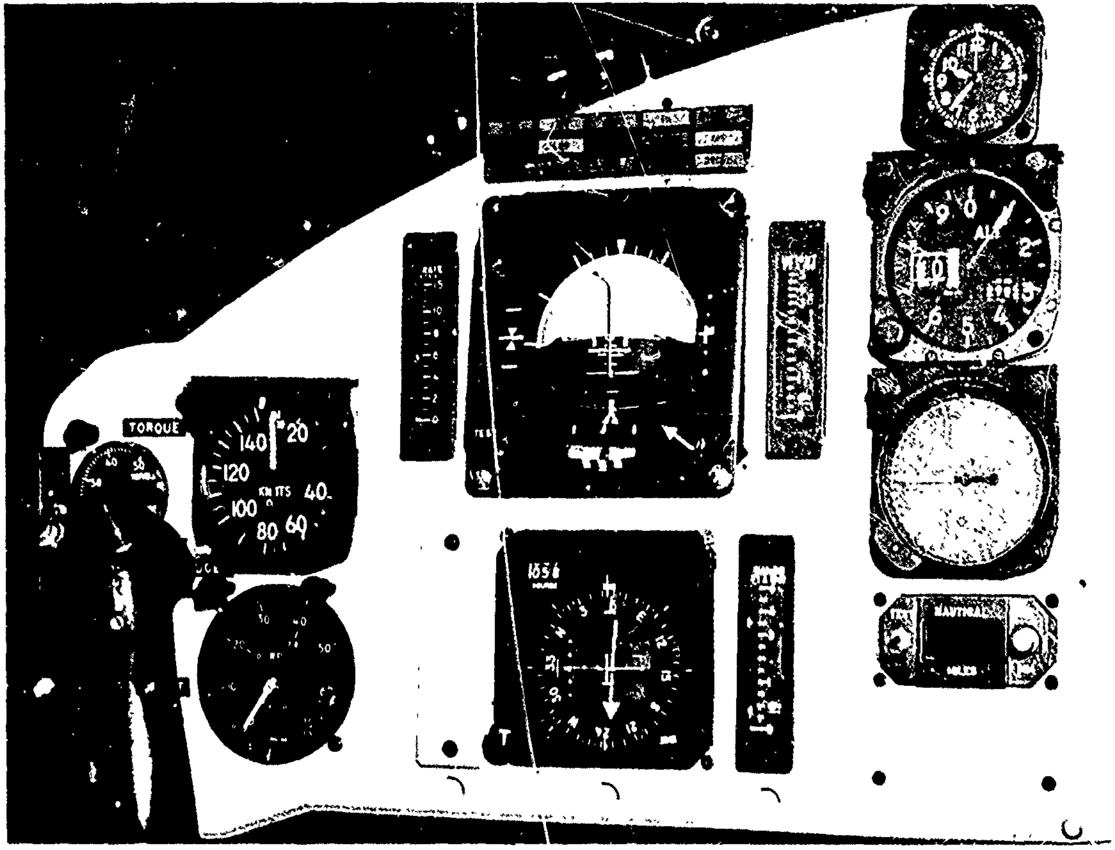


FIGURE 5: FOUR CUE FLIGHT DIRECTOR

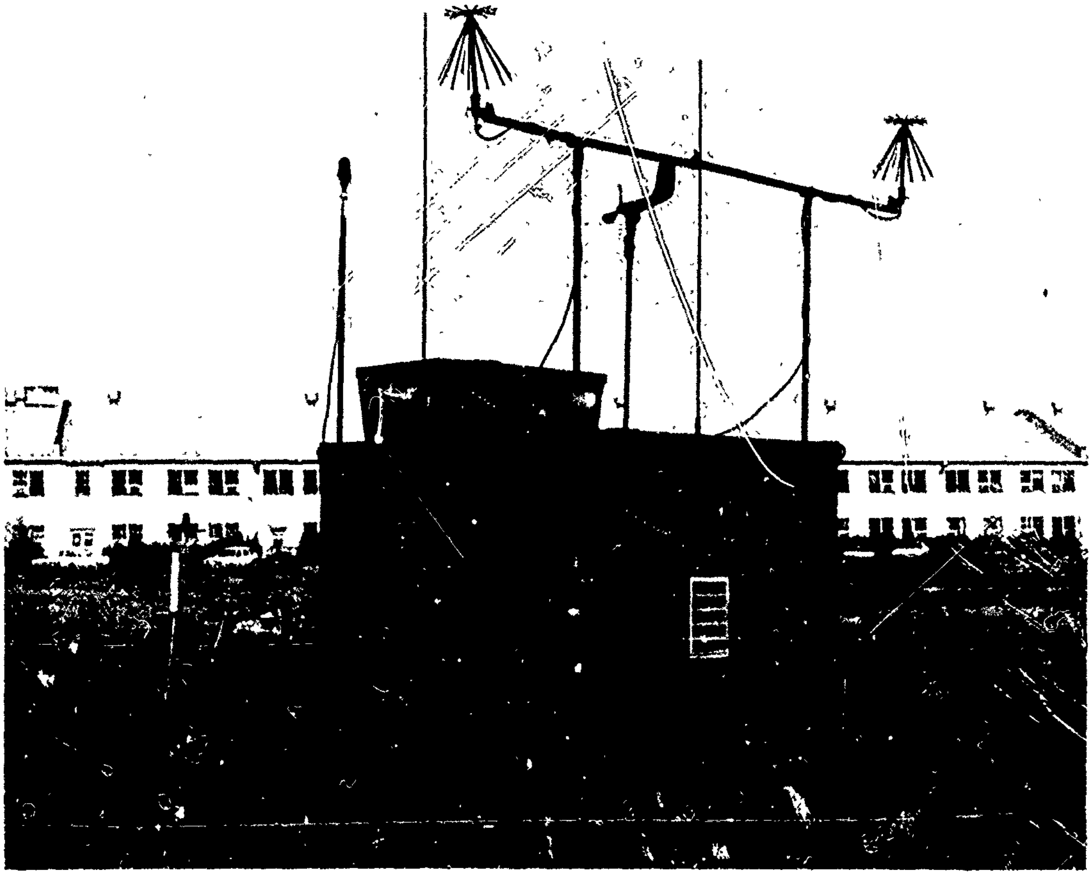


FIGURE 6: CROSSBANDED SYSTEM

UNIQUE FEATURES OF "CROSS-BANDED" SYSTEM

GARBLE FREE PRESENTATION OF CLOSELY SPACED AIRCRAFT

INCREASED INFORMATION RATE OF AIRCRAFT POSITION DATA

L-BAND INTERROGATING ANTENNA NOT REQUIRED

HIGH ANGULAR ACCURACY--DUE TO NARROW "INTERROGATING" BEAM OF THE LANDING SYSTEM

COMMON POLAR COORDINATES FOR PILOT AND CONTROLLER DISPLAYS

FIGURE 7

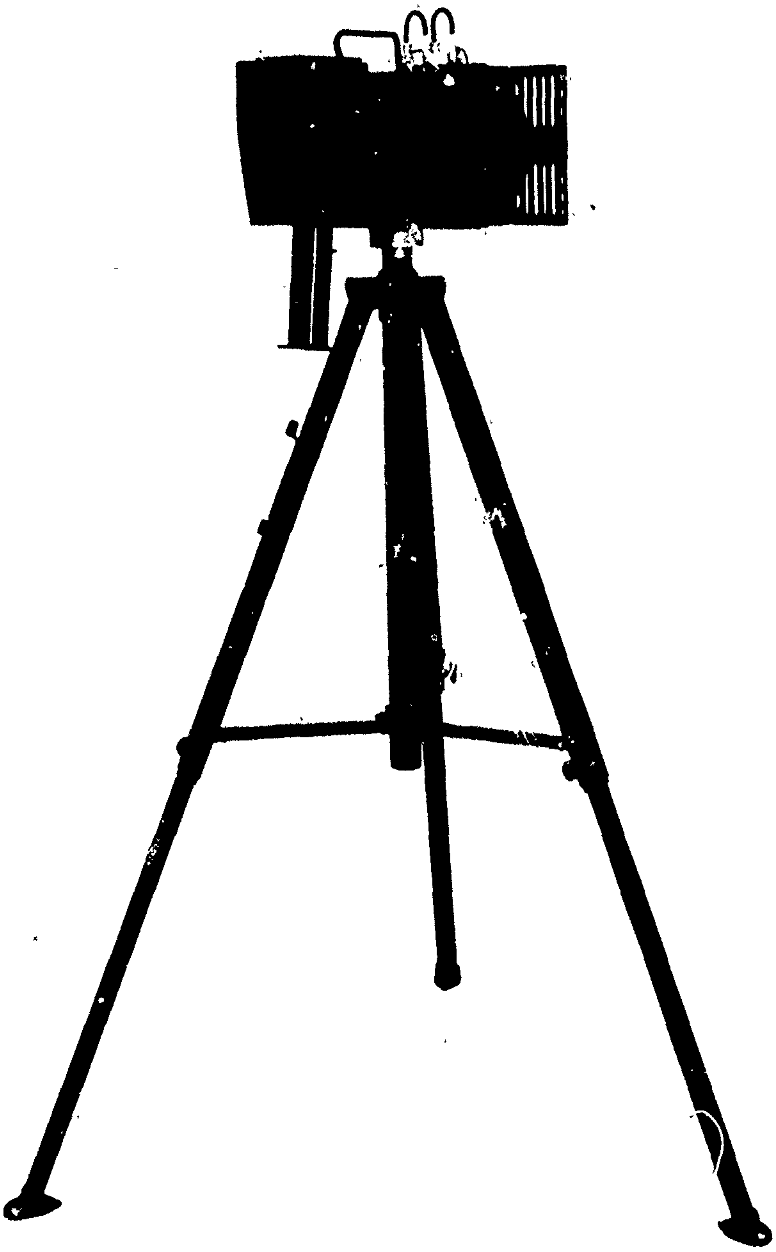


FIGURE 8: CONFIGURATION A OF VLATME (VERYLIGHT AIR TRAFFIC MANAGEMENT EQUIPMENT)

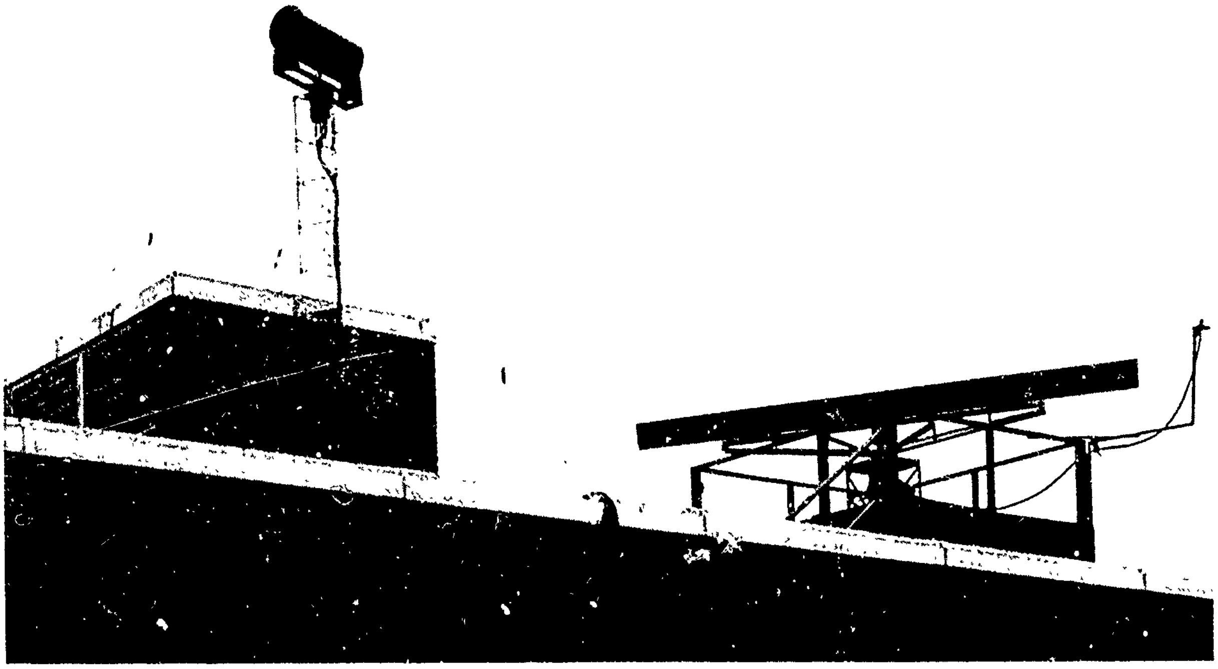


FIGURE 9: VLATME B AND C CONFIGURATION ANTENNA ADJACENT TO AN 18-FOOT (5.5M) ATCRBS ANTENNA

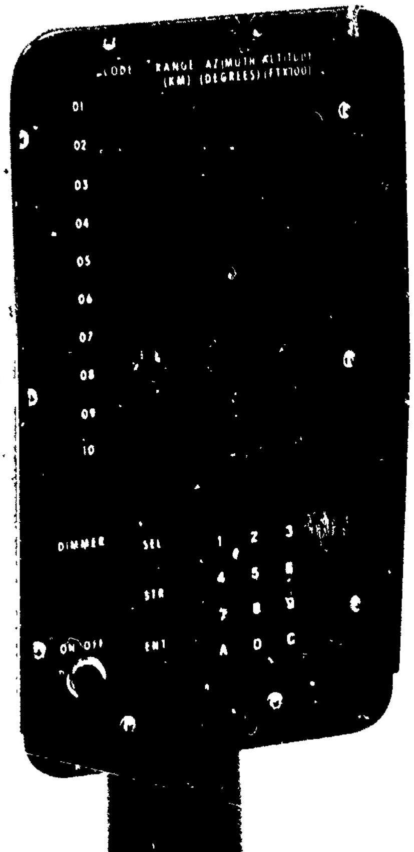


FIGURE 10: VLATME B CONFIGURATION "FLIGHT STRIP" DISPLAY

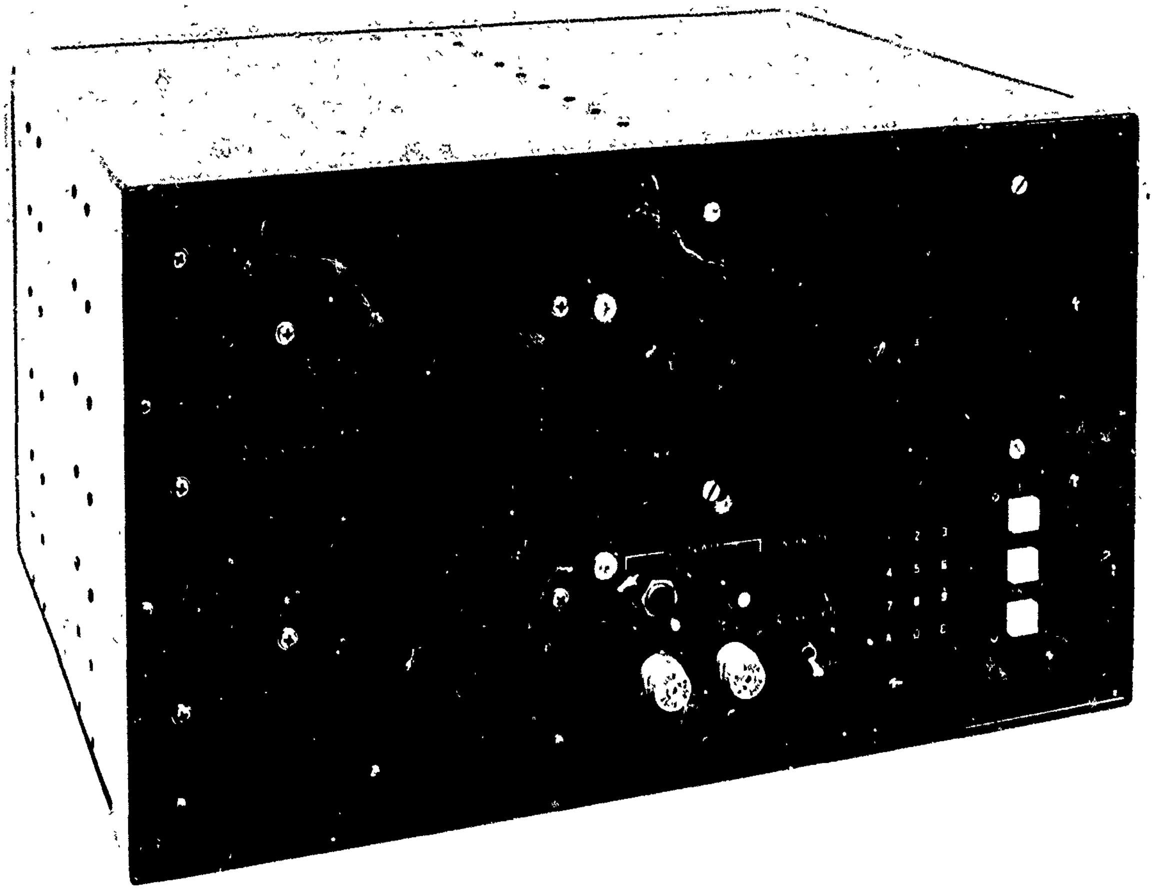


FIGURE 11: VLATME B CONFIGURATION 5-INCH (13 cm) PPI DISPLAY

FIGURE 12: VLATME C CONFIGURATION PLASMA DISPLAY

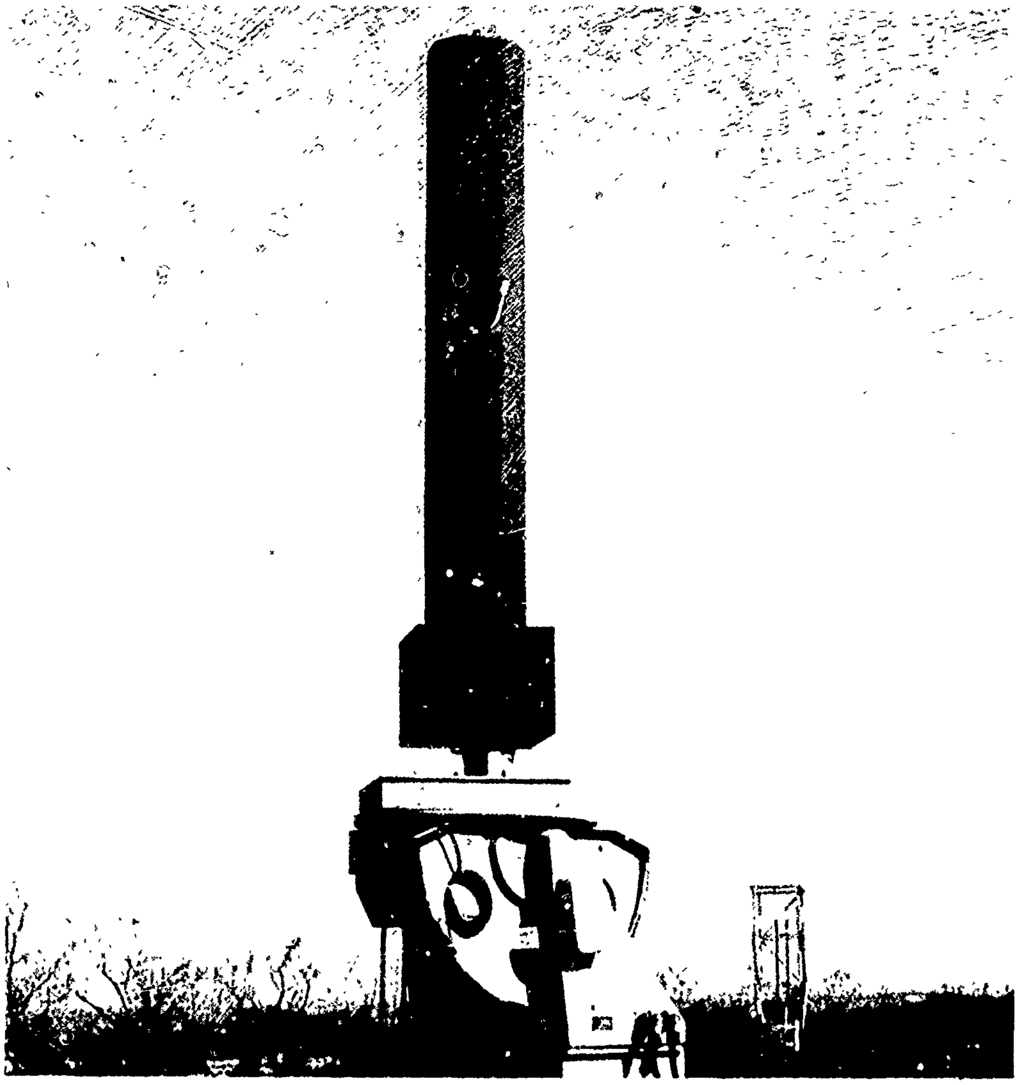


FIGURE 13: E-SCAN ANTENNA

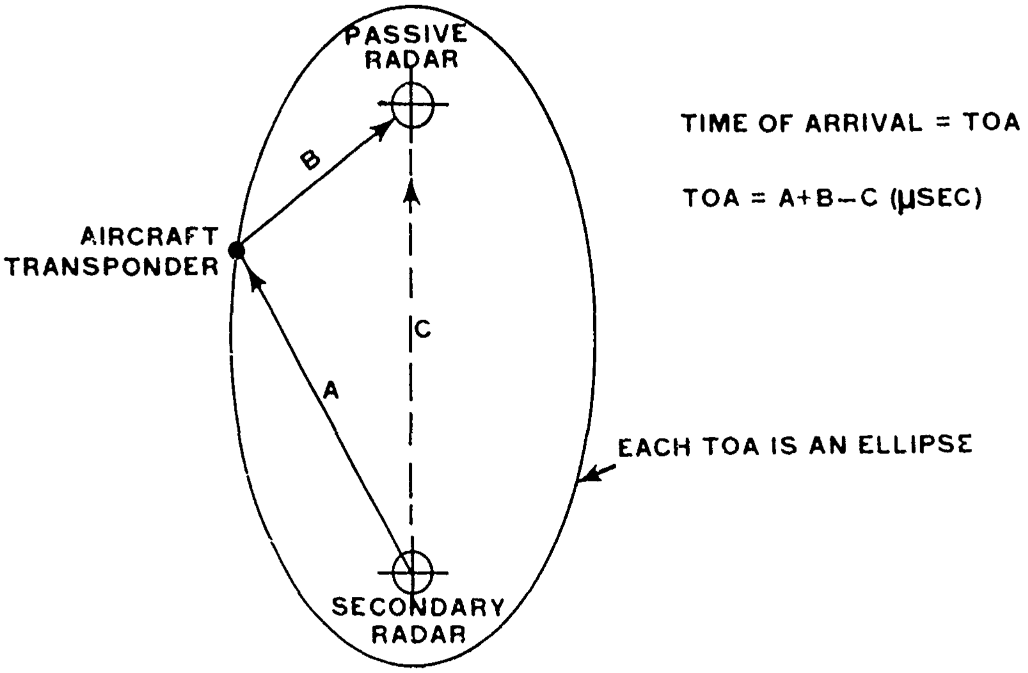


FIGURE 14: TIME OF ARRIVAL (TOA) MEASUREMENT

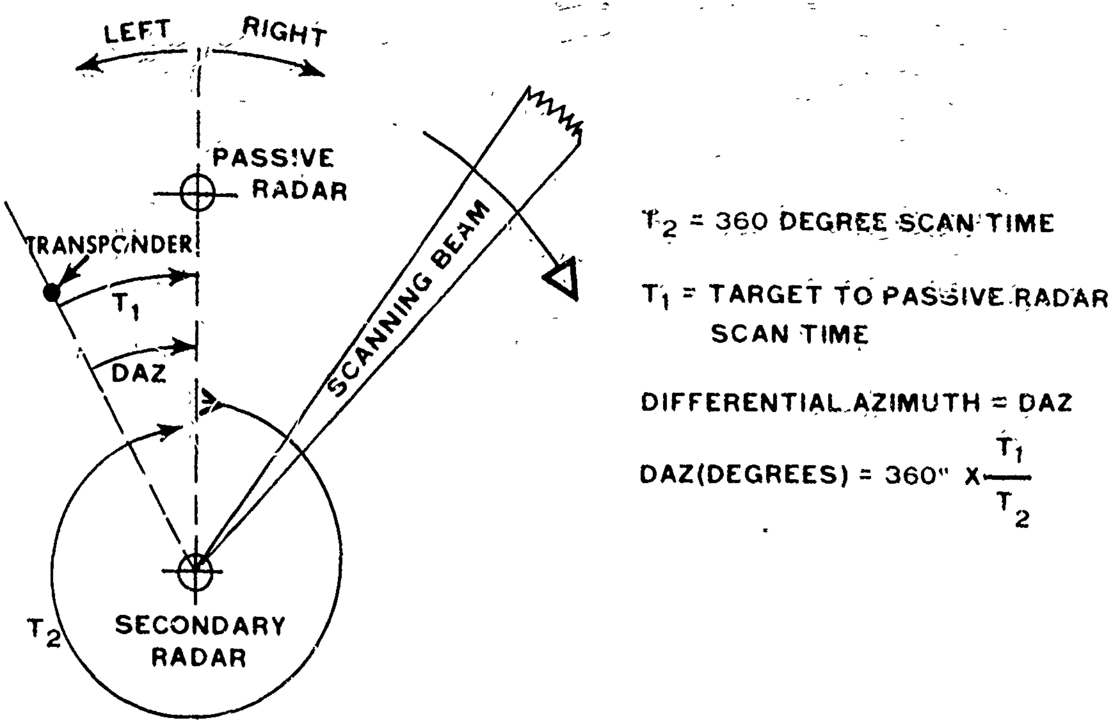
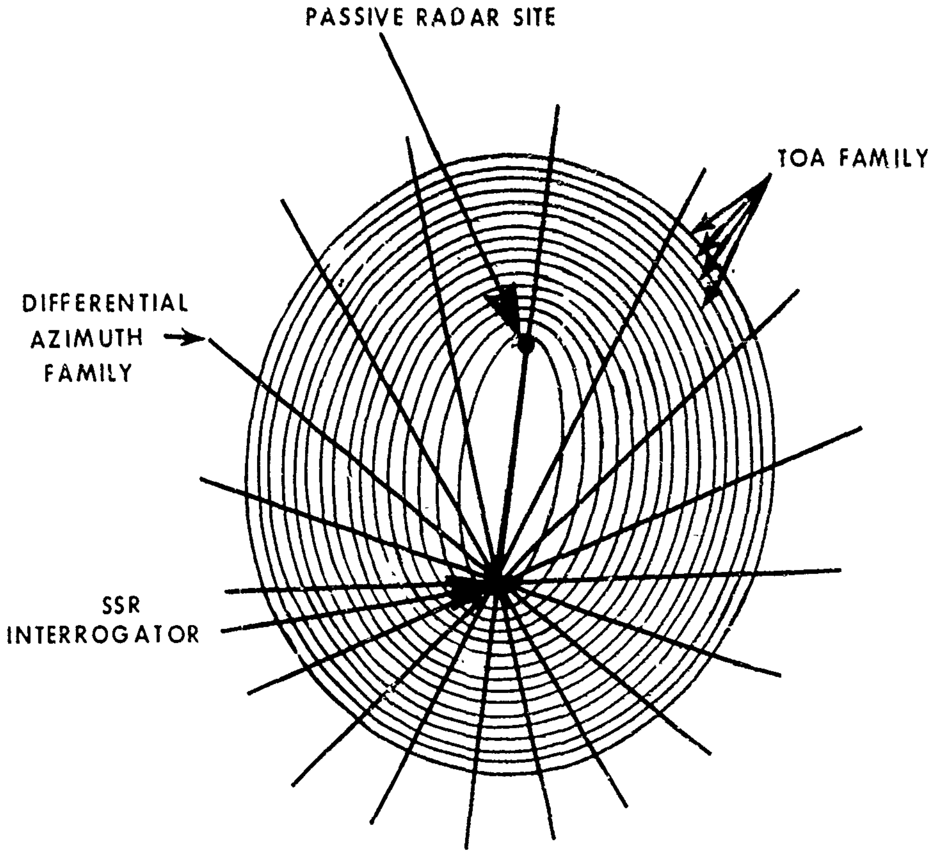
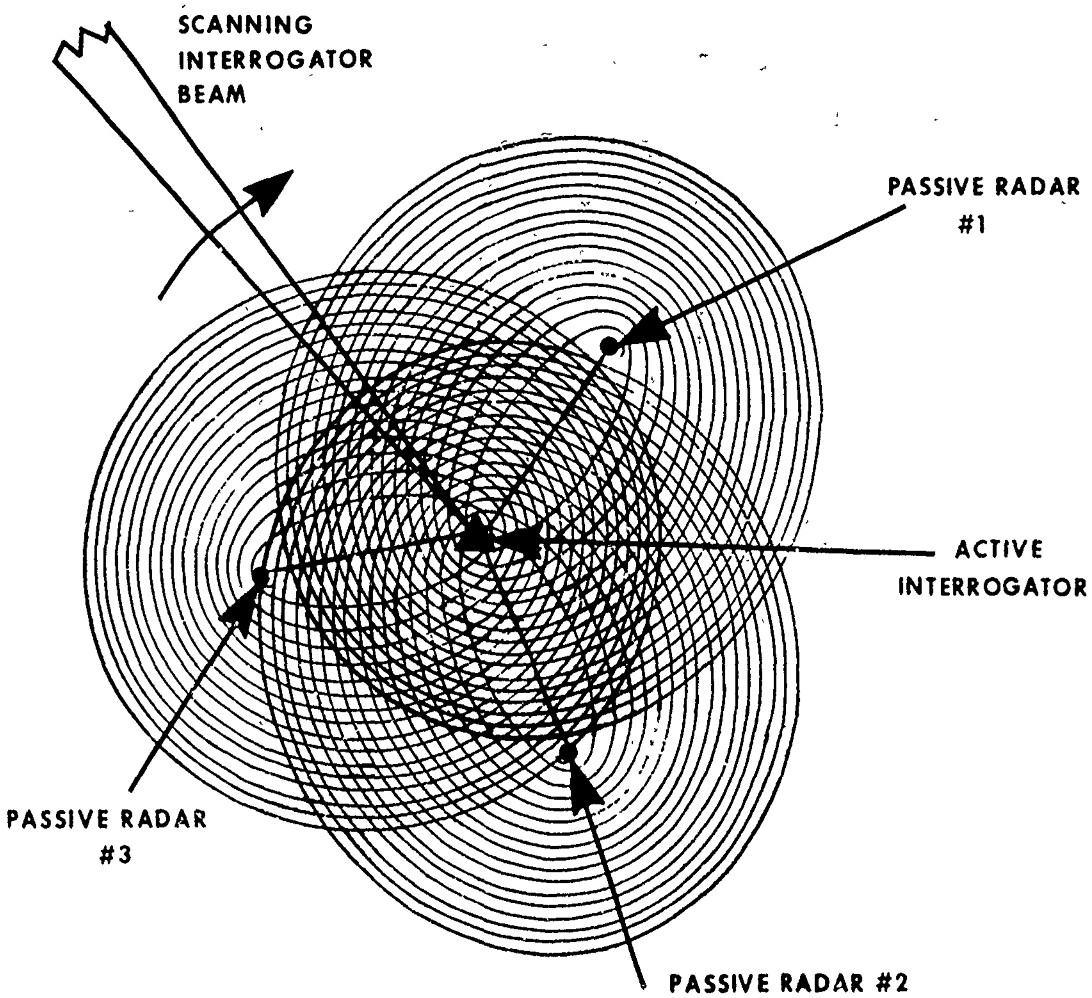


FIGURE 15: DIFFERENTIAL AZIMUTH (DAZ) MEASUREMENT



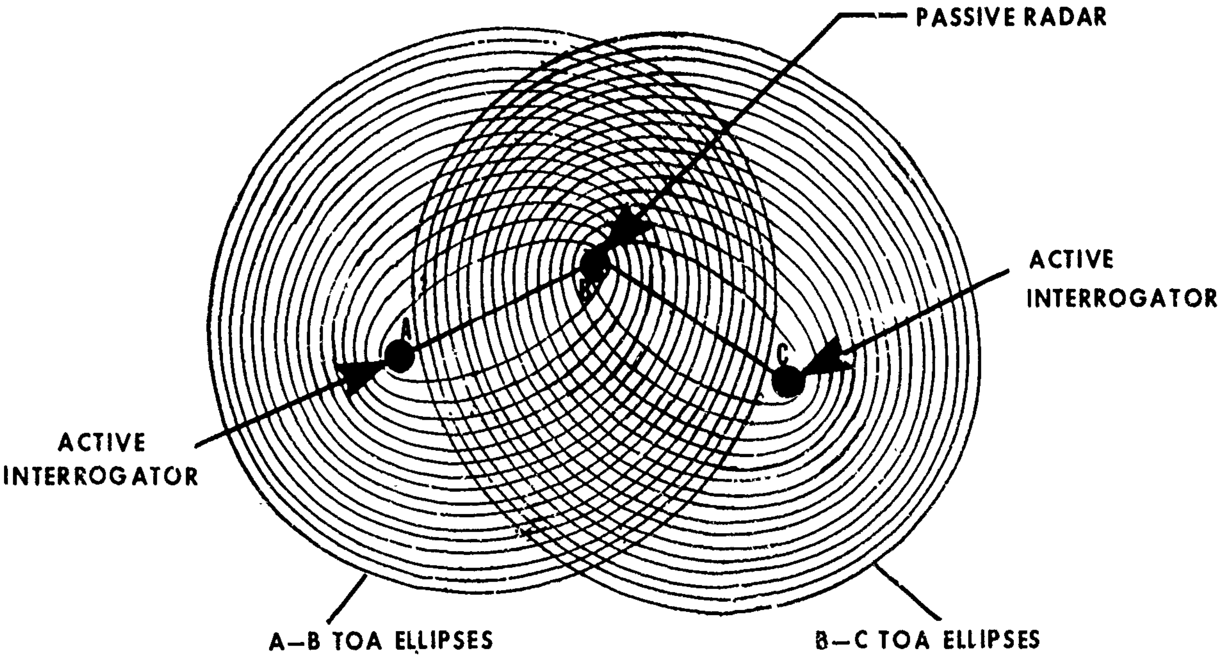
COMBINED COORDINATES OF TOA AND DIFFERENTIAL AZIMUTH

FIGURE 16



THREE PASSIVE RADAR SITES SERVED BY ONE ACTIVE INTERROGATOR

FIGURE 17



GUIDANCE AND CONTROL FROM PASSIVE SITE USING
MULTIPLE TOA MEASUREMENTS.
(HIGH ACCURACY CONFIGURATION)

FIGURE 18

INTERROGATOR TO PASSIVE RADAR DISTANCE	PASSIVE RADAR TO AIRCRAFT DISTANCE	PASSIVE RADAR RANGE ACCURACY (RMS)	PASSIVE RADAR BEARING ANGLE ACCURACY (RMS)
5Nmi(9 km)	5 Nmi(9 km) FORWARD OF PASSIVE SITE	± 0.02 Nmi (± 0.036 km)	± 0.38°
5 Nmi(9 km)	4 Nmi(7 km) REAR OF PASSIVE SITE	± 0.06 Nmi (± 0.1 km)	± 1.2°
26 Nmi(48 km)	4.5 Nmi(8.2 km) FORWARD OF PASSIVE SITE	± 0.06 Nmi (± 0.1 km)	± 1.67°
26 Nmi(48 km)	3 Nmi (5.5 km) FORWARD OF PASSIVE SITE	± 0.04 Nmi (± 0.07 km)	± 3.7°

PRELIMINARY PASSIVE RADAR PERFORMANCE DATA

FIGURE 19

A STUDY FOR DEVELOPMENT OF METHODS FOR AIR TRAFFIC MANAGEMENT

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SUMMARY

This paper deals with the study which has been carried out in order to identify and specify models and methods for optimal air traffic management. This study is a part of the multi-year project "Navigation aids and air traffic control", which has been funded by the Italian National Research Council (CNR) and is managed by Fondazione "Ugo Bordoni". The paper is composed of three sections. In the first one a review is made of the scope of the study on the context of CNR project. The second section deals with the software structure, its main characteristics and possible utilizations in the planning and management of air traffic system. Finally in the third section a description is given of more relevant used models and algorithms.

1. INTRODUCTION

Since July 1977, the Italian National Research Council (CNR) has been sponsoring the research project "Navigation Aids and Air Traffic Control". This project is managed by Fondazione "Ugo Bordoni" and consists of technical and scientific activities on a nationwide basis; it is scheduled to take place over a period of five years, with the purpose of giving the Italian decision-making and operating bodies in civil air transport sector the following aids:

- suggestions for medium-term interventions aimed at increasing safety and efficiency;
- methodological instruments for long-term planning and development of the Italian ATC system [1].

As a result of a feasibility study begun in 1974, research activities have been divided into four sub-projects, for which clear-cut objectives were identified. The four sub-projects have been defined as follows:

1. ATC simulation models and system management optimization
2. Secondary radar evolution and studies on discrete address systems
3. Improvements of primary radars
4. Increased safety in landing and take-off.

CNR ATC project interactions with ATC system planner's activities are depicted in fig. 1.

In the air transport process the air traffic evolution (output) is a result of the filtering of the air traffic demand (input) through the ATC system, which is made up of many different components.

A "theoretic" ATC planner has to forecast traffic demand and ATC system future status. Referring to this future situation, he has to evaluate the performance and safety of traffic evolution as well as the performance of the ATC system. When the performance is not satisfying, he has to identify the "best" improvement to the ATC system, using results of ATC research activities, in order to start (well in advance) the long term programming and procurement phase.

In this complex process the activities being carried out by this research team, which operates in the context of the first sub-project, have the purpose of identifying and developing methods and tools making the evaluations of an ATC planner easier and more quantitative.

After an initial study for identifying and specifying models and methods, a software developing phase is now in progress; first utilizations are foreseen in late 1979. The initial study has been developed according to the following phases:

- extensive review of current models and methodologies
- analysis of air traffic system operations and control procedures
- gathering and analysis of air traffic system data
- identification and specification of software tools for analysis and simulation of air traffic system.

2. SOFTWARE GENERAL STRUCTURE AND UTILIZATIONS

2.1 Software structure

The software is structured in four different areas, managed by a supervisor program:

- ATC data files management
- Air traffic data statistical analysis
- Air space structure analysis
- Traffic generation and ATC activities simulation.

The data files are ATC-oriented with respect to used language and classification, in order to make easy their updating and maintaining. Fig. 2 schematically depicts the data-base structure and its interaction with the computation and simulation software. The ATC-oriented input files are transformed by system and flights generators into two main files, oriented to the computation and simulation software. Due to the quantity, diversification and different utilizations of data, their management is quite complex.

The software for statistical analysis of air traffic data allows for the computation of:

- Space, time and type statistics of traffic demand
- Statistics of traffic demand deviations before flight actuality
- Statistics of deviations between traffic demand and actual flights at the moment of their input into the airspace.

Hence the software allows for a complete description of air traffic demand and its "noise".

Using ATC and traffic data the software for airspace structure analysis can compute many attributes of a given airspace structure:

- Geometrical attributes, as number and density of route intersections, route extra-mileage with respect to orthodromic length, route coverage by radioelectrical ATC facilities and interference of holding fixes
- Load attributes, as flows at intersections and along the air routes, global flown mileage, average number and density of expected flight conflicts, and expected workload in control sectors.

This software allows also for the computation of:

- The first N minimal paths between given input/output points in a complex airspace structure
- The preferential routings (given different alternatives) which minimize the air traffic extra-cost and do not violate traffic load in given airspace sectors.

The last software area, traffic generation and ATC activities simulation, allows for:

- Generation of traffic samples coherent with extrapolated traffic statistics
- Computation of theoretical flight profiles and routings
- Simulation of effective traffic evolution in the real ATC system.

The software for airspace structure analysis has been conceived mainly as an aid to select and evaluate different airspace structures; it is a tool to be used by ATC planners for identification of a limited number of optimal alternatives. Utilization in short term air traffic system management is also possible (par. 2.2).

Aim of the simulation software is:

- The generation of future traffic environment
- The evaluation of effective performance, stated in term of fuel extra cost and delays, of air traffic samples in a given ATC system.

It may be used by ATC planners for the refined evaluation of a limited number of optimal airspace structure alternatives, as well as for the evaluation of a new ATC system "status", different from the previous one in control procedures and/or operational characteristics of ATC facilities (par. 2.3).

2.2 Utilization of software for airspace structure analysis

As a matter of fact this software allows different utilizations. The various software modules used in this software area had been initially conceived for the simulation software; in order to maximize the software utilization effeciency and decrease the high risk associated to the single simulation use(as demonstrated by other researchers' studies) a multi-use structure has been researched and identified.

The main utilizations of the computing software are:

- evaluation of sectors traffic load and workload (par. 2.2.1)
- evaluation of different airspace structures (par. 2.2.2)
- identification of preferential routings in a given multi-connected structure (par. 2.2.3)

These utilizations serve the main purpose of the study, giving quantitative tools to ATC planners; however, this software can be extended to on-line use for air traffic management procedures (par. 2.2.4).

2.2.1 Evaluation of sector traffic load and workload

The following quantities are computed for every ATC sector:

- traffic flows distribution at the boundary and inside the ATC sector
- "instantaneous" number of aircraft inside the sector

- average transit time for every flow
- distribution within the sector of the expected number of flight conflicts (par. 3.1)
- expected sector workload (par. 3.2).

These computations are based on input data describing the airspace structure, the ATC sectorization and the traffic flows at the entering points into the airspace. Flows are generally dependent on time and distinguished according to their kinematic characteristics. The computed quantities may be used in an ATC sectorization design for rough evaluation of different alternatives and selection of the "best" one.

2.2.2 Evaluation of different airspace structures

The present airspace structure may be quite complex .see air routes of the Italian airspace, without SIDs and STARs in fig. 3.This structure is a result of a historical growth. The trade-offs between different users' requirements and various airspace constraints were carried-out at different moments and cannot guarantee that the present status is the optimal one for this structure.

Therefore a methodology has been researched in order to find and evaluate different airspace structures and identify the best one. Indeed this identification can completely be carried out only in the context of a global evaluation of ATC system. This is possible by using the simulation software, though in a limited set of airspace structure alternatives.

To find this limited set of alternatives including an optimal (or at least a sub-optimal) solution, a method has been defined, starting from a previous work [2]. This method requires the "manual" intervention of skilled ATC-structure designers in the alternatives generation phase, while the software for airspace structure analysis aids the description and evaluation phases.

The method works according to the following steps:

1) Evaluation of airspace structure for main traffic flows, in case of orthodromic point-to-point connections
2) Connections modification, according to minimum extra-mileage, in order to consider:
   - splitting of overloaded connections
   - connections matching to runway orientation
3) Connections modification according to minimum extra-mileage, in order to consider:
   - spatial constrainsts
   - localization of present radio aids
   - merging of not-separated routes and points
   - flows on secondary links
4) Computation of the attributes of the resulting structure
5) Identification of air-space structure alternatives, according to:
   - removing of low priority links from overloaded areas
   - rotation of terminal directions
6) Repetition of the activities starting from 3)
7) Scoring of the alternatives on the basis of structural attributes to limit the number of alternatives
8) Repetition of the activities starting from 1), with different conditions on air traffic and, if necessary, on ATC constraints
9) Merging of the sets of the alternatives, with reference to different conditions to obtain a single set
10) Evaluation of implementation cost for every alternative
11) Final scoring of alternatives on a cost-effectiveness basis

The usable, software-computed, attributes are:

- number and "density" of route intersections in every ATC sector
- route extra-mileage with respect to orthodromic length
- vertical coverage of routes (and traffic flows) by radioelectric facilities as radars, communication links, VOR's, etc.
- "interference" index for each holding fix
- load attributes as mentioned in par. 2.2.1
- global flown mileage and the difference with respect to the orthodromic routes
- rerouting capabilities and their effectiveness in balancing ATC sectors workload.

Clearly the mentioned attributes cannot be summarized into only one quality index. It is then left to the experience of the ATC structure designer a subjective scoring of the different quantities for a global rough evaluation.

2.2.3 Identification of preferential routings

Clearly most pairs of input-output points of the present Italian airspace (fig. 3) are multi-connected, as generally for the airspace of other countries.

The choice among alternative routings should be made theoretically according to a dynamic optimization of traffic performance (minimum delay and fuel extra-cost), by taking into account the load constraints, as well as the time - variability of ATC system.

However most present systems make use of this redundancy only in order to off-line state preferential routings. The reroutings, chosen according to ATC experience, are not necessarly optimal.

The software for airspace structure analysis allows for an identification of "optimal" preferential routings by:

- looking for the first N minimal reroutings for every connection (par. 3.3)
- optimizing the routing of a traffic sample of individual flights (par. 3.4).

By using this software for different traffic samples exploring the given traffic flows distribution, an indication of preferential routings may be obtained in term of:

- "static" preferential routings, ever (or nearly ever) chosen for individual flights and so adoptable as off-line procedures
- "dynamic" preferential routings, dependent on time and so not adoptable as off-line procedures, but only to be chosen real-time according to the traffic actualization.

2.2.4 Real-time utilizations

The designed software has been conceived as an off-line aid to ATC system planners. However, it is possible to adapt and use it in real-time airspace and traffic management (ASTM) to balance foreseen traffic load and system capacity (without any consideration of flight conflicts at this level).

Generally, these utilizations require the integration of software for structure analysis with a suitable information system, gathering data about foreseen traffic and ATC system evolution. Using these real-time data, load attributes (as flows distribution, expected number of conflicts, sectors workload, etc.) may be computed and used by ASTM, in order to monitor the system status and evaluate possible alternatives variations. Moreover, the software mentioned in par. 2.2.3 allows also for optimizing the management.

Indeed, suppose that the information system and the associated processing provide the following data:

- for every flight, all the acceptable alternative routings (if necessary real-time up-dated)
- for every flight, the cost (a weighted combination of flight time and fuel consumption), the involved sub-spaces and the corresponding time-overs, associated to every alternative routing
- the load capacity (if necessary real-time updated) in term of maximum number of flights entering every sub-space in a given time-interval.

By using these data the mentioned module identifies the optimal routing to be assigned to every flight. Indeed two different operational utilizations should be considered. In the first utilization every flight is supposed to be "inactive" for the system: no flight already planned or controlled by the ATC system ("active" flight) is being considered. This utilization applies to an ASTM operating well in advance with respect to flight actualization (at least, a few hours). In this case, the optimal management procedure will be repeated whenever a significant variation has modified the inactive traffic distribution or the ATC system structure or capacities; the assignment algorithm should consider the whole set of flights and the full-load capacities. In the second utilization, which is nearer to flight actualization, active flights should be considered too as candidates for routing variation; however in order not to create an operational interference between ASTM and the conflict avoidance activities, only the not yet planned part of active flights trajectories will be taken into account. Moreover, the load capacities have to be reduced according to the number of active flights already planned to enter a given sub-space. Both utilizations have the following operational features:

- a not significant feed-back is supposed in the ASTM optimization process by the successive control phases
- ASTM and the successive control activities operate without any interaction, allowing for an evolutionary improvement of present ATC system
- the real-time processing requirement is reduced, due to the relevant time interval before flights actualization in the first utilization, and the limited set of flights considered in the second utilization.

Finally, consideration should be given to the operational model represented in the optimization algorithm; this model could appear too simple since it takes only spatial reroutings, sub-space constraints and sequential fixed time intervals into account. Indeed this limitation can be strongly reduced by using:

- virtual reroutings, in order to represent delays as possible solutions for the assignment algorithm
- virtual sub-spaces, in order to represent different saturable space elements (as airports, holding fixes, etc.)
- interleaved variable time-intervals in order to establish constraints and evaluate loads in the operationally most suitable time reference.

Taking these last features into account, the optimization process seems to be very effective in representing the operational practice and suitable for an experimental real-time ASTM.

2.3 The simulation software

The simulation software has to be used as a tool for a refined evaluation of air traffic processes, which are different in one or more components of the ATC system (airspace structure, units organization, procedures, radioelectric facilities).

Keeping also in mind what has been experienced by simulation models already implemented, it seemed proper to choose the performance of air-traffic in term of delays and fuel consumption as a basic measure to be accomplished by the simulation software.

On the other hand, the direct simulation of the processes related to the flight safety and the evaluation of collision risk do not seem possible for the difficulty in modeling and evaluating this kind of processes. However, proper quantities which can supply an indirect evaluation of safety have been found and are computed in the simulation software.

In conclusion, the quantities, delays and fuel consumption for the measure of air traffic performance, together with the quantities related to traffic safety and ATC system performance, are the bases to evaluate the benefits brought by possible improvements. As a consequence the simulation software has been specified according to following main features:

- simultaneous simulation of all flight-phases
- careful computation of aircraft trajectory and fuel consumption, in order to evaluate the efficiency variations consequent to different assignments of flight levels
- generation of the traffic flow on the basis of realistic statistics as much as possible independent from the present structure of the air-space
- simulation in details of the "flow control" and planning activity because of the heavy incidence on the traffic performance
- simulation of whole considered air-space or even of one remarkable part of it, with different procedure and structure conditions
- computation of the relative weights of the different components (structure of air-space, control organization and procedures) which determine the efficiency actually reached by the air traffic.

Besides these major issues, the simulation software takes into account and examines (even if from a macroscopic point of view) some other aspects such as the tactical intervention and the characteristics of the surveillance, communication and navigation facilities. Fig. 4 is a simplified flow diagram of simulation software. A detailed description of this software is out of the scope of this paper. The following points should however be noticed:

- the flight generation is made according to traffic statistics
- the airspace and ATC structure is not an input file, but a time dependent file, pre-computed by using the software for airspace structure analysis
- the simulation of control activities is based on a representation of the actual traffic situation and foreseen evolution, which is quite similar to that one used in the present, strip-based ATC system
- simulation of flow control and flight planning is made with reference to manual, semiautomatic and automatic "environments".

Finally, the following main quantities are estimated by the simulation software:

- instantaneous number of flights within the system
- entering flows, kinematically distinguished
- flight time and fuel consumption, for every flow in "free" evolution or as filtered by the ATC system
- average number and waiting-time of aircraft queued in the various flight phases
- statistics of minimum distance between aircraft pairs (a quantity for the indirect measure of safety)
- workloads related to the various ATC activities and units
- statistics of overloading situations
- statistics of flow restrictions
- statistics of flight conflicts
- statistics of ATC modifications on flight trajectories

These quantities are generally analysed in their spatial and time distributions.

3. MAIN MODELS USED IN THE SOFTWARE

3.1 Expected number of flight conflicts

The study on this point started from previous works [2,3]. However different models were developed and adopted, in our opinion more adherent to ATC procedures.

The developed models take into account both spatial and time separations and cover every conflict situation. However the analysis distinguishes only crossing conflicts from overtaking ones.

3.1.1 Crossing conflicts

The analysis is valid both for vertical crossing (same horizontal route-projection) and horizontal crossing (different horizontal route projections) in case of level and/or transitioning aircraft. Suppose two flows f_i and f_k which originate the conflict type j (a flow is a set of aircraft flying on a route with the same kinematic characteristics).

Let's consider an aircraft of the slower flow, for example f_i. It is conflicting for a time interval

$$t_A = \frac{l_j}{V_i}$$

where:

l_j - distance (dependent on conflict type) flown during the conflict time interval

V_i - average aircraft velocity along l_j.

The space interval S engaged by the aircraft of the f_j flow on the route of f_k flow is for any type of conflict,

$$S = t_A V_k$$

The aircraft of the flow f_k contained in S are conflicting with the given aircraft and their average number is:

$$S/S_k$$

where:

$S_k = \frac{V_k}{f_k}$ = average separation between two contiguous aircraft of the flow f_k

Extending to all the aircraft of f_i flow, the average number of conflicts between the two flows is:

$$N_{jik} = f_i \frac{S}{S_k} = f_i \frac{t_A V_k}{S_k} = f_i f_k \frac{l_j}{V_i}$$

In case of spatial separation l_j is generally:

$$l_j = 2 X_j$$

where X_j is the spatial separation for the considered type of conflict.

In case of time separation l_j is generally:

$$l_j = 2 T_j V_i$$

where T_j is the time separation for the considered type of conflict.

Therefore the average number of conflicts may be computed as:

$$N_{jik} = \frac{2 f_i f_k X_j}{V_i} \qquad \text{(spatial separation)}$$

$$N_{jik} = 2 f_i f_k T_j \qquad \text{(time separation)}$$

According to the operational procedures, X_j and T_j could depend on the crossing geometry.

3.1.2 Overtaking conflicts

Let's consider two flows f_i and f_k on the same route of length l (two or more routes, vertically or laterally not-separated, must be considered as the same route). An aircraft of the flow f_i with velocity V_i is potentially conflicting with an aircraft of the flow f_k (with velocity $V_k \neq V_i$) during the interval time

$$t_A = \frac{l}{V_i}$$

The space interval S engaged by the aircraft during the conflict time in relative motion with respect to the f_k flow, is:

$$S = t_A \left| V_k \mp V_i \right|$$

where the sign + must be considered in case of flows in opposite directions.

The average number of conflicts is:

$$\frac{S}{S_k} = \frac{S f_k}{V_k}$$

Therefore the average number N_{ik} of conflicts between the flows f_i and f_k in the route of length l is:

$$N_{ik} = f_i f_k \frac{l}{V_i V_k} \left| V_k \mp V_i \right|$$

Notice that the number of conflicts is independent of separation.

3.2 Model for workload computation

The model adopted in our simulation and computation software may be considered a merging and extension of previous models [3,4] .

A control team is composed by the radar and planning controllers, in some cases aided by assistant controllers. The analysis for ATC capacity may be limited to main controllers because their functions are more critical and easily saturable. The tasks of each controller may be represented by specific activities, such as inbound coordination, position report, clearance issuing, observation of PPI, conflict solution, etc. These activities may depend on traffic or not. In the case of traffic dependence, each activity has a typical repetition frequency, possibly dependent on type and kynetic evolution of the aircraft and on the operational procedures adopted.

For each activity, the work developed may be splitted into different tasks, as t-b-t and phone communications, updating of data-base, etc. Some of these tasks may be performed together. For the evaluation of the global execution time it is necessary to consider the single execution time and their parallelism-degree. The execution time for each is generally dependent on:

- equipments and facilities for the ATC control (degree of automation)
- ATC procedures
- individual characteristics of controllers.

In the simulation software the workload W is computed according to the following model:

$$W = \sum_{p=1}^{P} f_p t_p + \sum_{n=1}^{N} F_n \sum_{q=1}^{Q} T_n f_{qn} \sum_{s=1}^{S} \tau_{qns} I_{qn} + \sum_{r=1}^{R} f_r t_r$$

where:

f_p - frequency of the p^{th} activity independent of traffic

t_p - time necessary to perform the p^{th} activity independent of traffic

P - number of traffic-independent activities

F_n - flow of the n^{th} type of traffic

N - number of different types of traffic

Tn - average transit-time for the n^{th} type of traffic

f_{qn} - frequency of the q^{th} activity performed for each aircraft of the n^{th} type of traffic

Q - number of different activities related to each aircraft

τ_{qns} - time necessary to perform the s^{th} task of the q^{th} activity

S - number of different tasks to perform the activities related to the control of each aircraft

I_{qn} - overlapping index of tasks for the q^{th} activity

f_r - frequency of the r^{th} activity for conflicts analysis and, if any, conflicts solution

t_r - time necessary to perform th r^{th} activity for conflicts analysis and, if any, conflicts solution

R - number of different activities for analysis and solution of conflicts

The control activities and the associated time to perform them are generally dependent on type and individual characteristics of each controller, degree of automation, characteristics of operational environment.

In the simulation software the quantities $f_p, t_p, f_{qn}, f_r, \tau_{qns}, I_{qn}$ have been assumed as input-data. Activities for the gathering and analysis of data are now in progress in order to evaluate the workload, according to the assumed model. The quantities F_n, T_n and f_r are computed by the software. It should be noticed that the activities of analysis and solution of conflicts are different on the basis of:

- type of potential conflict
- detection or not of the conflict and activities related to conflict solution, if foreseen by the controller.

For the evaluation of the f_r quantities every potentially conflicting aircraft pair is to be considered. This evaluation is performed starting from the formulas in par. 3.1. With the adopted model, the maximum workload will be evaluated, as in other methodologies, using the data of capacity indicated by controllers on the basis of their subjective experience.

3.3 Model for computation of minimum air-route length

The problem of determining the N minimal paths between two given points, has been often examined in the literature, mainly in the case when the elementary paths (that is, the paths which pass many times through the same point) must not be automatically excluded.

These methods, which have been studied by Hoffman, Parley, Sakarovitch, Bellman, Kailo and others are quite simple but it is not straight-forward to modify them in order to exclude the elementary paths (as it should be done in our case). The finally used algorithm, which takes into account this constraint, is the algorithm of Yen[5] . Roughly this algorithm implies the iterative use of some methods to determine the minimum path between two vertices of a given graph and the elimination of the undesired path; the method used in our case has been the Dijkstra's method which tourned out to be very general and flexible.

Obviously these two algorithms have been modified in order to take into account that only a few routes, between the computed ones, are ATC-acceptable routes. The main point is that a route can be considered admissible only if it does not make too long or irregular paths before reaching the destination point.

From a mathematical point of view, it can be said that a route can be considered admissible only if (outside of a given radius around the origin) each section of route forms an angle, with the preceding section, less than a given angle φ max and an angle with the local orthodromic which is less than another given angle θ max. The local orthodromic is the line which joins the considered point with the destination point. A radius around the origin (whether it's an aerodrome) is introduced in order to exclude angle limitation in the climbing and descent phases.

3.4 Model for computation of preferential routings

3.4.1 Mathematical description

Define the following entities:

$J = \{1, 2, \dots, n\}$ the index set of flights in the given air space

$I = \{1, 2, \dots, m\}$ the index set of control sectors

$K = \{1, 2, \dots, p\}$ the index set of the admissible routings for every flight

$H =$ the time interval of interest

$T = \{1, 2, \dots, h\}$ the index set of subintervals of H

$x_j^k = \begin{cases} 1 & \text{if the flight } j \in J \text{ is on the routing } k \in K \\ 0 & \text{otherwise} \end{cases}$

$c_j^k =$ the penalty coefficient of the flight $j \in J$ on the routing $k \in K$

$a_{ijt}^k = \begin{cases} 1 & \text{if the flight } j \text{ on the routing } k \text{ belongs to the sector } i \in I \text{ during the time-interval } t \in T \\ 0 & \text{otherwise} \end{cases}$

$b_{it} =$ the load capacity of the sector $i \in I$ during the time interval $t \in T$

Then the problem is embedded in the following ILP (Integer Linear Programming) formulation:

Problem: Minimize (with respect to all the variables x_j^k) the function:

$$z = \sum_{k=1}^{p} \sum_{j=1}^{n} c_j^k \, x_j^k \tag{1}$$

under the constraints

$$\sum_{k=1}^{p} \sum_{j=1}^{n} a_{ijt}^k \, x_j^k \leqslant b_{it} \tag{2}$$

$$\text{for } i \in I, \quad t \in T$$

and

$$\sum_{k=1}^{p} x_j^k = 1 \qquad \text{for } j \in J \tag{3}$$

The constraints (2) refer to the load condition, while conditions (3) express that each flight belongs to a unique routing. The stated problem is characterized by (n.p) variables and (m.h + n) constraints.

3.4.2 Some features of the implemented software and some results

A FORTRAN program has been written which provides the solution of the problem stated in 3.4.1. It develops the following functions:

- data generation, row by row, of the ILP tableau;
- memorization of the coefficient matrix in a compact form;
- elimination of all the not-effective constraints
- solution of the ILP problem by means of a branch-and-bound algorithm derived from the Land-Doig method [6] .

The first function has been introduced for the simulated testing of the algorithm; indeed the first obtained results refer to realistic situations (at least for the Italian case), generated in a statistical way. More precisely, in order to evaluate memory request and time consumption, a number of runs were carried out (on a CDC 7600 computer), considering 50 additional flights to be allocated to 30 sectors and two admissible routings for each flight. This testing refers to the optimization with already planned flights (see par. 2.4); the additional flights are then matched to the residual sector capacities.

In this cases the memory request was about 60.000 (octal) words on SCM (small core memory) and 16.000 (octal) words of LCM (large core memory). The typical CPU time was 3 s. It is interesting to note that in the majority of cases the LP optimal solution satisfies also the discrete 0-1 constraint.

3.5 Model for traffic generation

3.5.1 General description

In the simulation software the traffic generation is accomplished according to the following steps:

- extrapolation of present traffic data in order to represent a future situation statistically;
- extraction of the number of flights entering the airspace in a given time interval;
- extraction of flight attributes (arrival time at an input point, aircraft class, input and output points, distance from a departure airport to an input point, distance from an output point to an arrival airport);
- computation of flight optimal vertical profile and associated fuel consumption profile (par. 3.5.3);
- computation of flight path in the real airspace structure (at this traffic generation level the developed flight plans are then obtained);
- extraction of flight plan amendments before entering into the simulated airspace;
- extraction of navigation noise within the airspace;
- flights correction at entering points in order to establish proper input separations.

One or more traffic samples are then obtained through proper repetition of the above process. Every sample is composed of individual, completely characterized flights; for each of them a description is given of the "free" evolution as well as of the noise-affected evolution in the real constrained airspace structure. Different routings may be also considered for every flight with computation of the associated different costs.

Aircraft performance is properly considered in flight vertical profile, fuel consumption and time-overs computation (par. 3.5.2); aircraft navigation in the horizontal plane is simulated in a simplified way, in order to obtain correct time-overs, rather than an accurate position computation (this is a consequence of the macroscopic simulation of radar control).

Finally, two other points about the traffic generation model are to be remarked:

- only traffic statistics at the entering points (boundary and airports) of the Italian airspace are used as input data; however, the translation of computed traffic samples at the boundary of any inner airspace is possible;
- a suitable aggregation of traffic attributes is adopted in order to obtain significant statistics of present entering traffic; an aggregation has been chosen such as to guarantee that traffic attributes correlations are correctly maintained.

3.5.2 Aircraft performance representation

As it is well known, the Flight Performance Tables give a discrete description of the aircraft features, i.e. distances, time, levels, fuel consumption and so on. Such a type of description, while useful for design and test purpose, is not adequate for a fast-time simulation. This is the motivation for implementing some analytical models of aircraft performances.

In our approach the coefficients of fixed structured functions (polynomials) have been estimated from the data reported in the FPTs by using a package for multiple regression analysis. More precisely, by defining:

t = time
D = distance
l = flight level
w = aircraft weight
v = aircraft speed
T = air temperature
c = fuel consumption

for each aircraft class, [illegible]ng functions have been determined:

- for climb

$c_s = f_1\ (D,w,T)$
$l_s = f_2\ (D,w,T)$
$t_s = f_3\ (D,w,T)$

(In this case w represents the take-off weight).

- for cruise

$c_c = f_4\ (w,v,l)$

(In this case c is the specific (unit distance) consumption).

- for descent

$l_d = f_5\ (D)$
$t_d = f_6\ (D)$

Moreover the relationship between optimal cruise level and aircraft weight is used in the traffic generation model:

$l_o = f_7\ (w)$

In most cases, 3th degree polynomials have been found to give maximum percentage errors no greater than 10%, while general standard deviation is only a few points of percentage.

3.5.3 Computation of flight vertical profile

Given an aircraft type, a landing weight (extracted from given statistical data), origin and destination points, an iterative procedure determines a take-off weight.

Then from the knowledge of take-off weight and the distance between origin and a given trajectory point fuel consumption is computed. In such a way, actual weight (or consumption), time and flight level are known in any point of the route (wind effect on time-overs is taken into account in the navigation noise computation). The steps of the procedure are described as follows. Given:

- aircraft type
- total flight distance D_T
- temperature
- cruise speed
- landing weight

a) starting from landing weight compute the weight at the end of cruise, by considering an added fixed weight for the descent fuel consumption;

b) compute the cruise terminal level by using f_7 (par. 3.5.2) and choosing the nearest ATC admissible level. From this value and by use of f_5 the descent distance D_d is computed and the distance $D'_T = D_T - D_d$ results for the climb and cruise phases;

c) compute "backwards" the cruise fuel consumption (and therefore the weight) and the flight level profile for any distance value, using f_4 and f_7;

d) assume a temptative take-off weight $P_t(o)$ and put $i = 1$;

e) compute, by means of f_2 and f_1 relationships the distance $D_s(i)$ and the fuel consumption $c_s(i)$ during climb. The cruise initial weight $P_c(i) = P_t(i-1) - c_s(i)$ is then obtained;

f) on the basis of the supposed cruise distance $D_c(i) = D'_T - D_s(i)$ and the level profile computed in c), a new value $P_c^*(i)$ of the cruise initial weight is derived;

g) verify if $\left| P_c^*(i) - P_c(i) \right| < \Delta$ for a given small Δ;

h) if the previous inequality is satisfied, the procedure stops, otherwise set $P_t(i) = P_t(i-1) - \left[P_c^*(i) - P_c^*(i) \right]$ and return to point e).

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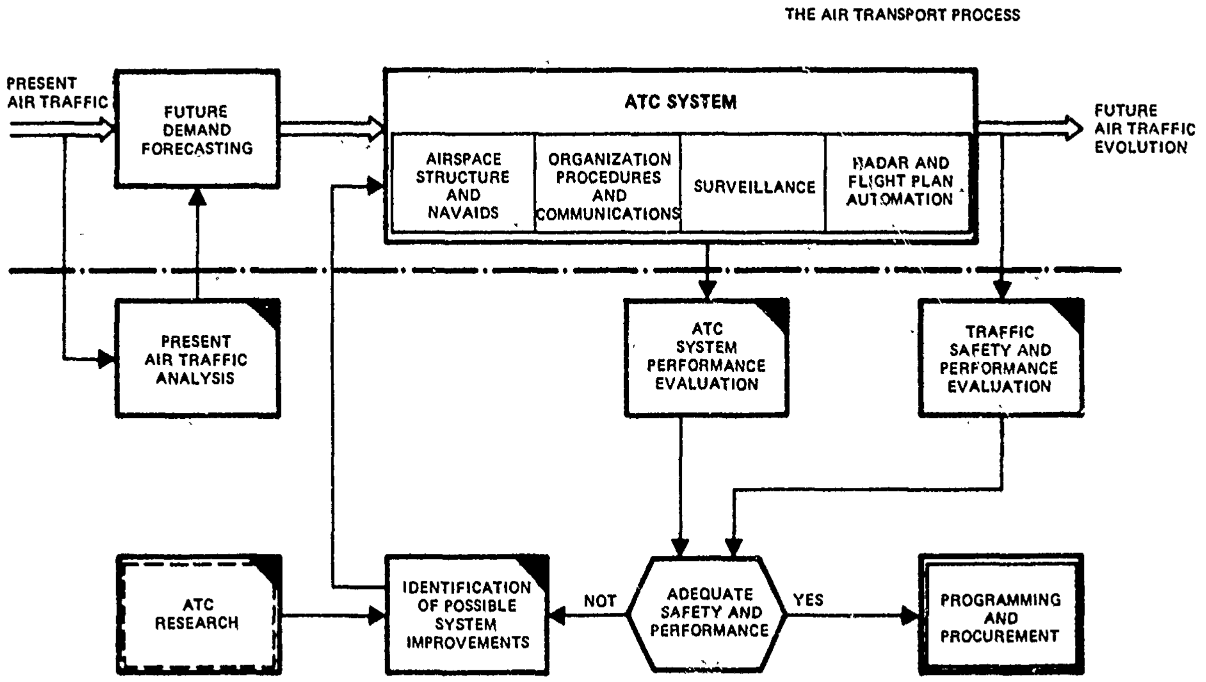

FIG. 1 - CNR RESEARCHES (◹) VERSUS SYSTEM PLANNER'S ACTIVITIES

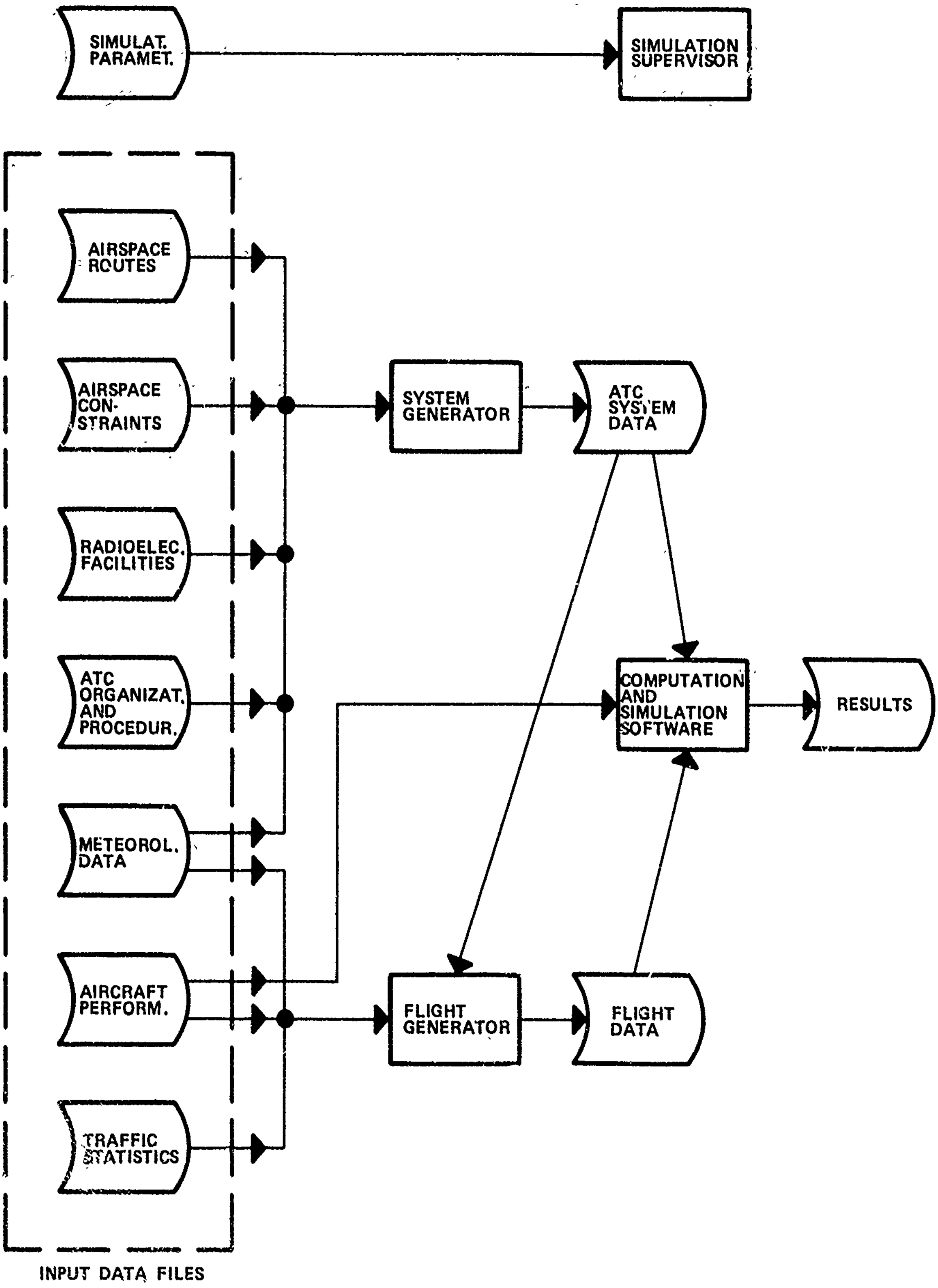

FIG. 2 - DATA-BASE STRUCTURE

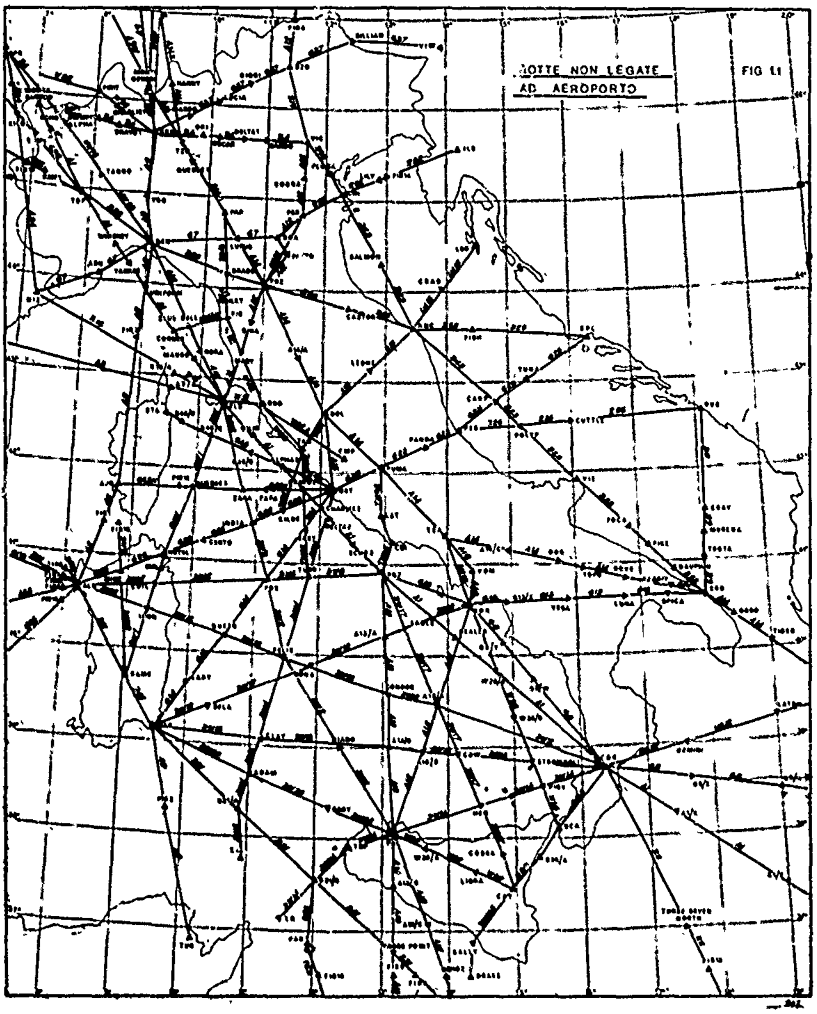

FIG. 3 - AIRWAYS AND ADVISORY ROUTES OF THE ITALIAN AIRSPACE (WITHOUT SIDs AND STARs)

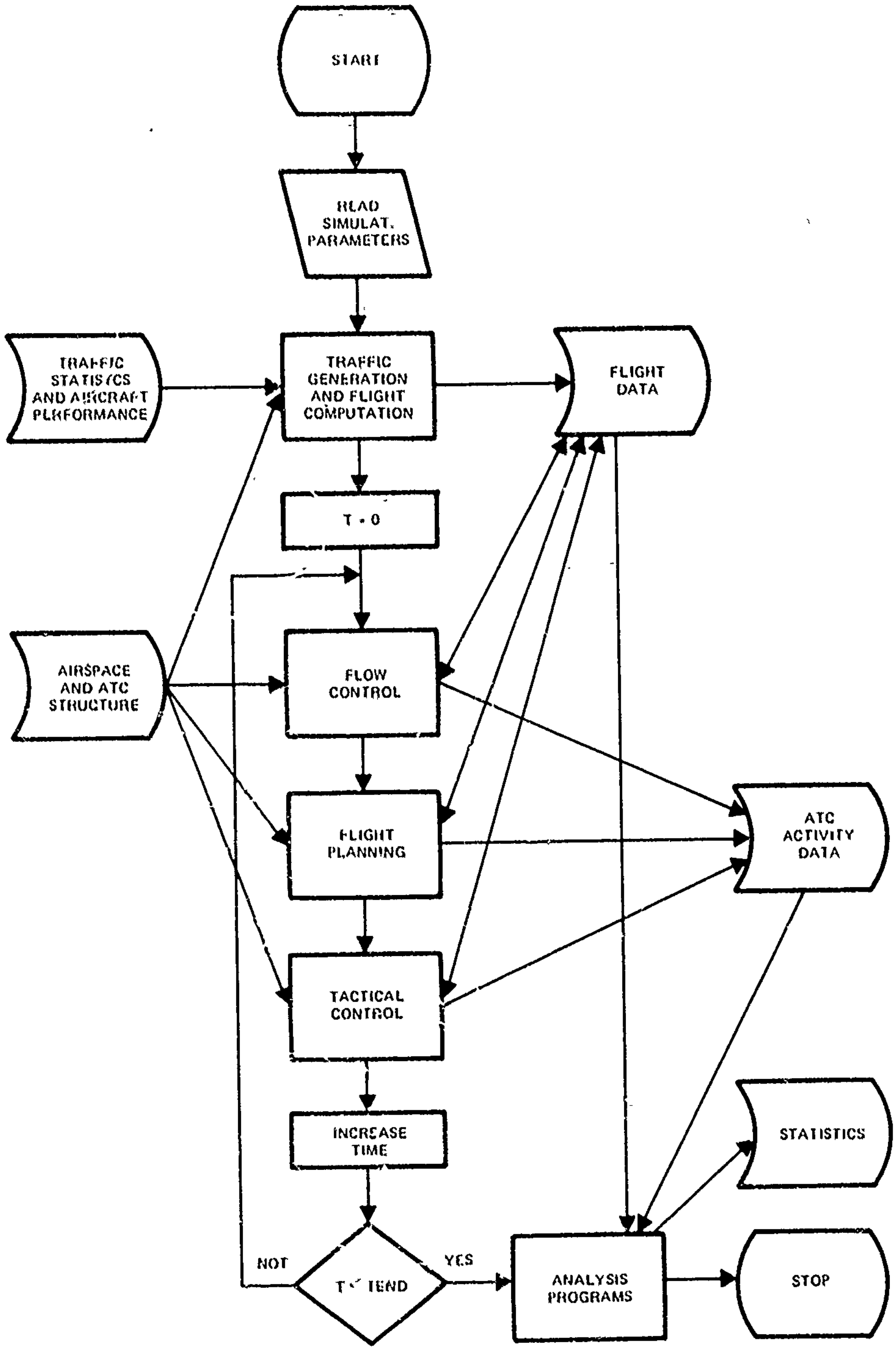

FIG. 4 - SIMULATION SOFTWARE STRUCTURE

SYSTEM, AIRSPACE, AND CAPACITY REQUIREMENTS FOR FUTURE ATC-SYSTEMS

by

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Summary

Based on control capacity measurements, a "theory of control capacity" has been developed.
The measurements were performed at a great number of radar control positions, and a smaller number of coordination or planning control positions in various ATC-systems. The ATC-systems included early ones, using analog radar only, and such with digital and synthetic information displayed and different data processing capabilities. Totally the measurements amounted to the coverage of about 2,500 aircraft movements and 1,500 six-minute intervals or 150 control hours.
The theory of control capacity allows to gain comprehensive knowledge concerning the relationship and interdependence of the following:

(1) The airspace configuration (including the present separation requirements), the traffic structure and the resulting conflict probability.

(2) The airspace capacity, the control capacity of the ATC-control positions (functional units) and their dependence on air traffic structure and the technical ATC-system features and capabilities.

The applicability of the theory will be demonstrated in a few examples, e.g.:

(1) The benefit on airspace capacity and control capacity, gained by the application of speed control in a given airspace.

(2) The effect on airspace and control capacity, resulting from measures of parting e.g. vertical and horizontal traffic portions.

On the basis of this demonstration of the theory of control capacity in its application to practical problems in airspace management and optimization, the "capacity" -- in terms of control capacity -- of ATC-systems is used as a measure to assess and compare ATC-systems of different technical structure.
Outdated, present day's, and future ATC-systems are compared, showing the effect certain technical components and/or system functions have on system capacity.

1. Performance of ATC-Systems

1.1 The ATC-System as Man-Machine-System (MMS)

The ATC-system is a very complex MMS. And in an MMS, performance does not solely depend on the technical qualities of the system plus the operational environment. In an MMS human performance is the third component, and is the filter, through which the total MMS-performance materializes itself. The block diagram of Fig. 1 shows the main features of interdependence within an ATC-system:

(1) The traffic demand constitutes load.

This load is not only time variable, but also element variable. Element variability is given by type of aircraft and type of aircraft operation (level cruise, climb, descent approach etc.).

(2) The operational organization represents a demand, as far as the workload of the controller is concerned.

The sectorization determines the time the aircraft are under control of a functional unit (= FU = control team), as well as the control responsibilities of each FU, such as the types of aircraft movements to be controlled.

The control team or FU-organization is different in the various existing ATC-systems. The type of organization determines the function assignment within the FU, and therewith the functional load on each member of the FU.

(3) The system demand is well known to be a constituent part of the workload of the human operator in an MMS.

The discussion of the interdependence between technical system features, controller workload and ATC-system performance is one main topic of this paper (see par. 4).

(4) Traffic, technical system and operational organization demand together cause a distinct amount of workload on the controller in controlling a given air traffic.

The output of the controllers' performance is the ATC-system performance in terms of control capacity in number of aircraft controllable per hour.

(5) Performance variability of the controller population is shown in Fig. 1 as influencing factor. This applies to all types of MMS.

Individual performance capabilities of the controllers add to the variability of the system performance. This variance can be assumed to be in the order of ±10 % to ±12.5 %. If greater differences are found, these can be considered to be beyond the variance of 1 σ.

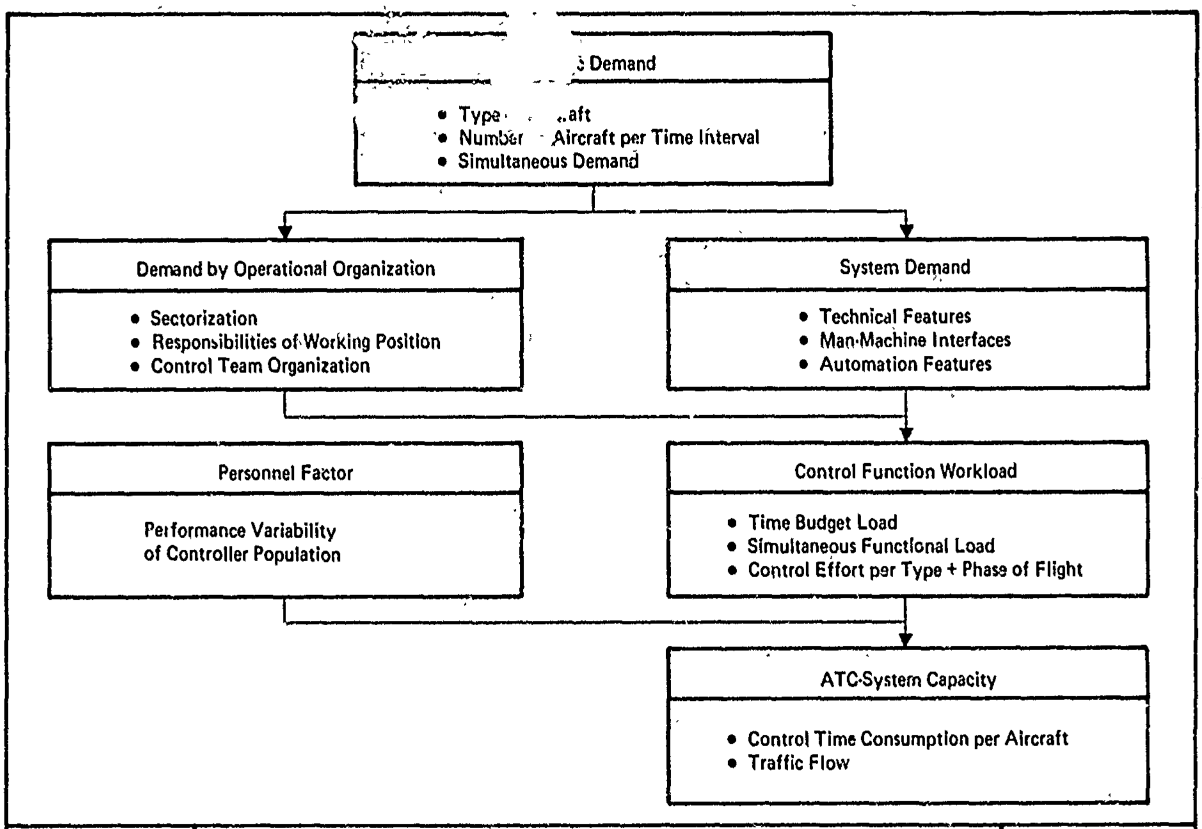

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Fig. 1 Interrelationship of factors influencing ATC-System capacity

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1.2 The "Control Time Budget" as Measure of ATC-System Performance

To control an aircraft flying from A to B imposes workload of different amount on the controllers depending on the control task in relation to flight phase or type of operation in the flight phases. The task to control an aircraft "cruising straight and level" through the sector contains less task elements, than the task to control an aircraft "by descent clearances and vectoring" on to an approach path.

From this follows:

- Each control task contains a defined number of task elements.
- The control task content is dependent on the aircraft and its type of movement in a given flight phase. We must not forget that this is not only obvious, but also internationally agreed within the ICAO regulations.
- The control tasks, therefore, are independent of the technical part of the ATC-system.
- Therefore, the control tasks represent a certain "amount of work to be performed" or a certain "control effort."

This is a fact already reported by ARAD in 1964 /1/. ARAD had the "control effort factor" for various control tasks rated by controllers. In his report, he published a rating scale of control effort factors, which is basically still valid.

This scale of control effort factors has meanwhile been extended and converted into an interval scale, based on a regression analysis of control time measurements. The new scale of control effort factors is presented in Fig. 2.

Contr. Effort Factor	S_N	Criterion	Weight Assigned	Used for	Origin
Basic Unit	S_0	Airline Carrier	1.0	(1) Traffic Structure Stat. (2) Flight Plan Scheduling (3) Control Capacity Measurements	ARAD
	S_1	Charter Flight	1.2		MBB
	S_2	Military Flight	1.5		MBB
Routine Increments	S_3	Level Change	.24		ARAD
	S_4	Vertical Hand-/Takeover	.26		ARAD
	S_5	Enroute/Approach Control Hand-/Takeover	.28		ARAD
	S_6	Vectoring (Approach Contr. Mandatory)	.3		MBB
Non-Routine Increments	S_7	Receipt of Flight Plan via R/T (Pop-Up)	.7	Control Capacity Measurements only	ARAD
	S_8	Conflict Solution (both aircraft)	1.4 (x2)		ARAD
	S_9	Weather Report via R/T	.3		MBB
	S_{10}	Target Warning	.2		MBB
	S_{11}	Holding Procedure Applied	.6		MBB
	S_{12}	R/T Communication Difficulties	.6		MBB

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Fig. 2 Scale of Control Effort Factors

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During the years 1972 to 1975 the control effort was measured in nearly 195 control hours. During this control time more than 2200 flights were measured and analyzed. The measurements were performed in ATC-systems of different type and operational organization. These were the analog radar ATC-system and the DERD-system (= Display of Extracted Radar Data) in the FRG, the EUROCONTROL-system in Maastricht, and the NAS-system (= en Route National Airspace System) in the U S A.

The number of data collected allowed a regression analysis over control time and therewith an interval scaling of the control effort factors. Fig. 2 shows, that we must basically discriminate between the types of flight:

- "airline", which means all regular, repetitive carrier flights,
- "charter", which includes all non-scheduled, non-regular carrier, business and other controlled flights,
- "military", flights of military aircraft .

All other factors represent increments added to the respective basic unit as applicable. The routine increments are additive factors.

Example: Airline + level change + hand-over to approach: $S_0 + S_3 + S_5 = 1.52$

The main advantages are the following:

(1) The scale of control effort factors is an interval scale, based on a quantitative interdependence between control effort and active control time (not flying time in the sector).

(2) The scale is valid for all existing types of ATC-systems.

For future ATC-systems the scale will be valid as well, as long as we do not change the nature of the control task of the (radar) controller.

(3) The difference in performance of the various ATC-systems results in a change of time consumption per control task, and therewith per control effort factor.

This fact allows to compare the performance capabilities of ATC-systems:

> The control effort factor S_0 represents an amount of control work, which is named Work Unit (WU). To-days ATC-systems show a time consumption per WU of 60 s to 72 s, which means a maximum of 5 WU per 6-min interval .

Comprehensive information about the investigations is documented in /2/.

2. Theory of Control Capacity

2.1 General

The theory of control capacity is a necessary tool to quantitatively determine the relation between the traffic flow in an airspace sector (= ATC-system performance) and controller workload. The theory of control capacity is required to have the capability to quantify the influence of:

- Traffic characteristics
- Sectorization
- Control task/team organization
- Technical features of the system, e.g. degree of automation

Comprehensive knowledge of the effects these factors have is required in case one of the following tasks shall be solved:

(1) Evaluate/assess measures proposed to gain control capacity.

(2) Compare performance of different ATC-systems.

(3) Specify an ATC-system with a predetermined performance capability.

In the following, the workload of the radar controller is used as a measure to determine control capacity. For the coordinator (or planning controller) a similar measure was developed, and can be used accordingly.

2.2 Traffic Flow and Controller Workload

Based on the above mentioned measurements covering more than 2,200 flights and nearly 195 control hours, the interdependence between controller workload and amount of traffic controlled was quantified. To gain higher accuracy in the measurements, the control hours were broken down into time interval (T_i) of 6 min. duration. In these measurements it was found that controller workload is increasing with the number of aircraft under control (N_{sim}) in a quadratic function. Fig. 3 shows this function T(A), and its two major components (derived by Och /3/):

- the routine work per aircraft $T(A_1)$, and
- the conflict solution work per aircraft $T(A_2)$

The routine work is increasing linearly with the number of aircraft under control. It comprises the task elements "initial/final contact", "clearance delivery", "flight survaillance" etc. as required.

The conflict solution part increases with the number of aircraft controlled according to a quadratic function comprising:

- all controller actions required to solve the conflict after its recognition (e.g.: vectoring of one or more aircraft).

Both portions are contributing additively to the total workload.

The control capacity in a time interval (T_i) is reached, when the control time required (T_A) to handle a given number of aircraft ($\bar{N}_{max}$) equals the time interval T_i (in this case T_i = 360 s).

The number of aircraft controllable differs:

(1) from sector to sector, due to airspace and air traffic characteristics, effecting the mean control effort $\bar{S}_N$ within the sector,

(2) from ATC-system to ATC-system, due to system specific control procedures demand, effecting the control or working time required per WU (see par. 1.2).

The first step to quantify these relationships is to develop a formula, which allows to calculate capacities. This formula can easily be derived from the function T(A) shown in Fig. 3:

$$F_{max} = \frac{K}{\overline{S_N}} \text{ aircraft per } T_i$$

The terms have the following meaning:

F_{max} = Maximum traffic flow controllable in the sector regarded within a six minute interval (≈ capacity)

K = Maximum number of work units a controller can perform within six minutes, using the ATC-system regarded.

$\overline{S_N}$ = Average number of work units required to control one aircraft in the sector regarded.

Traffic flow F_{max} and aircraft under control $\overline{N}_{max}$ are linked closely by the average flight time through the sector T_F.

The value of $\overline{S_N}$ represents the slope of curve L_R in Fig. 3, as a sector dependent characteristic.

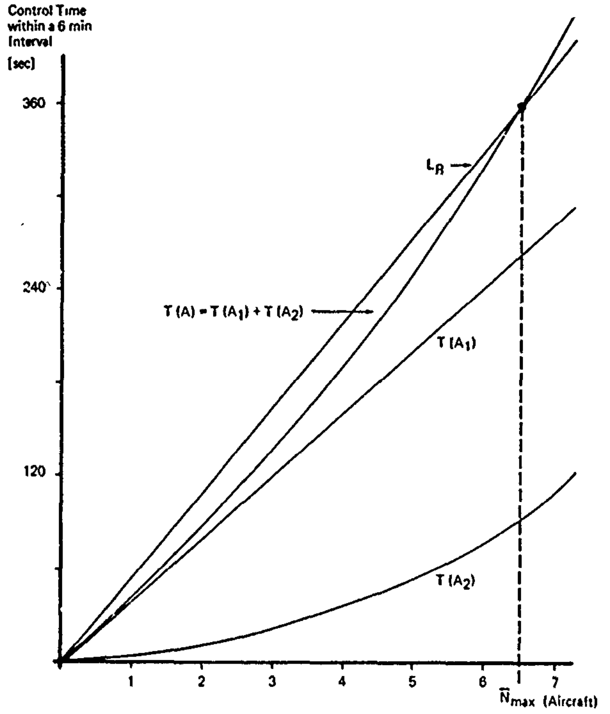

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Fig. 3 Total Control Time T (A) per 6 min Interval and its Components Routine T (A_1) and Conflict Solution T (A_2), versus Number of Aircraft under Control. (Sector Example: $\overline{S}_N = 1.15$; $T_F = 9$ min)

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The system capacity K comprises the influence of the technical features of the ATC-system, which may facilitate the performance of the control tasks or it may lengthen the working time required and therewith deteriorate the performance of the system. Par. 4 contains a detailed description of these relations as well as influences on K caused by control task or - team organization.

The control effort factor $\overline{S_N}$ and its effecting parameters are described hereunder.

3. Effects on the Control Effort S_N

3.1 Traffic Characteristics

As already stated in par. 1 a scale of control effort factors (difficulties) was developed by using workload measurements and statistical, mathematical methods.

By means of this scale, distinct control effort factors S_N were assigned to the various types of flight (= basic value) plus type of operation (= increment for e.g. level cruises, climb etc., see Fig. 2).

An average value $\overline{S_N}$ is calculated for each control sector according to its specific traffic characteristics. Changes in the percentage of one of the traffic portions will result in a change of the average value $\overline{S_N}$ and consequently in a higher or lower control capacity F_{max}.

3.2 Sectorization

3.2.1 Influence on the Control Effort

The total amount of work units required to control one aircraft in a given sector is composed by the two portions routine work $T(A_1)$ and conflict solution work $T(A_2)$ as shown in Fig. 3. In terms of control effort factor this can be expressed mathematically:

$$\overline{S_N} = \underbrace{S'_N}_{\text{Routine part}} + \underbrace{S''_N \cdot C_S \cdot \frac{T_i}{T_F} \cdot \overline{N}}_{\text{Conflict Solution Part}} \; ; \quad \text{WU per aircraft}$$

A change of the sector structure may effect both, the routine work as well as the conflict solution work.

The routine work is changed if either new or additional instructions are to be transmitted to the pilot or former routine transmissions (e.g. position reports) are dropped. The former increases, the latter decreases the routine work time S'_N within the total control time per aircraft.

The conflict solution work is changed if means are applied changing C_s. C_s represents the factor for sector complexity.

C_s comprises:

- the conflict probability at airway intersections,
- the overtaking probabilities on airways,
- the conflicts expected due to vertical movements.

$\bar{N}$ in the above formula represents the number of possible conflict partners. This is a very critical term. The number of possible conflict partners $\bar{N}$ increases controller workload quadratically.

This fact must be considered in airspace management when civil on-route traffic and military off-route traffic is mixed in one sector, and is possible handled by different control teams or functional units (= FUs).

When an off-route flying aircraft is entering that sector, its routine work S'_N only affects the off-route FU. But the conflict solution work, which may be the greater portion, affects both FUs. The result is an increase of $\overline{S_N}$, the mean control effort factor for the on-route FU, and a drop in capacity F_{max}.

3.2.2 Airspace Capacity

The sector complexity C_s does not only affect the controller workload, it does moreover serve as a means for quantifying the airspace capacity.

To ensure air traffic safety, a number of separation regulations is given, which must not be violated.

The structure of a controlsector comprising a size, a number of airways, a number of flight levels and of crossings or intersections determines -- by the separation regulations -- the maximum number of aircraft , which can be "put" into the sector until it is "full".

Applying the conflict theory this term or status "full" can be determined exactly:

> In case the traffic flow F increases, the number of conflicts to be expected within T_i increases accordingly. The airspace capacity of a sector is reached if one more aircraft entering the sector within T_i does -- by separation regulations -- automatically create one more conflict within T_i.

As the mathematical interdependence between traffic flow and conflict probability is known (described in detail in /3/), this status can be derived as

$$F_s = \frac{1}{2C_s} \; ; \quad \text{aircraft per } T_i$$

Main component of the airspace capacity is the sector complexity C_s. A factor, which turns to be the most important connector between sector- and traffic-structure on the one hand and traffic flow capacity on the other.

Any change in a control sector leads to a change of C_s, which results in a change of control capacity, respectively airspace capacity. On the basis of this fact, an airspace optimization programme can be conducted.

The basic rule is:
The airspace capacity F_s of a sector shall be greater than the control capacity of the executive and the planning controller.

If this is not the case the controllers will be loaded -- especially under high density traffic -- with an unwarranted high conflict solution workload.

Quantitative examples showing the influence of certain changes applied within a sector are presented in the appendix.

3.3 Control Task / Team Organization

According to Fig. 4 each task element contributes to the total amount of control work imposed on a control team by one aircraft.

Any change of this organization will affect immediately the time budget of the radar controller and/or his coordinator and thus results in a gain respectively loss of capacity.

The team organization can e.g. be changed by assigning a third controller to the FU. This controller can be given the task to perform the "hand-over" or transfer of control of the aircraft to the next sector.

Assuming the working position and the procedures allow this allocation of a third man. smoothly the time budget of the radar controller can be relieved. The routine part S'_N of his control work could be reduced by about 5 s per aircraft. In an ATC-system in which one WU does consume 72 s, this does result in a capacity gain of 7 %. In a sector with an F_{max} of 43 aircrafts per hour this would result in a gain of 3 aircraft , leading to an F_{max} of 46 aircrafts per hour.

This is not a mere calculation. This method is applied e.g. in the NAS-system. A "hand-over controller" is allocated to an FU when the workload is going up to about 70 %. The capacity increase achieved by the hand-over controller was measured. And, in the NAS environment this gain of 7 % can be observed. The automation features plus the hand-over controller give the NAS-system the highest system capacity of the ATC-system of to-day.

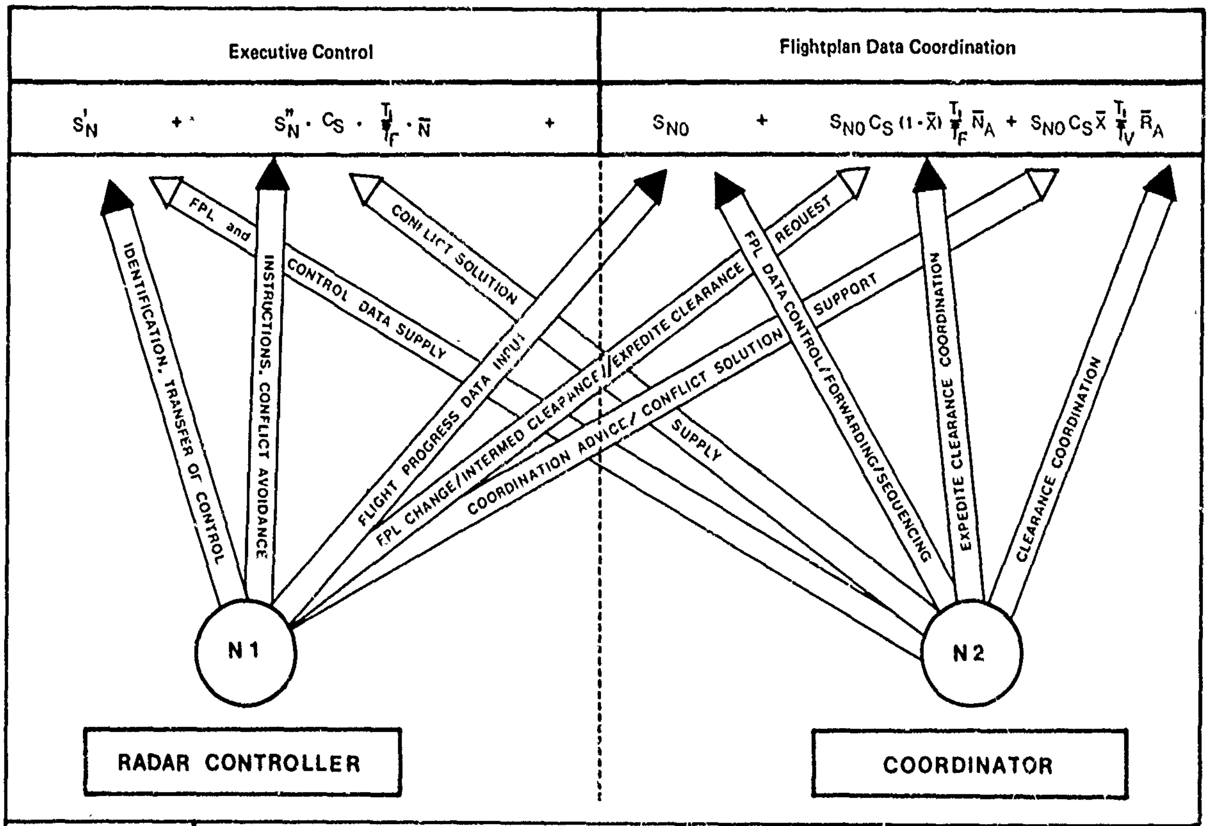

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Fig. 4 Control Task/Team Organization within one Functional Unit and the Assignment of Control Load Portions imposed by one aircraft.

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ATC-System Component/Function	ATC-System Structure I	II	III
Radar			
Analog Primary		X	
Analog Secondary			X
Digital Secondary			
Control Data			
Control Strip (manual), manual updating	X	X	X
Control Strip (printed), manual updating			X
Synthetic Aircraft Symbol Display with Label			
System Capacity in Work Units/Hour	30	40	50

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Fig. 5 ATC-System Structure and Control Capacity
Conventional Systems

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ATC-System Component/Function	ATC-System Structure IV	V	VI	VII
Radar				
Digital Secondary	X	X		
Digital + Analog (selectable)			X	X
Control Data				
Control Strip (printed) manual updating	X	X	X	X
Control Strip (printed) off-line updating		X	X	X
Automatic Radar-Tracking of A/C		X	X	X
Synthetic Aircraft Symbol Display with Label (PVD)	X	X	X	X
Electronic Display of Flight Progress Data			X	X
Semi-automatic Transfer of Control				X
System Capacity in Work Units/Hour	54	55	57	60

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Fig. 6 ATC-System Structure and Control Capacity
Present Systems

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ATC-System Component/Function		ATC-System Structure VIII	IX	X
	Radar			
	Digital + Analog (selectable)	X	X	X
Generation	**Control Data**			
	Automatic A/C Identification	X	X	X
	Automatic Radar Tracking	X	X	X
	Autom. Correlation of Flight-plan and Radar Data	X	X	X
	Autom. Transfer of Control	X	X	X
Display	Synthetic A/C-Symbol Display with Label (PVD)	X	X	X
	Display of Flight Progress Prediction Data (PVD)	X	X	X
	Display of Autom. updated Flightplan Data (EDD)	X	X	X
Clear. Data Conflict Data	Conflict Alert (PVD)	X	X	X
	Conflict Detection (Plan Conflict - EDD)	X	X	X
	Conflict Solution (PVD/EDD)	X	X	X
	Data Link		X	X
	Autom. Clearance Delivery			X
	System Capacity in Work Units/Hour	65	70	75–80

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Fig. 7 ATC-System Structure and Control Capacity Future Systems

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4. Comparison of ATC-Systems

In par. 1.2 it was said that the technical layout of the ATC-system results in a change of the "system demand" on the controller resulting therewith in a change of workload. The change of workload means that the time changes, the time required to perform a given control task. In other words, one Work Unit (WU) differs in time consumption from system to system.

The technical features influencing system capacity are shown in Fig. 5, 6, and 7. The ATC-systems with the Structures I to III are lower grade systems still existing in some countries.

Our first measurements in 1971 to 72 were performed in a III-type system. In some cases, during radar maintenance hours, we were able to measure under degraded conditions down to Structure I.

The gain represented by Structure IV is only becoming valid if the manual "button pushing" required to link the label to the aircraft can be done off-line, that means: not done by the executive controller.

The Systems V to VII (Fig. 6) are our to-days' systems from DERD (= Display of Extracted Radar Data) over EUROCONTROL to the NAS (= En Route National Airspace System). For all these systems it can be said that the capacity gain is only partially due to their automation features. Partially it is due to their greater man-power requirements. -- The term "semi-automatic transfer of control" in Fig. 6 refers to the third controller, the "hand-over controller" allocated to the FU, and the capacity gain given thereby.

The ATC-systems in Fig. 7 show that a great amount of automation and economic investment is required to design a greater capacity gain into a system. VIII represents the features specified for TARK (= Part Automated Radar Control).

The investment required to gain capacity beyond that of our to-days' systems must include the following:

(1) An absolute necessity is the feature "automatic correlation of flight plan and radar data."

This is the means to increase the planning capacity and to drop the requirement for control strips.

On the other hand a number of other features are required to achieve this means. Especially a data exchange programme is required to be implemented on an international basis. Data to be exchanged are SSR-code, flight plan and flight progress data.

The data are needed for the planning controller on his EDD, and for the radar controller on his PVD to allow presentation of preprocessed predictive data.

(2) Conflict detection is another feature reducing controller workload.

Conflict alert for the radar controller does only require processing of radar data. But, plan conflict detection for the planning controller or coordinator does require the above mentioned feature of correlation between radar and flight plan data.

Those are the requirements to be specified in detail for an ATC-system with the Structure VIII. A further increase up to 70 WU/hour does already require "conflict solution information" to be generated and displayed. It shall be explained here "why":

The system improvement is described in terms of increased number of WU performable per hours. The problem is, that the maximum traffic flow does not increase in parallel to the same amount. This is because of the quadratically increasing conflict solution work as portion of the total work to be performed (as shown in Fig. 4).

Increasing system capacity from 50 WU/h to 65 WU/h means an increase of 30 %. The increase of traffic flow is -- in any case -- less than 30 %. For a control sector with a mean control effort factor of $\overline{S_N} = 1.22$, this increase amounts to 22 % only. Because of the quadratic increase of the conflict solution portion of the control work the mean control effort factor increases to $\overline{S_N} = 1.3$, therewith limiting the increase of F_{max} (Fig. 8).

If this is extrapolated further, a point can be defined, at which an increase in "control work" will become ineffective.

If we are not able to automate conflict prediction, conflict solution, and conflict prevention the ATC-system of Structure VIII will be the last part-automated one, which can economically be recommended.

Before we discuss the future integrated system concept, some words need to be said concerning the "possibilities" given for airspace management and civil/military coordination by ATC-systems of the Structures VIII and IX.

With systems of these features described above a greater safety can be achieved together with an optimum freedom of airspace use by military aircraft , if -- and that is the critical point -- if a) an additional civil/military data exchange programme is implemented on a national or NATO basis, and if (b) a ground/air data link can be provided for the military aircraft. Such a programme would allow to provide the military aicraft with automatically generated, transmitted and displayed conflict alert information. The rule applied would be: the military aircraft flying operationally off-route, having the greater manoeuvre capabilities to be alerted of conflicting traffic, enabling him to avoid the conflict.

With such a capability installed the number of near misses would drop considerably

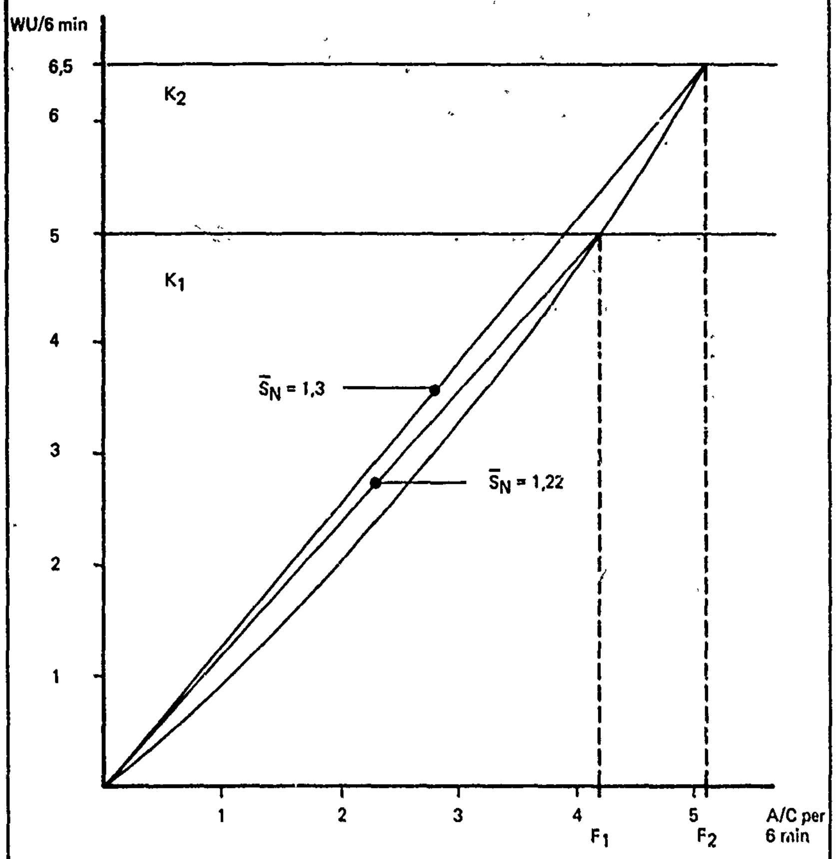

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Fig. 8 Increase of System Capacity versus Usable Gain in Traffic Flow Controllable

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5. The Future of ATC

If we think of years from 2,000 on we must think of an integrated system, integrating

- the ATC-system of the Structure X (Fig. 7)
- the aircraft, by improving flight management and the flight control accuracy
- the ground facilities to improve ground movements and airport capacity.

The year 2,000 seems to be far in the future. But, we have to take into account the tedious implementation procedures. The MLS (= microwave landing system) is to replace the ILS. But, from the decision by ICAO in 1977 to the world wide replacement of ILS in 1995, a time of 18 years is elapsing. To-day we are designing civil carrier aircraft with electronic display capabilities (the Boeing B767 and Airbus A310). So we will have the capabilities to provide a better linkage between flight management and ATC. But, the implementation of respective procedure does deperd on legal implications as well -- and that takes time.

The integrated air traffic control, and management system comprises the following features:

(1) ATC

Greatly automated capabilities concerning

- conflict prevention management,
- clearance calculation and delivery in terms of optimum airspace use,
- generation and preprocessing of flight management and flight control data to be transmitted via ground/air data link or depending on the flight phase via GPS (global positioning system) data link.

(2) Flight Management and Control

Capabilities for on-board processing of ground/GPS derived data to allow

- greater flight control accuracy including flight path and time control,
- better flight management concerning user demands, e.g. flight economy,
- to take over the responsibility to fly within a "clearance path and time slot"; this responsibility is presently lying solely on the ATC-controller,
- enrichment of the environmental scenaria information in the cockpit to allow conflict prevention by the flight crew, especially effective in military aircraft with high manoeuvrability.

(3) Ground Facilities

This does apply more in civil aviation. Means shall be installed to improve airport capacities. The means shall allow:

- automatic deceleration and taxiing control for clearing the runway via high speed exits,
- improved and safe taxiing performance,
- improve information of ground movement control in the TCC (= terminal control center)
- reduction of time lags in ground movement control by TCC personnel.

A research programme leading into this direction is performed by NASA in cooperation with DOT-FAA in their TCV (= Terminal Configured Vehicle) programme, reported by Reeder et al. /4/.

APPENDIX

Airspace Versus Controller Capacity: Quantitative Assessment of Examples

1. General

As changes of sector- or traffic-structures may result in several opposed effects on the sector capacity it is necessary to calculate these effects quantitatively to assess whether the desired objective was obtained or not.

Additionally certain changes will influence the adjacent sectors, therefore requiring a balancing of changes according to all of their effects.

In the follwing three measures are evaluated regarding their effects on control capacity and airspace capacity in a control sector of a given structure.

The influencing criteria and results are presented in the examples. the calculations are emitted; they would exceed the scope of the paper.

Sector specific parameters which are used in the calculations are:

- Number / length of airways
- Portion of climbing / descending traffic
- Mean flying speed
- Mean flying speed of the slower aircraft
- Mean flying speed of the faster aircraft
- Portions of slower / faster aircrafts
- Climbing / descending rates
- Number of flight levels
- Number of intersections
- Angles of airways at the intersections
- Statistical distribution of traffic

Statistical data from an existing sector were used to derive the following sector characteristics.

Sector parameters defined as basis for the examples, (1) in Fig. A-1.

Radar Controller Capacity	$F_{max}(1)$	=	43 aircraft per hour
Airspace Capacity	$F_S(1)$	=	40 aircraft per hour
Average Control Effort	$\overline{S_N}$	=	1.15 WU per aircraft
Sector Complexity	C_S	=	0.123
Average Flight Time	T_F	=	9 min
Average Flying Speed	$\overline{V}$	=	375 kn - 460 kn

2. Examples of Change Measures and their Evaluation

2.1 Speed Control as Change Measure

Speed control can be applied, for example, in two ways:

a) by advising the pilots of the fast aircrafts to reduce speed down to that of the slower aircrafts, or

b) by reducing the number of slower aircrafts in the sector regarded.
(By deviation or flight level allocation)

2.1.1 Reduce Speed of Faster Aircraft when Entering the Sector

If the speed of the faster aircraft is reduced after entering the sector two opposed effects will occur:

- Overtake conflicts will decrease,
- Traffic density in the sector will increase and so does in consequence thereto the conflict probability in general.

Quantitative result of the measure:

Average Flying Speed $\overline{V}$ = 375 kn
Increased Control Effort $\overline{S_N}$ = 1.23
Increased Sector Complexity C_S = 0.145

<u>Decreased</u> RC-Capacity $F_{max}(2)$ = 41 aircrafts per h
<u>Decreased</u> Airspace Capacity $F_S(2)$ = 34 aircrafts per h
(See example (a) in Fig.A-1)

The desired effect was not obtained because speed reduction was not advised before entering the sector boundary, and additionally this advise consumes extra time by routine for each flight (e.g. 3 s ≙ 0.04 work units per aircraft).

2.1.2 Reduce the Portion of Slower Aircraft in the Sector

If the portion of the slower aircraft is reduced the

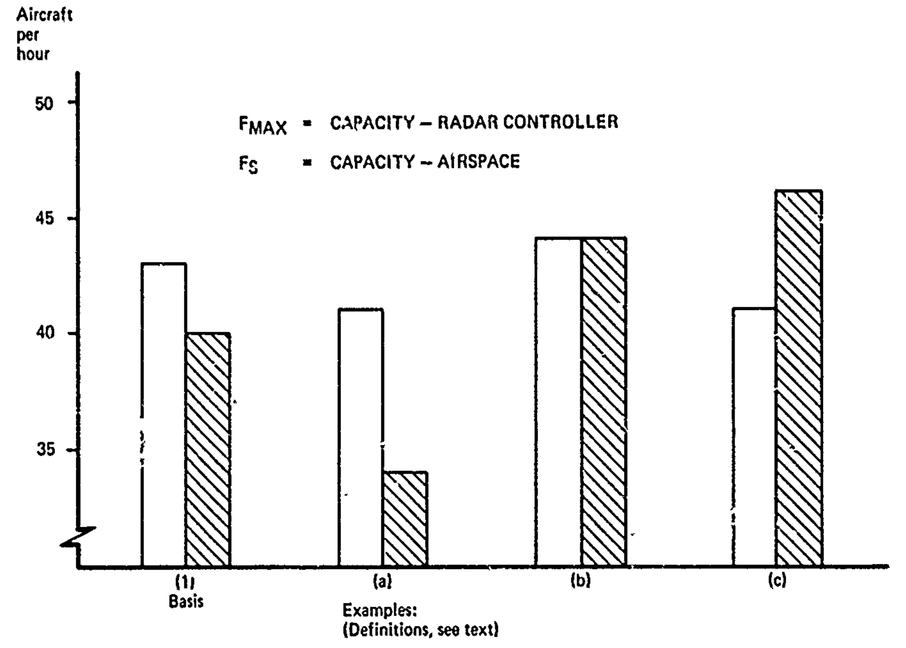
- overtake conflicts will decrease and
- conflicts in climb/descend phases will decrease

Quantitative result:

Average Flying Speed $\overline{V}$ = 460 kn
Decreased Control Effort $\overline{S_N}$ = 1.14
Decreased Sector Complexity C_S = 0.112

<u>Increased</u> RC-Capacity $F_{max}(3)$ = 44 aircrafts per h
<u>Increased</u> Airspace Capacity $F_S(3)$ = 44 aircrafts per h
(See example (b) in Fig.A-1)

The desired effect could be obtained. As airspace capacity was increased by 10 %, the traffic flow now is not limited before reaching the capacity of the radar controller.



Anthropo-technik

Fig. A-1 Quantitative evaluation of change measure referencing control and airspace capacity

MBB

2.2 Separation of Descending Flights from all Others in the Sector

By separating the descending flights from the other traffic, the

- conflict probability while passing the lower flight levels can be avoided, but
- routine work for the RC increases by additional instructions required.

Quantitative results, if 14 % descending flights are assumed in the airspace above Fl 250 and 42 % between Fl 80 and 240:

Increased Control Effort $\overline{S_N} = 1.20$
Decreased Sector Complexity $C_S = 0.108$

<u>Decreased</u> RC-Capacity $F_{max}(4) = 41$ aircrafts per h
<u>Increased</u> Airspace Capacity $F_S(4) = 46$ aircrafts per h
(See example (c) in Fig.A-1)

Assuming one additional instruction of about 8 s duration (≙ 0.11 work units) for each descending flight, the increased routine work results in a higher mean control effort and thus in a decreased RC-capacity.

On the other hand, the airspace capacity is increased by 15 %. This is due to the reduced sector complexity C_S resulting in a reduced amount of conflict solving work to be performed. Safety is increased by decreasing sector complexity.

2.3 Different Sector Complexity Resulting from Traffic Structure Variation

In the Munich UIR traffic samples measured showed great differences in the proportion of on-route to off-route traffic. In a given sector two structures are compared:

a) 100 % on route traffic

b) 75 % off-route operational aircraft and 25 % on-route traffic

a) Results in: $C_S = 0.048$
$F_S = 100$ overflights per hour

b) Results in: $C_S = 0.125$
$F_S = 40$ aircrafts per hour

In such a case technical means are required to allow a greater portion of off-route traffic without unduely increasing the conflict solution workload on the controller.

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AIR TRAFFIC CONTROL AUTOMATION: ITS IMPACT AND USE IN THE SELECTION AND SCREENING OF AIR TRAFFIC CONTROLLERS

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SUMMARY

Historically, automation in occupational fields result in some changes in job attitudes, workload and task complexity, and personnel selection and training procedures. The recent advancements in automation in air traffic control seem to be following this established trend in that the Federal Aviation Administration (FAA) has uniquely combined the skills of its air traffic, engineering, and personnel research staff to design and construct a radar facility in Oklahoma City to aid in screening appropriate personnel for automated air traffic control.

The approach is based on the idea that limited exposure to the actual automated radar situation in a controlled and measured environment will lead to the identification of persons who possess the skills and attributes necessary for success in automated air traffic control jobs. The evaluation process consists primarily of computer-derived measures as well as rating scales based on expert observation. Manipulation and statistical processing of the data are achieved by means of a computer-based data management system. This paper discusses the impact of automation in air traffic control on personnel screening and focuses on the mathematical and technical aspects of the computer software/hardware configuration and the derived performance measures as they are currently being developed.

The evolution of current complex occupations, such as air traffic control (ATC), has inevitably led to the use of recent advancements in automation. The literature related to man's interaction with machines has shown that automation usually tends to create a new set of personnel needs. For example, job attitudes are often affected as a result of automation. Workload and the complexity of work behavior are affected in the process of converting manual tasks to automated tasks. However, perhaps the greatest impacts of automation in an occupational field are in the area of employee selection and employee training. Many potential personnel shortcomings can be prevented if selection and training procedures are developed that accurately reflect the tasks involved in the new automated procedures.

The purpose of this paper is first to review briefly some of the pertinent research conducted by the Civil Aeromedical Institute (CAMI) on the personnel needs noted above for air traffic control specialists (ATCS), viz, attitudes, workload and complex work behavior, and vigilance and monotony, and then to cover in some detail employee selection procedures and employee training procedures that use a new, automated ATC environment. The main emphases of the paper are (i) a detailed description of the newly developed Radar Training Facility (RTF) at the FAA's ATC Academy in Oklahoma City and (ii) a description of how the facility will be used to prevent later personnel-occupation mismatches by evaluating the performance and characteristics of the trainees in an automated training environment and screening out those individuals who do not demonstrate potential to become successful at automated ATC work.

The Impact of Automation on ATCS Attitudes, Workload, and Vigilance.

Work Attitudes. Past studies have demonstrated that successful air traffic controllers seem to enjoy the challenging, fast-paced, and constantly changing nature of automated radar ATC work. They also view their profession as having a considerable degree of prestige. Negative job attitudes expressed by successful ATCSs were not related to automation but to management, work schedules, and career progression plans. However, other studies have shown that ATCSs report field training in radar ATC to be the area needing the most change in their work. Training dealing with the automated aspects of air traffic is presently conducted in the field.

Workload and Complex Behavior. The work of an ATCS requires performance on several concurrent tasks. In studies conducted at CAMI, workload and complex behavior effects on task performance similar to that required of ATCSs were assessed. In one study the effects of a perceptual-motor tracking task on monitoring, information processing, pattern discrimination, and problem solving were studied. In general it was found that the tracking task affected a person's performance on all the other tasks, and performance on the tracking tasks decreased as workload in the other tasks increased. Other studies performed at CAMI support the notion that as task complexity and workload increase, task performance decreases. The implications of these findings for automation are clear: If automation results in less complex tasks and a decrease in workload, an improvement in performance would be expected.

Vigilance, Monotony, and Boredom. One confounding factor to the notion that decreases in task complexity and workload result in improved performance is the effects of monotony and boredom. Several studies at CAMI have demonstrated that, in tasks requiring the detection of infrequent events, performance typically decreases as the frequency of the events to be detected decreases. Further, it was found that extroverted persons show a tendency toward increasing lapses of attention, while introverted subjects fail to show any evidence of a decline in attention. Another study on vigilance at CAMI using a visual display that approximated a futuristic, highly automated ATC radar display yielded no evidence of any significant difference between men and women in the decline of alertness as tasks were made more monotonous. From these studies it appears that the decreased workload associated with automation may produce diminishing returns in improving performance once a "baseline" reduction of workload is achieved.

ATCS Automation and Employee Selection and Training. Successful ATCS employees who have made a transition from manual to automated ATC appear to prefer the advantages in the automated environment. However, some prospective ATCSs do not perform successfully in the automated radar environment. Successful employment in the automated radar environment requires that a person possess certain aptitudes, attitudes, motivation, and certain personality factors such as confidence. It is in the interest of the FAA and the prospective ATCS to determine as soon as possible if the prospective ATCS possesses the aptitude, attitudes, and personality factors necessary to cope successfully with the workload in the automatic radar ATC environment. The philosophy of the FAA in regard to this selection process is that the best way to measure these attributes is to place the prospective ATCS in an automated laboratory environment and perform a systematic, objective appraisal of the person's potential. To this end the FAA has constructed a Radar Training Facility (RTF) at the FAA Academy in Oklahoma City, Oklahoma. The training/screening process involves a mini-radar training program with rigorous assessment which occurs over a 4- to 5-week period. During this period, the trainee receives basic radar training sufficient to allow systematic evaluation of his or her performance. Those who demonstrate potential to become successful ATCSs are retained and those who do not are screened from the program. To explain this system, the RTF background, positions, system operation, and the evaluation process are described in detail below.

Background. The original simulators used in FAA ATC training were "patches" developed for the operational automated field systems. The "patches" permitted flexible training at designated positions without interfering significantly with the operational positions. Experiences with these prototype simulators resulted in at least two major notions related to using simulation for radar training. First, the value of computer-driven simulation for training purposes was firmly established. Second, several problems associated with using operational field systems in a training mode were identified. An Institute for Defense Analyses (IDA) study on the training of air traffic controllers discussed some of these problems and suggested that a standardized computer-driven program should be established by the FAA to provide basic radar training. The IDA study further suggested that the radar training should be pass/fail to screen out those persons who did not demonstrate the potential to perform proficiently in a radar environment.

In July 1976, engineering requirements were completed by the FAA for a radar training system. During that same month the FAA Administrator approved the procurement and construction of the RTF to be located at the FAA Academy in Oklahoma City.

In October 1977, the FAA completed a program implementation plan that outlined the development and implementation of the RTF. The contract for the development of the computer-driven simulator training system was awarded to Logicon, Tactical and Training System Division, San Diego, California, in January 1978. Groundbreaking for the construction of the new RTF at the FAA Academy was held on December 22, 1977.

RTF Training System and Laboratory Configuration.

The primary objective of the RTF is to closely duplicate the specialized operational environment existing at automated Terminal and En Route facilities as well as have the capability of synthesizing and presenting a wide variety of air traffic control situations. These situations would be based on a reference data base created through scenario programs with a full range of control necessary to establish a realistic simulation of actual aircraft traffic under a variety of conditions.

To accomplish this objective, four independent laboratories are utilized. Figure 1 describes how the laboratories are configured.

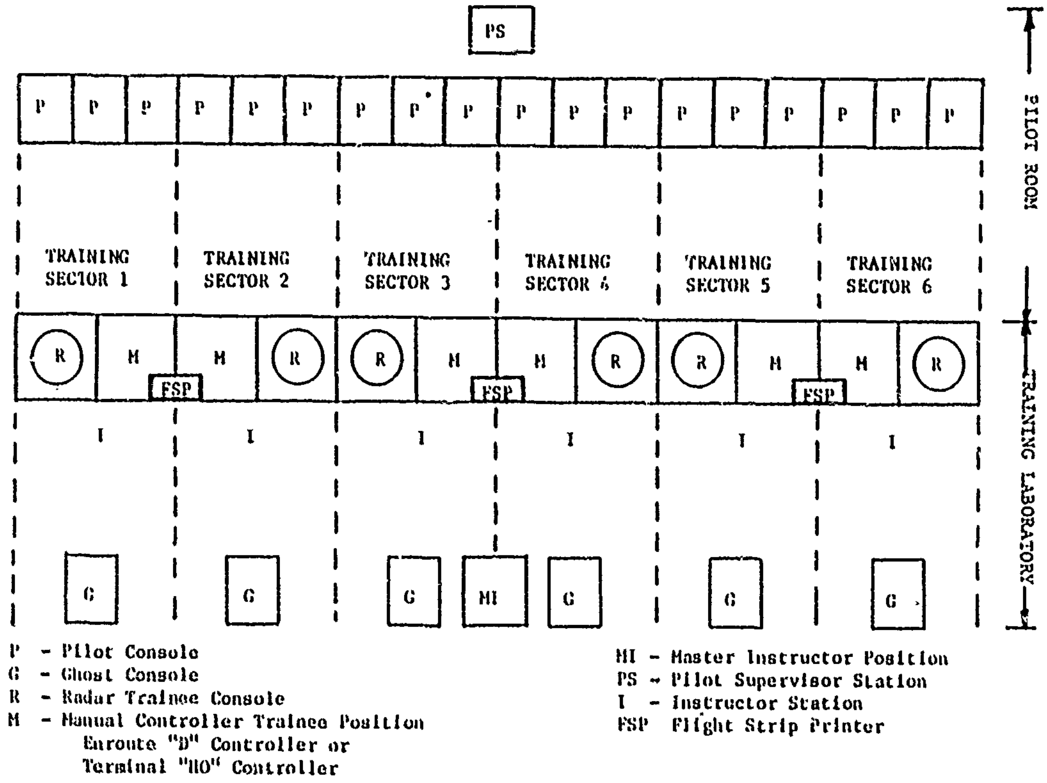

Figure 1. Laboratory configuration.

Positions. There are Trainee positions and Supervisory and Support positions/stations corresponding to each radar training sector. At a "position," the operating personnel have input/output (I/O) equipment access to the system with associated voice communications. A "station" has no I/O equipment access but is equipped with voice communications for monitoring, instructing, and supervisory functions.

Trainee Position.

1. Radar Control Position (R). The R controller positions (six in each lab) have a display console, (PVD) for En Route and (DEDS) for Terminal. They have associated voice communications. The displays and voice communications are similar to those at field facilities. Displays include maps, weather, aircraft position symbols, alphanumeric readouts, and other digital and symbolic data.

2. Nonradar Controller Position (HO/D). The "D" controller for En Route and the "HO" position for Terminal (six in each lab) have the capability of making and accepting handoffs. This position also permits training for manual or nonradar control by using flight progress strips generated by the flight strip printers.

3. Pilot Position (P). Three pilot positions are associated with each sector (18 in each lab). These positions are in a separate room. Each position operator performs at a console with a tabular display and keyboard for data entry with associated voice communications. These operators simulate aircraft pilots during the exercise by actual responses to ATC clearances/instructions.

4. Ghost Position (G). This position is associated with each R and/or HO/D position. There are six ghost positions in each lab. The position console and display are identical to those of the pilot position. The ghost position operator adds realism to the exercise by performing related functions of adjacent centers, terminals, flight service stations, and positions/sectors. Functions include initiating handoffs, accepting handoffs, and generally ghosting functions of other facilities/sectors.

Supervisory and Support Positions/Stations.

1. Instructor Station (I). An instructor station is provided at each sector (six in each lab). The instructor has voice communication with each student and monitors the overall exercise from behind the trainee positions.

2. Pilot Supervisory Station (PS). This position (one in each pilot room) has voice communications for supervising, monitoring, and instructing operation of pilot positions as well as for coordinating activities with the master instructor station and the system monitor position.

3. Master Instructor Station (MI). This position (one in each lab) controls the exercise within the lab. The position has a tabular display, a data entry keyboard, and associated voice communications with each trainee and with each operator of ghost, instructor, and pilot positions in the lab. The master instructor station will permit setting clock time, starting, monitoring, freezing, backing up, replaying, and restarting the exercise as necessary. The position also provides for data recording and analysis of the exercise.

4. System Monitor Position (SM). One position is provided for each lab. The position will have voice communications with two master instructor positions and two pilot supervisor positions. The position will permit computer operation and operational and maintenance monitoring.

Figure 2 describes the system configuration for operating the positions and stations in each laboratory. The training sectors are controlled by a Digital Equipment Corporation (DEC) PDP 11/60 computer with a PDP 11/34 computer serving as an interface between the PDP 11/60 and the operating positions.

The training process involves three sequential systems of operation: (1) SCENARIO GENERATION ---→ (2) REAL-TIME ---→ (3) PERFORMANCE MEASUREMENT. Scenario generation, illustrated in Figure 3, is the non-real-time process of building exercises and evaluation problems for the system. Aircraft characteristics, flight plans, and other essential information of this type are stored in the Universal Data Files (UDF). The exercise is built by first selectively retrieving intermediate files and then creating other intermediate data files from the universal data base through the scenario management program.

The real-time component, illustrated in Figure 4, utilizes the scenario management files to generate the actual radar simulation exercise. The real-time component drives the display at the radar position. Aircraft movement is controlled through the pilot and ghost positions according to the instructions the operators of those positions receive from the controller trainee or, in some cases, from a scenario prompt which appears on the cathode-ray tube (CRT) at the pilot or ghost positions. During the operation of the real-time training exercise, all actions taken during the exercise are recorded.

At completion of the exercise, the computer will analyze the recorded actions to determine violations of separation standards and to quantify other pertinent performance information, such as delay times, in order to evaluate the student's ability to move air traffic "safely and expeditiously." The process of student performance measurement is illustrated in Figure 5.

Table 1 contains a list of the measures to be employed in evaluating the students' performance on a given problem.

Student Evaluation. The general model for the automated method of evaluation (see Figure 6) is based on the use of latent trait theory applied to adaptive testing in this training situation. It is assumed that each trainee possesses a latent ability in radar air traffic control that is being measured inferentially through testing. This general latent ability consists of several subskills. Assessment of the general latent ability offers an overall evaluation (test score), while assessment of the subskills offers a means to structure a program designed to strengthen a trainee in areas where weaknesses are exposed. In this

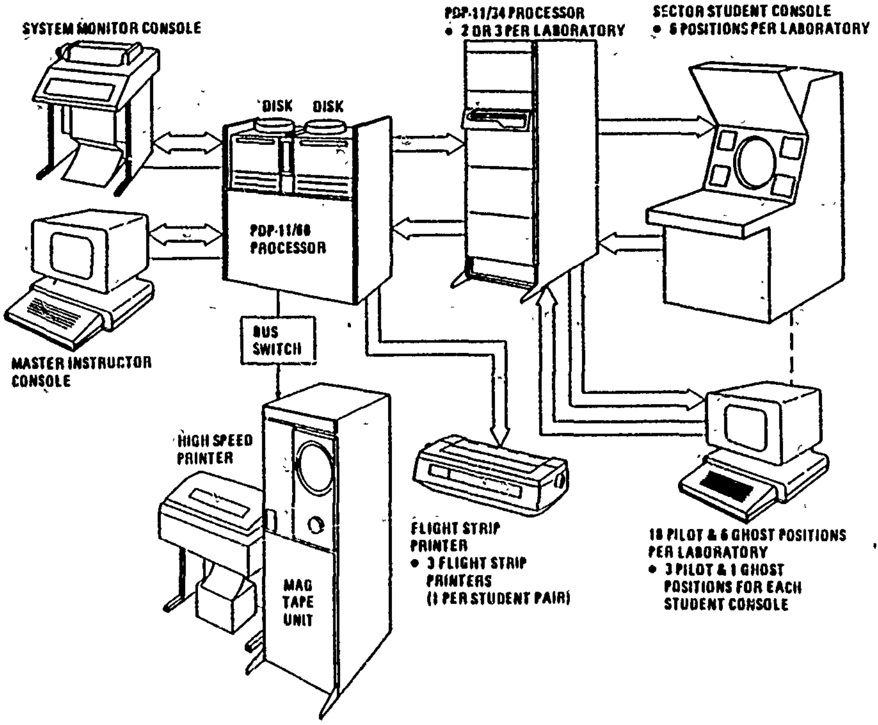

Figure 2. Computer system configuration.

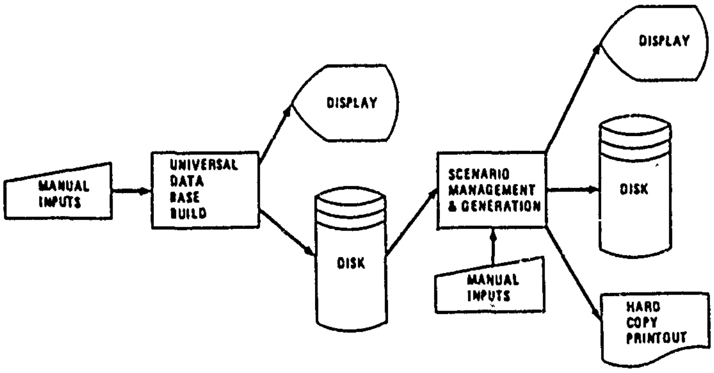

Figure 3. Components of scenario generation.

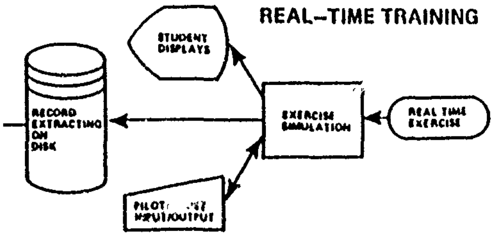

Figure 4. Components of the real-time training system.

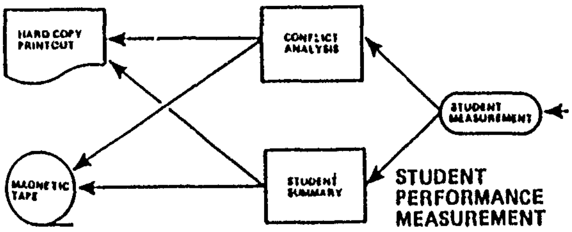

Figure 5. Components of the student performance measurement.

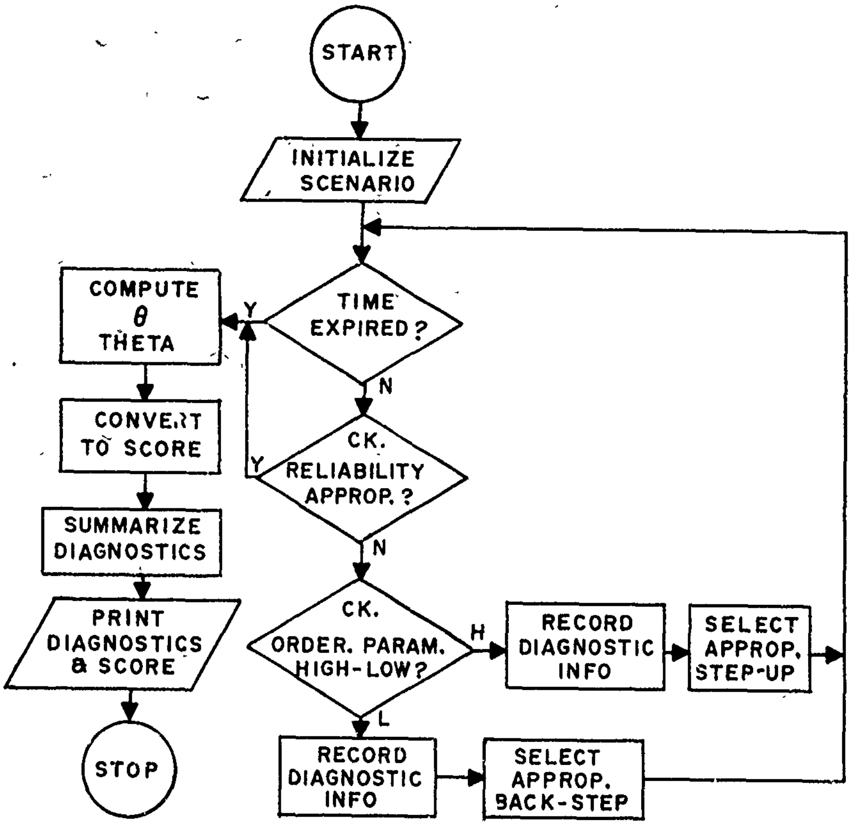

Figure 6. Diagram of the evaluation process.

Table. 1. List of RTF Measures

1. Number of aircraft in the sample.
2. Ideal aircraft time in system (based on filed flight plan).
3. Ratio of the ideal aircraft time in system and the number of aircraft in the sample.
4. Number of completable flights.
5. Data period duration.
6. Number of arrivals.
7. Number of departures.
8. Arrival/departure ratio.
9. Arrival rate scheduled per hour and departure rate scheduled per hour.
10. Conflicts--Terminal (3 nautical miles (NMI)).
11. Conflicts--En Route (5 NMI).
12. Number of delays (start time).
13. Delay time (start time).
14. Number of delays (hold and turn).
15. Delay time (hold and turn).
16. Number of delays (arrival).
17. Delay time (arrival).
18. Number of delays (departure).
19. Delay time (departure).
20. Number of delays (total).
21. Delay time (total).
22. Aircraft time-in-system (real).
23. Number of aircraft handled.
24. Number of completed flights (total).
25. Number of arrivals achieved.
26. Arrival rate achieved per hour.
27. Number of departures achieved.
28. Departure rate achieved per hour.
29. Number of air-ground contacts.
30. Air-ground communications time.
31. Number of altitude changes.
32. Number of headings changes.
33. Number of speed changes.
34. Number of path changes (altitude, heading, and speed).
35. Number of handoffs.

manner trainees can progress as swiftly as their ability allows, while maximizing their ability through immediate feedback and a tailored curriculum.

Training exercises are executed by means of two files. First, a basic problem scenario file will be built consisting of a series of timed events, such as entry of various aircraft on specified air routes with a specified flight plan, a Visual Flight Rules pop-up, or an emergency procedure. A second fixed file will contain a list of addressed events and corresponding parameter information that will be used to determine when the event will be introduced into the basic scenario. At specified times during the execution of the basic scenario, an index will be calculated that measures how well the aircraft are being separated and the potential for conflictions. Based on this information and the parameter information from the events in the fixed events file, an event from the fixed events file will be introduced into the problem. This process will be continued until the trainee reaches a plateau or the scenario time limit expires.

During the execution of the problem, cumulative totals will also be calculated on measures such as conflicts, delay time, number of aircraft handled, number and duration of communication transmissions, etc. This information will be stored on the trainee's training record where it can be retrieved immediately in the form of a printout or reviewed later for the purpose of designing the trainee's curriculum. These measures would also be added to a separate master file that contains summary records for all trainees. The master file will be employed to calculate normative information used in comparing a particular trainee's progress at a particular stage in training with that of all others who have been through the program. Figure 6 is a diagram of the evaluation procedure.

Conclusions.

The prime purpose of automation is to operate and complete a set of tasks more efficiently and more accurately than can be done manually. In the case of ATC work, automation has certainly achieved this goal. However, it is debatable whether automation in ATC work has decreased the controllers' workload, and certainly automation has not decreased the complexity of the tasks involved in ATC work. Further, as more and more automation occurs, ATCSs may be faced with the problem of monotony.

Implementing automation in ATC work is opening a Pandora's box in the sense that no one can put automation back in the box and return entirely to a system of manual control. Automation is an established reality, and whatever side effects it produces must be considered and reasonably resolved. The best solution to automation's side effects is to prevent as many of these effects as possible. The FAA has initiated several programs to achieve this goal. The chief program is the implementation of the Radar Training Facility.

The philosophy behind the RTF is to place the ATCS trainee in the automated environment for a brief and intense period of training and to rigorously evaluate how well the trainee operates. If the workload or complexity of the tasks is beyond or outside of the trainee's aptitudinal capabilities, it is directly observed. The observation is systematic and contains sequential steps. The trainee is given direct feedback at each step in training. If a trainee fails to proceed at a successful rate, the trainee may be screened from the program. Early detection of those who are unable to operate successfully in the automated radar ATC environment accomplishes at least two things: First, it allows the failing trainee to enter another occupational field much sooner, and second, it lessens the impact of automation on ATCS personnel by helping to insure that the persons operating in the automation radar environment are better matched with the job requirements. It is believed that employing this facility as a mini-laboratory for observing ATCS trainee behavior can serve as a major impetus in lessening the impact of automation on ATC personnel needs.

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DATA LINK - THE KEY TO IMPROVEMENTS IN CIVIL/MILITARY AIR TRAFFIC MANAGEMENT ?

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SUMMARY

In recognition of the fact that the definition and development of any major upgrading of the ATC system must be an iterative process, some experimental work is being undertaken both to explore how an air/ground data link might be exploited for future ATC purposes and to determine its possible capacity requirements. In describing much of this work, this paper gives details of the form and functions of experimental equipment built to investigate what is believed to be the major problem area influencing communications improvements - the pilot/link interface.

Details are also given of studies investigating the possible use of the link in transferring aircraft-derived data both to yield improvements in the precision of meteorological forecast data and to enhance the performance of radar-based tracking and conflict-alerting systems. Capacity requirements and the feasibility of realizing a link for these purposes within the next two decades are also discussed. Finally, the paper draws attention to certain factors that could influence the definition and development of a system employing some or all of these features.

Although much of the work is at a preliminary stage, because of the long period required to plan and implement a major system change, it is felt that the results may still be helpful to those engaged in the longer-term aspects of civil/military air traffic management.

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1. INTRODUCTION

In Western Europe, because of essential military needs, there are many areas in which either civil and military aircraft use the same airspace - effectively on a time shared basis - or very busy air routes and military airspaces are juxtaposed. Any lack of precision either in navigation or in the timing of aircraft movements can therefore result in a less then optimum use of a given airspace. Furthermore, considerable reliance must be placed on radar monitoring to ensure that adequate separation is maintained between the two categories of traffic.

Recent forecasts of traffic growth suggest that, within the next two decades, civil air traffic movements in Europe will increase by at least a factor of two (refs. 1 and 2). On the assumption that the current level of military movements will remain unchanged, and if the present estimate of collision-risk is to be maintained or even improved, this projected growth in civil traffic could increase significantly the task of civil/military air traffic management.

At first sight the problem might be ameliorated by a number of measures including the following :

- civil aircraft could be obliged to fly an increasing number of non-optimum trajectories ;
- increased demands might be placed on radar monitoring and short-term conflict alerting techniques ;
- aircraft could be fitted with some form of collision avoidance system (CAS).

These solutions would however fail to promote more efficient operations and, furthermore, would contain continuing, if not increasing, cost penalties for the civil operator ; in consequence they would be unattractive as longer-term measures. Accordingly, it is necessary to consider what other approach might be made to provide scope for improvements in civil/military air traffic management without transferring the penalties to the military users.

During recent years EUROCONTROL, with support from its Member States and other bodies engaged in aviation, has undertaken a series of fundamental studies aimed at determining the degree of precision possible in predicting the trajectories subsequently flown by aircraft. The work has extended to all phases of flight and has covered look-ahead periods ranging from a few minutes up to one hour. Ref. 3 discusses prediction methods and accuracies achievable, particularly in the climb phase, i.e. the most difficult region ; the question of exploiting this capability in future systems of ATC is discussed in refs. 4 and 5.

In these latter references it is suggested that a precise flight planning or trajectory prediction capability would enable a system of control, based on a 'strategic' principle, to be established : it would appear that this type of system possesses two features of possible help in alleviating the problem raised above, viz :

- the volume of airspace required to protect each aircraft can be reduced without increasing the need for human intervention ;
- the ATC authorities will possess a good knowledge of the most likely evolution of the traffic pattern over many minutes ahead, thereby enabling the airspace available for military purposes to be readily assessed.

Compared with present day systems however, any 'strategic' one would most probably require a considerably larger two-way exchange of information between ATC and each aircraft under control and a reduction in control-loop reaction time - a critical factor in reducing the effects of 'blunder' errors or equipment malfunctioning. With an ever increasing trend towards the use of digital techniques and more automation, it is not surprising that an air/ground data link has been proposed to facilitate this exchange, thereby permitting the full capability of this type of system to be exploited (refs. 4, 5 & 6).

In the next section, a brief description is given of the possible requirements for data interchanges to assist both ATC in predicting trajectories, and aircrews in maintaining them. The main purpose of the paper is however to discuss, in the light of some preliminary results from experimental work, the feasibility of using a data link in some of the applications cited, particularly in assisting aircrews in maintaining trajectories and in facilitating meteorological and radar tracking improvements. The final sections of the paper discuss the capacity requirements of the link and consider the feasibility of using ADSEL/DABS in what may be the last step between the present and the ultimate satellite-based system.

Although all aspects of this feasibility study have not been completed, it is hoped that this paper will provide those responsible for the further development of ATC systems handling both civil and military traffic with a range of potential link applications and other information that could be helpful in their future thinking. No attempt is made to define either the total structure or every detailed aspect of an emerging system.

2. PROBABLE DATA TRANSFER REQUIREMENTS

2.1. Trajectory Prediction - General Considerations

If we define the complete time-referenced trajectory of an aircraft as the path that it follows in four dimensions when moving from its point of departure to its destination, then trajectory prediction means estimating either, for some instant in time, the most probable position of the aircraft, or the most probable time at which a given position and/or altitude will be reached.

A range of prediction techniques are available to cover all or a selected part of a flight. Long-term predictions can be made off-line, before take-off, to cover periods extending from several minutes to an hour or so ahead, to assist traffic planning in real time. Once an aircraft becomes airborne, any long-term prediction can be updated in time by means of radar data. Additionally, radar-based predictions can also be made, extending from look-ahead times of seconds up to several minutes, for application in tracking and automatic conflict alerting systems, and in providing direct aid to controllers in their task of maintaining safe separation between aircraft.

The precision of any prediction will depend on a number of factors, e.g. :

- algorithm used ;
- nature and quality of data available ;
- phase of flight and look-ahead time.

In this paper, our interest will centre on the sources of data used to support prediction, the precision of the data and the problem of their transfer, rather than on the prediction techniques themselves.

2.2. Data Requirements for Predicting and Maintaining Trajectories

Table 1 below indicates the nature and availability of information either required by ATC, to make a range of predictions, or made available to pilots to assist them in maintaining a specific trajectory (clearance). It is divided horizontally into four sections to show data currently available before and after take-off together with an indication of the additions that might be made in the future.

To make accurate predictions before take-off would require all of the information shown to be presently available, apart from TAS, together with that expected to be available in the future. Current thinking indicates that the latter might be obtained by a supplement to the flight plan and would therefore not be dependent on the existence of a data link.

The non-availability of the link would nevertheless preclude the automatic transfer of data after take-off, i.e. as listed in the unshaded part of Table 1 and it will be seen later that this could have an impact on the quality of the meteorological information available for the prediction, the degree of time synchronization possible between aircraft and the ATC centre, and on the pilot's ability to maintain his clearance. As a consequence, the precision of any long-term prediction would be reduced, and its value as an aid to traffic planning diminished correspondingly.

Precise short-term predictions for aircraft in flight can range from the simple track extrapolation - based solely on radar-derived data - to more complex ones employing the route and meteorological data as available before take-off. The actual level of data used will depend on the application and the phase of flight.

With these types of prediction, the position of the aircraft (at the instant of prediction) and its horizontal speed-vector are derived by filtering or 'tracking' the preceding sequence of positional data. Vertical speed can be derived in a similar manner from Mode C data.

Because the tracking process serves to remove radar 'noise', which may result from a number of causes, it also restricts the rapid detection of manoeuvres, e.g. heading or vertical speed changes, and thereby gives rise to problems in short-term predictions. This is another area in which aircraft-derived data show considerable promise and this application, together with the exploitation of the other parameters given in the unshaded part of Table 1, are discussed in subsequent paragraphs.

2.3. Data Transfers

Fig. 1 shows, in schematic form, the data paths necessary to achieve the transfers introduced above; it will be noticed that communications are included. This has been done because once the availability of a link is assumed, both the nature and the quantity of information to be transmitted by R/T can be reappraised. Furthermore, the organization and handling of communications must also be taken into account when the requirements of the link terminal in the aircraft are considered, as will now be discussed.

3. THE AIRBORNE LINK TERMINAL (ALT)

3.1. General Considerations

In this section a description is given of some experimental hardware that has been constructed and is now being evaluated in an attempt to determine the possible role and form of the link/pilot interface, the prime function of which is to provide pilots with a display of the relevant information being transmitted to them by means of the link.

3.2. Historical Development

In commencing the development of the ALT it was necessary to consider two important questions :

a) Assuming the existence of a data link, how might the control of air traffic be modified to take advantage of such a facility?

b) Taking due note of the effect of any such changes on the total communications required between ATC and aircraft, how should the communications be shared between the data link and R/T?

In consequence, two main roles have been proposed for the equipment :

i. to assist the pilot in maintaining accurate trajectories ;
ii. to facilitate improvements in two-way communications by minimising the need for R/T.

Following preliminary studies, some initial proposals were made for the functioning of the ALT and its display layout, the latter being revised following demonstrations, by means of simple simulations, to various IFALPA and IATA members and airline staff. The DFVLR Institute, Braunschweig, then investigated the problem of constructing such a device and subsequently developed and built prototypes and an engineered model - the latter being the subject of the evaluation (ref. 7).

3.3. ALT functions

3.3.1. General

Fig. 2 illustrates the ALT which comprises three elements :

- Electronic Display Unit (EDU)
- Miniature Printer
- Computer/Interface

The first two of these items will be mounted on the flight-deck and serve to provide the pilot with the ATS information appropriate to his flight. This can be grouped, for convenience, into four broad classes :

i. long messages, such as initial clearances and advisory (e.g. ATIS) information ;

ii. short messages of a semi-tactical or procedural nature e.g. push-back and take-off clearances ;

iii. details of VHF/VOR frequencies and other navigational data, required for the flight and updated essentially, in accordance with along-route progress, i.e. largely on a way-point by way-point basis.

iv. indications or warnings, as derived by ATC ground monitoring, to advise the pilot that the aircraft is seen to be diverging from its clearance (laterally, vertically and along-track(time)).

The printer copies all messages arising under classes (i) and (ii) above. Classes (ii)-(iv) appear in specific areas on the EDU. This latter unit is also equipped with eight special functions keys (SFK's) which serve to generate short messages of a preformed nature as required either in conjunction with the operation of the link or to request, from the ground, the transmission of certain information, e.g. a message repeat or a request for destination weather. The functions listed above have been defined largely as a basis for initial evaluations. Adequate flexibility has been incorporated in the ALT design to enable lay-out reconfigurations to be made in the light of results.

3.3.2. Divergences from clearance

The provision of means for displaying automatically an aircraft's divergence from a predicted position along its cleared flight path (class (iv) above) is intended primarily as an aid to communications, rather than for navigation and, since it is such an important application of the link, merits further description. Fig. 3 illustrates the form of display being examined. Effectively, it indicates to the pilot, in a simple pictorial way, how ATC 'sees' him relative to his clearance and thereby enables him both to visualize how his situation compares and to understand how it is evolving, relative to his planned flight.

With the present equipment the pilot is advised when :

a) his altitude or lateral position is observed beyond given limits from that expected; e.g. ± 300 ft, ± 500 ft and ± 3nm, ± 5nm respectively;

b) a given difference in time is detected between the predicted value and that actually elapsing during progress along route, e.g. ± 0.5 min with increments of 0.5 min.

With improvements expected in both navigational capabilities and procedures, the probability of lateral limits (or boundaries) being crossed must be very low, irrespective of the phase of flight. Whenever a deviation is detected, however, the pilot will be given a very early indication and thereby helped in avoiding the possible build up of a gross error as could arise from 'blunder' or an undetected equipment malfunction.

Figs. 4 and 5 are examples of the type of error that can arise; both occurred during a short exercise aimed at determining the reaction time required for a pilot to regain route centre-line, following a request to do so after being observed crossing a 4 nm threshold. In fig. 4 the wrong route was being followed; the error continued to develop while pilot disbelief was gradually broken down. Fig. 5 shows a deviation continuing to increase due basically to a language problem; neither pilot nor controller was speaking in his mother tongue and, in consequence, the pilot had great difficulty understanding that he was off-track and required to take corrective action.

During the cruise, the vertical indications can serve a purpose similar to that of the lateral warnings. Similarly, in climb/descent, they could serve to reveal differences between intended and actual performance, e.g. incorrect speed law selected. Different threshold values could of course be considered. No attempt has yet been made however to establish, with airlines, the feasibility of deriving suitable crew procedures to compensate for differences in climb performance as might arise from incorrect data being available in respect of mass, temperature and wind-vector, etc.

The along-track progress error indicator serves essentially to advise the pilot in accordance with (b) above and thereby provides him with the greatest possible time to effect small compensations by speed adjustment. Its use would be particularly appropriate during the cruise phase and would help to ensure the precise arrival of an aircraft at some point/time relating to its destination, to assist approach sequencing.

As stated earlier, these indications are all of an advisory nature. Nevertheless, in complying with them a pilot could expect to proceed without the need for re-clearances. Furthermore, if all aircraft were close to the 'centre' of their clearance at the time of a major control system failure, the traffic pattern could continue to evolve safely and thus provide a maximum period of time for the system to be restored.

3.3.3. Time synchronization

Any system exploiting trajectory prediction techniques in which along-track progress and the start of manoeuvres must be precisely time-referenced will require a high degree of time-synchronization between centres and aircraft, otherwise significant positional errors could result, particularly in the vertical plane. Although it is believed that a gradual improvement has taken place since 1972, when a data collection showed that 95% of aircraft maintained flight-deck time to within 2 min. of GMT, provision has been made for the ALT indication of time to be synchronized, on request, with centre-time.

3.4. Initial acceptance tests

During August, 1979, the ALT was installed in an A 300 B Airbus flight simulator and subjected to an 'acceptance test' by three crews of Lufthansa (the German national airline) prior to a more detailed evaluation. Two-way data and R/T exchanges were carried out in accordance with agreed flight scenarios ; pilot reaction was assessed by means of a questionnaire.

Following this acceptance the equipment will be modified to provide :

- an aural warning whenever the display of data is changed in any way;
- a readout on the EDU of all messages, irrespective of their length.

Although only a small number of pilots participated in these tests, their overall reaction was most favorable and this fact, together with the modifications being planned, provide grounds for some cautious optimism in respect of the future evaluation of the ALT.

3.5. The ground link terminal

Studies of the ground link interface problems will not be commenced until the ALT has been more fully evaluated.

4. METEOROLOGICAL ASPECTS

4.1. The problem as seen today

4.1.1. The effect of meteorological errors on prediction accuracy

Assuming a constant IAS/Mach, a wind-vector change will modify an aircraft's ground speed by the component of this change along its route, irrespective of flight phase. Thus the precision of any prediction of along-track progress, based on the use of wind-vector data, will be directly related to, and probably limited by, the quality of the wind data used.

Temperature errors have the most significance during the climb phase. From ref. 8 it will be noted that, during a climb to 25,000 ft, a 1°C error in temperature gradient may, depending on conditions, result in a prediction error of around 300 ft at the top of a climb.

4.1.2. Contributory factors

To many, a lack of precision in current meteorological forecasts appears to be a factor that renders futile any attempt to exploit longer-term prediction methods for ATC purposes.

This view is perhaps understandable and it doubtless arises from three factors :

- the variability of wind-vector and temperature in Western Europe (worst cases 55 kt 2 sigma and 5.5°C 2 sigma respectively over 6hr period);
- the limited number of measurements made daily in the upper air on which forecasts are based (twice daily from 30 or so stations in Western Europe);
- the coarse resolution of forecast data, currently supplied to meet present ATC requirements (typically 4 six-hour forecasts daily, on a grid mesh of 300 km centered at 8 pressure levels).

Whereas we have no power to change the first of these, the exploitation of aircraft-derived data appears to show considerable promise in overcoming the limitations of the last two, as will be discussed below.

4.2. Sources of wind/temperature data

Western European ATC Services currently use meteorological forecasts of wind and temperature data that are derived by the Regional Meteorological Centre from twelve-hourly (H hour) radiosonde measurements. These are made internationally at 0000 and 1200 hours by a number of upper-air sounding stations. The measurements are processed to provide 'field actuals' in the form of grid point data (usually on a 300 km mesh) from which wind and temperature forecasts in a similar format are derived for the 6 hr periods commencing at (or centred on) H + 12 and H + 18 hr.

4.3. Data link potential

4.3.1. The precision of aircraft-derived data

During the last four years a number of related studies have been carried out to :

a) determine precise techniques for predicting the along-track progress of aircraft in cruise ;

b) demonstrate the potential of a data link as a means for enhancing the quality of wind/temperature data for use in ATC centres.

From an early stage, the meteorological aspects of the work have been undertaken in close collaboration with the Regional Meteorological Office, Bracknell U.K. Radar predictions have been assessed both with and without pilot cooperation. Results from some of the prediction work are summarized in fig. 6. They give a guide to the relative accuracy of both wind-source data and different prediction methods. Temperature measurements made on board aircraft have generally been in close agreement with radiosonde measurements (approx ± 1.5°C 2 sigma).

4.3.2. The exploitation of aircraft-derived data

Because of its precision in measuring change of position, it would not have been unreasonable to have assumed that an INS system would provide a good indication of wind-vector. This has nevertheless been confirmed and the Meteorological Office has since been examining how to accept aircraft data, which are asynoptic, in order to correct or update the background fields (dynamic data bank). Figs. 7 & 8 respectivily give a typical temperature background field and the locations from which aircraft data were obtained for use in its updating. The changes resulting in the original background field (fig. 7), following the introduction of the aircraft data, are shown in fig. 9. Fig. 10 shows the result of taking similar steps with the wind background field. It will be noted that in both these cases the resolution of detail is far more appropriate to the 50 km mesh as denoted by the wind direction arrows.

Because no data link capabilities exist at present, the actual data inputs were provided by means of a number of recordings made by certain European airlines during one day in June, 1978. This date was chosen to minimise the risk of high wind variability and therefore only small differences in the wind-vector field were expected. Work is continuing to determine the gain in precision that can be achieved. Without discussing these experiments further, it can be concluded that a data link could increase enormously the provision of precise meteorological data for use by the Meteorological Services, particularly at the geographical locations and in the altitude bands where traffic density is greatest. In consequence, ATC could expect to benefit from forecasts more closely matched to future needs as a result of :

- increased precision of data ;
- more frequent updates ;
- smaller grid dimensions, e.g.50 km could be meaningfully used ;
- analysis matched to specific flight-levels (e.g. FL's 310, 330 and 350 instead of 300 and 250 mb etc.) ;
- provision of more altitude bands.

Collectively, these changes should make it possible to improve considerably the quality of forecast data. A halving of the RMS errors in today's forecasts of both wind and temperature would seem to be a reasonable target.

4.4 Duplication with ASDAR

At first sight there might appear to be some duplication between ASDAR (Aircraft to Satellite Data Relay) and any other proposal to transfer aircraft-derived data by means of a data link. Although perhaps similar in principle it is thought that, in practice, they would be complementary, for the following reasons. In a description of ASDAR (ref. 9), it is stated that the ASDAR system is a geostationary satellite-based system serving to relay aircraft-derived data, at precisely timed intervals (approx. 400 seconds) from a number of large suitably equipped aircraft, to a Data Acquisition station. The aircraft being fitted with the appropriate transmitter and aerial are wide-bodied jets flying primarily on intercontinental routes. These will thus provide data from a large part of the earth's surface including oceanic and sparsely populated regions. In using an alternative link, e.g. ADSEL/DABS, data could be acquired at any point within the coverage of the link. In an area such as Western Europe this would complement ASDAR in the following ways :

- it could provide vertical profiles in the vicinity of airports as a much faster data rate, e.g. every 10 seconds during climb ;
- it would not be restricted to routes flown by ASDAR equipped aircraft and would thus cover a much wider range of altitudes, locations and times of interest to ATC ;

- in conjunction with ground-based radar measurements of track and groundspeed, measurements of TAS and heading transferred from non-INS equipped aircraft might also yield useful wind data.

One major advantage of the data link approach is that, in using ADSEL/DABS, the carriage of other transmitters etc. would be unnecessary. Furthermore, the problem of data collection/exploitation may also be simplified.

5. SURVEILLANCE AND MONITORING

5.1. General Considerations

In today's radar tracking and radar-based short-term conflict alert (STCA) systems essential velocity vectors are derived from sequences of positional data - range/bearing (Rho θ) and Mode C ; the precision or quality of these vectors is degraded both by measurement 'noise' in the positional data and by corrupted or missing data. Filtering or 'smoothing' is often employed in an attempt to minimise the effect of data imperfections but this measure tends to delay or obscure the detection of any real change in conditions, e.g. as may occur during aircraft manoeuvres. On many aircraft, particularly modern commercial ones, velocity vector data and even acceleration data are readily available. If these parameters could be sampled, say at 10 second intervals, and transferred by data link, it is clear that they would be far superior in precision to those derived today from imperfect positional data.

If however the link is established by means of ADSEL/DABS (this possibility is discussed in the next section) then, for various reasons, an improvement in the precision of bearing information should be expected and, furthermore, greater consistency in Mode C data might also be feasible. Despite these improvements, it is still believed that aircraft measurements of roll-angle and vertical speed could be of considerable assistance in tracking and STCA applications, as will now be briefly discussed. For successful exploitation, a very large number of the aircraft will be required to provide these parameters.

5.2. Possible tracking improvements

During mid 1980 it is intended to recover, on-line, ADSEL Rho θ data together with corresponding sets of data measured on board particular aircraft. In anticipation of this, Manchester University has undertaken some preliminary work to assess the significance of each aircraft parameter in tracking applications and to develop an experimental tracker (for use in the horizontal plane) to exploit those thought to be most effective.

Much of the work done to date is described in ref. 10 and it shows that provided measurements of groundspeed (or wind-corrected TAS) can be obtained from an aircraft to within ± 25 kt of the actual value, these can be used to enhance the precision of velocity and position estimates ; in particular they can enable the transient response of the tracker to be improved.

Another outcome of the study was a proposal to use measurements of roll-angle to improve manoeuvre detection in the horizontal plane. The method proposed employs a first-order tracker for steady state conditions, and a second-order one for use immediately a significant value of roll-angle e.g. ± 3°, is detected. To assess the improvement possible, two experimental trackers have since been constructed; one based on a first-order Kalman filter and representative of the best currently available for multi-radar tracking, the other, employing a second-order Kalman filter and accepting an input of lateral acceleration (roll angle). Both have been driven with the same positional input data and the results compared. Fig. 11 shows their respective responses to identical radar plot data from a partial orbit. Although these are very preliminary results, it appears that the availability of a roll-angle signal could be extremely helpful in the detection and tracking of manoeuvres.

5.3. Short-term conflict alert

Short-term conflict alert facilities are being increasingly incorporated in advanced systems of control to provide a back-up or 'safety net' to controllers who may be working under very considerable pressure. A number of different forms of 'safety net' exist, both in Europe and in the U.S.A. ; a typical development is discussed in ref. 11. In an ATC system the essential feature of this type of facility is to provide automatically an indication each time a conflict situation is either detected or predicted as being likely to occur within a short period of time. The design requirements of individual safety nets will be influenced by the action that is required once a conflict has been detected. Accordingly, varying degrees of importance may be placed on parameters such as the probability of detecting a conflict, the extent of warning time given and the false alarm rate.

Whatever the design criteria, however, it is clear that the quality of the data employed will have a direct bearing on both the performance of the STCA and on the degree of confidence placed in any alert generated.

As with tracking, the greatest benefits of aircraft-derived data are likely to result during aircraft manoeuvre ; roll-angle and ground speed assisting predictions in the horizontal plane, and vertical speed ($\dot{Z}$) - predictions of climb and descent. Fig. 12 helps to illustrate the reason for the usefulness of the $\dot{Z}$. It gives aircraft measurements of altitude and vertical speed together with corresponding values of Mode C data obtained in an ATC centre where, as is normal practice, a value equal to the last correct reading has been substituted in the place of any missing plots. No attempt is made to show a value of $\dot{Z}c$ as derived from Mode C, but whatever the method of filtering used, a reliable value would be considerably delayed on that received from the aircraft, which closely follows the descent rate calculated from consecutive readings of pressure altitude.

6. FEASIBILITY

6.1. Principal factors

The feasibility of using a data link at some future date, for the applications discussed above, will depend on a variety of factors. In this paper, discussion is restricted to a number of technical points, as follows :

- timescale and candidate link systems ;
- the capacity required in both directions ;
- the capability of individual aircraft to provide data ;
- future aircraft AIDS fits ;
- the expected performance of ADSEL/DABS ;
- other aircraft system developments.

6.2. Timescale and candidate link systems

Apart from the provision of meteorological data, the link applications discussed above will only enable major changes to be introduced in the ATC system when a majority of aircraft are 'link' equipped. Accordingly, an installation programme spanning 10-15 years will be necessary if expensive retrofits are to be avoided. Thus, if the system is to be modified before the turn of the century, two conditions must be met by the mid 1980's :

- requirements for changes in aircraft installations must be specified ;
- the data link system must be defined.

Although the transfer of data, as envisaged, could be accomplished with virtually any type of link, for the timescale under consideration ADSEL/DABS must be regarded as the most likely candidate and its use will be assumed throughout the remainder of the paper. A major factor in its favour is that it could be introduced as an evolutionary development of the present SSR equipment.

6.3. Ground/air and air/ground capacity requirements

6.3.1. ADSEL/DABS data transmission

In principle, this can be thought of as an extension of the present transfer of Mode C data in so far as data blocks of 56 or 80 bits are incorporated in the interrogation and reply messages. Full descriptions of this system are given in Papers 75-77 of this symposium.

6.3.2. Ground/air loading

Data transfers from ground to air will be greatest at times close to take-off and landing. Based on a scenario covering a flight of approximately 35 minutes in duration, and including 20 min and 5 min for the periods prior to and after the flight respectively, it is estimated that an average of three 80-bit data blocks per minute should be adequate to meet the needs of message classes (i) (ii) and (iii), as defined in 3.3.

The class (iv) messages (deviations from clearance can be conveniently transmitted in each Surveillance or Comm 'A' message ; only 12 bits are required. Covering three axes, this appears to represent a very efficient alternative to the use of 16 bits as proposed for an altitude-echo(AL-EC) function.

6.3.3. Air/ground loading

On the assumption that there will be no requirement for the return transmission of critical messages received from the ground, the loading on the down link for pure communications is likely to be very small. Using the same method of estimation as in 6.3.2., it amounts to approximately twenty SFK operations per hour and is thus insignificant when compared with the possible loading from aircraft-derived data.

Table 2 indicates the range of functions that could be acquired from a typical INS equipped wide-bodied jet ; the six different formats given have been selected for some experimental work involving Tristars of British Airways. For initial loading estimates, an average of 1.2 56-bit data blocks per interrogation appears to be a reasonable figure.

6.4. Individual aircraft capabilities

The availability of the parameters given in Table 2 depends of course on both aircraft equipment fit and the sophistication of its AIDS (Airborne Integrated Data System). Many new commercial aircraft are being fitted with AIDS systems either equivalent or superior to that defined in ARINC 573 and this level of fit is ideal for use with a data link. Although present ADSEL transponders require a special interface to acquire data from AIDS systems, future developments should obviate this need.

6.5. Future civil air traffic and AIDS

Present aircraft data recording capabilities depend on the regulations of the country in which the aircraft is registered; even in Western Europe there are considerable differences in minimum requirements. As might be expected, minimum requirements are often sub-divided to cater for different weights and/or operating altitudes. In an unpublished study report on work undertaken for EUROCONTROL in 1977, SFIM (Société de Fabrication d'Instruments et Mesure) Paris, estimated that, in 1980, around 30% of all aircraft operating above FL 250 will be equipped at least to ARINC 573. In climbing from FL 125 to FL 250, they will be outnumbered 3 to 1 by aircraft with little or no AIDS capabilities suitable for interfacing with a data link.

By 1990, 70% or more of the aircraft operating above FL 250 will carry suitable AIDS and some improvement can be expected below this level. However, before widespread use can be made of aircraft data, a revision of regulations would seem desirable to ensure that 'business jets' (operating beyond FL 250) and other aircraft operating in the range FL 120-250, meet a minimum level of requirements. Although there is an increasing use of AIDS on military aircraft to assist engine life/performance monitoring, there appears little likelihood of these systems providing data outputs for ATC purposes.

6.6. ADSEL/DABS performance

In proposing the use of the ADSEL/DABS data link capability, it has been assumed that the system will be developed to operate compatibly with present SSR systems and provide a high degree of performance, even at ground level, in the vicinity of major airports. As regards capacity, there seems to be little information to indicate how far the link can be loaded before the prime surveillance function is significantly impaired. Discussions with experts from the Royal Signals and Radar Establishment, UK, have indicated that the loadings proposed in this paper are well within the capacity expected to be available and, in consequence, some other applications could even be considered.

6.7. Related developments in other airborne systems

As aircraft systems become more numerous, and the number of control units and displays on the flight deck grow likewise, considerable attention is being directed towards the development of techniques for sharing common facilities. Typical examples emerging are electronic flight instruments (ref. 12) and digital frequency/function selection facilities. This trend is likely to be followed on many of the aircraft to be constructed during the next twenty years and any future realization of the ALT functions would most probably follow this line; for example, the display could be combined with electronic flight instruments, and the printer/SFK's with the printer/keyboard used for RNAV and/or ACARS (ARINC Communications Addressing and Reporting System).

7. SYSTEM DEVELOPMENT CONSIDERATIONS

7.1. General

A move from the present SSR data transfer capability (Mode A and Mode C) to that afforded by ADSEL/DABS offers great scope to ATC systems designers for the two-way interchange of data. In the foregoing discussions on 'link applications' it has really been a case of indicating how this increased capability might be used advantageously for ATC purposes, viz :

- for communications, to improve quality and response ;
- to transfer ground-derived data for use in overcoming limitations in airborne elements or sub-systems ;
- to transfer aircraft-derived data for use with ground-based elements.

The notion of an increase in the transfer of data between airborne and ground elements, as a means of enhancing the overall performance of the system of control, and the higher traffic densities that might result, give rise to many other questions. Two points thought to need very early consideration are :

- system definition ;
- performance assessment and checking.

Accordingly, brief discussions on these topics follow below.

7.2. Definition of requirements

In the U.S. the development of ADSEL/DABS has reached such an advanced stage that :

- in 1981, it is likely that all carrier airframes will be wired for, and probably equipped with, ADSEL/DABS transponders ;
- in 1985, the carriage of this type of transponder may become mandatory.

In addition, the basic signal formats of the system, including the data blocks, have been defined to a stage at which they could be submitted to ICAO within the near future. The exploitation of the data blocks is however a very different matter - it is not just a question of two-way digital data interchanges but rather one of system philosophy. Any changes introduced are likely to serve to bridge the gap between the performance of today's systems and that expected from a largely satellite-based system of the future.

Despite the magnitude of this task, because of the developments taking place in aircraft systems (see 6.7), there is a case for the possible future requirements of ATC being made known to operators as early as possible in order to avoid the unnecessary 'building out' of any features that may be required subsequently. It is also believed that operators would prefer a 'total requirement' for changes together with an indication of the operational benefits likely to result from them. This would be of more value in their long-term planning than a series of small requirements, e.g. the application of the down link for STCA purposes followed, a few years later, by one or two up-link applications giving only minor, if any, operational advantages.

7.3. Performance assessment and checking

If traffic densities may be increased as a consequence of exploiting the link it is perhaps worth considering whether the link can also assist in future tasks of assessing and maintaining the level of safety in the system. A guide to system performance might be obtained by monitoring :

- the extent to which deviations from clearances occur (navigation);
- signal reliability/error rates (communications).

A number of factors will govern any measurements of these system parameters, e.g. signal environment, airborne equipment and surveillance performance ; detailed analyses would be required to isolate the reason for any limitation or deterioration in system performance. Tasks of this nature can be greatly facilitated if details of aircraft type, registration, navigation fit and operator are readily available.

Because some decisions may be taken in the very near future with regard to ADSEL/DABS message formats and to the criteria for code allocations, a plea is made at this early stage for this need to be borne in mind and, hopefully, accommodated in an efficient manner.

8. CONCLUSIONS

A doubling of European civil air traffic over the next twenty years could considerably increase the problem of civil/military air traffic management and also necessitate improvements in the present system of control.

During recent years a number of applications of a two-way air/ground data link have been cited as means likely to facilitate an upgrading of the ATC system to achieve : improved airspace utilization, more economic aircraft operation and a raising of its overall level of efficiency. Experimental work is now under way to demonstrate the feasibility of exploiting the link in a number of these applications and to estimate the capacity required, in particular, when it is used in :

- improving communications and, indirectly, the overall performance of aircraft navigation;
- enhancing both the quality of meteorological data (in particular, for prediction purposes) and the performance of radar-based tracking and STCA systems.

Initial results show considerable promise and although they must be validated before any firm conclusions can be drawn, they indicate that the capacity required for these purposes should be well within that expected from ADSEL/DABS.

They also highlight however that if a fully effective link is to be realized in an economical manner within the next two decades, early action will be required to :

- define the link to be employed;
- agree the requirements for changes in aircraft installations.

Because of the current pace of developments in both ADSEL/DABS and aircraft system integration, any significant delay in this action could prove very costly to ATC and aircraft operators alike.

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10. ACKNOWLEDGEMENTS

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11. DISCLAIMER

The views expressed in this article are those of the author - they do not necessarily reflect the policy of the EUROCONTROL Agency.

12. ABBREVIATIONS AND SYMBOLS USED

A/C	: Aircraft
ADSEL/DABS	: Address Selective/Discrete Address Beacon System
AIDS	: Aircraft integrated data system
ALT	: Airborne link terminal
ARINC 573	: Aeronautical Radio Inc. specifications for AIDS
ASDAR	: Aircraft to satellite data relay
ATC	: Air traffic control (in general)
ATS	: Air traffic services
DFVLR	: Deutsche Forschungs - und Versuchsanstalt für Luft - und Raumfahrt
EDU	: Electronic display unit
FL	: Flight level
GMT	: Greenwhich mean time
IAS	: Indicated air speed
IATA	: International Air Transport Association
ICAO	: International Civil Aviation Organisation
IFALPA	: International Federation of Airline Pilots Associations
INS	: Inertial Navigation System
mb	: Millibar
MODE C	: Pressure altitude transmission
RMS	: Root mean square
RNAV	: Area navigation
R/T	: Radio telephony
SSR	: Secondary surveillance radar
TAS	: True air speed
$\dot{z}$	: Vertical speed
$\dot{z}_c$	: Vertical speed derived from Mode C data.

DATA AVAILABILITY		DATA APPLICATION	
		ASSISTING PREDICTIONS	ASSISTING ADHERENCE TO CLEARANCE
BEFORE TAKE-OFF	PRESENT	CENTRE TIME, ROUTE, CRUISE ALTITUDE & TAS, WIND/TEMP. FORECAST, A/C TYPE	
	FUTURE ?	A/C VERSION (INCL. POWER PLANT) TAKE-OFF MASS, CLIMB/CRUISE SPEED LAWS	
AFTER TAKE-OFF	PRESENT I.E. WITHOUT DATA-LINK	SSR-DERIVED POSITION AND VELOCITY DATA INCLUDING MODE C & $\dot{Z}_C$	NO DATA-ONLY ACHIEVED BY : (i) PILOTS ADHERING TO DECLARED INTENTIONS ; (ii) R/T INSTRUCTIONS FROM ATC IN EXCEPTIONAL CASES
	WITH DATA LINK	AIRCRAFT-DERIVED FLIGHT DATA/ SETTINGS DESIRABLY INCLUDING VERTICAL SPEED & ROLL ANGLE (ALL A/C). WIND VECTOR AND TEMPERATURE FOR FORECAST IMPROVEMENTS (SOME A/C)	TIMING DATA FOR PRECISE SYNCHRONIZATION OF CENTRE & A/C TIMES, CLEARANCE DETAILS & AUTOMATIC INDICATION OF DEVIATIONS FROM CLEARANCE

TABLE 1. DATA AVAILABLE TO ASSIST THE PREDICTION OF TRAJECTORIES AND THE ADHERENCE TO CLEARANCES BASED ON THEM.

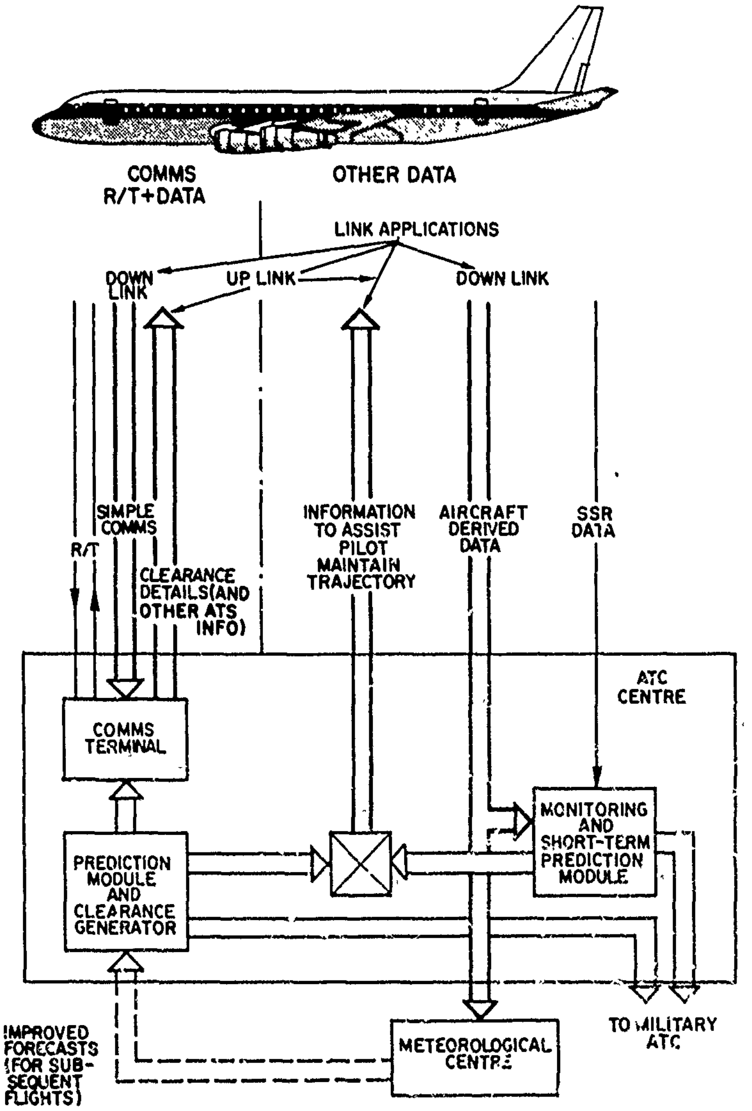


FIG.1 DATA FLOW PATHS – USING LINK

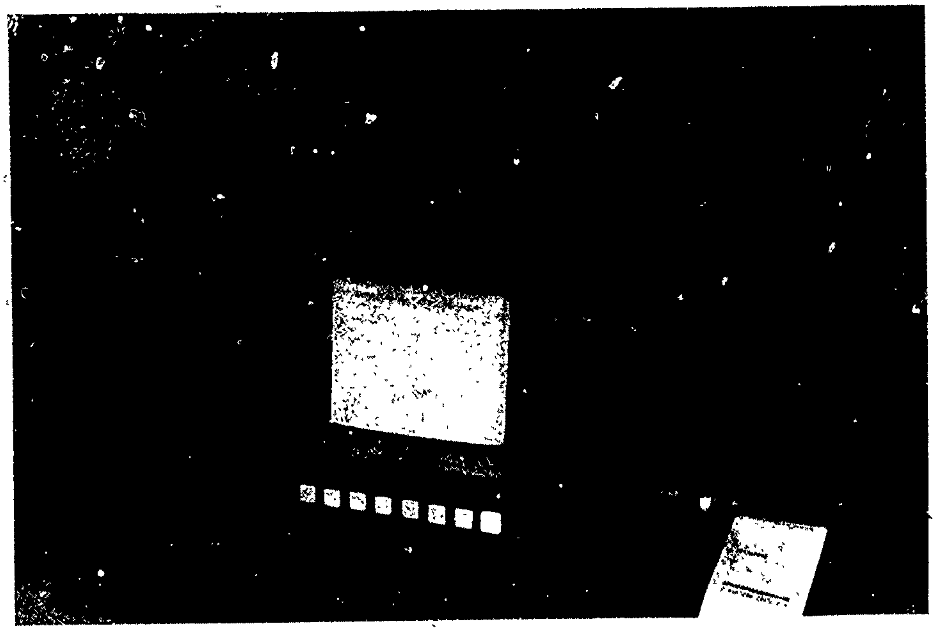
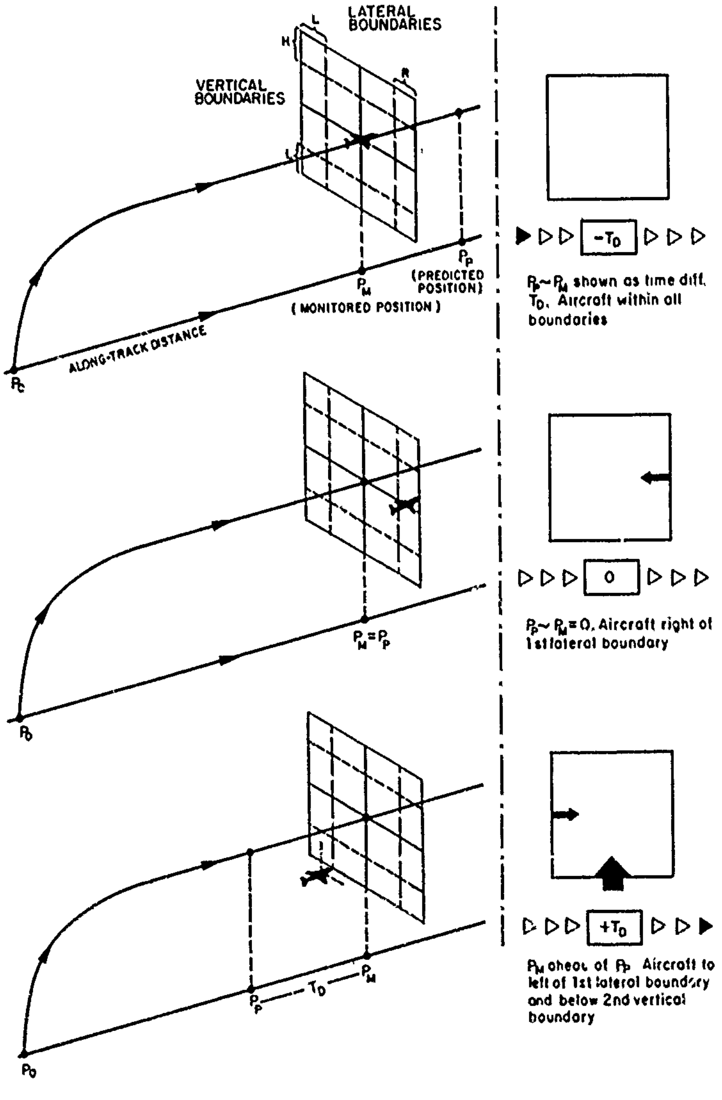


FIG 2 – THE AIRBORNE LINK TERMINAL EXPERIMENTAL EQUIPMENT.

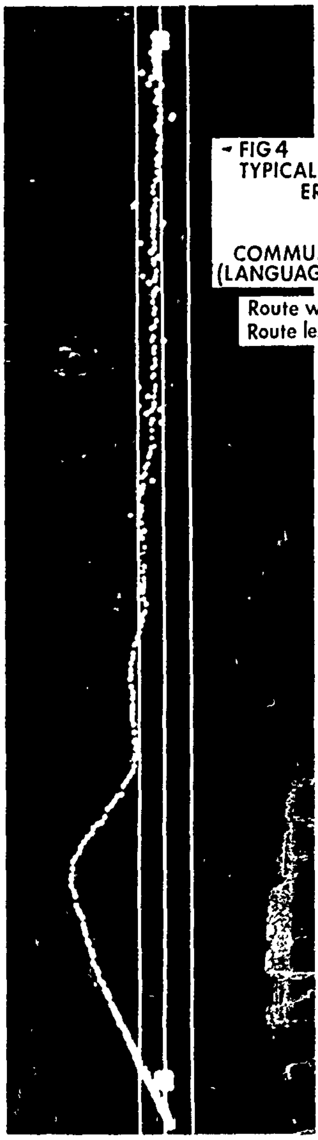
FIG.3 DISPLAY INDICATIONS RELATING POSITION OBSERVED TO THAT PREDICTED



$P_P \sim P_M$ shown as time diff. T_D. Aircraft within all boundaries

$P_P \sim P_M = 0$. Aircraft right of 1st lateral boundary

P_M ahead of P_P. Aircraft to left of 1st lateral boundary and below 2nd vertical boundary



◂ FIG 4
TYPICAL 'BLUNDER' ERROR

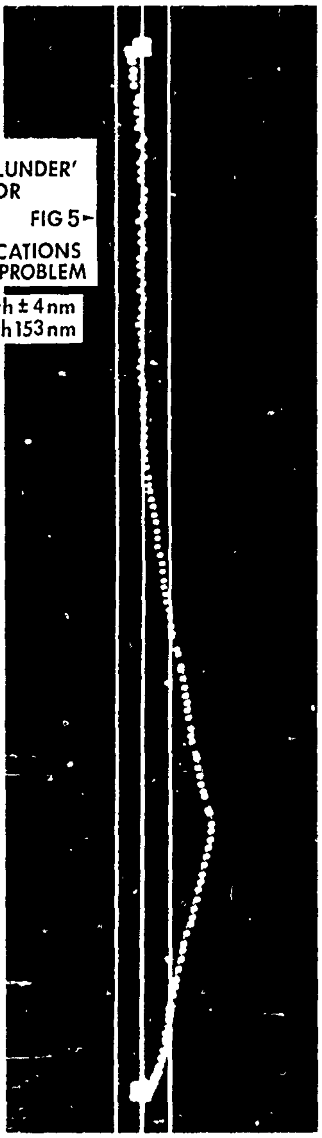
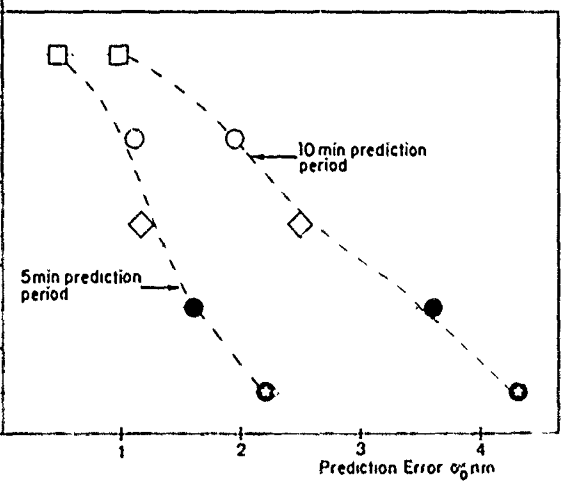


FIG 5 ▸
COMMUNICATIONS (LANGUAGE) PROBLEM

Route width ± 4 nm
Route length 153 nm

FIG. 6
PROBABLE ALONG-TRACK PREDICTION ACCURACY WITH DIFFERENT METHODS AND LEVELS OF DATA

DATA SOURCE		SYMBOL
SPEED	WIND	
A/C	INS	□
Radar*	—	○
A/C	'Actuals'	◇
A/C	Forecasts	●
PLN	Forecasts	✪



* GROUNDSPEED OVER 3min WITH PILOT HOLDING DECLARED MACH

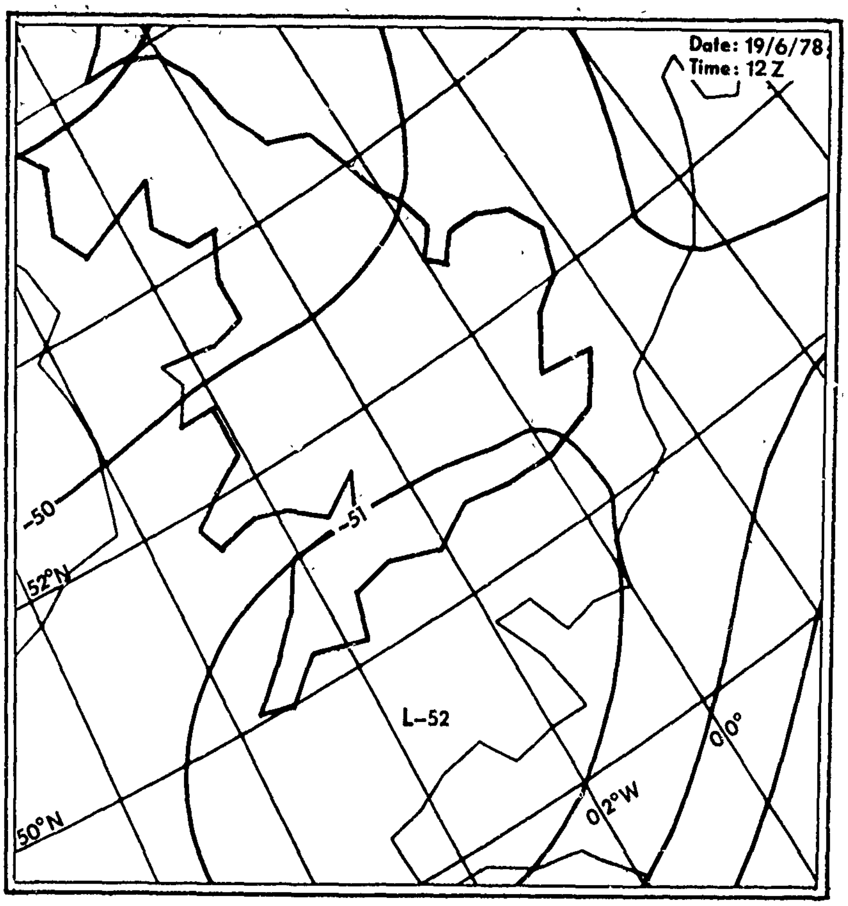


FIG 7 TEMPERATURE BACKGROUND FIELD FL 330 263 MB

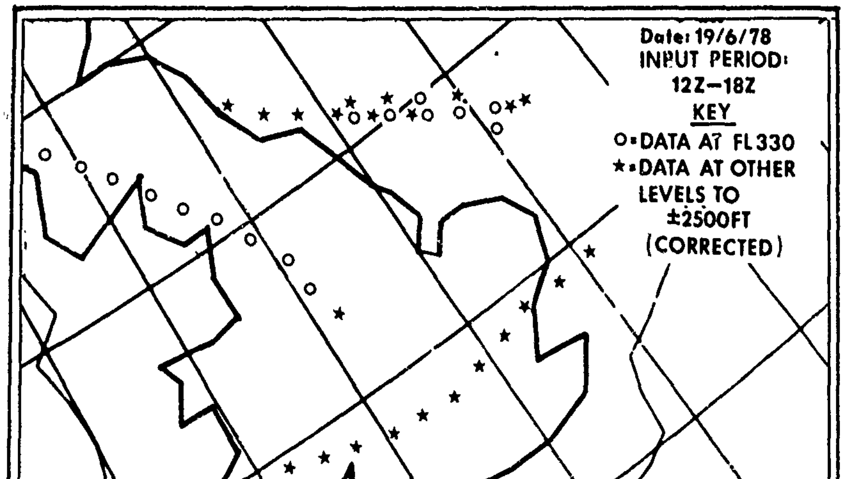


FIG 8 DATA INPUTS DERIVED FROM AIRCRAFT WITHIN RANGE FL 330 ± 2500FT

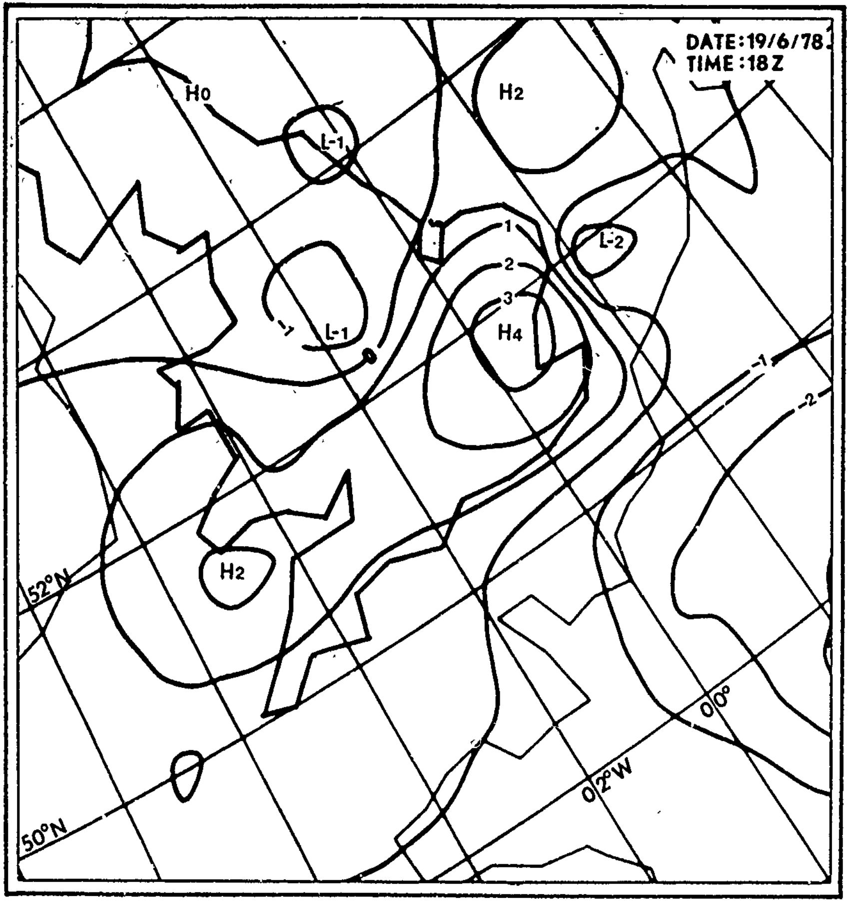


FIG 9 CHANGES TO TEMP. BACKGROUND FIELD FL 330·263MB

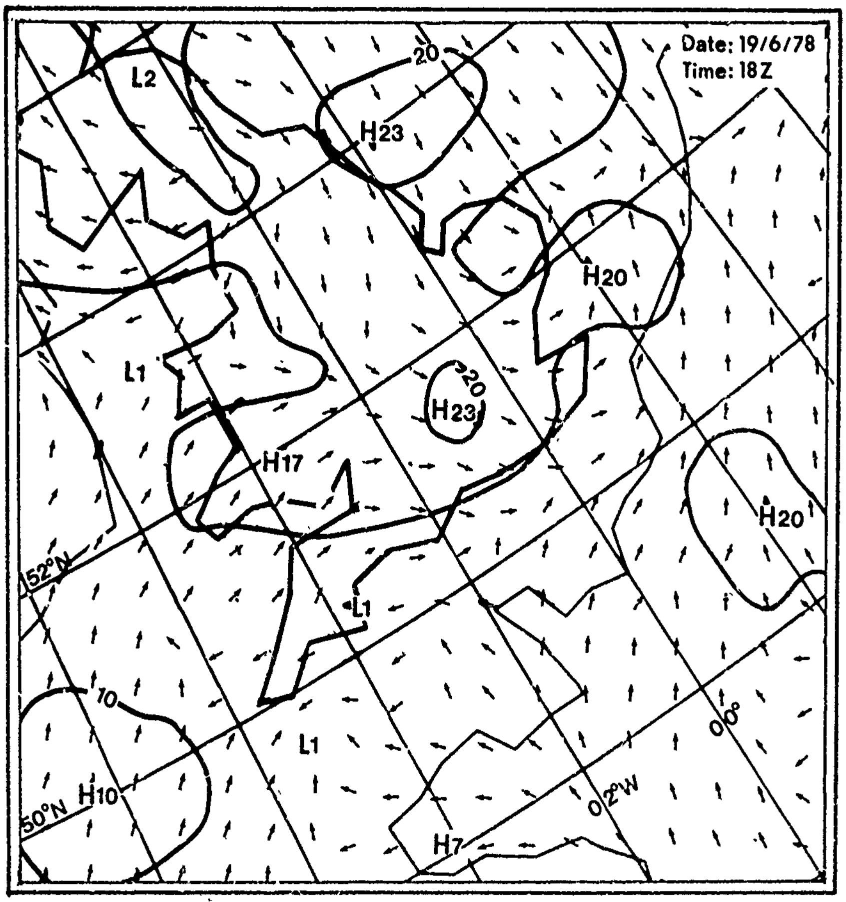
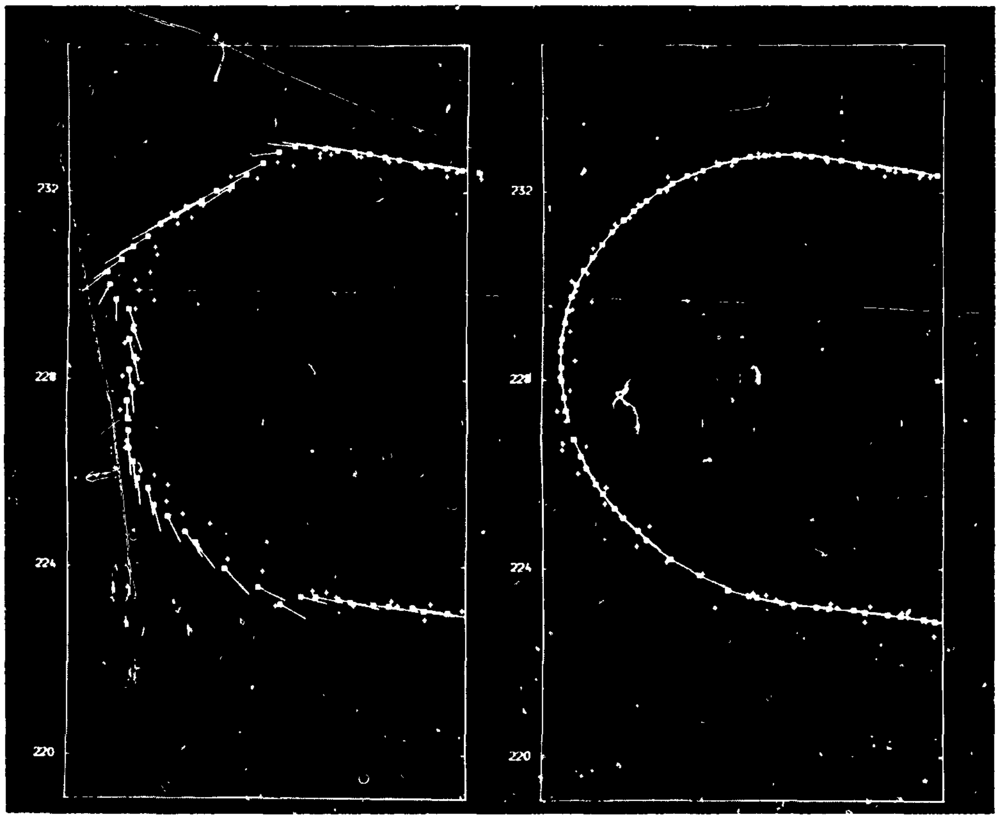


FIG 10 CHANGES IN WIND BACKGROUND FIELD FL 330 263MB



1st Order Tracker

2nd Order Tracker
(with roll-angle input)

KEY

+ =radar plot position
□— =smoothed position with 5sec velocity leader
Scale (nm) relates to an ATC system grid.

FIG 11 TRACKER PERFORMANCE COMPARISON

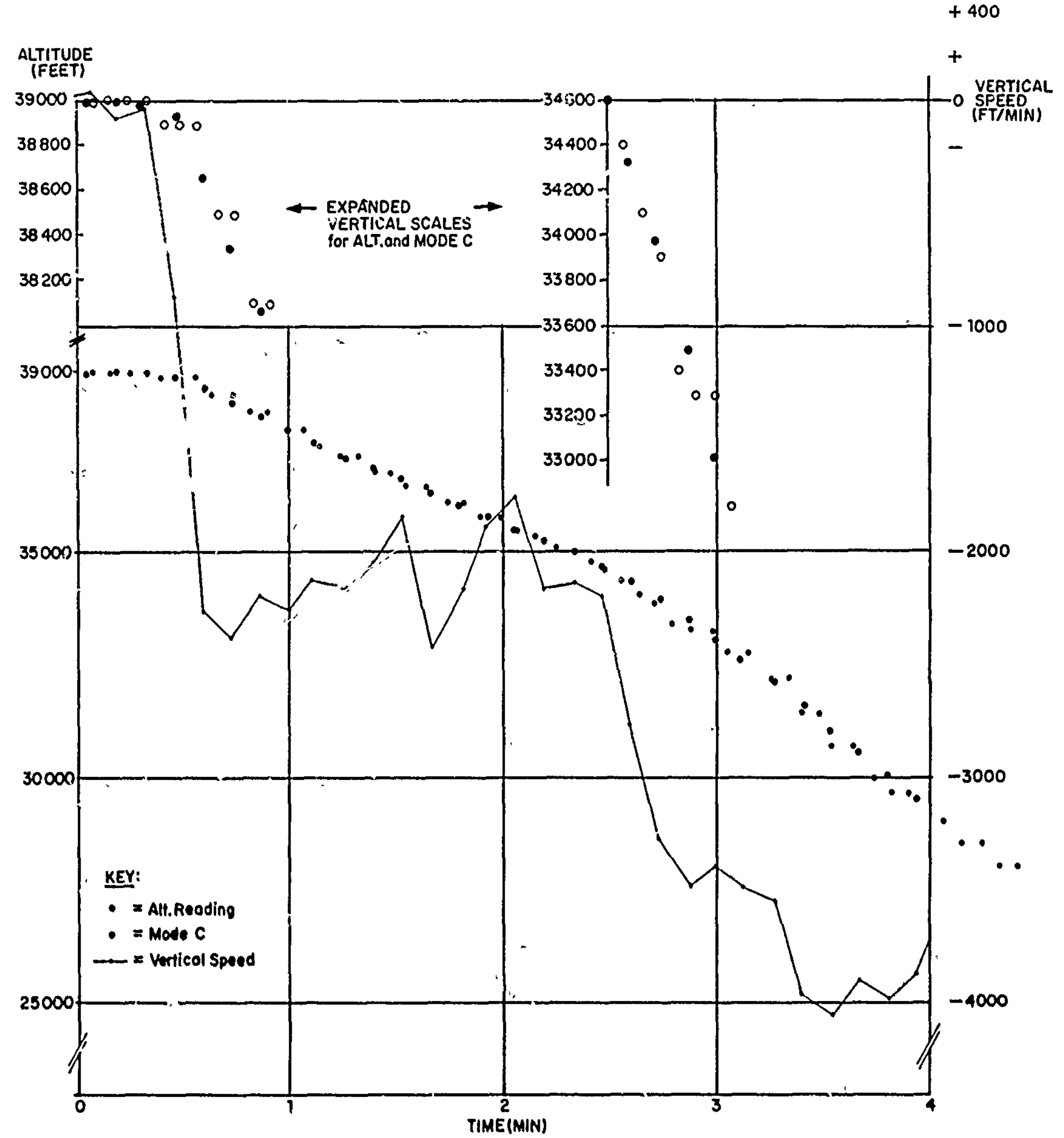


FIG.12 TYPICAL GRAPHS OF AIRCRAFT ALTITUDE, VERTICAL SPEED AND RELATED MODE C DATA RECOVERED IN ATC CENTRE.

M S R C (MESSAGE SOURCE) CODE

'01		'02		'03		'04		'05		'06	
PARAMETER	N° of BITS	PARAMETER	N° of BITS	PARAMETER	N° of BITS	PARAMETER	N° of BITS	PARAMETER	N° of BITS	PARAMETER	N° of BITS
RATE OF DESCENT	6	RATE OF DESCENT	6	RATE OF DESCENT	6	RATE OF DESCENT	6	RATE OF DESCENT	6	RATE OF DESCENT	6
ROLL ANGLE	10	ROLL ANGLE	10	ROLL ANGLE	10	ROLL ANGLE	10	ROLL ANGLE	10	ROLL ANGLE	10
GROUND SPEED	10	GROUND SPEED	10	GROUND SPEED	10	GROUND SPEED	10	GROUND SPEED	10	GROUND SPEED	10
TAT	8	HEADING	9	LATITUDE(1)	13	TRACK ANGLE	9	FLAP ANGLE	6	↑ SPARE ↓	
WIND SPEED	9	AIRSPEED	9	LONGITUDE(2)	12	PITCH	6	AIDS STATUS	2		
WIND ANGLE	9	LONG.ACCLRN.	8	———	———	CURRENT WEIGHT	11	GMT A/P STATUS	12 2		
DBU STATUS	1	DBU STATUS	1	DBU STATUS	1	DBU STATUS	1	SLAT HANDLE POSITION	1		
LABEL (001)	3	LABEL (010)	3	LABEL (011)	3	LABEL (100)	3	GROUND PROX. WARNING	1		
								DBU STATUS	1	LABEL(110)	
								LABEL (101)	3		
TOTAL	56	TOTAL	56	TOTAL	56	TOTAL	56	TOTAL	56		

(1) LATITUDE RANGE 49 - 00 - 00 (N) → 55 - 49 - 35 (N) ≡ 0 — 8191 COUNTS (13 BITS)

(2) LONGITUDE RANGE 3 - 00 - 00 (E) → 3 - 40 - 30 (W) ≡ 0 — 4095 COUNTS (12 BITS)

A/P = AUTO PILOT; DBU = DATA BUFFER UNIT (EXP. INTERFACE); TAT = TOTAL AIR TEMPERATURE

TABLE 2 - FORMATS FOR THE EXPERIMENTAL TRANSFER OF AIRCRAFT AIDS DATA USING ADSEL/DABS 56 BIT DATA BLOCKS.

MIDAIR CONFLICTS AND THEIR POTENTIAL AVOIDANCE BY PROGRESSIVE IMPLEMENTATION OF AUTOMATION

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SUMMARY

The paper deals with analyses of actual midair conflicts between civil and military aircraft in German airspace provided that at least one of the airplanes involved was flying under visual flight rules. Operational, environmental and human factors, which contributed to the accidents, and the limits of the "see and avoid" concept for collision avoidance are treated in detail. In addition, some shortcomings of the present Air Traffic Control System are mentioned. Taking the actual midair conflicts and some simulated three-dimensional flights as examples, the improvement of collision avoidance by progressive implementation of advanced techniques is discussed. The lead time to the potential conflict or to a circular zone of protection, the distance at the closest approach and some other thresholds, estimated by means of a ground-based radar system or an airborne electronic collision avoidance system, are used as main criteria for an automatic conflict alert. Potential advantages of a data link to detect sudden manoeuvres in time are mentioned.

1. INTRODUCTION

The existing Air Traffic Control System within Germany is very effective in preventing midair collisions. In the six-year period from 1973 to 1978, the author analyzed eight actual midair conflicts: seven midair collisions (MACs) and one near midair collision (NMAC) where several passengers were injured during the evasive manoeuvre. The author's analyses have been accomplished as scientific support to the official investigations being made by Luftfahrt-Bundesamt, General Flugsicherheit in der Bundeswehr and district attorneys.

The eight midair conflicts can be divided into three categories:

Civil / civil airplanes: 3 MACs

Civil / military airplanes: 1 NMAC and 3 MACs

Military / military airplanes: 1 MAC

Midair conflicts between two gliders or two military aircraft have not been treated, except for the last midair collision where a typical executive jet aircraft was involved. This accident also caused the highest number of fatalities (five persons) per single midair conflict which the author analyzed during the last six years. The total number of fatalities due to all midair collisions in this long period is much lower than the number of all transportation fatalities per day.

However, this favourable record should not be overestimated. The San Diego crash between an airliner and a light aircraft in 1978 shows clearly that many people on bord or on the ground can be killed if a wide-bodied civil aircraft or an equivalent small military aircraft with large fuel capacity crashes into a crowded street, for example. Regarding these four civil / military midair conflicts in German airspace only, two of them could have caused catastrophic results. A Boeing 737 was involved in the dangerous near midair collision and a F-104 crashed on the ground in the neighbourhood of a hospital after colliding with a glider. Therefore, the actual and potential risks of midair collisions indicate the necessity of new studies to verify current collision avoidance concepts.

Theoretical and experimental studies concerning conflict detection and resolution in visual meteorological conditions especially by means of the "see and avoid" concept have been undertaken by the DFVLR Institutes for Flight Mechanics and for Atmospheric Physics at Braunschweig and Oberpfaffenhofen. These studies are parts of a joint research programme for the German Ministry of Transport.

The primary object of this paper is to give a brief review of our studies on actual and simulated midair conflicts in visual meteorological conditions. In keeping with the theme of this symposium, attention will be focussed on the operational scenario of midair conflicts and on their potential avoidance by progressive implementation of automation.

2. FLIGHT VISIBILITY AND RULES OF THE AIR

In visual meteorological conditions (VMC) *flight visibility* shall be at least 8 km in most parts of German airspace (figure 1). 1.852 km are equivalent to one nautical mile (NM). Flight visibility can be defined as the range in which a pilot receives the first visual information from an approaching aircraft. This range depends among other things on the size and the silhouette of the approaching aircraft. As flight visibility cannot be determined on board during routine flights, an auxiliary parameter is generally used. At many airports the visibility of extended earth-fixed objects - of large buildings or woods, for example - is estimated or measured by meteorological observers on the ground. HOFFMANN [1] calls this parameter the *standard horizontal visibility*. He compared the standard horizontal visibility to the range in which a low flying light aircraft can be acquired by observers on the ground who approximately know the sector and the time of approach. By means of flight tests he found out that the acquisition range of light aircraft approaching head-on can be much lower than the standard horizontal visibility measured in the same direction; he obtained, for example, an acquisition range of 2.5 NM at a standard horizontal visibility of 5 NM. If an aircraft with a span width of 30 feet (ft) is visually acquired at 2.5 NM by a pilot on board another aircraft, the apparent size of the approaching aircraft will be 2 mm on a fictitious windshield being 1 m away from the observer's eyes [2, 3]. Obviously, it would be questionable to generalize HOFFMANN's low-level results to medium or high flight levels. Nevertheless, an apparent size of 2 mm is assumed as a first acquisition threshold for the following accident analyses. Further details of the correlation between the acquisition range and the standard horizontal visibility or the brightness of the sky have been treated in HOFFMANN's paper [1].

Figure 2 shows the field of view in a G-91 cockpit in straight and level flight and in a horizontal left turn. The "see and avoid" concept is based on the visual information which can be obtained in the cockpit:

- the position and the apparent motion of the intruder on the windshield
- the perspective and the apparent size of the intruder and their variations with respect to time
- the translation and the rotation of the observer's aircraft.

Unfortunately, this principle was not consequently applied when the German rules of the air were laid down [4, 5]. The official translation of the original German rule for overtaking aircraft runs as follows:

> "An aircraft is overtaking another when it approaches the other from the rear *in a direction of flight* forming an angle of less than 70 degrees with *the direction of flight* of the other aircraft."

Without doubt, the boundary between converging courses and overtaking has been defined by means of an angle between two directions of flight, i.e., primarily with respect to an earth-fixed system in the no-wind case. Except for some special encounters, this angle cannot directly be observed by both pilots. Three examples are represented in figures 3, 4 and 6.

Contrary to the German version, the International Civil Aviation Organization (ICAO) published the following rule [6]:

> "An overtaking aircraft is an aircraft that approaches another from the rear *on a line* forming an angle of less than 70 degrees with the plane of symmetry of the latter, i. e., is *in such a position with reference to the other aircraft*...".

In this rule the boundary has been defined with respect to the cockpit of the slower aircraft. The critical angle can directly be observed by the pilot of the slower aircraft at 03^h40^m or 08^h20^m in his cockpit system or it can easily be estimated from the perspective of the slower aircraft by the pilot of the faster aircraft provided that the apparent size of the slower aircraft is sufficiently large. As far as converging courses are concerned, there is a similar discrepancy between the original German and the ICAO rules of the air.

3. ACTUAL ACCIDENTS

In order to present an overall picture of the operational scenario in German airspace in visual meteorological conditions, one near midair collision and four midair collisions will be treated in this chapter. The relatively frequent encounters between military aircraft and gliders are probably a German peculiarity [2, 3, 7, 8].

3.1 Near midair collision 2 G-91s / Boeing 737

This encounter happened in 1975 near the intersection of two airways (figure 3). Two G-91s flying under visual flight rules (VFR) and a Boeing 737 flying under instrument flight rules (IFR) at FL 240 approached each other approximately head-on at a rate of closure of 850 knots (kts). The military airplanes were nominally flying 500 ft lower than the carrier aircraft. This conflict situation is a typical one of mixed VFR/IFR traffic in the enroute environment.

The G-91 pilots did not see the Boeing 737 in spite of its large size as the carrier aircraft was obscured by the right window post being 15 degrees (deg) away from the reference point of the G-91 cockpit (figure 2). Furthermore, the altitude of the sun was relatively low and the azimuth unfavourable with respect to the G-91 cockpit.

The actual vertical separation between the Boeing 737 and the military aircraft is unknown, especially as the individual position errors of the static pressure systems of the aircraft involved are not available. Although the Boeing copilot at first had the impression that the G-91s were flying lower than his aircraft, the Boeing crew initiated a rapid descent some seconds before the encounter. Some passengers were injured during this evasive manoeuvre. Regarding the probable cause of the pilots' action, a reliable estimation of small vertical differences between aircraft in straight and level flight seems to be difficult or even impossible, particularly, if the rate of closure is high.

Whether the G-91s were approaching the Boeing head-on or from the left side may be crucial in court with respect to an adequate evasive manoeuvre. The Boeing crew had the impression that both G-91s were approaching approximately head-on at the 11 o'clock position. Figure 3 shows that the actual position of the G-91s was at 11^h30^m and the angle between the directions of flight was 150 deg.

As the secondary radar transponders of the G-91s had not been switched on, the military aircraft could not be detected on the radar screen as secondary radar targets. The German Air Traffic Control officially stated that the G-91s were also invisible as primary radar targets. First countermeasures of the German Ministries of Transport and Defence are discussed in section 3.5.

3.2 Midair collision G-91 / HFB 320

In 1976, an executive jet HFB 320 and a G-91 collided while approaching a navigation aid (figure 4). The HFB 320 was flying IFR in straight and level flight at FL 95. The controller had cleared the HFB 320 to this unusual IFR flight level on demand as the HFB 320 was to perform a special military ECM task. FL 95, however, was a desirable, but not a necessary altitude for this task. The two-seat tandem G-91 was on a navigation training flight, operating VFR at the same flight level according to the Table of Cruising Levels [4-6]. Some minutes before, the G-91 had left a Temporary Reserved Airspace (TRA) [4, 5] at FL 100. The TRAs are reserved for uncontrolled visual flights of military high performance jet aircraft and they are under military radar surveillance. After leaving the TRA, the secondary radar transponder of the G-91 was not used. Therefore, the G-91 could not be detected as a secondary radar target in the civil air traffic control centre. According to an official statement of the German Air Traffic Control, it was also invisible as a primary radar target.

At first the G-91 was flying in straight and level flight; during the last 25 seconds (sec), however, it was performing a left turn. The rate of closure was 145 kts; that is very low for jet aircraft. The pilot of the G-91 did not detect the executive jet at all although the direction of the line of sight was favourable to his cockpit taking only the operational situation into account. Again, the altitude of the sun was low and the angle between the line of sight and the direction to the sun was small so that the performance of the pilot's eyes may probably have been reduced. During the left turn, the HFB 320 was obscured by the left window post in the G-91 cockpit (figure 5). Before bank establishment of the G-91, the executive aircraft apparently moved across the central part of the windshield. The wing span of this aircraft had a sufficient apparent size not later than 40 sec before collision. However, the silhouette was unfavourable during this time because the G-91 pilot could observe the HFB 320 only from behind. The additional workload due to navigation training probably had a minor bearing on the accident.

This collision would also have occurred if the HFB 320 had been flying VFR instead of IFR. Therefore, the accident described above is a good example of a VFR/IFR collision at a low rate of closure.

3.3 Midair collision 4 F-4 Phantoms / powered glider

In 1976, a formation of 4 F-4 Phantoms were flying VFR in a horizontal left turn at 3500 ft (figure 6). No. 2 crashed into a powered glider operating VFR in straight and level flight. The rate of closure was higher than 360 kts. The pilot of the crashed Phantom could not detect the powered glider since it was masked by an extended horizontal structure in the left upper edge of the Phantom cockpit during the last 30 sec (figure 5). The pilot sitting on the left seat of the powered glider could not sight the four Phantoms because a passenger, sitting side by side with him, was shadowing the Phantoms.

Considering the situation some seconds before the collision, the right-of-way of the Phantoms depended on the angle used as the criterion. Provided that the angle between the flight directions had been used according to the German rules of the air, the Phantoms would probably have overtaken the powered glider which then would have had the right-of-way. If the angle β_2 (figure 6) had been derived from the perspective of the powered glider according to the ICAO rules, the courses would probably have converged and the Phantoms would have had the right-of-way.

A few seconds before impact a member of the Phantoms' crews believed that a glider was flying head-on although the propeller was running in reality. As the propeller of a powered glider is relatively small, the pilot of an approaching aircraft can only distinguish at a very short distance whether the propeller is running [2]. If not, the glider has the right-of-way in all operational situations. Regarding the right-of-way, it must be emphasized that pilots are obliged to come to a decision by means of operational parameters that they cannot observe directly in some important cases [2, 3].

3.4 Midair collision 2 F-104s / glider

In 1977, two F-104s (single seat) performed a radar training flight at 2400 ft in straight and level flight. The left airplane was flying VFR and for this reason, its pilot was responsible for "see and avoid". The right airplane collided with a glider which was probably at first in straight and level flight and during the last seconds in a left turn (figure 7).

During the crucial phase before the accident, the visibility of the glider was strongly reduced for the pilot of the left F-104 by a structure being approximately 8 deg away from the cockpit reference point and somewhat smaller than the distance between both eyes. Therefore, the target could be detected at least by one eye, in principle. However, if a target is very small and the sky without any contour like a cumulus cloud, the eyes will in most cases accommodate automatically to the structure of the cockpit, and a far distance target will not be noticed. By disregarding this human factor, some pilots apparently have a false sense of security.

The apparent size of the glider was below threshold for a long time and its silhouette unfavourable, particularly because the fuselage of this glider is rather thin. The pilot of the left F-104 was flying behind the right F-104. Therefore, he had to observe this aircraft very often. As the direction to the sun was not far away from the line of sight between the two F-104s, the ability of the left F-104 pilot to detect the glider may have been reduced significantly.

The pilot of the glider believed that military jet aircraft were not allowed at this altitude because low level operations - according to the regulations [5] - are flights which are conducted by military jet aircraft at a height of 1500 ft GND or less during day-time. A superficial study of some publications could lead to this erroneous conclusion. Obviously, this accident would also have occurred if both F-104s and the glider had been flying at 1500 ft or less. Therefore, this accident may be a good example of the limits of the "see and avoid" concept in the German Low Flying System.

Another example is the collision between a Mirage and a circling glider in 1973. The apparent wing span of the glider was sufficient for detection not later than 20 sec before the collision, but the silhouette was very thin from -20 sec to -10 sec. A temporary disappearance of a circling glider can easily be observed, particularly when the observer and the glider are approximately in the same level. The apparent length of the fuselage is larger than the threshold during the last 10 sec. At first, the thin silhouette and the lack of contrast between the glider and the background, and later on a short distraction from normal visual scan caused by cockpit duties may have resulted in the Mirage pilot's failing to detect the circling glider early enough.

3.5 First countermeasures and potential success

After the NMAC between two G-91s and a Boeing 737, the restricted area ED-R9 was established in Germany [4]. Since this time, VFR flights have generally been prohibited between FL 100 and FL 200. A few exceptions have been allowed. By means of this countermeasure, the total number of *reported* NMACS has been reduced significantly and the flight safety within ED-R9 has been improved. Especially the short-haul services of air carriers often operate within this airspace. It should be kept in mind, however, that the VFR traffic has become more dense below FL 100 by the new restrictions. As pilots who fly VFR very often hesitate to report dangerous encounters, NMAC statistics may have been improved more than safety.

As a countermeasure after the MAC between a G-91 and a HFB 320, all military aircraft have been obliged to switch on their transponders under similar operational conditions. If the HFB 320 had been a general aviation aircraft flying VFR, however, this collision would not have been prevented because the HFB would have been invisible as a secondary radar target.

In principle, the three collisions between military aircraft and (powered) gliders described above can be prevented by separation, by collision avoidance systems or pilot warning indicators on board or by advanced ground-based radar systems. A reasonable separation of the different users by means of restricted areas or times of activity should be considered, keeping the balance between flight safety and freedom of airspace for all civil and military users. Automatic conflict alert by means of airborne or ground-based electronic systems will be treated in chapter 4.

4. AUTOMATIC CONFLICT ALERT

Under visual meteorological conditions, separation between aircraft is assured by means of the "see and avoid" concept if at least one aircraft is operating VFR. The midair conflicts described in chapter 3 show that this concept cannot always prevent collisions or dangerous near misses. Therefore, the question is whether these midair conflicts could have been avoided by means of electronic devices in all probability. Many collision avoidance systems or pilot warning indicators have been proposed, developed or even tested under operational conditions. The bibliography on collision avoidance, including the period from May 1972 to November 1977, contains 859 papers [9]. In 1978 and during the first half of 1979 several other important publications were issued [10-12].

Two advanced collision avoidance systems and their progressive implementation have been analyzed in our institute, largely without considering hardware problems [8]:

- a ground-based secondary radar system measuring slant ranges and bearings of aircraft involved, and receiving their flight levels determined on board by encoding altimeters
- an independent airborne electronic system measuring the range to an intruder, the range rate, and the altitude of an intruder.

A *secondary* radar system has been chosen for our analysis because

- the German Air Traffic Control stated after two accidents described above that a G-91 could not be detected as a primary radar target
- accurate altitude information seems to be necessary to avoid collisions at a low rate of false alarms.

As a minimum a transponder and an encoding altimeter are needed on board. FAA Administrator Bond recently said, transponders would cost $ 550 - 850 and encoding altimeters $ 600 - 950. As far as gliders and powered gliders are concerned, the power supply for these devices should also be kept in mind. The initial phase of such a system is already operational in most of the U.S. National Airspace System.

Obviously, protection is not provided outside radar coverage, i.e., in most parts of Low Flying Systems, for example.

Airborne electronic collision avoidance systems are much more expensive for aircraft operators. An airborne system which will be compatible with future ground-based radar systems is now under development in the United States, called the "Full-capability BCAS" [10, 12]. According to FAA, this advanced system will also give protection outside the coverage of any beacon radars and will provide service "well into the 1990 time period".

4.1 Parameters and thresholds

Neglecting measurement errors and low antenna-rotation rates of secondary radar systems, the relative position of two (or more) aircraft threatening each other and their velocity vectors can be computed as functions of time from the original radar measurements and the received altitudes. From these three vectors several conflict parameters have been derived with respect to some simple alert thresholds, for instance:

(a) the 2-D or 3-D minimum ranges d_{min} or D_{min} at the closest approach

(b) the lead time Δt_{min} to the closest approach

(c) the lead time T_{THR} to a circular or spherical zone of protection around the intruder aircraft and moving with it (radius of the zone = ρ_{THR})

(d) the lead time Δt_H to a relative altitude threshold H_{THR}

(e) the lead time $\tau = -D/\dot{D}$ or $-d/\dot{d}$ to the encounter.

The accuracy of these data depends on the difference between the actual and predicted tracks (measurement errors have been excluded earlier). In our computations, a linear track model has been used, i.e., the velocity vectors of both aircraft have been assumed constant during the lead time. If both aircraft are actually flying with constant velocity vectors before an encounter, the parameters (a) - (d) are accurate; the τ-criterion, however, provides an exact solution only for collisions, and a reliable one for near midair collisions as long as the range between both aircraft is large compared to the range at the closest approach. Some exceptions will be discussed later on. The computer of the airborne collision avoidance system is assumed to derive the lead times Δt_H and τ as well as the computer of the ground-based radar system (see (d) and (e)).

4.2 Actual accidents

4.2.1 Near midair collision 2 G-91s / Boeing 737

Figure 8 represents the conflict alert parameters of this NMAC. The tracks of both G-91s were changed somewhat compared to figure 3. It has been assumed that both G-91s were flying a right turn with a roll angle of 10 deg during the last 35 sec. In spite of these turns the overall situation remains very close to a *nominal encounter* [11]. The principal characteristics of nominal encounters are that they involve two aircraft with similar speeds, with neither accelerating as the conflict develops. This NMAC can be avoided without an expensive independent airborne system because the flight levels used by these three aircraft are within radar coverage in Germany. Therefore, an automatic conflict alert system could soon be implemented, in principle. As far as the operators of the aircraft are concerned, no additional equipment will be needed if the conflict alert is transmitted via voice channel from the control centre to the pilots.

Whether or not a conflict alert is caused depends on the relative altitude threshold H_{THR}. Provided that this is larger than the actual difference between the altitudes of the airplanes, an alert is automatically issued in time even if random measurement errors and a lag due to the low antenna-rotation rate are taken into account. In the error-free case, the predicted minimum range D_{min} at the closest approach is always shorter than the radius ρ_{THR} = 1.2 NM of the zone of protection moving with the Boeing (the scales are different in figure 8). The lead times Δt_{min} and τ to the encounter are sufficiently accurate except for the last seconds of τ. 30 sec before entering the zone of protection at -6 sec, the lead time $T_{THR} = T_{30}$ to this event is only 2 sec too short. Considering the potential deficiencies of radar systems, the rotation of the velocity vector of the G-91s is delayed for some seconds after initiating the right turn. Therefore, the minimum range D_{min} decreases some seconds later.

If the threshold H_{THR} is lower than the actual difference between the altitudes, an automatic conflict alert will not be caused at all. As the Boeing crew does not know after the visual acquisition of the intruders whether the collision avoidance devices - especially the encoding altimeters - are working within their proper tolerances, the Boeing crew will probably again initiate a rapid descent, perhaps due to the potential optical illusion described in section 3.1. In this case, it may be crucial whether the pilots' confidence in the overall system has earlier been undermined by some false or missing conflict alerts.

4.2.2 Midair collision G-91 / HFB 320

Although the MAC between the G-91 and the executive aircraft HFB 320 was a non-nominal encounter because the speeds were greatly dissimilar and the G-91 was accelerated as the conflict developed, this accident could have been prevented by a ground-based conflict alert system. As represented in figure 9, the predicted minimum range d_{min} is smaller than the range threshold ρ_{THR} during the last minute. The lead times Δt_{min} and τ to the encounter are a little too short during straight and level flight and afterwards rapidly converging to the accurate lead time to the collision. The zone of protection moving with the HFB 320 is penetrated at 32 sec before impact and the lead time to the penetration is predicted exactly since both aircraft have been in straight and level flight before this event. Considering the potential deficiencies of radar systems, an important negative influence on flight safety could not be found in this case as most conflict parameters were decreasing below their thresholds before the G-91 pilot initiated the left turn.

4.2.3 Midair collision 4 F-4 Phantoms / powered glider

The MAC between a powered glider and No.2 of a formation of four Phantoms occurred at 3500 ft (figure 10). As all aircraft involved were flying VFR, the author does not know whether these aircraft were within secondary radar coverage.

Provided that the aircraft had been flying high enough for radar surveillance, an automatic conflict alert by a ground-based system would have been possible, in principle. It should be kept in mind, however, that the capacity of the German Air Traffic Control System must be significantly enlarged if all aircraft flying VFR are to be included in some kind of future air traffic control like Intermittent Positive Control, for example. Neglecting potential radar deficiencies, the predicted minimum range d_{min} at the closest approach will only be shorter than ρ_{THR} if the prediction is made at the earliest at 29 sec before the potential accident. Therefore, a lead time T_{THR} to the penetration of the zone of protection moving with the powered glider does not exist before this period; later on it will be obtained a few seconds too long. The lead time Δt_{min} to the closest approach is always predicted too short, but it is converging very early to the real value. Therefore, in the error-free case, an automatic conflict alert can be issued in due time.

Regarding potential deficiencies of radar systems, the rotation of the large velocity vector of the Phantoms (1.5 deg per sec) will be delayed, particularly because the antenna-rotation rate is low. Assuming that a data rate of one position measurement every 4 sec can be achieved and that two new positions are necessary for detecting a heading change, the lag will be in the order of 12 deg. Due to such a lag, the predicted minimum range d_{min} will cross the range threshold ρ_{THR} at 22 sec before the collision, i.e., 7 sec later than in the error-free case. For this reason, an automatic conflict alert is possible even taking lags due to deficiencies into account. Obviously, the time between conflict alert and potential conflict can be extended by increasing the thresholds used above.

An independent airborne system deriving $\tau = -d/\dot{d}$ will also issue a safe automatic conflict alert at least during the last 40 sec. At first, the predicted lead time is too long, later on, however, it converges to the real time very well. Therefore, this collision could have been prevented even if the aircraft involved had been outside radar coverage, due to low altitude for example.

4.2.4. Midair collision 2 F-104s / glider

In order to make this encounter worse, the glider is assumed to perform a left turn during the last minute (figure 11). This accident is then very similar to the collision between a glider and a Mirage mentioned in section 3.4. As the speed ratio of the aircraft involved is very large (8:1) and the glider is turning at a high heading rate

(11 deg per sec), the F-104 conflict is a good example of an extremely non-nominal encounter.

Although such collisions are more probable in the German Low Flying System where a radar coverage does not always exist, conflict alert parameters derived by a ground-based radar system are represented in figure 11. Considering the error-free case at first, the predicted minimum distance d_{min} at the closest approach is lower than the range threshold during the last 80 sec (the scales are different in figure 11) and its graph is similar to a damped oscillation. The lead times Δt_{min} and τ are also oscillating. Their deviations from the real lead time, however, are so small that good predictions can be obtained. The zone of protection moving with the glider is penetrated about 10 sec before impact. The predicted lead time T_{THR} to this event also exists during the last 80 sec and it is alternately somewhat shorter or longer than the real value. Taking potential deficiencies of radar systems into account, the results remain unchanged, in principle, as long as the velocity of the glider is not enlarged too much due to measurement errors. As mentioned in [11], velocities will generally be underestimated if their vectors rotate. Under this condition, a lag in the rotation of the glider's velocity vector is of minor importance. The phases of the oscillations are shifted and their amplitudes remain unchanged or decrease. In the extreme case where the glider is erroneously determined as a motionless radar target, the true solution is evident.

Provided that the aircraft involved are operating outside radar coverage, an independent airborne system has to be used. It will determine the lead time τ which is a good approximation to the real lead time in this case. Therefore, this accident could have been prevented by a ground-based system as well as by an independent airborne system with a high level of probability.

4.3 Simulated conflicts

Several midair and near midair collisions have been simulated in our institute during the last years, including three-dimensional tracks as well as true airspeeds below 250 kts, i.e., the operational scenario in the neighbourhood of airports. The primary object of these simulations was to get an impression of the operational limits of collision avoidance systems using a linear prediction model. Among other things, there are two crucial questions to be answered:

- Under which operational conditions does the pilot receive an automatic conflict alert even though the minimum range at the closest approach would be sufficiently large?
- Are encounters possible where an automatic conflict alert warns the pilot too late because the conflict develops too fast?

Two examples will be discussed in this section.

4.3.1 Symmetrical flights I

Figure 12 represents the tracks and conflict-alert parameters of a 3-D encounter. Aircraft I is descending to 3000 ft at 2000 ft/min, performing a left turn during the last 30 sec. Aircraft II is flying at 3000 ft, performing a right turn during the last 45 sec. At the closest approach, the two airplanes are operating side by side. Whether the encounter will be a collision, a near miss, or a safe approach can hardly be decided in time by means of the "see and avoid" concept. If the minimum range at the closest approach is increased from D(0) = 0 to 0.3 NM (1800 ft) or further to 1.0 NM, the perspective and the apparent motion of the intruder on the windshield remain practically unchanged during the common ninety-degree turns; only the apparent size of the intruder depends on the minimum range. Therefore, a reliable automatic conflict alert would be desirable in this case.

As shown in figure 12, the predicted minimum range will be close to zero, if the prediction is made between -30 sec and -10 sec. This is even valid for large actual minimum ranges because those encounters that are predicted during the last 30 sec are always midair collisions, considering 2-D solutions only. The predicted lead times Δt_{min} and τ are somewhat shorter than the actual lead times, except for the last 10 - 20 sec. Taking potential lags of the velocity vectors due to radar deficiencies into account, the overall situation will not be changed. If the lags of both velocity vectors are of equal size, a collision will be predicted again in the 2-D case. However, the predicted lead times would be significantly shorter than in the error-free case. Regarding a potential violation of the zone of protection moving with the upper aircraft (in airspace and figure 12) as the crucial parameter, a conflict alert will be issued at T_{15}, T_{15}^{*}, or T_{15}^{**}, i.e., at least 27 sec before the closest approach, provided that a lead time of 15 sec to the zone is chosen. A relative altitude threshold of 400 ft is achieved at 12 sec before the potential conflict. Assuming a lead time of 15 sec again, a future loss of vertical separation will be indicated 27 sec in advance.

Considering all the parameters and thresholds represented in figure 12, a conflict alert will automatically warn the pilots even if the actual miss distance is relatively large. For that reason, the pilots' confidence in the collision avoidance devices can be undermined, no matter whether it is a ground-based or an independent airborne system. Non-linear track prediction would solve this problem, in principle. Radar measurement errors, however, may be obstructive.

4.3.2 Symmetrical flights. II

Figure 13 represents a collision where an automatic conflict alert warns too late. Aircraft I is climbing, aircraft II is descending at 1000 ft/min. At first, both pilots are operating at the same heading approximately 2 NM from each other. The visual acquisition of the other airplane can be difficult if the captain of the left airplane and the copilot of the right airplane are responsible for "see and avoid" since the other airplane is then obscured by the copilot or by the captain. About 27 sec before the potential conflict, right and left turns are initiated. 15 sec later, the intruder will be observed at $1^{h}30^{min}$ or at $10^{h}30^{min}$, i.e., 45 deg away from the observer's direction of flight. As the range between both aircraft is larger than 1.2 NM at this moment, a 30 ft object would be smaller than 4 mm on the windshield. Therefore, a visual estimation of the threat from the size, perspective and apparent motion of the intruder would be difficult.

As shown in figure 13, a conflict alert cannot be issued before the two turns are initiated. During the next 10 - 15 sec the lead times Δt_{min} and τ are predicted by far too long. This is also valid for the lead time to the penetration of the zone of protection moving with the descending right aircraft. About 12 sec before actually violating this zone, the pilot of the left aircraft gets the prediction T_{30} = 30 sec; a few seconds later the predicted value already decreases to T_{15} = 15 sec! Considering potential lags of the velocity vectors due to radar deficiencies, the estimated lead times will become significantly longer than in the error-free case where the predictions are already too long. Therefore, flight safety will be reduced further by radar errors in this conflict situation. A potential loss of vertical separation will be indicated 27 sec in advance as described in section 4.3.1.

4.4 Potential advantages of a data link

As mentioned in section 3.1, several problems associated with the prediction of accurate conflict alert parameters can be overcome by means of an estimation model which is nonlinear and free of significant lags. Regarding radar measurements only, it seems that these conditions cannot be achieved since the measurement errors are sometimes too large and the usual antenna-rotation rates rather low. Provided that a data link between cockpit and control centre is available, the overall accuracy of the estimation process can be much improved by transmitting additional flight data to the control centre. Figure 14 represents some flight parameters recorded or derived by means of an Aircraft Integrated Data System (AIDS) during the descent of a wide-bodied aircraft. Considering the no-wind case, the direction of the velocity vector is determined by the heading of the aircraft. Therefore, transmission of heading to the control centre would be very useful provided that the airborne heading sensor is insensitive to manoeuvre accelerations. Since the heading rate is proportional to the tangent of the roll angle and inversely proportional to the true airspeed, the roll angle also indicates immediately whether a turn has been initiated and how fast the heading is changing. For that reason, radar measurements of curved tracks can be significantly improved if they are optimally combined with the headings - the airplanes or with their roll angles, for example. Obviously, this concept has been well known for many years [13, 14]. The author supposes that the transmission of heading via data link may be more advantageous since this parameter includes the full information on the direction of the velocity vector even if the antenna-rotation rate is low or some data have been lost.

5. CONCLUDING REMARKS

Fortunately, the number of fatalities due to midair collisions under visual meteorological conditions has been low in German airspace during the last years. Consequently, only a small sample of actual midair conflicts is available for deriving trends and their relation to operational, environmental and human factors. Therefore, this overview of our accident analyses and theoretical studies on collision avoidance by means of the "see and avoid" concept or the implementation of automation is by necessity sketchy and incomplete. In spite of these shortcomings, some common features should be mentioned:

All five actual accidents analyzed above were caused by several factors acting simultaneously. The "see and avoid" concept ceased to be operative because of opaque structures in the cockpits, unfavourable silhouettes of the intruders, low altitude of the sun, additional workload during special flights, and a probable misjudgement of relative altitude, for example. Several countermeasures against midair collisions under visual meteorological conditions were implemented after these actual accidents. According to the German Near Miss Statistics, flight safety seems to be improved. However, these countermeasures cannot even prevent all those future midair conflicts that will be similar to the actual accidents treated in this paper.

Considering ground-based or independent airborne collision avoidance systems using a linear prediction model, all actual accidents could have been avoided by progressive implementation of such systems, in principle. However, this is not valid for two simulated three-dimensional encounters where two aircraft are turning simultaneously. In these cases, an automatic conflict alert will be issued too late or as a false warning. This problem can probably be solved by implementation of a data link transmitting the instantaneous heading or the roll angle of the aircraft to the control centre. As far as ground-based radar sytems are concerned, the detection and estimation of lateral accelerations of manoeuvring aircraft in due time as well as the determination of the real radar coverage taking light aircraft and gliders at low altitude into account may be crucial problems.

Even when using the latest technology, the author - as well as FAA [12] - does not believe that it is possible to develop a single collision avoidance system that will meet the need in all environments. A mix of collision avoidance devices will be required. Independent but coordinated airborne and ground-based solutions are needed. The crucial parameters and alert thresholds of collision avoidance systems have to be tailored to the individual features of the airspace used by civil and military aircraft at the same time.

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NOTATION IN FIGURES 8 TO 13

V_κ = true airspeed of aircraft κ
ρ_κ = radius of turn of aircraft κ
t_Z = time ($t_Z < 0$ before conflict)
d = horizontal range between aircraft
D = slant range between aircraft

ϕ_κ = roll angle of aircraft κ
P_C = collision point
d_κ, D_κ = range between aircraft at κ sec before entering the ρ_{THR}-zone
ρ_{THR} = range threshold (1.2 NM)

Linear predictions by a ground-based radar system:

$$\left.\begin{array}{l} d_{min} \\ D_{min} \end{array}\right\} = \left\{\begin{array}{l} \text{minimum range between a/c} \\ \text{at the closest approach} \end{array}\right.$$

T_{κ} = T_{THR} is equal to κ sec

Δt_{min} = time to the closest approach

T_{THR} = time to the ρ_{THR}-zone

T_{max} = maximum of T_{THR} ($D_{min} = \rho_{THR}$)

Predictions by a ground-based radar system or an independent airborne system:

$$\left.\begin{array}{l} -d/\dot{d} \\ -D/\dot{D} \end{array}\right\} = \text{time to the conflict}$$

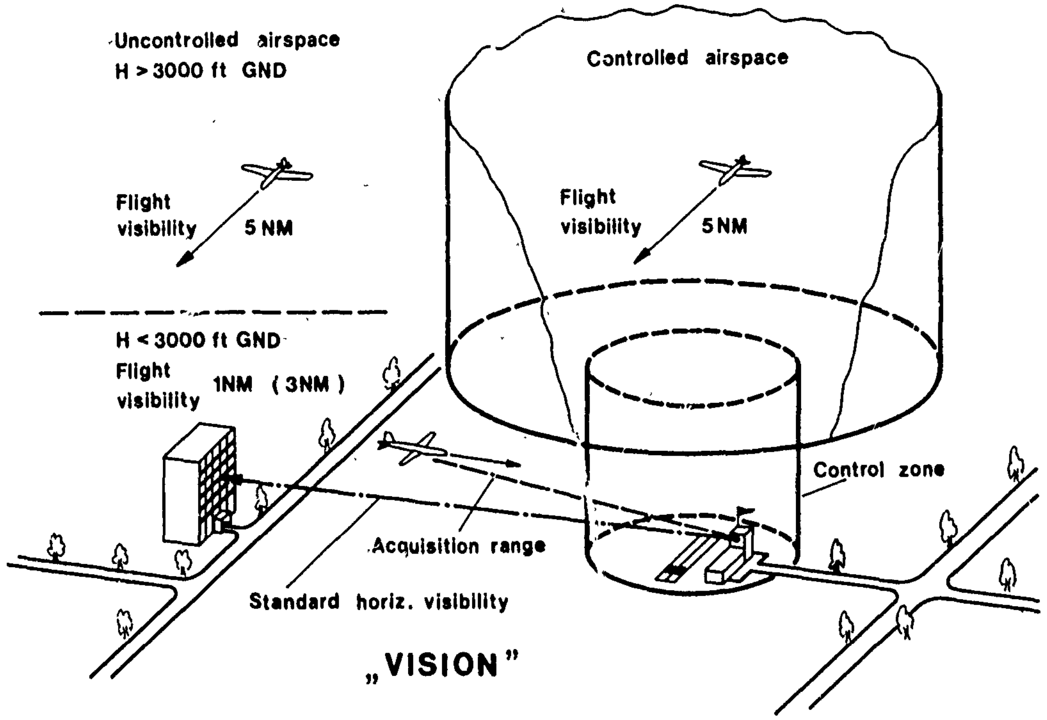
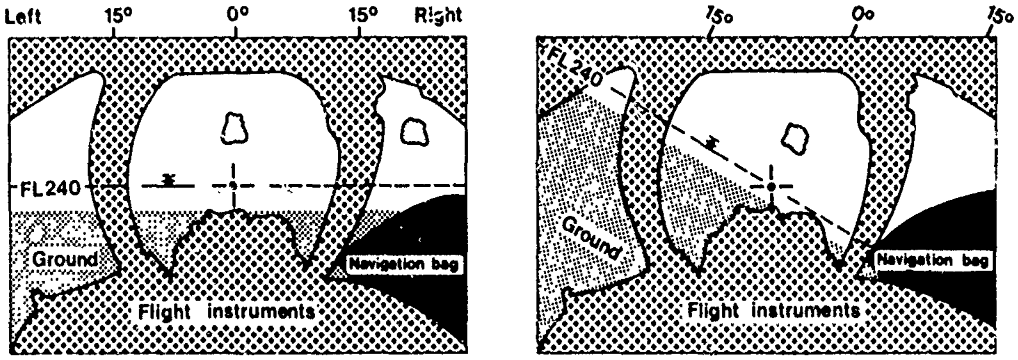


Fig. 1 Acquisition range, standard horizontal visibility and minimum flight visibility in visual meteorological conditions.



Straight and level flight   Horizontal left turn (Φ = 30°)

Flight level 240 (24000 ft)

Fig. 2 Field of view in a G-91 cockpit (one eye). Relative position, perspective and apparent size of an intruder aircraft. Dip of the visible horizon.

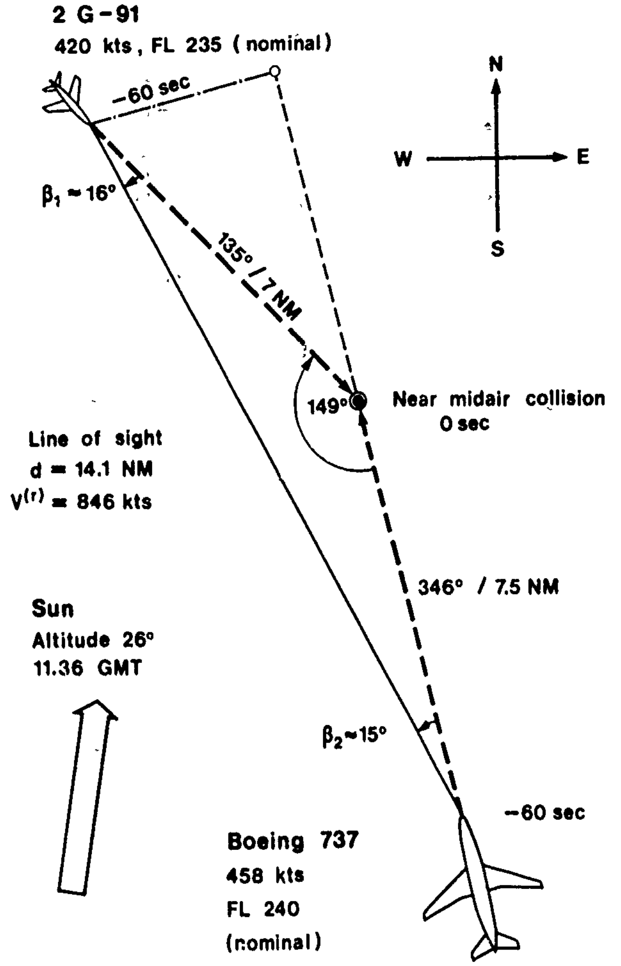


Fig. 3

Near Midair Collision
2 G-91s / Boeing 737.

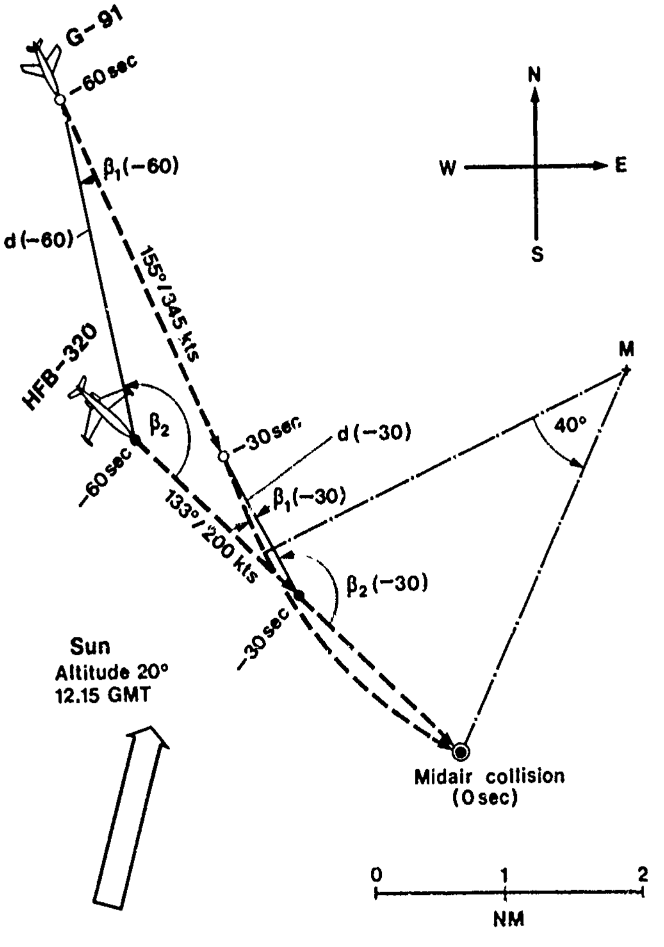


Fig. 4

Midair Collision
G-91 / HFB 320.

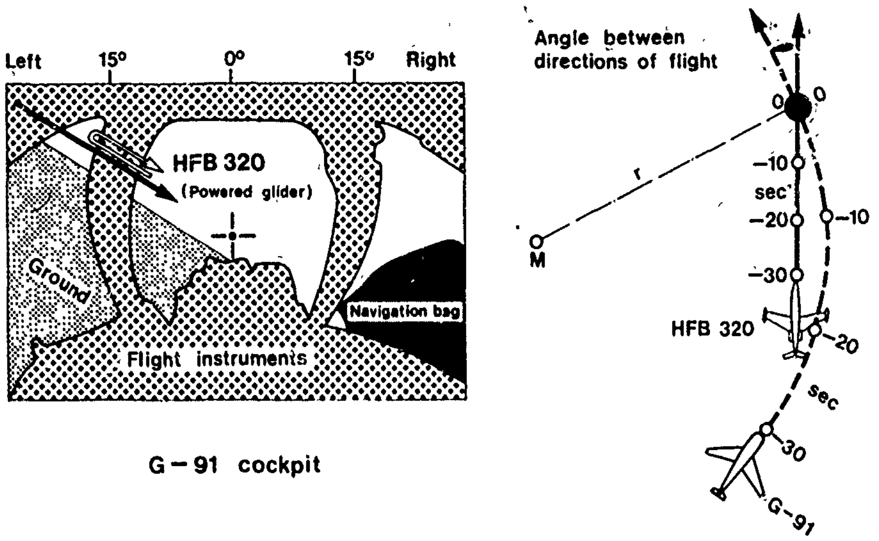


Fig. 5 Apparent track of the HFB 320 (powered glider) in straight and level flight on the windshield of the G-91 (F-4 Phantom) flying a horizontal left turn.

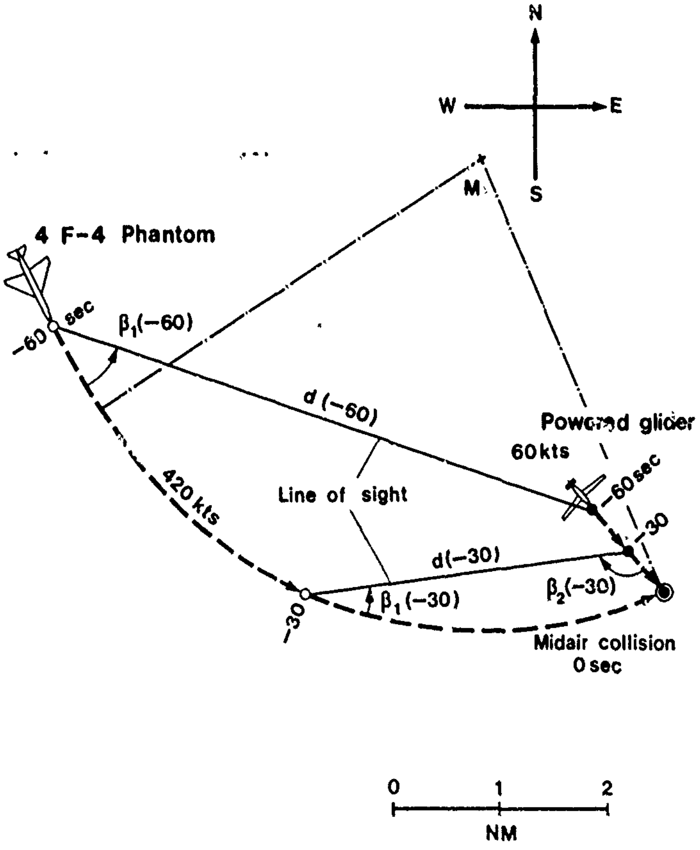


Fig. 6 Midair Collision 4 F-4 Phantoms / Powered Glider.

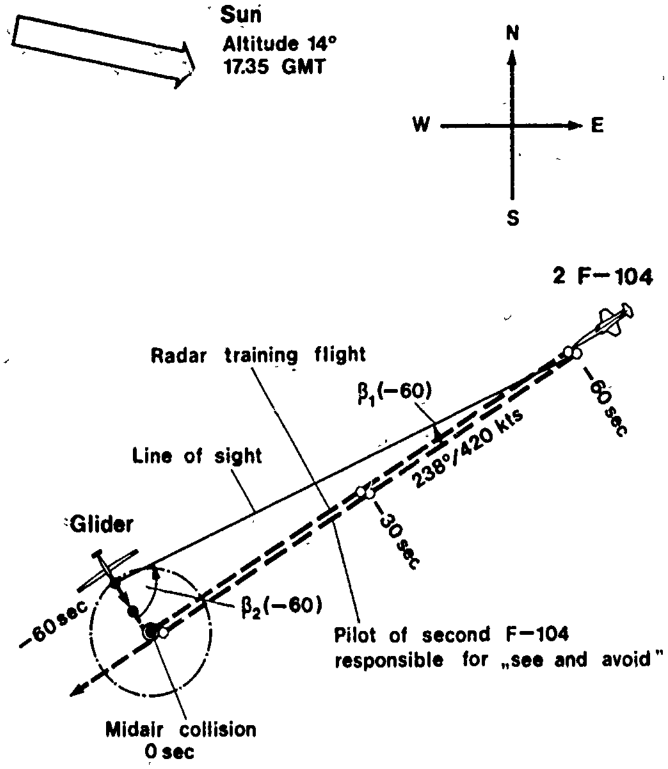


Fig. 7 Midair Collision 2 F-104s / Glider (Mirage / Glider similar).

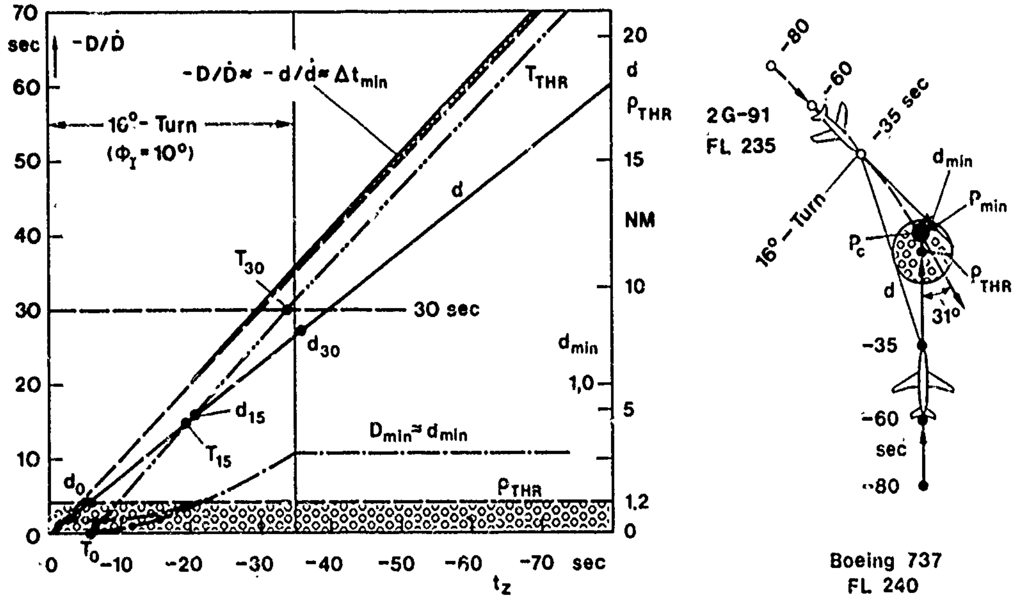


Fig. 8 Conflict alert 2 G-91s / Boeing 737. Notation as on page 10.
Right side: Prediction at 35 sec before the near midair collision.

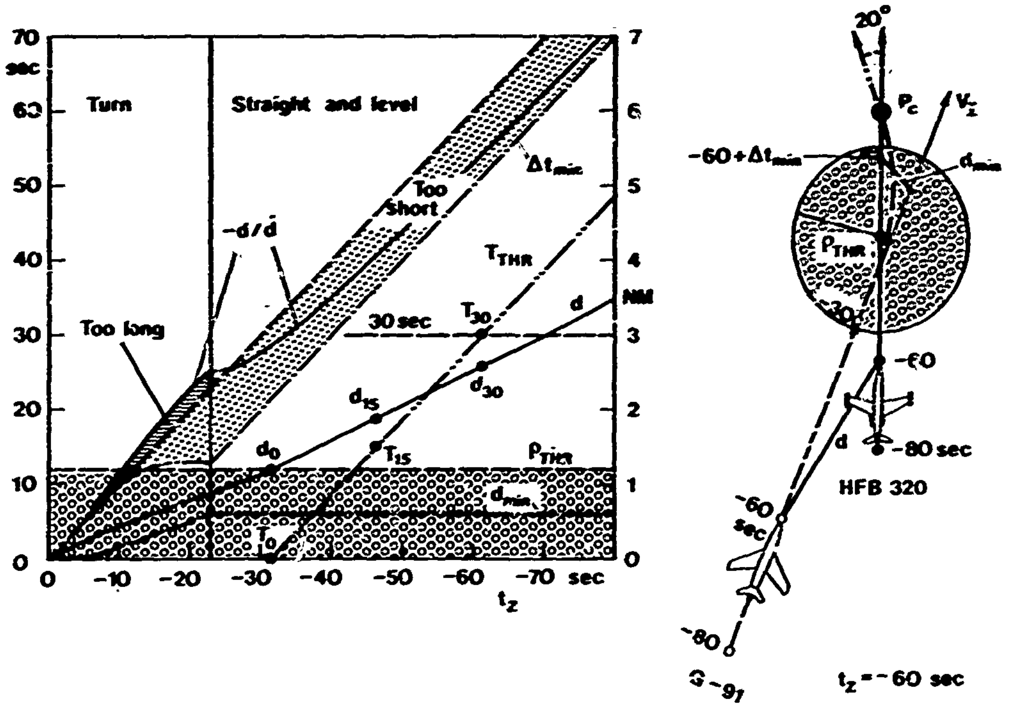


Fig. 9 Conflict alert G-91 / HFB 320.
Right side: Prediction at 60 sec before the collision.

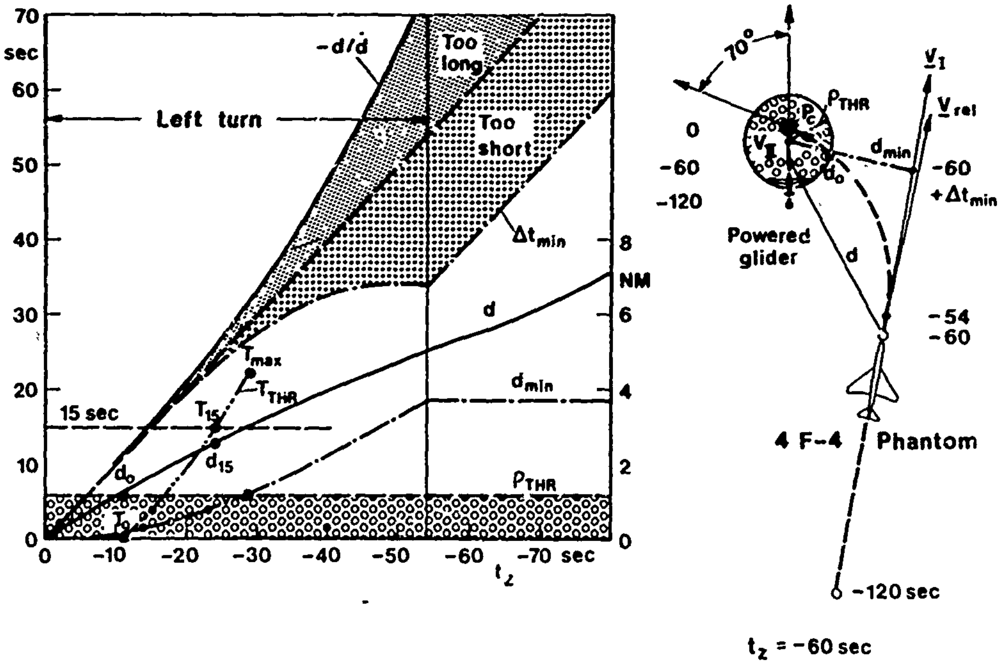


Fig. 10 Conflict alert 4 F-4 Phantoms / Powered Glider.
Right side: Prediction at 60 sec before the collision.

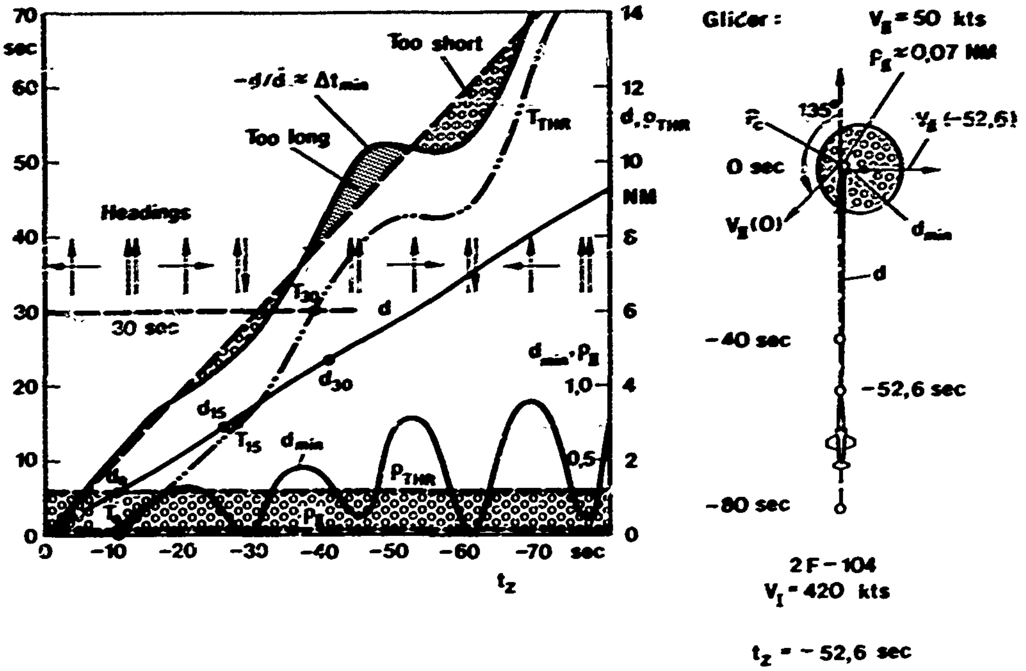


Fig. 11 Conflict alert 2 F-104s / Glider.
Right side: Prediction at 53 sec before the collision.

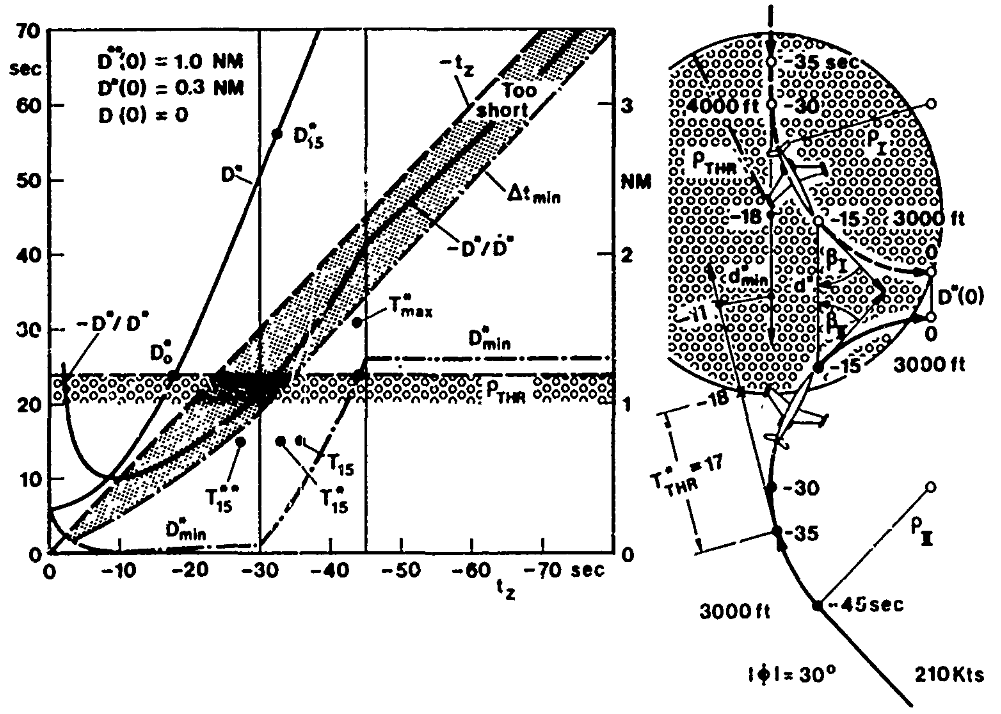


Fig. 12 Conflict alert simulated symmetrical flights I.
Right side: Predictions at 35 and 15 sec before the near miss.
** data for a simulated minimum range of 1.0 NM
* data for a simulated minimum range of 0.3 NM
data for a simulated midair collision.

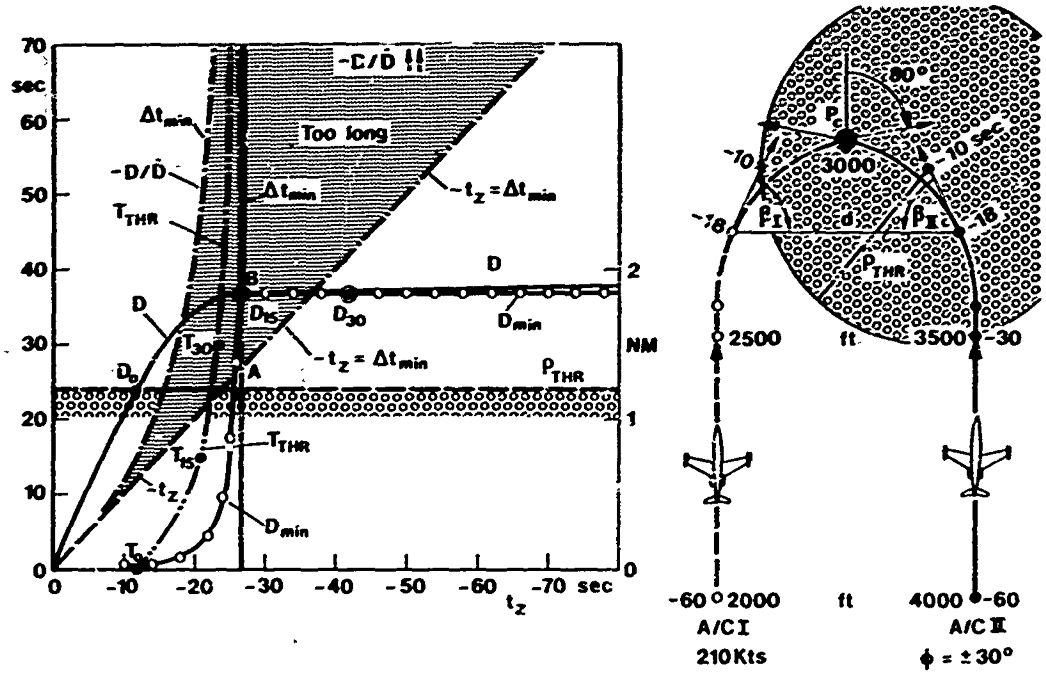


Fig. 13 Conflict alert simulated symmetrical flights II.
Right side: Prediction at 17 sec before the collision.

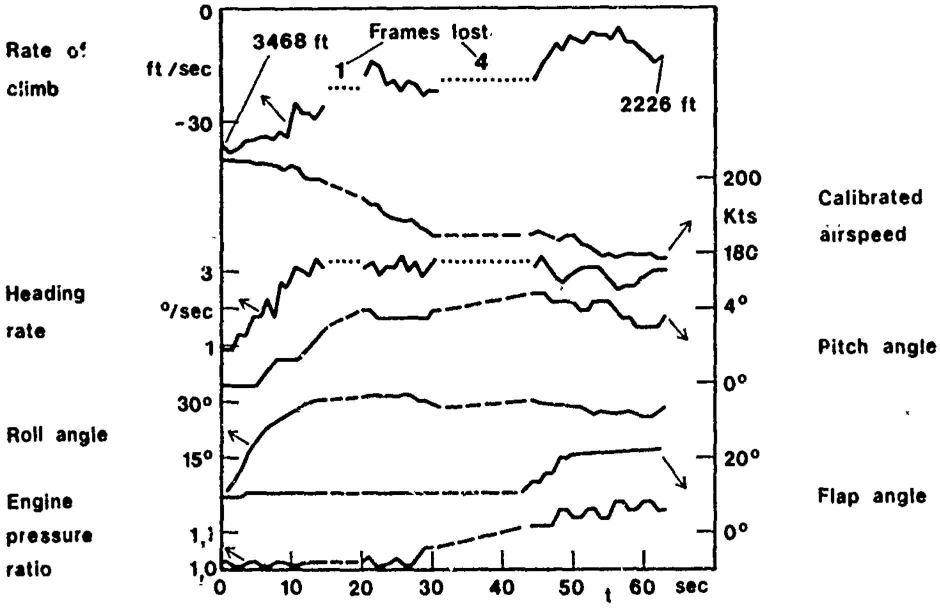


Fig. 14 Flight recorder data (AIDS) of an approach of a three-engine jet aircraft in the Terminal Area.

DETERMINATION OF THE SAFETY IN A NORTH ATLANTIC ORGANIZED TRACK SYSTEM WITH REDUCED LATERAL SEPARATION

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This study has been carried out under contract for the Netherlands Department of Civil Aviation.

SUMMARY

The paper is an exposition of the work on collision-risk-modelling done by the authors for the North Atlantic Systems Planning Group (NAT/SPG). It concerns part of the study on the reduction of lateral separation from 120 NM to 60 NM at any fixed level in the North Atlantic Organized Track System.

Requirements on the navigation performance are described which aircraft must be able to meet if this reduction would be implemented. Two statistical tests are derived which can be applied to the measured number of navigation errors to determine whether the actual navigation performance is such that the system with 60 NM lateral separation meets a Target Level of Safety. The first test which belongs to the standard equipment of the NAT/SPG for judging the safety of the track system is based on one random model for all navigation errors. The second test is applicable for the case different types of navigation errors can be distinguished and modelled separately. The different contribution of each type of error to the total risk is taken into account by the use of weighting factors. This test, however, is still in discussion in the North Atlantic Systems Planning Group.

1. INTRODUCTION

Since its inception in the early 1960's the North Atlantic Systems Planning Group (NAT/SPG) has used mathematical models and statistical techniques along with operational experience in its assessment of minimum separations in the North Atlantic (NAT) Region. The main emphasis of its work has been until now on the assessment of a safe lateral separation for the NAT Organized Track System. This is an essentially parallel track system across the North Atlantic between Europe and Canada and the USA with relatively few crossing aircraft.

The latest development in this field is the establishment of a Minimum Navigation Performance Specification (MNPS) for part of the North Atlantic Region. This specifies the minimum navigation performance which aircraft must be able to attain if they are to be allowed to fly in the "MNPS Airspace". It has been shown in reference 1 that a lateral separation between the tracks of 60 NM would meet the "Target Level of Safety" proposed by the NAT/SPG if all aircraft flying in the MNPS Airspace would meet these criteria.

The implementation of the 60 NM lateral separation in the MNPS Area was planned in two steps:

1. The implementation of the MNPS by ICAO as a mandatory requirement for all aircraft wanting to fly in the MNPS Area. This was done on 29 December 1977 in the existing NAT Organized Track System.
2. The reduction of the lateral separation between tracks to 60 NM. It was agreed that this would only take place after it had been shown that the aircraft did meet the MNPS requirements. This would be based on an analysis of radar measurements of the deviations from track near the landfall points on both sides of the ocean. This trial period still continues at the present time, but it seems likely that the reduction of the lateral separation can be inplemented in the near future.

In this paper the statistical methods used in the analysis of these radar data are described.

2. THE RELATIONSHIP BETWEEN COLLISION RISK AND NAVIGATION PERFORMANCE

2.1 The risk model

The assessment of a safe separation is based on the use of a mathematical model for the calculation of collision risk and on the comparison of the calculated collision risk with a maximum allowable value of that risk which has been called the Target Level of Safety. The risk is expressed as an average number of aircraft accidents during 10 million flying hours.

The collision risk formula is given as eq. (1) in reference 1, together with the definitions of all parameters in the equation and the values used for most of these parameters. The most important parameters in this model are:

- the probability of lateral overlap of aircraft nominally flying on adjacent tracks
- the probability of longitudinal overlap of aircraft nominally flying on adjacent tracks at the same flight level.

The probability of lateral overlap is determined from actual measurements of the lateral deviations of aircraft. The derivation of the MNPS requirements concerning lateral deviations is briefly described in section 2.2. The probability of longitudinal overlap (expressed in the parameters E_y (same) and E_y (opp) in reference 1) must be determined from actual data on North Atlantic traffic, which must then be adapted to the new track system.

The Target Level of Safety has been derived by the NAT/SPG from general considerations and from comparison with other modes of transport. A value of one aircraft accident due to collision in fifty million flying hours has been adopted.

2.2 Derivation and monitoring of the MNPS requirements

Using this value of the Target Level of Safety and a few assumptions about the general shape of the distribution of the lateral errors, three requirements about the navigation performance required for a 60 NM lateral separation were derived in reference 1 from the collision risk formula. These are:

1. the standard deviation of the lateral deviations from track shall be less than 6.3 NM
2. the proportion of the total flight time spent by aircraft 30 NM or more off track shall be less than 0.00053
3. the proportion of the total flight time spent by aircraft between 50 and 70 NM off track shall be less than 0.00013.

Since 29 December 1979 only aircraft which have been certified to meet these requirements are allowed to fly in the MNPS Airspace. As it was realized that it is not possible for States to ensure that the aircraft will always meet these requirements, it was agreed that monitoring of the actual deviations occurring in the NAT Region will be an essential part of the MNPS. Effective and precise monitoring can in practice only be done by radar stations at the ends of the oceanic routes. Extensive discussions within the NAT/SPG have shown that the assumption that the navigation errors found at the end of the oceanic routes are representative for the whole MNPS Airspace will in practice produce only slightly cautious results. This means that the last two requirements can be expressed in the proportion of flights measured by radar at or beyond 30 NM and in the range of 50-70 NM, instead of proportions of time spent at those distances.

3 SEQUENTIAL ANALYSIS OF NAVIGATION PERFORMANCE

As the lateral motions of the aircraft are subject to random fluctuations, statistical methods have to be used for establishing whether the MNPS requirements are met. In this respect the requirements have different properties. It is relatively easy to obtain from the radar a sample of the lateral deviations to determine the standard deviation with the required accuracy. But the deviations of 30 NM and above and, to an even greater extent, those between 50-70 NM are very rare occurrences and statistical methods must be used to take into account the effect of random fluctuations properly.

During the discussions within the NAT/SPG about the methods to be used, the advantages of sequential methods were pointed out. One of their advantages is that they indicate at an early stage that a trend is changing. Though it was found that none of the available sequential tests could be directly applied to the verification problem, it was found that a sequential test could be derived for a slightly simplified version of the problem. This test and its limitations in the application to the present problem are described below.

Consider the third of the MNPS requirements which in many aspects is the most important one. According to the interpretation of this requirement given in section 2 before it has to be determined whether for the probability p on an error at the exits of the Organized Track System holds $p \leq 0.00013$ or $p > 0.00013$. Suppose for the moment that instead of this continuous range of p values there are only two possibilities p_0 and p_1 where $p_0 = 0.00013$, i.e. just equal to the MNPS upper bound and $p_1 = 0.00026$ i.e. equal to twice this upper bound. Then the decision to be made is whether $p = p_0$ or $p = p_1$. Let n flights in the NAT system have been observed of which ξ_n were found to exhibit an error between 50-70 NM. The occurrence of these errors satisfies the binomial distribution law with parameters n and p. For a given value of p the probability on finding ξ_n errors between 50-70 NM in n observed flights is

$$\text{Prob}\ (\xi_n | n,p) = \frac{n!}{\xi_n!\ (n - \xi_n)!}\ p^{\xi_n}\ (1-p)^{n-\xi_n}$$

Thus for p_0 and p_1 this probability can be computed and it is denoted by $P_0\ (n)$ and $P_1(n)$ respectively. The ratio of these two probabilities is called the likelihood ratio function:

$$L(n) = P_1(n)/P_0(n)$$

and it is clear that for small values of L it is very likely that $p = p_0$. A suitable test, therefore, will be (Reference 2 and 3)

(i) $L(n) \leq A$, then $p = p_0$
(ii) $L(n) \geq B$, then $p = p_1$
(iii) $A < L(n) < B$, then a decision cannot be made with sufficient confidence; more measurements are required.

Though it is thus very likely that $p = p_0$ if L is small, there is a (small) probability that in fact $p = p_1$. In such cases the test results in an incorrect decision. Two types of incorrect decisions can be distinguished:
type 1: $p = p_0$ is decided (on the basis of $L(n) \leq A$) though $p = p_1$
type 2: $p = p_1$ is decided (on the basis of $L(n) \geq B$) though $p = p_0$

The probabilities of these incorrect decisions, usually denoted by α and β, determine the constants A and B in the test. In practice it is often considered acceptable to take α and β equal to 5 %. This corresponds with a confidence level of 95 % of the resulting decision.
The sequential character of the test is expressed by the variable n in the likelihood ratio L(n), i.e. each measurement can be processed at the moment at which it becomes available.

The application of the test is made easier by the fact that the test for L(n) can be transformed into a test directly for ξ_n (Reference 2 and 3):

(i) $\xi_n \leq an + b_1$, then $p = p_0$
(ii) $\xi_n \geq an + b_2$, then $p = p_1$
(iii) $an + b_1 < \xi_n < an + b_2$, then a decision cannot be made with sufficient confidence; more measurements are required.

The parameters a, b_1 and b_2 are determined by p_0, p_1 and the values adopted for α and β (i.e. 5 %).

Though the usefulness of the test is demonstrated below it must be realized that in reality the probability p of occurrence of an error between 50-70 NM is not restricted to the values p_0 and p_1 but that the values of p can extend over a continuous range. The response of the test in a situation with arbitrary p is presented in figure 1 in the form of the probability that the test results in the decision $p = p_0$ as a function of p. For p = 0.00013 and 0.00026 these probabilities of course are equal to 95 % and 5 % respectively. Moreover it is seen that a consequence of the restriction to two possible values of p (i.e. p_0 = 0.00013 and p_1 = 0.00026) in the derivation of the test is that for a system characterized by a value of p significantly above the bound given by the MNPS the decision $p = p_0$ may result with a probability considerably higher than 5 %. However, noticing the uncertainties involved in the basic assumptions used in the risk analysis it is not yet considered necessary to take this into account (a possibility, of course, would be to introduce a more sophisticated sequential test).

The most convenient way to present the test results is in a graphics as shown in figure 2. The vertical co-ordinate is the number of errors between 50-70 NM, the horizontal co-ordinate is the total number n of flights observed by radar. The test criteria $\xi_n = an + b_1$ and $\xi_n = an + b_2$ produce parallel straight lines. The broken line represents the number of errors that is found and increases with a unit step for each error between 50-70 NM at the value of n where it occurred. If the broken line cuts the lower of the two parallel lines, then it is decided that the MNPS requirement for errors between 50-70 NM is met. If at the other hand the upper of the two parallel lines is cut then it is decided that the MNPS is not met. In case that the broken line is between both parallel lines no decision can be taken until more data are available. An advantage of this graphical presentation is that significant increases or decreases in the error rate are readily apparent. The broken line of figure 2 shows the number of errors (between 50-70 NM) for part of the Oceanic boundary during the second half of 1978. The total data set for that period, which was not available to the authors at the time of writing would probably have shown slightly better results but not sufficient to decide that the lateral separation could be implemented. The main reason for these unexpected results seems to be that during the first year after the MNPS was introduced there was still a number of flights for which the navigation equipment and/or the pilot proficiency were not up to MNPS standards. A careful analysis of the causes of all errors above 25 NM and wide publication of the lessons learnt from these analyses helped to reduce the number of large errors considerably during 1979 and it is now expected that the 60 NM lateral separation will be feasible in the near future.

4. ATTEMPT AT A MORE REALISTIC APPROACH

The investigation of the causes of all errors above 25 NM which was carried out by the ATC authorities in co-operation with the operators showed that there were a few types of errors which did not completely conform with the random model used in the derivation of the MNPS criteria. In several cases these errors had been due to wrong waypoint insertion and, due to the relative geographical situation of the tracks and the radars, these were usually measured very near their peak values. In a few other cases the aircraft seemed to have been about on track during a large part of the oceanic crossing, and then deviated at a rather large rate from its cleared track. A third category seemed to have flown for some not inconsiderable time at 60 NM from its cleared track. The results of the radar measurements seemed to confirm this: the error distribution showed a small but significant peak at 60 NM which could not be explained by the model.

In order to investigate the effect which these specific types of errors could have on the overall risk, calculations of the collision risk associated with each type were made using somewhat simplified models (Ref.4). The results were expressed as 'weighting factors' for the errors in the range of 50-70 NM which are the ratios between the collision risks as calculated from these special models and from the general model.
The results can be summarized as follows:

- A complete flight on a wrong track 60 NM from its nominal track in a track system with 60 NM lateral separation would have a weight of about 1.1.
- A single wrong waypoint insertion would have a weighting factor of 0.4. In this calculation it was assumed that for each waypoint error measured by radar there would have been a similar error at each waypoint along the track, which would then not be measured by radar.
- An error linearly increasing with time to 60 NM or more would have a weighting factor of about 0.2 to 0.6 depending on the value of the measured error and the point at which the aircraft started to deviate. The simple model used in this calculation will probably give values which are somewhat lower than the actual risk.

The results of these calculations seem to indicate that the actual collision risk will in general be somewhat lower than as calculated in the method using the general model. The application of this "weighting" method is, however, rather cumbersome because the actual trajectories of all errors between 50-70 NM would have to be known with some accuracy. For the time being, therefore, the NAT/SPG has not yet agreed to use this method.

5. SEQUENTIAL ANALYSIS OF NAVIGATION PERFORMANCE USING WEIGHTING FACTORS

If the weighting factors described in the previous section should be applied, the sequential test described in section 3 should also be modified. This is because the binomial probability law used in the previous derivation does not hold in this case and the MNPS requirements have to be interpreted anew. Following the line of the previous derivation the modified test is described below.

Consider again the third MNPS requirement. Denoting the weighting factors by w_i and the probabilities of the individual error types by p_i (i = 1,2,...) it follows that this requirement can be interpreted as a limit for the weighted sum of the probabilities of the individual error types. Thus, it has to be determined whether

$$\sum_i w_i p_i \leq 0.00013 \text{ or } \sum_i w_i p_i > 0.00013 \qquad (*)$$

As in section four the problem is simplified by considering only two possibilities for this sum, i.e.

$$\sum_i w_i p_i = 0.00013 \text{ or } \sum_i w_i p_i = 0.00026$$

Let n flights in the NAT system have been observed of which ξ_{n_i} exhibit an error between 50-70 NM of type i ($i = 1,2,\ldots$). The joint occurrence of these errors satisfies the multinomial distribution law with parameters n and p_i ($i = 1,2,\ldots$). For given values of the p_i the probability of realising the observed ξ_{n_i} deviations jointly in n observed flights is

$$\text{Prob}(\xi_{n_1},\xi_{n_2},\ldots|n,p_1,p_2,\ldots) = C\, p_1^{\xi_{n_1}}\, p_2^{\xi_{n_2}} \ldots (1-p_1-p_2-\ldots)^{n-\xi_{n_1}-\xi_{n_2}-\ldots}$$

$$\text{where } C = \frac{n!}{(\xi_{n_1})!(\xi_{n_2})!\ldots(n-\xi_{n_1}-\xi_{n_2}-\ldots)!}$$

However, in contrast with the situation described in section 4 the individual probabilities p_i are not known. Therefore, in the present representation of the test it is assumed that the relative probabilities of the different error types are known (Ref.5). Using the constraints (*) derived from the MNPS requirement the individual probabilities p_i ($i = 1,2,\ldots$) can then be computed for both cases resulting in p_i^0 and p_i^1 ($i = 1,2,\ldots$) respectively. Thus, Prob $(\xi_{n_1},\xi_{n_2},\ldots|n,p_1,p_2,\ldots)$ can be computed for both sets of p_i and in the same way as in section 4 the likelihood ratio function:

$$L(n) = \frac{\text{Prob }(\xi_{n_1},\xi_{n_2},\ldots|n,p_1^1,p_2^1,\ldots)}{\text{Prob }(\xi_{n_1},\xi_{n_2},\ldots|n,p_1^0,p_2^0,\ldots)}$$

Again, the test $L(n) \leq A$ and $L(n) \geq B$ can be rewritten as a test for the number of deviations ξ_n directly:

(i) $\xi_n \leq cn + d_1$, then $p_i = p_i^0$ ($i = 1,2,\ldots$)
(ii) $\xi_n \geq cn + d_2$, then $p_i = p_i^1$ ($i = 1,2,\ldots$)
(iii) $cn + d_1 < \xi_n < cn + d_2$, then a decision cannot be made with sufficient confidence; more measurements are required.

where $\xi_n = \sum_i \xi_{n_i}$ (summation over all types of errors)

The difference with the test of section 3 is found in the values of the coefficients c, d_1 and d_2 which are now also determined by the mean weight $\bar{w}$:

$$\bar{w} = \sum_i w_i p_i / \sum_i p_i$$

Thus the weighting factors are used not to modify the count of errors between 50-70 NM, each error is counted again as unity as it occurs, but to determine the test lines.

The graphical representation of this test for the data collection described globally in section 3 is shown in figure 3. The mean weighting factor $\bar{w} = 0.63$ has been computed on the basis of the following classification of the observed errors:

type	number	weighting factor
complete crossing on a wrong track	1	1.1
single waypoint errors	3	0.4
linearly increasing errors	2	0.2
errors according to general MNPS model	3	1.0

The modified test does not yet yield a decision, but the broken line tends to be in the undesirable part of the test graphics.

Though the test using weighting factors has not yet been accepted by the NAT/SPG it indicates that the method of section 3 which is already in use for judging the safety of the track system is at the cautions side.

6. CONCLUDING REMARKS

The sequential test technique is a valuable tool for judging the safety of the Organised Track System. It is applicable for the case that all errors satisfy the same random model and for the case that different types of errors can be distinguished and modelled separately.

7. REFERENCES

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8. ACKNOWLEDGEMENT

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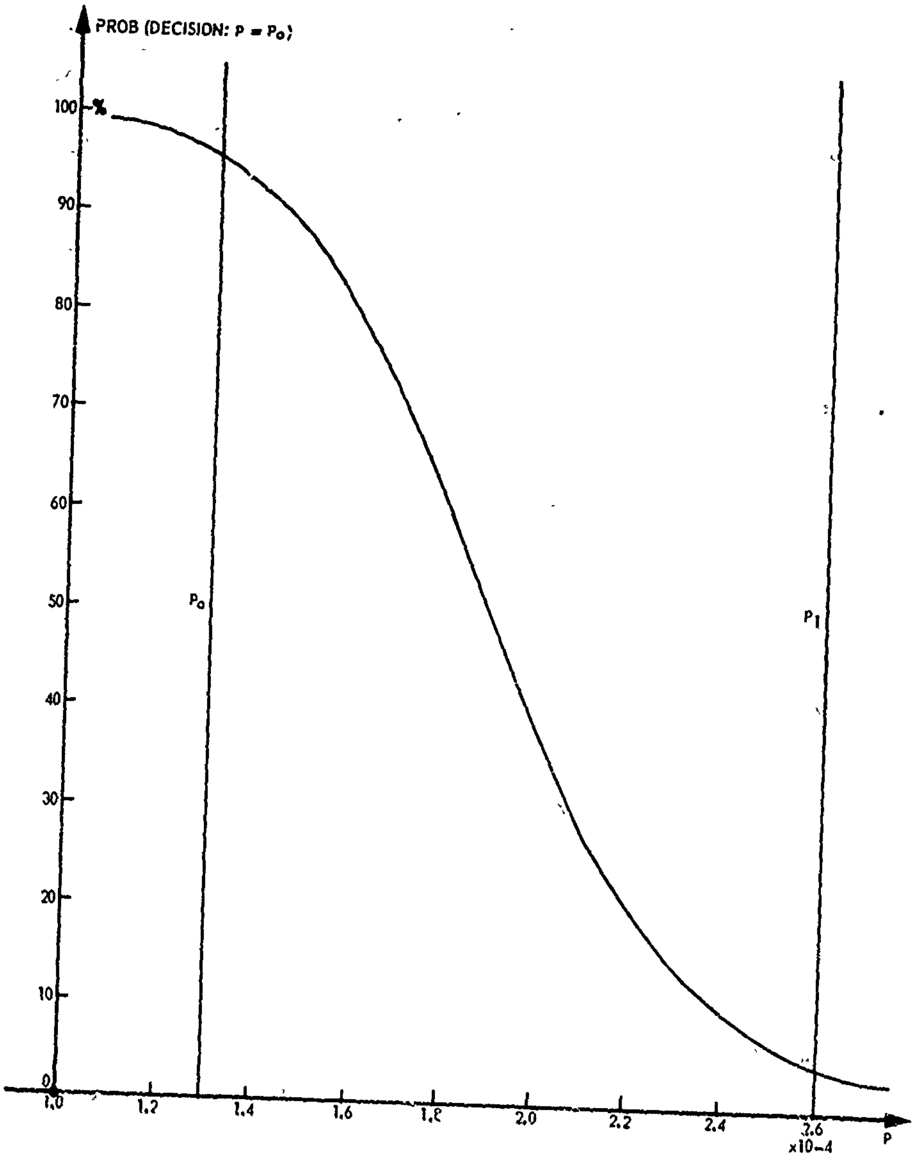

Fig. 1 Probability of the decision $p = p_0$ as a function of p

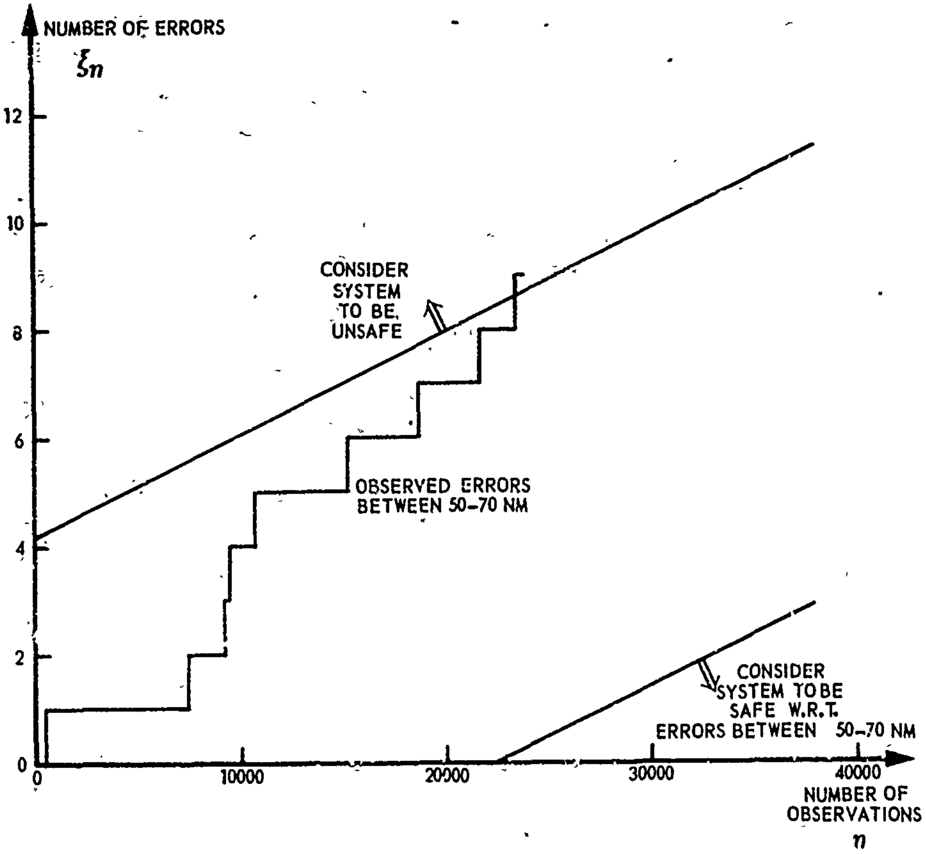

Fig. 2 Test lines for errors between 50-70 NM and observed number of errors for part of the Oceanic boundary in second half of 1978

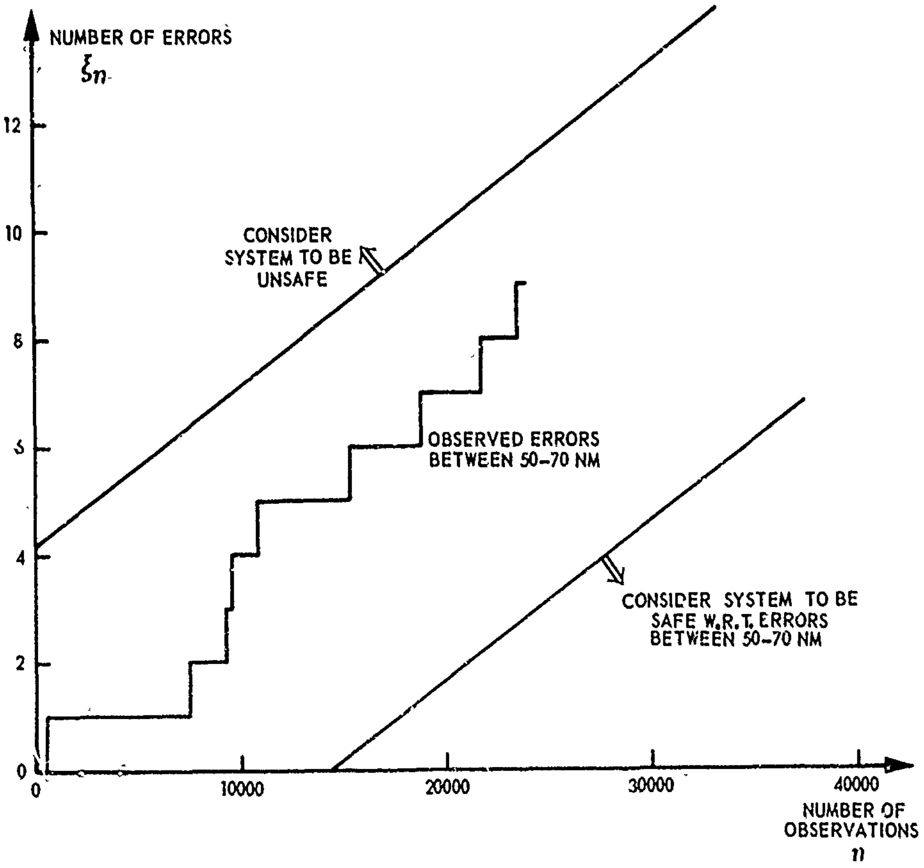

Fig. 3 Modified test lines for errors between 50-70 NM and observed number of errors for part of the Oceanic boundary in second half of 1978

U.S. ARMY USERS OUTLOOK ON AIR TRAFFIC MANAGEMENT

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SUMMARY:

The principle objective of this paper is to show that the U.S. Army has "come-of-age" in realizing the need for air traffic control (ATC) not only in support of its fixed base peace-time mission but also its tactical mission. By presenting the U.S. Army's user outlook on air traffic management as it existed during Vietnam and as it has evolved during the 1970's, it is hoped that other nations will benefit from our experience. It goes without saying, that most of us in NATO are convinced that Europe is where the action is. As far as the U.S. Army is concerned, the European scenario literally dictates doctrine for hostile operations in a mid-intensity environment. The major portion of this paper will therefore, address itself primarily to what is happening and planned from an ATC viewpoint in support of U.S. Army/Europe (USAREUR). Our former USAREUR Commander-in-Chief (CINC), Gen Blanchard, as well as our present CINC, Gen Kroesen, have challenged each member of the command stationed here in Europe to prove or disprove existing Army doctrine and, if necessary, to rewrite it as we go along. We in ATC feel that this challenge is particularly applicable to us as, air traffic management in the NATO arena is one of the most dynamic fields of Army endeavor in which one can make a significant contribution. At the conclusion of this paper, the reader will have a better understanding of U.S. Army ATC today, how it got here and its future.

BACKGROUND:

Our main customer is Army Aviation which in a tactical sense consists almost exclusively of helicopter operations. Army Aviation has the mission to support the ground commander 24 hours a day, anywhere on the battlefield, in near all weather conditions. Our mission in ATC is to support Army Aviation wherever and whenever needed; it's regrettable how controversial and misunderstood this mission has remained over the last 20 years. Much of the problem can be traced back to the very simple fact that the Army's main mission--unlike the Air Force-- is not flying. Army Aviation, therefore, spends an inordinate amount of time educating ground commanders and their staffs on the value of air mobility on the battlefield. Their key objective is to convince the ground commander--who is usually "up to his ears in alligators" planning the ground battle--to employ Army Aviation as an integral part of his battle plan--in essence, to think three dimensional. ATC has an analogous problem with Army Aviation. ATC is generally looked upon by the aviation community as something that restricts or limits its freedom of operation and is intrinsically "bad". This outlook on the part of Army Aviation toward ATC has been in existence for quite some time, at least 20 years. During the Vietnam conflict, there was an almost complete lack of interest and resultant lack of command emphasis on the part of Army Aviation. The few adequate ATC facilities we had could best be described in "NATO Terms" as a cross between a "Gypsy Caravan", "Piccadilly Circus" and "Coney Island." The rest of the ATC facilities were simply "an accident looking for a place to happen." That was the fixed-base picture--there was no tactical ATC. The general feeling of the Army aviation community was, "don't call us, we'll call you." According to most Army aviators, ATC was an expensive solution to a problem that didn't exist; except, during moments of stark terror such as thunderstorms, monsoons, fog banks, B-52 strikes, blown-up tail booms, etc. The name of the game in Vietnam was "1500 feet AGL", or, if possible, head for the Vietnamese "Autobahn" which was the shoreline. We lost many aircraft and, more importantly, lives, attempting "to do our thing" while our ATC equipment rusted from lack of use.

When Vietnam ended, we turned our attention to the European theatre and found things in pretty bad shape across the board. Slowly but surely we all--even us in Army Aviation--started to realize that we were in a new ball game. The Vietnam lessons-learned were rather inappropriate up against the Warsaw Pact mid-intesity threat. We would probably no longer "own the skies" in a European conflict like we did in Vietnam. Surviveability for helicopters meant Nap-of-the-Earth (NOE) flying which to the Army Aviation community again appeared to negate the requirement for air traffic control. Well, just about this time, which was back around 1974, someone had the foresight to stop the "merry-go-round" and the decision was made at the Department of the Army level to take the Army' air traffic control responsibility away from Army Aviation and turn it over to an organization with a world-wide communication's type mission. The Army Communications Command fit the bill. The Commanding General of the US Army Communications Cmd (USACC) took the mission, but, very wisely decided to do it in two phases: first of all take over and upgrade the fixed-base mission and at a later period, grapple with the tactical mission.

USAREUR FIXED-BASE ATC PICTURE

USACC has the Army's air traffic control responsibility worldwide. The Commander, 5th Signal Command has this responsibility in Europe and it includes all fixed-base as well as tactical ATC. The Commander of the 59th ATC Battalion has direct responsibility for the performance of his mission. The 59th is organized with three ATC companies and the Army Flight Operations Detachment (AFOD). Its first fixed-base mission is to provide terminal air traffic control services at ten instrument flight rule (IFR) airfields throughout Central West Germany. At each location there is an ATC tower facility with a full complement of UHF, VHF, and FM radios and a rather sophisticated dictaphone tape recorder. There is also a Ground Controlled Precision Radar Approach and a Non Precision Radio Beacon Approach. Both personnel and equipment are provided by the 59th. Five of these IFR facilities have the additional mission of providing a manual (non-radar) approach control function. These approach controls take traffic handoffs from Frankfurt, Stuttgart, and Nuernberg civilian approach controls. The next mission, is to provide terminal ATC service at nine visual flight rule (BFR) Army airfields and heliports. At each location, the 59th operates and maintains tower services only. The three fixed-base missions just discussed are all provided by the three numbered TOE companies. We'll look at the Army Flight Operations Detachment.

AFOD has the mission of providing a central coordination and control point for Army flight operations in Europe. This includes special missions, medevac, and search and rescue. It provides for USAREUR, services similar to those provided by an FAA flight service station in the United States. The Army Flight Operations Detachment also acts as CINCUSAREUR Sector Operation Center for the ADIZ. It operates two Flight Operations Centers (FOC) in the ADIZ to help prevent accidental violations of the political boundary. From those two FOCs, control and flight following is provided primarily for "Army" aircraft operating in, and near this sensitive area. In general terms, a pilot must file a flight plan with AFOD one hour prior to take off, have radio contact with either center, and report predetermined check points.

The last fixed base mission of the 59th is to provide equipment and maintenance at 15 advisory airfields and heliports. The radio operators are provided by the host unit. Advisory service should not be confused with air traffic control, in that a pilot is merely "advised" of winds and reported traffic and lands "at his own discretion." In providing the ATC services thus far described, a major contributing factor to the reliability, availability, and maintainability of our fixed base ATC facilities has been the ATC facilities up-grade program which was completed at all 19 IFR and VFR airfields and heliports in October 1977. This upgrade consisted of everything from "A to Z" as far as the ATC facility was concerned. It included such major items as a new family of radios, consoles, separate receive and transmit antenna locations, more stable and reliable power equipment and, where necessary, new tower structure and tower cabs. This completed our first major goal upon assuming USAREUR's fixed base ATC mission back in 1975.

OPERATIONAL NEED FOR TACTICAL ATC

As has been mentioned earlier, Army Aviation is our primary costumer and, in a tactical scenario, is almost synonymous with helicopter operations. For example, our customer is a UH-1 helicopter besieged by the low ceilings and the poor visibility of the European winter; a CH-47 Chinook heavily laden with critically needed fuel and ammunition supplies; a medevac Huey fighting against the clock to speed sick and wounded back to a field hospital; a division intelligence gathering/target acquisition aircraft launched regardless of weather conditions to obtain vital enemy movement information; a tank-killing AH-1 Cobra inadvertently trapped in a fog bank on his hasty return to the rearm and refuel point. In the past, especially in Vietnam, these aircraft were left to fend for themselves, The results were the loss of many lives and millions of dollars worth of aircraft. Regrettably, these losses were thought to be acceptable as they were associated with combat operations or realistic combat training. In reality, many of these accidents probably could have been averted if tactical ATC had been given more than just "lip-service." Today the Army realizes that conventional fixed-wing airfields or landing strips, capable of accepting C-130 type aircraft will be the exception rather than the rule in the division rear area. More reliance, therefore, is being placed on the helicopter to ensure continuous resupply and medevac in addition to its basic airmobile and anti-tank roles. It is imperative that these operations continue in near all weather conditions as it is a foregone conclusion that the military forces of the Warsaw Pact countries will use periods of adverse weather to launch their attacks. In a nutshell, this is the operational need for Army tactical ATC on the battlefield. A key point to keep in mind throughout this portion of the paper is that, doctrinally speaking ATC stops in the division rear area and all aircraft operating in the forward areas will be under "procedural control" of their unit operations. Now let's address the users stated need.

THE USER'S STATED NEED FOR TACTICAL ATC

The results of a study conducted by a cross section of combat arms personnel representing our customer - Army Aviation - revealed the following:

I. In the Brigade Area:
  - No Flight Plans
  - Procedural Control
  - Tactical ATC Teams Required

All flying is to be procedurally controlled by individual aviation units and by mission tasking. There is a need for tactical heliport and/or pathfinder teams. Tactical heliport teams are to operate VFR heliports. Pathfinder teams set up landing and pickup zones, refueling and rearmament points. These teams, which are organic to the division, must have radio beacons to which the aircraft can navigate and have communications, but will not actually have to control the aircraft.

II. In the Division Area:
  - No FCC Flight Plan
  - Procedural Control
  - Tactical ATC Teams
  - Capability to Cross Division Boundary
  - Capability to Fly Above Coordinating Altitude
  - Multiple Instrumented Heliports/Landing Sites

- Flight Advisories

Again in the Division Area, the user wants procedural control over his flying. Once he starts flying across Division boundaries, however, he wants some procedure to preclude flight within hazardous areas. Our user has stated very clearly that he must have the ability to fly above the Army/Air Force coordinating altitude.

III. In the Corps and COMMZ Areas:
- No Flight Plan in VMC
- Capability to Fly in IMC
- Tie-In with Air Force
- Capability to Fly above Coordinating Altitude
- Flight Following on Request
- Instrumented Airfields
- Flight Advisories
- Enroute System of Beacons

As one can readily see, our customer has recognized that there is a hierarchy of requirements that he needs as he flies from the Combat Zone back through Division, Corps and COMMZ areas in near all weather conditions, day or night.

TACTICAL ATC ORGANIZATION IN USAREUR

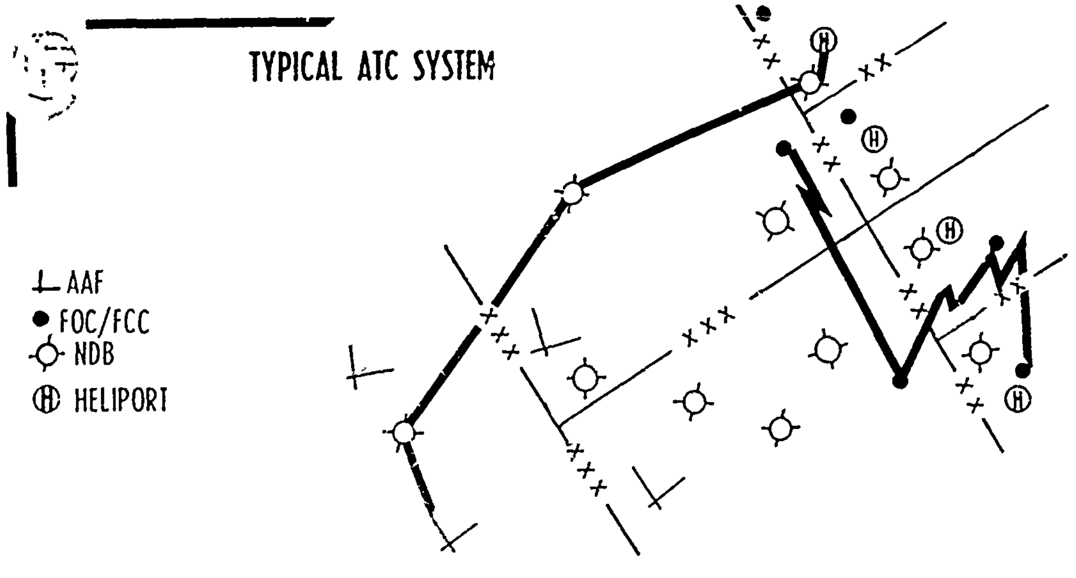
As mentioned earlier, the Army Communications Command's first major goal was "to get a handle" on the fixed base ATC mission. Our second major goal was to reorganize existing piecemeal ATC assets into a single organization. This was accomplished here in Europe by the assumption of, initially, the Corps' and a year later the Division's tactical ATC mission and the consolidation of all the Army's ATC assets in Theatre under a single battalion. This two year effort was finally accomplished last fall with the activation of the 59th ATC Bn. The battalion is structured on a basic building block concept. The basic unit is the ATC platoon which provides direct support to a division. The platoon is capable of providing the following tactical ATC support to the division:
- Terminal IFR operations at the division heliports
- A flight coordination center (FCC) in the division area
- Non-directional beacons to terminate an enroute system
- ATC liaison team in the Division Airspace Management Element (DAME)
- Tactical Team to set up and operate a VFR heliport

Currently the 187th and 189th ATC Companies (FWD) provide direct support to V and VII Corps respectively of the Corps support platoons. Each of the two forward ATC companies can currently provide the following tactical ATC support to the Corps:
- Terminal IFR operations at the Corps main airfield
- A flight operations center (FOC) in the Corps area
- An enroute non-directional beacon system
- An ATC liaison team in the Corps Airspace Management Element (CAME)

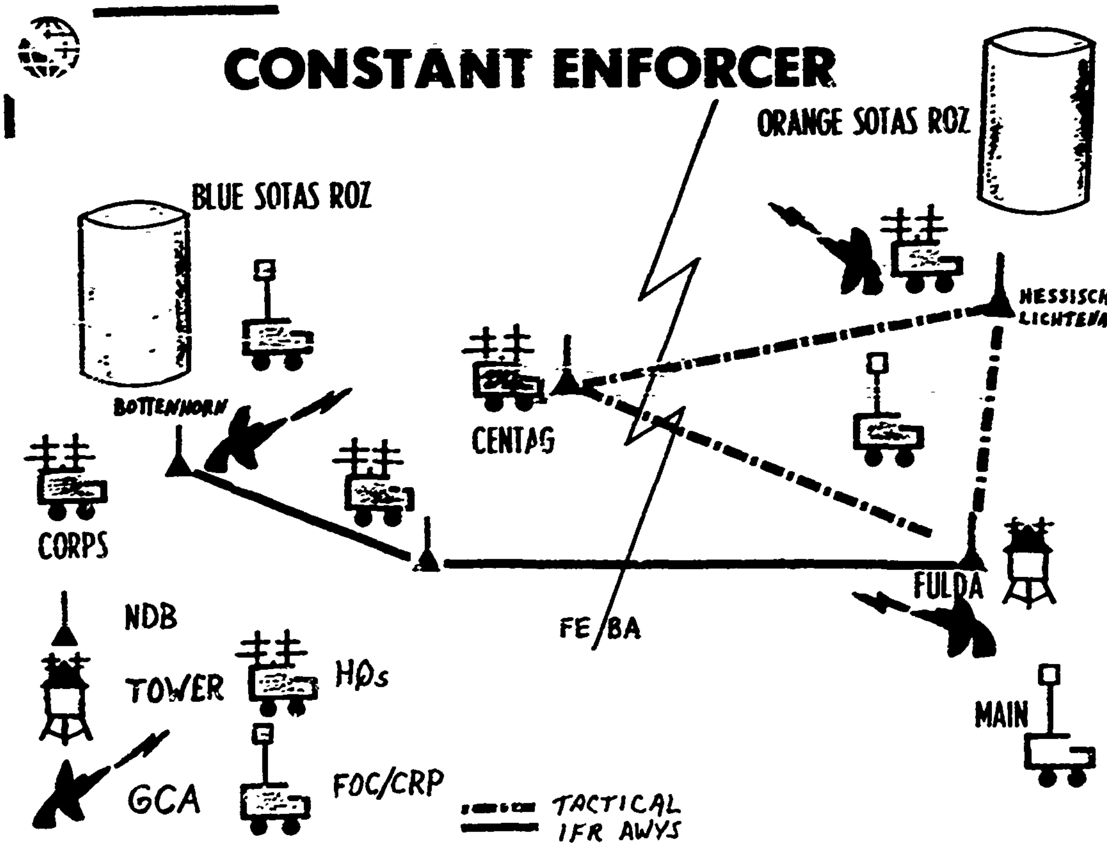
The word "can" rather than "will" was purposely used as it is envisioned that several of the fixed base airfields may remain operational initially to serve as assembly areas. As the battalion is not staffed to accomplish both its fixed base as well as its tactical mission simultaneously, contingency plans have addressed in detail the transition from one to the other. In addition, the 240th ATC Co (COMMZ) can provide terminal ATC services at up to four airfields in the COMMZ area. The Headquarters provides the normal command and control functions and also has a small aviation section to support the deployed units and to flight check the terminal facilities and the enroute navaids. No tactical mission has yet been defined for the Army Flight Operations Detachment. However, it is possible that AFOD might have a very key mission in assisting large numbers of helicopters transiting from European ports into the combat zone.

TACTICAL ATC-CONCEPT OPERATION

Graphically this is a rather simplified version of the Army's portion of a tactical ATC system with Army airfields and heliports.



Each has a precision ground controlled radar masked by terrain, as much as possible, and the radar signal turned off when not in use. The flight operations center (FOC) is the hub of our IFR system. It will colocate with or be electrically connected to the Air Force Control and Reporting Post (CRP) to coordinate joint use of the airspace. The FOCs are netted with the division's flight coordination centers (FCC) to form an enroute system providing WX, NOTAMs, flight following, and other services as required to in flight aircraft. The FOCs and FCCs are also netted with the Corps and Div airspace management elements, respectively, for artillery and air defense coordination. Transient routes are established strategically by placing non-directional beacons throughout the Corps to assist aircraft transitioning between the COMMZ and the Combat Zone during periods of adverse weather. This is a schematic of the Army's tactical ATC system fielded for the recently completed Constant Enforcer Exercise.



You can quickly see that this was not a typical deployment, but even with the artificialties of peacetime safety and the small airspace we were pressed into, our training objectives were met. Fulda served as a rear area airfield for both the Blue and Orange forces from which tactical IFR flights down the three airways were initiated. Three of the airfields had a precision radar approach as well as a non-precision NDB approach. Bottenhorn served as the Blue Corps airfield. There was also a Blue Division VFR heliport that moved several times during the exercise. In the center was CENTAG's neutral VFR heliport. Hessisch-Lichtenau served as the Orange Division's heliport. The FOC was colocated with the Air Force Control and Reporting Post on a mountain top and two divisions FCCs were deployed as depicted. Two permanent restricted operations zones (ROZ) were established to allow both divisions the freedom to launch their Stand Off Target Acquisition System (SOTAS) aircraft day or night. This was the first time that the 59th ATC Battalion tactical operations center was established in the field and, as a result, many statistics are available from the operation. The battalion logged a traffic count of almost 10,000 air movements during the exercise. Over 100 of these were under tactical instrument control (10 times more than on any previous exercise) and just as important, there were no accidents. This concept and organization has passed the test on the last three Reforger exercises and we feel certain it will work effectively in wartime. Throughout this paper, we have emphasized that our main customer is Army Aviation; however, it goes without saying, that the Army's ATC system (both the fixed base as well as the tactical) is available and, indeed here in Europe, does support all the allied forces of NATO.

Lastly, without discussing in detail the Army's worldwide ATC structure and contingency plans to support an all out war here in Europe, it is adequate to say the following:
As combat divisions arrive, so will the ATC units which presently support them

- With the arrival of these forces each Corps ATC support would be expanded from a company to a battalion
- The ATC battalions would be controlled by an ATC Group (the nucleus of this Group would be formed by the ATC Office of 5th Signal Command which presently functions as USAREUR's Theatre ATC staff.)

WHAT IS NEEDED IN THE FUTURE

We in the Army's ATC business realize the importance of our day to day responsibility for the lives of the people we serve. It is this "life and death" mission that demands the best possible equipment available be put in the hands of the Army controller to allow him to perform in the most professional manner possible. We feel the most important requirement as far as tactical ATC is concerned is a communications system that will permit adequate contact between ground stations (FOC, FCC, and tactical ATC facilities) and aircraft flying in a Nap-of-the-Earth mode. In the forward areas, a truly manportable radio configuration for tactical ATC teams and pathfinders is required. The equipment in the inventory now will suffice in the interim, however, it is actually too heavy and too bulky to be employed in the forward areas of a division combat zone. The U.S. Department of Defense has stated a requirement for a tactical version of the ICAO approved microwave landing system and has appointed the Army as its military coordinator for the system known as the Joint Tactical Microwave Landing System (JTMLS). However, due to a number of international economic and political considerations, it is becoming quite clear that JTMLS may be delayed until the 1990s or beyond. The Army has needed this capability for years and can ill-afford to wait another ten to twenty years. We are presently looking into the possibility of an interim system which could be made compatible, in the future, with JTMLS. Also, as an interim measure substantial improvements must be realized in tactical ground controlled approach radar systems. Specifically, the following capabilities are considered mandatory and have been identified to our combat developer: a moving target indicator (MTI) capability to eliminate ground clutter that could be experienced in a combat zone; an improved IFF capability and a large shelter to accommodate the operators; and an ASR mode compatible with MSL. Substantial improvement is required in our non-directional beacons. These improvements are electronic and should provide a capability to remotely actuate the beacons from the aircraft or from the ground stations. Also monitoring equipment is required to permit a remote station to monitor the NDB's performance. Although positive enroute control is not required at the present time, there is a real possibility of it being required in the areas behind the division in the very near future because of all the evolving doctrine and associated technological developments in the Position Identification and Navigation (POS/NAV) area. In fact with the Global Positioning System just over the horizon, positive control throughout the battlefield is very possible. Finally, as far as the tactical arena is concerned, there is a need for a completely tactical aircraft control tower for use at division heliports and Corps airfields. These facilities must have a capability of being set-up and removed within a 2-hour time frame.

Turning now to the fixed base mission, a number of capabilities require development. In the area of precision landing equipment, our ground controlled approach radar systems require improved reliability, i.e.: greater meantime between failure; improved meantime to repair; and MTI. This development work should not reduce the effort being placed on the portable version of the ICAO approved MLS. MLS could resolve a majority of the problems associated with the precision terminal landing systems currently in use. Therefore, the Army supports the adoption of MLS in support of its fixed-base ATC mission worldwide. The Army is continuing its efforts in the area of tower consoles and associated communications systems along with developing a standard family of ATC towers for its fixed facilities.

CONCLUSION:

This paper has covered a considerable amount of information dealing with the Army's users outlook on ATC. We have attempted to take the reader from the U.S. Army's user outlook on ATC as it existed back in the Vietnam era of the 1960s, to Europe in the 1970s to the future potential of a Global Positioning System. About mid-way into this treatise we stated that the Army transferred the responsibility for the ATC mission from Army Aviation to the U.S. Army Communications Command (USACC). Since 1974 USACC has intensively managed the mission worldwide by concentrating initially on the fixed base mission and, more recently, on the tactical mission. The experience that USACC has built up over the last five years in the field of ATC is quite broad, but it is learning more and more every day as it strives to provide the user with the best air traffic control in the world.

THE DEVELOPMENT AND TEST OF A TACTICAL SELF-CONTAINED LANDING SYSTEM

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SUMMARY

The requirement to tactically operate a helicopter in the nap-of-the-earth (NOE) environment has previously accelerated the development of two equipments, the primary functions of which are unrelated to the IMC landing maneuver. The first is a digital symbol generator (DSG) whose basic function is to compute and display the augmenting symbolic data necessary to operate a helicopter in the NOE environment via a FLIR presentation of the contact world. The second equipment is a digitally-generated topographic map display (DMG). This research effort shows the existence of a tactically-viable, precision navigation capability is sufficient justification to consider adaptation of the DSG and DMG equipments to the reversionary function of providing IMC terrain-following and tactical landing capabilities. The paper develops the control/display architecture necessary to use a radar altimeter (AN/APN-209) to control the elevation flight path of the aircraft and a doppler radar (AN/ASN-128) to control the deceleration of the aircraft. The assumed precision navigation system provides the Northing/Easting aircraft position: 1) to permit the aircraft to be steered along the prescribed ground track to the landing zone, 2) to provide a starting point for interrogation of the DMG terrain elevation data for purposes of generating anticipation for the TF system, and 3) to act in concert with the velocity output of the AN/ASN-128 for purposes of following a preprogrammed deceleration profile to the landing zone. The paper also describes a multi-phase simulation and flight-test program to assess the performance of the complete system in the NOE environment.

INTRODUCTION

The landing system described within this paper has evolved from the requirement for a helicopter to operate in close proximity to the terrain if it is to survive the threat of radar-directed anti-aircraft weapons. While the accuracy of these weapons may increase under environmental conditions compatible with tracking in the infrared or visual spectrums, the lethality of the weapons in the radar-guided mode is sufficient to demand that aircraft remain in proximity to the terrain regardless of the existing environmental conditions. There exists a myriad of sensors by which a pilot can attain, under certain environmental conditions, sufficient perception of the contact world to takeoff and maneuver a helicopter at nap-of-the-earth (NOE) altitudes to a distant destination. The source of this perceptual information (i.e., a pilotage system) varies from the unaided eye for clear daylight conditions, to the PVS-5 night vision goggles for quarter-moonlight conditions, to a FLIR imaging system for starlight conditions and perhaps to a high-resolution radar imaging system for an IMC environment. It is presumed that if environmental conditions are such that an aircrew has sufficient perception of the contact world to takeoff and tactically maneuver the aircraft to its distant destination via one of the pilotage systems described above, then no additional aids are required to decelerate and land the helicopter at the destination (i.e., if one can see, one can land). It certainly seems to follow that if the aircrew has the capability to tactically maneuver in an IMC environment then there would not be a requirement for a dedicated tactical landing system. The general niche for the dedicated system is to assist an aircraft landing under environmental conditions which are incompatible with the perceptual capabilities of its resident pilotage system. One should note that the effectiveness of a dedicated tactical landing system in alleviating this situation cannot be accurately assessed in isolation from the associated problem of tactically maneuvering the aircraft to within the approach corridor. In the high-threat, tactical environment, the aircraft is never released from its commitment to fly in close proximity to the terrain. One may conclude that a helicopter operating in the high-threat, tactical environment must be equipped with either (1) a high resolution radar imaging system (i.e., an IMC pilotage system) or (2) a non-IMC pilotage system and a reversionary capability consisting of IMC terrain-following and tactical landing systems.

In this paper *unattended* landing refers to a landing at an arbitrary site about which little is known (e.g., obstacle location, and hence the "safe corridor" is unknown). As such, an unattended landing can only be made under environmental conditions which are compatible with the ability of the resident pilotage system to perceive the terrain, avoid obstacles, and generally establish a safe corridor to the landing zone. These functions are not unique to landing as they are routinely performed during tactical enroute maneuvers at NOE altitudes. If one associates the capability of instantaneously establishing a safe corridor (and hence performing an unattended landing) with the resident pilotage system, then landing research as an entity is involved with *attended* landing sites where the safe corridor is known from observations made under more favorable environmental conditions. Ground personnel may or may not be at the landing zone at the time of the landing. Knowledge of the safe corridor is the differentiating characteristic between attended and unattended sites. The more specific niche for the dedicated tactical landing system is to assist aircraft equipped with 1) the unaided eye, 2) night vision goggles, 3) a FLIR imaging system in making an attended landing when environmental conditions preclude an unattended landing.

When used in the context of an attended-area landing, the term *self-contained* solely implies the lack of a ground-based landing aid at the landing zone. This has an immediate implication as to the frame-of-reference used for geographical location of the landing zone and the using aircraft. In contrast to the ground-based landing aid which operates in a relative grid sense, a self-contained,attended-area landing aid must operate in an absolute grid sense (e.g., UTM). The primary technical barrier to a self-contained,attended-area landing is one of relative positioning accuracy of the aircraft and LZ in the absolute or UTM frame-of-reference. The two questions of interest are; to what accuracy can the using aircraft position itself in the UTM frame-of-reference and to what accuracy can one position the LZ and its associated *known* safe corridor in the UTM frame-of-reference? The latter is much less a technical barrier than the former. In contrast to the usual requirement to publish the azimuth of the corridor and the approximate location of the LZ, one would have to promulgate (1) the nominal azimuth and width of the safe corridor, (2) the minimum approach angle into the LZ and (3) a more precise UTM location of the LZ (i.e., the apex of the safe corridor). Therefore, the primary technical barrier to achieving a self-contained,attended-area landing capability is the accuracy to which the using aircraft can position itself in the UTM frame-of-reference. One might note in passing that the *unattended* landing capability associated with an NOE pilotage system is inherently self-contained and,in fact, operates in a relative grid sense via visual feedback to the pilot, rather than an absolute grid sense.

In at least this author's mind, the fundamental difference between the high-threat, tactical environment and all other environments is the role of terrain. In more benign military and conventional civilian environments, it is quite acceptable to control the elevation flight path of the aircraft relative to a space profile during the approach maneuver and to vector the aircraft to the approach corridor via some form of radio navigation. When terrain masking is essential to aircraft survival, logic indicates the control/display architecture of the system incorporate the idea that aircraft elevation relative to the terrain (in lieu of relative to a space profile) is one of the system states to be controlled. The ineffectiveness of the *isolated* ground-based landing aid in the high-threat, tactical environment may be emphasized by consideration of the range at which a helicopter is likely to receive useful broadcast information. The helicopter must certainly be within line-of-sight of the ground-based aid to receive any information at all but even this is insufficient. An optimistic estimate of the range of interest results from assuming a flat,although not obstacle-free,earth and a nominal aircraft altitude above the terrain of 200 feet. If the encoded minimum safe approach angle into the landing zone is N degrees, then the aircraft must be within at least 3.6/N kilometers of the LZ for the information to be truly useful (i.e., for the aircraft to initiate a descent into the acquired safe corridor). The most likely effect of terrain contours upon the above result is a further reduction in the acquisition range due to line-of-sight constraints. In any event, the geographical area over which a ground-based landing aid provides a haven for aircraft blinded by environmental conditions is very small. To make effective use of this type of landing system in a high-threat, tactical environment, the non-IMC pilotage system must be augmented with an IMC terrain-following (TF) capability. This TF capability would allow the aircraft to maintain at least some degree of terrain masking and cover while maneuvering to within the approach corridor defined by the ground-based landing-aid.

An operational scenario based upon the use of a non-IMC pilotage system (e.g., naked eye, night-vision goggles, FLIR) for mission accomplishment with a safety-of-flight reversionary capability consisting of an IMC-terrain-following system and a ground-based landing aid is technically sound, particularly if one assumes that control of aircraft elevation relative to the terrain during the actual landing maneuver is perhaps a desirable, but not an essential system characteristic. However, it is the contention of this paper that a viable, perhaps even preferable alternative exists which *adapts* other required NOE mission equipment to achieve firstly, the mandatory IMC terrain-following capability and secondly, within the attended-area framework previously described, a self-contained tactical landing capability. Justification for consideration of such an alternative for the high-threat tactical environment may be found in one or more of the following; 1) the tactical undesirability of locating radiating equipment at a landing zone, 2) unfavorable economics associated with dedicated reversionary equipment as compared with adaptation of mission equipment to achieve the reversionary capability, 3) a desire for a back-up reversionary capability in instances or geographical areas where ground-based landing equipment is nonexistent, inoperative, destroyed by enemy action, in-transit, etc.,.

SYSTEM DESCRIPTION

The objective of this section is to suggest a means to achieve the safety-of-flight reversionary capability described in the introduction. The reversionary IMC TF capability described within this paper is not inexorably linked with the concept of a self-contained, attended-area landing. In principle, the TF concept to be described could be used in conjunction with a ground-based aid to steer the aircraft down the safe corridor to the landing zone. In practice,however, the nature of the TF concept is such that one is reluctant to do so. The TF concept happens to require an accurate estimate of aircraft position in UTM coordinates. Since the introduction suggested this is also the primary technical barrier to a self-contained, attended-area landing, the association of the two capabilities is irresistible. To repeat, *the fundamental assumption associated with the suggested system configuration is the existence of a tactically-viable,accurate navigation system.* Whether the NOE navigation capability is achieved via an externallyreferenced or a self-contained technique is immaterial to the essence of the reversionary concept.

One of the most difficult operational problems associated with helicopter flight in the NOE environment is geographic orientation. It has been generally accepted that a topographic map display is an essential ingredient in a complement of avionics equipment for NOE flight. This is especially true for NOE flight under night or reduced visibility conditions where the aviator's perception of the contact world is obtained via FLIR imagery. Modern technological advances have spurred the development of a digitally-generated topographic map display, cartographically supported by the digitized terrain elevation data files currently being produced by the Defense Mapping Agency Topographic Center. The IMC terrain-following capability will be evolved as a consequence of the nature of this map display and the assumed accurate navigation system. As a necessary prelude to the discussion of the TF concept, consider Figures 1 and 2 which provide a functional description of the digital map generator (DMG).

The Raymond 6420 tape loader (capacity: 24 million bits, 22 second search time over the complete tape length) contains terrain elevation data in a uniformly-spaced 100 meter grid. To circumvent problems associated with tape search and access times, the data are organized in 64 files or blocks, each of which represent a geographical area of 12.8 kilometers by 12.8 kilometers. Associated with each file is a header containing the block number, and hence the geographical location of the elevation data, and a base altitude and scale factor for the associated 128 by 128 eight-bit relative elevation data words. For example, if the maximum variation in elevation over a given 12.8 kilometer by 12.8 kilometer area was 510 meters, the above structure could represent this elevation variation to the nearest 2 meters. In response to the output of the navigation system, the magnetic tape controller loads various blocks of elevation data into a 512 by 512 word random access memory referred to as the "small scale memory" (SSM). The SSM always contains the most appropriate 16 blocks of elevation data as determined by the current location, speed, and direction of flight of the aircraft. The blocks of data are loaded into the SSM in a geographically noncontiguous fashion and a directory is used to relate a SSM block address to the appropriate block number, base altitude and scale factor extracted from each incoming header. The objective of this data manipulation is to continuously maintain in the SSM a display area at least equal to 25.6 kilometers by 25.6 kilometers, centered about the instantaneous location of the aircraft. This is assured by loading the block of data enclosing the current aircraft position plus the eight geographically contiguous data blocks. The remaining seven blocks in the SSM are loaded in anticipation of future needs based upon the current speed and direction of flight of the aircraft. A similar objective exists for data to be stored in the large scale memory (LSM). The SSM must contend with the search and access time of the tape loader to achieve the desired 25.6 by 25.6 kilometer display area. Similarly, the LSM must contend with the execution time of the elevation interpolation software. As the block structure and geographically noncontiguous loading of the SSM circumvent the former, a sub-block structure and geographically noncontiguous loading of the LSM is used to circumvent the latter. The LSM is a random access memory equivalent in size to the SSM (i.e., 512 X 512 eight bit words). The geographical area represented within this memory is a function of the map scale factor (e.g., SF = 1, 2, 4, 8) chosen by the user as is the display area which must be continuously maintained about the instantaneous location of the aircraft. For a scale factor of 8, the LSM encompasses a total geographical area equal to 6.4 by 6.4 kilometers to achieve its end objective of continuously maintaining a display area of 3.2 by 3.2 kilometers, centered about the instantaneous location of the aircraft. Each block of data in the SSM is partitioned into 64 sub-blocks of 16 by 16 elevation data words (i.e., each encompasses a geographical area equal to 1.6 by 1.6 kilometers). The terrain elevation interpolation software interpolates each data sub-block which is to be loaded into the LSM in accordance with the selected map scale factor. For example, if the selected map scale factor is 2, 4, or 8 then each sub-block will occupy 32 by 32, 64 by 64, or 128 by 128 words respectively in the LSM. Equivalently, if the selected map scale factor is 2, 4, or 8 then each sub-block must be interpolated to obtain elevation data in a uniformly spaced grid of 50 meters, 25 meters, or 12.5 meters respectively. As determined by the speed and direction of flight of the aircraft as well as the chosen scale factor, the LSM is continuously updated to contain the most appropriate, interpolated, data sub-blocks. Since the data are loaded in a geographically noncontiguous fashion, a large scale directory is used to relate a LSM sub-block address to the appropriate block and sub-block numbers of the elevation data base. The DMG provides an EIA standard RS-170 (525 line interlaced) video output from either the SSM or LSM. The terrain data output from both the SSM and LSM is a half-resolution presentation of 256 by 256 words completely updated to account for aircraft translation at 30 frames per second. The orientation of the 25.6 by 25.6 kilometer SSM map is always in a grid-north-up format. The terrain data output from the LSM is characterized by variable map scale factor and continuous angular reorientation. For efficient presentation of the elevation data on the CRT, the 8 bit elevation data are decoded into a completely flexible 3 bit format as it is read from either the SSM or LSM. The 3 bit format is used to generate 8 distinct video levels or shades of gray on the CRT. One of the levels is used to present conventional elevation contour lines while the remaining seven are used to augment the contour data with elevation-coded gray tones (i.e., bands of contour lines at lower altitudes are shaded lighter than bands of contour lines at higher altitudes as shown in Figure 3 . The user of the DMG may independently select the contour interval and gray tone augmentation of both SSM and LSM map presentations.

In addition to the frantic interrogation of the SSM and the LSM for purposes of generation of the map displays, the memories may also be occasionally queried for more docile purposes. In a related program, consideration is being given to continuous updating of the AN/ASN-128 doppler navigation system via terrain correlation processing techniques.1

The technique compares an instantaneous measurement of the terrain height beneath the aircraft, as sensed by radar and barometric altimeters, against the stored terrain height at the current estimated position of the aircraft. The stored terrain height is obtained by interrogation of the LSM at the appropriate UTM coordinates. A new estimate of aircraft position is chosen such that the associated stored terrain height matches the measured terrain height in a statistically optimum sense (i.e., a Kalman filter). Although this effort could result in a very accurate *self-contained* navigation system, the viability of the configuration of this paper does not demand it. Accuracy obtained by any tactically-viable technique, such as the Global Positioning System, is sufficient. The IMC terrain-following system of the paper is another biproduct of one's ability to interrogate the SSM and LSM. The essence of the TF system is the radar altitude control loop depicted in Figure 4. The nominal commanded altitude (H_{REF}) is stabilized by the AN/APN-209 absolute altimeter and the inertial climb rate output ($\dot{H}$) of the AN/ASN-128 doppler radar. The signal ΔH_{REF} has the function of providing anticipatory information to the control system in the form of sporadic increases in the commanded radar altitude (i.e., ΔH_{REF}, is always greater than or equal to zero). Consider a brief description of the generation of ΔH_{REF} and the associated inertial altitude rate command ($\dot{H}_{CMD}$) of Figure 4.

Based upon the measured ground velocity ($\vec{V}_G$) output of the AN/ASN-128 doppler radar, the memory interrogation software generates a scan vector ($\vec{S}$) whose orientation is defined by,

$$\frac{\vec{S}}{|\vec{S}|} = \frac{\vec{V}_G + \tau\vec{\dot{\Psi}}\times\vec{V}_G}{|\vec{V}_G + \tau\vec{\dot{\Psi}}\times\vec{V}_G|} \tag{1}$$

The misalignment of the scan vector from the orientation of the ground velocity provides additional anticipation to the radar altitude control loop during turns. Using the scan vector and the position output ($\vec{P}$) of the assumed accurate tactical navigation system, the DMG is interrogated to provide the terrain elevation (H_T) along the track $\vec{P} + \vec{S}$. The quantity $\Delta H_{REF}(\vec{S})$ is the variation in terrain elevation, along the specified track, relative to the terrain elevation at the current aircraft position ($\vec{P}$). The required increment (ΔH_{REF}) to the altitude command is the peak value of $\Delta H_{REF}(\vec{S})$. The frequency of interrogation of the DMG, and hence the frequency of update of ΔH_{REF}, is on the order of once per second. The amount of anticipation provided to the radar altitude control system is controlled by the length of the scan vector $\vec{S}$. One may provide t_{GO} seconds of anticipation if the length of the scan vector is

$$|\vec{S}| = |t_{GO}\vec{V}_G| \tag{2}$$

and if the response of the radar altitude control loop is appropriately fast. Based upon past efforts[2], the following form is suggested as a means of achieving the required compatibility between $|\vec{S}|$ and the bandwidth of the radar altitude control loop.

$$\dot{H}_{CMD} = \left(\frac{4}{t_{GO}}\right)(H_{REF} + \Delta H_{REF} - H_{RADAR}) \tag{3}$$

In a simplistic fashion, equation (2) controls when an aircraft climb will be initiated and equation (3) controls how far the aircraft will have translated before the correcting climb is completed. The commanded climb rate $\dot{H}_{CMD}$ is compared with the measured climb rate ($\dot{H}$) and the difference is displayed to the pilot for interpretation as a differential collective pitch command.

Amongst the problems associated with helicopter flight at NOE altitudes, geographic orientation is rivaled in difficulty by the requirement for a pilot to stabilize and precisely control the airframe via his night vision system. Current interest in the U.S. is focused on a FLIR-derived scene presented to the pilot on a helmet-mounted display system (HMD). The FLIR is mounted on a two-axis gimbal whose commanded orientation relative to the airframe coincides with a similar orientation of the pilot's helmet as sensed by an infrared or magnetic helmet-tracker. To partially compensate for perceptual problems associated with this and similar forms of pilotage systems, aircraft situation and/or command information is used to augment the FLIR-derived visual scene. These data are symbolically presented as an overlay on the small CRT associated with the HMD system. Technology has also spurred the development[3] of a digital symbol generator (DSG) which accepts sensor data inputs (e.g., AN/ASN-128 doppler navigator, AN/APN-209 radar altimeter, heading and attitude reference systems etc.), processes these sensed data into driving signals for the symbology, generates the proper symbology formats in accordance with pilot-actuated control inputs, and electronically overlays the resulting information on the visual output of the FLIR. Considerable research[4] in the form of analysis, simulation and flight-test has also been required to develop specific NOE symbology formats to the point where they usefully complement the imagery from the pilotage FLIR. In a manner similar to the adaptation of the DMG to terrain-following, the DSG/HMD system may perform the important secondary role of acting as the IMC processing and display medium when environmental conditions, enemy action, etc., have nullified the FLIR's ability to present adequate perceptual information. In addition to the obvious economic advantage, the technical advantages of using the DSG/HMD system to functionally replace the usual electro-mechanical flight director are several. Primarily, use of the DSG/HMD system as an IMC display medium would seem to have all the advantages of a heads-up display system in a more conventional perceptual environment. That is, one avoids the human-factors engineering-related difficulties associated with transition from one display to another during a period of high workload/stress. The pilot would be able to make effective use of the FLIR visual presentation if and when it became available during the reversionary landing procedure. This is especially important near the landing zone where the pilot attempts to terminate his landing maneuver in a low altitude hover under the assumption that the FLIR would be used to execute the actual touchdown. Although the pilot may not demand the reversionary TF/landing data when the FLIR is functioning, its ease of utilization under non-adverse conditions should significantly contribute to its acceptance under IMC conditions.

In this author's opinion, an equally important factor in the acceptance of the configuration is the compatibility of the LAND symbology format of this paper with other NOE symbology formats previously developed and flight-tested[4]. While a constrained design approach will not tend to produce a globally optimum landing display, the LAND symbology format was developed as an intentional variation of the existing TRANS and BOB-UP symbology modes. Within the context of the given NOE pilotage system, the LAND symbology is considered to be the most desirable presentation of the state and command information necessary to execute a decelerating approach in the hostile NOE environment. The basic thrust of the NOE symbology is to present sufficient information to stabilize and control the ground velocity of the aircraft as sensed by the AN/ASN-128 doppler navigator. The transition (TRANS) mode of Figure 5 is designed for moderate speed flight (i.e., less than 80 knots) at NOE altitudes. The central portion of the display depicts a top view of the helicopter in a horizontal situation. The display is an own-aircraft-centered, heading-up format (i.e., the positive X_B axis is aligned with the nose of the aircraft and the positive Y_B axis is aligned with the right "wing" of the aircraft). The triangle is a *stationary* symbolization of the helicopter. The triangle portrays the aircraft location relative to other situation information on the display. The line vector emanating from the center of the display depicts the state of the aircraft ground velocity. The length of the line vector is linearly related to the ground speed of the aircraft and its angular orientation portrays the direction of motion relative to the airframe. The latter is especially important for obstacle clearance in the NOE environment. If the Y_B component of this line vector is zero, the pilot is assured that the nose and tail of the aircraft will pass through the same point in space. Given this state display of the aircraft ground velocity, consider the augmentation of the format with additional information to assist in its stabilization and control.

It is well known that variations of aircraft pitch and roll attitude have a first ordered effect on translational stability and control. That is, if one is able to establish the steady-state pitch and roll orientations necessary to maintain a desired ground speed and direction of motion, then perturbations in aircraft roll and pitch attitude about this trim state produce first-ordered perturbations in the length and orientation of the vector. To compute these attitude variations, the DSG incorporates an autotrim capability as functionally depicted in Figure 6. The autotrim mechanization operates on the principle that large attitude variations ($\Delta\Phi,\Delta\Theta$) imply a transient condition rather than a retrimming condition. During this transient period, the trim state is maintained by setting the averaging time constant to infinity. For example, suppose the aircraft roll attitude has been trimmed to produce a null heading rate. If the aircraft is subsequently rolled to execute a bank-to-turn maneuver ($|\Delta\Phi|>\Delta\Phi_R$), the original trim state is maintained for ease in re-establishing the null heading rate. For safety-of-flight, the authority of the roll axis autotrim is also limited. The computed attitude perturbations ($\Delta\Phi,\Delta\Theta$) are displayed to the pilot via the motions of the small circle of Figure 5. The pertinent characteristics of the small circle motions are its point of origin and its orientation relative to the attitude components ($\Delta\Phi,\Delta\Theta$). The point of origin for the circle motion is the moving vector tip (i.e., for $\Delta\Phi$ and $\Delta\Theta$ equal to zero, the small circle is positioned at the vector tip). The orientation is such that nonzero $\Delta\Theta$ produces a small circle deflection along the X_B axis and nonzero $\Delta\Phi$ produces a deflection along the Y_B axis. The relative dynamic behavior of the small circle and the velocity vector is transmuted by how the pilot chooses to control the aircraft heading during the transient maneuver. If the pilot maintains a *constant* heading during the maneuver, then small circle deflections in the X_B and Y_B directions tend to produce gravity-proportional translational accelerations in the X_B and Y_B axes respectively. As a result, the velocity vector follows the small circle motion across the screen. Stabilization of the small circle relative to the screen acts as a direct and stable control of the length and orientation of the ground velocity vector. For example, stabilization of the small circle at the center of the display will bring the helicopter to a stable hover. If the pilot chooses to allow the heading to *vary* during the transient maneuver (e.g., he chooses to execute a coordinated bank-to-turn maneuver), then the relative behavior of the small circle and the velocity vector in the Y_B direction, and in the Y_B direction alone, is modified. The gravity-proportional translational acceleration still exists (e.g., $g\tan\phi$ for the coordinated bank) but the heading-up display format has changed the pilot's perception of it (i.e., he is now in a rotational frame-of-reference). The rotating frame-of-reference tends to produce a steady-state Y_B circle deflection, generally indicative of the turning rate of the aircraft. The flexibility of the TRANS format will be apparent in later discussions of the LAND format. There, the pilot may choose how he wishes to correct a cross-course position error, either by sideslip, coordinated bank, or some arbitrary combination of both.

An additional feature of the TRANS mode is the presentation of navigational state and steering information. The purpose of presenting this symbolic information is to generally guide the pilot from checkpoint to checkpoint in the midst of the myriad of course perturbations associated with NOE flight. One might note in passing that the primary function of a topographic map display in the NOE environment is to assist the pilot in *selecting* these course perturbations so as to maximize cover, concealment, etc. The symbolic presentation of the navigational data is keyed to the coordinate system of Figure 7. The origin of the X_EY_E coordinate system is at the checkpoint to which the aircraft is proceeding. The orientation of X_EY_E coordinate system is such that the X_E axis is aligned with the desired course (Ψ_C) to the checkpoint and hence, the nominal groundtrack to the checkpoint is along the positive X_E axis. Referring to the TRANS format of Figure 5, the pointers (∇,Δ) are keyed to the moving heading tape. The index (∇) continually points to the desired true course (Ψ_C) while the index (Δ) continually points to the bearing-to-destination-from-true-North (β_N). Since the centerline of the heading-up display format marks the true heading (Ψ) of the aircraft, the angular deflections of the indices (∇,Δ) relative to this centerline have the useful interpretations of heading error ($\Psi_E=\Psi_C-\Psi$) and bearing-to destination-from-heading (β) respectively. Similarly, the angular difference between the two pointers themselves is a direct indication of the crosstrack error (λ_H). That is,

$$\lambda_H = \mathrm{SIN}^{-1}(Y_E/R) = \beta-\Psi_E \tag{4}$$

The lack of groundtrack curvature information ($d\lambda_H/dR$) on the display, coupled with the aircraft heading-up display format, makes precise stabilization and control of λ_H a nontrivial problem. To improve point-to-point navigational performance, the pilot has the option to select a steering indicator ($\square$) in addition to the indices (∇,Δ) previously described. If the steering indicator is driven *relative to the centerline* of the display (Figure 5) in accordance with

$$\square = n\lambda_H + (\dot{\vec{R}}/|\dot{\vec{R}}|)R\,\frac{d\lambda_H}{dR} \tag{5}$$

then the pilot's task is to execute the necessary maneuvers to cause the indicator deflection to be zero. It is important to emphasize that the pilot has complete freedom as to the *technique* by which he corrects a crosstrack error (λ_H). Equation (5) may be satisfied (i.e., $\square = 0$) by sideslipping, drifting in a crosswind, coordinated bank-to-turn maneuvers, or some arbitrary combination of any of the above. Causing the steering indicator deflection to be zero at *any* aircraft heading satisfies the steering equation,

$$n\lambda_H + (\dot{\vec{R}}/|\dot{\vec{R}}|)R\,\frac{d\lambda_H}{dR} = 0 \tag{6}$$

where by reference to Figure 7, one may show;

$$\frac{d\lambda_H}{dR} = \frac{1}{R}\,\frac{X_E\dot{Y}_E - Y_E\dot{X}_E}{X_E\dot{X}_E + Y_E\dot{Y}_E} = \frac{1}{R}\,\mathrm{TAN}(\gamma_D-\beta) \tag{7}$$

The stable solution to (6), subject to the initial condition (λ_0,R_0), is;

$$\left(\frac{\lambda_H}{\lambda_0}\right) = \left(\frac{R}{R_0}\right)^n \tag{8}$$

From (8), one may immediately see that a value for the gain constant (n) greater than unity improves system stability near the checkpoint. That is, as the range (R) approaches zero, λ_H and $d\lambda_H/dR$ also approach zero. Further insight into the behavior of the steering equation can be obtained through the use of a small angle assumption for β and γ_D. The deflection of the steering indicator ($\square$) relative to the center of the display may be approximated by

$$\square = n\lambda_H - \gamma_D + \beta \tag{9}$$

If the pilot chooses to correct his crosscourse error via bank-to-turn maneuvers, the position of the steering indicator *relative to the heading tape* suggests a corrective heading (Ψ_{CMD}). That is,

$$\Psi_{CMD} = \Psi + \square = \Psi_C + (n+1)\lambda_H - \gamma_D \tag{10}$$

The appearance of γ_D in equation (10) compensates for miscoordination during the turn and/or for the effects of existing crosswinds. Alternatively, the pilot may choose to maintain a particular heading (e.g., $\Psi=\Psi_C$) and slip the aircraft to correct the crosstrack error. Assuming the aircraft is aerodynamically capable of generating a sufficient sideslip angle, the steering indicator may be nulled while maintaining the chosen heading angle. In both cases, the sense of the steering indicator in the heading-up frame of reference of the display is "fly-to". That is, deflection of the indicator (□) to the right of the display-center elicits a right bank of the aircraft. The characteristic behavior of the linearized steering equation (9) is basically unmodified by inclusion of the nonlinear effects of equations (5) and (7). The nonlinearity $(\dot{R}/|\dot{R}|)$ insures that the only *stable* solution to equation (6) which exists, is one which corresponds to monotonically decreasing range (R). The nonlinearity represented by the tangent function insures that once Ψ_{CMD} is within ±90 degrees of the desired course (Ψ_C), it will remain so regardless of the chosen value for the gain constant ($n \gg 1$). One should also note that the TRANS mode presents these angular steering data in what amounts to a linear format. That is, the indicators (∇,Δ,□) refer to a linear heading tape with a range of ±30 degrees about the current aircraft heading. As a result, this presentation is generally unsuitable for use near the checkpoint due to stability problems caused by increased display sensitivity with decreasing range (R).

The BOB-UP mode is designed to allow the pilot to hold horizontal ground position during terrain unmasking and remasking tactical maneuvers (i.e., vertical ascents and descents). The aircraft heading and horizontal position,at the time of the BOB-UP mode engagement, are designated as reference quantities. Deviations from these reference quantities are portrayed by the open box symbol of Figure 8. The angular orientation of the open box relative to the heading-up display portrays the heading error (Ψ_E) and the position of the box portrays the location of the hover point in the display frame of reference (i.e., "a landing pad"). The position of the box relative to the center of the display is linearly related to the position of the hover point relative to the aircraft. The BOB-UP mode possesses certain characteristics which are relevent to adaptation of the format to a landing maneuver. In preparation for this adaptation, a discussion of these pertinent chacteristics follows.

A situation display is designed to emphasize,to the pilot, the current state or situation of the aircraft. In contrast to the situation display, the command display emphasizes the corrective action necessary to change the current state of the airframe to the desired state (e.g., hover over a particular point on the ground or follow a specified deceleration profile during a landing maneuver). The symbology format of Figure 8 may be interpreted as either a situation or a command display. If one considers the situation content of Figure 8, a reasonable objective would be to manipulate the controls, and hence $\Delta\Phi$,$\Delta\Theta$ and Ψ,so as to continuously point the line vector at the box. This results in a reduction in the radial position error, although the corrective path of the aircraft over the ground is arbitrary. If one wished to approach the hover point along some specified course (e.g., $Y_E=0$), then the controls must be manipulated such that the line vector not only points to the hover point,but is also aligned with the desired course. To provide for a reasonably stable correction of the position error, one must also manipulate the controls to decrease the length of the line vector as the box approaches the center of the display. There are an infinite number of functional relationships between ground velocity and position error which will achieve the desired hover state and a situation display would not make any attempt to dictate to the pilot which one he should choose. However, the presentation of the situation information in Figure 8 encourages continuously maintaining the tip of the line vector at the center of the box. The most direct, although not unique, implementation of this philosophy is to maintain the small circle at the center of the box while manipulating the pedals to hold heading. As previously discussed, the velocity vector will follow the small circle,and hence the box, across the screen. Due to the aforementioned *linear* relationship between box movement and aircraft movement, and between vector length and ground speed, the control strategy is equivalent to prescribing a linear variation of ground speed with position error. This may be expressed mathematically through the use of the following definitions:

$\vec{P}_R$ = the vectorial location of the box relative to the center of the display

$\vec{P}_{\dot{R}}$ = the line vector on the display

$\vec{R}$ = the vectorial location of the hover point relative to the aircraft

$\dot{\vec{R}}$ = the ground velocity of the aircraft

K_R = the constant display gain relating inches of box motion to feet of position error

$K_{\dot{R}}$ = the constant display gain relating inches of vector length to feet per second of ground speed

The control philosophy is equivalent to,

$$\vec{P} = \vec{P}_{\dot{R}} \qquad (11)$$

Since,

$$\vec{P}_R = K_R\vec{R} \qquad (12)$$

$$\vec{P}_{\dot{R}} = -K_{\dot{R}}\dot{\vec{R}} \qquad (13)$$

The velocity/position-error functional relationship associated with maintaining the vector tip at the center of the box is,

$$\dot{\vec{R}} = -(K_R/K_{\dot{R}})\vec{R} \qquad (14)$$

The BOB-UP symbology format has been shown to possess two characteristics which, although relatively immaterial to a hovering maneuver, are very significant in the context of a decelerating landing. These are firstly, the ability to drive a position error to zero while following a specified course and secondly, the ability to produce a specific functional relationship between ground speed and position error during the execution of the former.

To establish the design scenario for the IMC reversionary capability, consider Figure 7. Assume that an attended-area landing site exists at the origin of the X_EY_E coordinate system and that the safe corridor lies along a specified course (Ψ_C). The first phase of the scenario consists of terrain-following flight along the X_E coordinate axis at a nominally constant altitude above the terrain (H_{REF}). The second phase of the scenario is initiated at a nominal range (R_A) from the landing site. At this range, the aircraft initiates a simultaneous deceleration and descent through the safe corridor to establish a stable low altitude (H_{HOV}) hover at the landing site. During the decelerating approach, the aircraft must continue to maintain the specified nominal groundtrack along the X_E coordinate axis. The third phase of the flight is to establish and hold a precise hover at the designated altitude (H_{HOV}). It is assumed that sufficient perceptual information can be obtained from the FLIR at this altitude to land the helicopter. The first and third phases of the scenario can be accomplished by the existing TRANS and BOB-UP modes given that the TRANS mode has been augmented with the terrain-following capability previously described. The second phase of the scenario requires development of a LAND format to control the deceleration/descent while maintaining the specified groundtrack. As previously mentioned, the LAND format will be developed as a variation of the TRANS and BOB-UP modes. The LAND format must incorporate three characteristics which do not exist, or which exist but are not fully utilized,in the TRANS and BOB-UP modes. These are;

1) A method to smoothly transition from flight at H_{REF} above the terrain to the hovering altitude (H_{HOV}) above the terrain.

2) A method to command the aircraft to follow a predetermined deceleration profile to the landing site.

3) A method to maintain the specified groundtrack as the range to the landing zone continually diminishes toward zero.

In the introduction, control of aircraft elevation relative to the terrain,in lieu of relative to a space profile,was suggested to be a desirable system characteristic for a tactical landing maneuver. This idea was embodied in the suggested method to achieve characteristic 1) in the above list of three. The LAND symbology format incorporates the terrain-following capability of the TRANS mode in a slightly modified form. The commanded absolute altitude (H_{REF}) of Figure 4 is altered to $H_{REF}(R)$. The nondimensional function

$$\hat{H} = \hat{H}_H + \hat{\gamma}_F\hat{R} + [(m+2) - (m+1)\hat{\gamma}_F]\,\hat{R}^{m+1} + [m\hat{\gamma}_F - (m+1)]\,\hat{R}^{m+2} \qquad (15)$$

where

$\hat{H} = H_{REF}(R)/(H_{REF} - H_{HOV})$

$\hat{H}_H = H_{HOV}/(H_{REF} - H_{HOV})$

$\hat{\gamma}_F = \gamma_F/(H_{REF} - H_{HOV})/R_A$

$\hat{R} = R/R_A$

satisfies certain constraints at the nominal LAND engagement range and at the landing site. These are;

$R = R_A \qquad H_{REF}(R) = H_{REF}$

$\qquad\qquad dH_{REF}(R)/dR = 0$

and,

$$R = 0 \qquad H_{REF}(R) = H_{HOV}$$

$$dH_{REF}(R)/dR = \gamma_F$$

Additionally, $H_{REF}(R)$ is everywhere limited to be less than or equal to H_{REF}. Figure 9 emphasizes the primary difference between a terrain-based tactical maneuver and its space-based civilian counterpart.

To address system characteristic 2), one should recall the previous discussion of the BOB-UP mode where a linear relationship between range rate ($\dot{R}$) and range-to-go (R) was demonstrated. As the BOB-UP mode was created from the TRANS mode by the addition of the open box symbol of Figure 8, so will be the LAND mode. In contrast to the constant gains K_R and $K_{\dot{R}}$ associated with the BOB-UP mode, two scalar functions of range-to-go (R) will be developed to position the line vector and open box for the LAND mode. *A fundamental assumption which is contained throughout the following mathematical development is that the ground velocity of the aircraft* ($\dot{R}$) *is aligned with the range* (R) *from the aircraft to the destination.* This is completely analogous to the hover control philosophy of pointing the line vector directly at the box. Define two scalar functions f(R) and g(R) such that

$$\vec{P}_R = f(R)\ \vec{R} = f(R)\ R\ \vec{I} \tag{16}$$

$$\vec{P}_{\dot{R}} = -g(R)\ \dot{\vec{R}} = g(R)\ \dot{R}\ \vec{I} \tag{17}$$

For the hovering display, the scalar functions f(R) and g(R) are equal to the constants K_R and $K_{\dot{R}}$ respectively. As in evidence by (14), the ratio of the scalar functions is sufficient to define a specific relationship between R and $\dot{R}$. The deceleration profile[5] most often suggested for the IFR landing maneuver is,

$$\dot{\vec{R}} = -\dot{R}_A\ (R/R_A)^{1/2}\ \vec{I} \tag{18}$$

where $\dot{R}_A$ and R_A are the nominal acquisition ground speed and range respectively. The additional constraint necessary to explicitly solve for the scalar functions is assumed to be,

$$\frac{d\vec{P}_R}{dt} = -\frac{P_{RA}}{t_A}\ \vec{I} \tag{19}$$

where P_{RA} is the position of the box on the display screen at acquisition and t_A is the total time of flight from acquisition to the destination. This constraint is designed to provide an obvious time scale on the display. If the box is constrained to move across the display at a constant rate, then the distance of the box from the center of the screen is a linear indication of time-to-go. One may solve for the total time of flight (t_A) by integrating the deceleration profile. One finds,

$$t_A = 2(R_A/\dot{R}_A) \tag{20}$$

Combining (16), (19) and (20), the desired scalar function is equal to the particular solution of,

$$df(R)/dR + f(R)/R = P_{RA}/(2R_A^{1/2}\ R^{3/2}) \tag{21}$$

The result is,

$$\vec{P}_R = P_{RA}(R/R_A)^{1/2}\ \vec{I} \tag{22}$$

If the vector tip is maintained at the center of the box, the desired deceleration profile (18) will be followed if,

$$\vec{P}_{\dot{R}} = (P_{RA}/V_{GA})\ V_G\ \vec{I}' \tag{23}$$

The unit vector $\vec{I}$ has been primed ($\vec{I}'$) to allow for the fact that the actual velocity V_G of the aircraft will not always lie along R although the pilot is making every attempt to achieve this.

As previously mentioned, the BOB-UP mode was created from the TRANS mode by the addition of the open box symbol of Figure 8. Not mentioned was an increase in the sensitivity ($dP_{\dot{R}}/dR$) of the velocity vector from its constant value in the TRANS mode (K_T inch/ft/sec) to its constant value in the BOB-UP mode ($K_{\dot{R}}$ inch/ft/sec). In the interest of maximizing compatibility with the TRANS and BOB-UP modes, system characteristic 2) is achieved for the LAND format by retaining the TRANS mode velocity sensitivity (K_T) and adding a BOB-UP type open box driven in a position in accordance with (22). That is,

$$\vec{P}_R = V_{GA}\, K_T\, (R/R_A)^{1/2}\, \vec{I} \tag{24}$$

If,

$$\begin{aligned} \vec{I} &= \mathrm{COS}(\beta)\, \vec{i}_B + \mathrm{SIN}(\beta)\, \vec{j}_B \\ \vec{I}' &= \mathrm{COS}(\gamma_D)\vec{i}_B + \mathrm{SIN}(\gamma_D)\vec{j}_B \end{aligned} \tag{25}$$

$$\begin{aligned} \vec{P}_R &= P_X\, \vec{i}_B + P_Y\, \vec{j}_B \\ \vec{P}_{\dot{R}} &= P_{\dot{X}}\, \vec{i}_B + P_{\dot{Y}}\, \vec{j}_B \end{aligned} \tag{26}$$

then

$$\begin{aligned} P_{\dot{X}} &= K_T\, V_G\, \mathrm{COS}(\gamma_D) = K_T\, V_H \\ P_{\dot{Y}} &= K_T\, V_G\, \mathrm{SIN}(\gamma_D) = K_T\, V_D \end{aligned} \tag{27}$$

$$\begin{aligned} P_X &= K_T\, V_{GA}(R/R_A)^{1/2}\, \mathrm{COS}(\beta) \\ P_Y &= K_T\, V_{GA}(R/R_A)^{1/2}\, \mathrm{SIN}(\beta) \end{aligned} \tag{28}$$

Equations (27) and (28) represent the LAND component equations for the line vector and the open box position in the heading-up frame of reference. Under the fundamental assumption that the pilot manipulates the controls to keep the tip of the vector in the center of the box, the equations are sufficient to insure adherence to the deceleration profile specified in equation (18), and are thereby sufficient to satisfy system characteristic 2). The LAND symbology format is completed in Figure 10 with the portrayal of the aircraft heading error (Ψ_E) via the rotational degree of freedom of the BOB-UP type open box. Subsequent discussion will show that by use of this symbol, one is able to quickly deduce the current state of the aircraft relative to the X_EY_E coordinate system. Comparison of the TRANS, LAND, and BOB-UP modes of Figures 5, 10 and 8 emphasizes the *transitive* nature of the formats which is thought to be essential for pilot acceptance of the reversionary capability.

System characteristic 3) is concerned with the general topic of the stability and control of the crosscourse error (λ_H) of the aircraft throughout the design scenario. The LAND symbology format provides two distinct methods for control of the crosscourse error, these being either via the indicial steering data associated with the TRANS mode or the display-center symbology associated with the BOB-UP mode. The general character, and in particular the stability, of the two methods of control differs significantly. The factors which influence their relative stability are;

1) The format of presentation of the required angular data such as β, λ_D, Ψ_E and λ_H.

2) The piloting technique (e.g., sideslip, bank-to-turn) by which the aviator may execute crosscourse corrective maneuvers.

3) The method by which the stabilizing effects of aircraft roll attitude are introduced into the system.

As a prelude to a short discussion of these factors, consider how the appearance of the open box symbol in the LAND mode improves the pilot's ability to *perceive*, although not necessarily to control, his situation relative to the X_EY_E coordinate system.

Assume an idealized case where the pilot has continuously maintained the steering indicator (□) near its null position throughout the first phase of the design scenario. The resulting steady-state solution to the steering equation (6) is $\lambda_H = d\lambda_H/dR = 0$. In terms of the heading-up angular variables of Figure 7, an examination of equations (4) and (7) shows this solution is uniquely equivalent to $\beta = \Psi_E$ and $\gamma_D = \beta$. Therefore, when the pilot enters the idealized second phase of the design scenario by manually switching from the TRANS mode to the LAND mode, the velocity vector or its extension will be seen to pass through the center of the box ($\gamma_D = \beta$) *and* to be parallel to the sides of the box ($\beta = \Psi_E$). This behavior should be expected as firstly, the LAND format is conceptually equivalent to the BOB-UP mode and secondly, previous characterization of the BOB-UP mode indicated that if one wished to approach the hover point along a specified course then the controls must be manipulated such that the line vector not only points at the open box but is also parallel to the specified approach (i.e., parallel to the X_E coordinate axis). The particular heading angle achieved during this steady-state condition is not unique, being a function of the magnitude and orientation of the wind as well as how the pilot has *chosen* to trim the aircraft (e.g., zero sideslip, zero sideforce, zero roll attitude, zero heading error, etc.,). One should note that if the aircraft is *also* following the nominal deceleration profile, the length of the vector will be such that its tip just touches the box center. This ideal display state is depicted in Figure 11. In summary, the display-center symbology of the LAND format explicitly portrays to the pilot, the angles β, γ_D and Ψ_E in a *polar* format. By the relative angular position of the appropriate symbols, he is also able to implicitly deduce the error with respect to the $X_E Y_E$ coordinate system (i.e., $\lambda_H = \beta - \Psi_E$ and $d\lambda_H/dR \approx \gamma_D - \beta$).

As previously noted in the characterization of the TRANS mode, the stability of λ_H control via the steering indicator deteriorates with decreasing range (R). The root cause of the stability problem is the presentation of the required angular data (i.e., β, γ_D, Ψ_E in equation 9) in a *rectilinear* display format. The display-center symbology of the LAND mode would seem to have the potential to improve system stability since these same angular data are explicitly portrayed in a *polar* format. The expected improvement in system stability is contingent on the assumption that the display-center information may be given an adequate *command* interpretation. While one's intuition might suggest a similar short-range stability problem with the open box driving equation (24), the region of excessive sensitivity (dP_R/dR) is too small to be detrimentally perceived on the display screen.

System stability is also transmuted by the piloting technique used to correct crosscourse errors. Interwoven with the technique of error correction is the structure of the command presentation (i.e., how does the control structure of the rectilinear format compare with that of the polar format?). As previously noted during the characterization of the TRANS mode, the rectilinear format is compatible with *any* piloting technique for correcting a crosscourse angular error (λ_H). In all likelyhood,however, throughout the first phase of the design scenario and well into the second phase, the pilot will utilize bank-to-turn maneuvers to null the steering indicator (□). At some point during the decelerating landing maneuver, the expected stability problem will arise, perhaps exacerbated by the increasing bank-to-turn sensitivity ($\partial\Psi/\partial\Phi$) associated with the aircraft following the deceleration profile. System stability may be temporarily improved by a transition to sideslip control of the steering indicator but the ever increasing sensitivity of the rectilinear format must prevail. A substantial improvement in short-range system stability may be achieved if the pilot *follows* his discretionary transition to sideslip control with a similar transition to the polar format. The central theme of the associated command interpretation of the LAND display-center symbology is, as was the case for the BOB-UP mode hovering task, control of the magnitude and orientation of the line vector via cyclic action concurrent with stabilization of aircraft heading to some constant value via pedal actions. In other words, if the pilot holds heading via pedal action and manipulates the small circle about the screen via cyclic action, the tip of the line vector will follow in a very stable fashion. The concept was extended in the BOB-UP mode where a *specific* screen location for the small circle was suggested (i.e., at the center of the open box). This reduced the pilot's hovering problem to a tracking task in exchange for an arbitrary nominal corrective groundtrack (i.e., $\gamma_D = \beta$). Whereas the command interpretation of the BOB-UP mode is equivalent to specifying an aircraft attitude, the command interpretation to be given the LAND mode is that of a specified orientation of the aircraft ground velocity. In general, the orientation is that of Figure 11 where the ideal vector for λ_H control is oriented to pass through the center of the open box ($\gamma_D = \beta$) *and* to be parallel to the sides of the open box ($\beta = \Psi_E$). The difficulty of *achieving* this state via cyclic manipulation of the small circle while maintaining heading is transmuted by the particular magnitude of the heading being maintained (i.e., the particular magnitude of the heading error Ψ_E). Maximum compatibility between the motions of the X_B and Y_B components of the small circle and between the X_B and Y_B components of the line vector is achieved for an aircraft heading equal to Ψ_C. To summarize, the pilot's discretionary transition of λ_H control to the polar format is to be accompanied by a transition in piloting technique equivalent to sideslipping perturbations about a nominally zero drift angle (γ_D). In contrast to Figure 11, Figure 12 depicts the command display state for the polar format.

The third factor which has influence over the relative stability of the rectilinear and polar formats is the method of integration of roll attitude information into the system. Previous discussion has emphasized the flexibility associated with the rectilinear format in that the steering indicator (□) can be nulled by *any* control technique such as bank-to-turn, drifting, slipping, etc. Since all these control techniques imply different roll attitude transients, to achieve this flexibility one must exclude roll attitude information from the steering equation (5) and rely on the small circle situation display of $\Delta\Phi$ to stabilize the motions of the steering indicator. By contrast, the polar format incorporates roll attitude information in a more stabilizing sense if one views the small circle as the predicted location of the velocity vector tip rather than as a situation display of $\Delta\Psi$ and $\Delta\Phi$. As one might expect, a reduction in flexibility of piloting technique is the price extracted for this increase in system stability. At some point very late in the scenario, an even further increase in positional stability will occur as the pilot gradually adopts the BOB-UP strategy of specifically placing the small circle in the center of the box. The display architecture is therefore, not only transitive in appearance from the TRANS to LAND to BOB-UP modes, but is also transitive in its functional operation.

TEST PROGRAM

The US Army Avionics Research and Development Activity (AVRADA), Advanced Systems Division is currently conducting a multi-faceted simulation and flight-test evaluation of the system concepts of this paper. The total system is referred to within AVRADA as the Night Navigation/Pilotage (NNP) program of which the self-contained, attended-area, landing capability is but one facet. The intent of this section is to describe those aspects of the NNP program, and in particular those hardware test configurations, which have a direct bearing upon the developmental testing of the reversionary TF/landing capability previously described.

The computational heart of the NNP developmental test program is a Singer-Kearfott SKC-2000 general-purpose flight computer. The Advanced Systems Division (ASD) of AVRADA maintains two identical SKC-2000 installations to support the developmental test program, one in the Tactical Avionics System Simulator (TASS) and one in the CH-53 Experimental Vehicle for Avionics Research (EVAR). The TASS is a general-purpose, real-time simulation facility which provides a unique capability for the *analysis* of total aircraft/avionic systems while EVAR is a helicopter dedicated to the *test* and evaluation of NOE avionic system concepts developed in the TASS.

A Phase 1 hardware configuration, depicted in Figure 13, is currently undergoing validation experiments in the TASS in preparation for a September,1979 flight-test evaluation in the EVAR. The objective of this phase of the total effort is a determination of the pilot's capability to execute, *solely* via the information contained within the TRANS, LAND, and BOB-UP symbology formats, the maneuvers required for adherence to the IMC design scenario. The current lack of a *precise*, operational,NOE navigation system compels one to perform this phase of the test effort with *simulated* radar altitude information. Referring to Figure 13, the sensed motions of the aircraft (V_H, V_D, $\dot{H}$, Φ, Θ, Ψ) enter the SKC-2000 airborne computer for processing into the various display formats. The components of the measured aircraft ground velocity (V_H, V_D) are transformed through Ψ_E to the chosen approach coordinates ($X_E Y_E$) and integrated from an arbitrary starting point to obtain the reference position ($\vec{R}$ or R, β) of the aircraft. This position need *not* be related to the actual geographical location of the aircraft since the flight-test will utilize synthetic terrain to generate simulated radar altitude information. The reference aircraft position ($\vec{R}$) and the computed scan vector ($\vec{S}$) are used to interrogate a *one-dimensional* terrain profile stored within the SKC-2000 flight computer. The output of the interrogation process is the altitude of the synthetic terrain [$H_T(\vec{R})$] at the current aircraft position ($\vec{R}$) and the altitude of the synthetic terrain [$H_T(\vec{R}-\vec{S})$] along the track $\vec{R}-\vec{S}$. The former is combined with the time integral of the measured altitude rate ($\dot{H}$) to form the simulated radar altitude of the aircraft (H_{RADAR}) while the latter is processed to form the terrain-following anticipatory signal (ΔH_{REF}). The one-dimensional representation of the terrain is the result of SKC-2000 random-access memory limitations, a condition which will be rectified in the Phase 2 hardware configuration. In response to pilot-actuated mode control signals, the symbol generation software updates the selected symbology mode (e.g., TRANS, LAND, BOB-UP) at an approximate 30 complete frames per second. These data, in the form of a 256 by 256 by 1 bit data array, exit the SKC-2000 computer via a 32 bit parallel interface and are loaded into the display memory associated with the Digital/Video Converter-Model 1. (DVC1). The DVC1 equipment contains two memory planes (256 by 256 by 1 bit) operating in a ping-pong fashion. As the SKC-2000 loads one of these memory planes with the updated symbolic data, the video processor expels the contents of the other plane in an EIA standard RS-170 (525 line, interlaced) video format for presentation on a helmet-mounted or panel-mount CRT display. It is anticipated that Phase 1 simulation and flight-test results will be available for dissemination in January,1980.

As suggested earlier in the paper, the primary function of a map display in the NOE environment is tactical route *selection*, not point-to-point navigation. There is little doubt that the indicial steering data (e.g., TRANS symbology format) can successfully guide the NOE pilot from one checkpoint to another, at least to within the accuracy of the aircraft navigation system. Current display capabilities (e.g., paper map, projected map display) require the copilot to *orally* communicate tactically-inspired deviations from the nominal straight-line ground track associated with the steering data. The foremost objective of the Phase 2 hardware configuration, as shown in Figure 14, is the flight demonstration of a TASS simulation-validated capability for unilateral route-selection and point-to-point navigation by the pilot. The DMG implementation of Figures 1 and 2, characterized by 30 per second translational and rotational display updates, will be incorporated into the Phase 3 test effort. The DMG implementation of Phase 2 is an interim one using an Ampex 48 million bit tape unit, the SKC-2000 airborne computer, and the Digital/Video converter-model 2 (DVC2) as the storage, computing, and display-memory media respectively. The low update rate (~once per 2 minutes) of this implementation is circumvented by a NAV symbology mode[4] which portrays a moving aircraft symbol as an overlay on the fixed topographic display.

The configuration of Figure 14 incorporates a dedicated Digital Symbol Generator[3] (DSG) which (1) accepts sensor data inputs from the SKC-2000, (2) processes and formats the sensed data into display quantities (e.g., $\Delta\Theta$, $\Delta\Phi$, $\dot{H}_E$, etc.), (3) generates the required symbology format to visually portray the display quantities, (4) alternatively loads the symbolic data into one of two memory planes (512 by 512 by 1 bit) operating in a ping-pong fashion, and (5) alternatively expels the contents of the other memory plane in the EIA standard RS-170 (525 line, interlaced) video format. In lieu of generation of either the TRANS, LAND, or BOB-UP formats, the DSG is also capable of generating the NAV symbology mode for use with the digitally-generated topographic map.

The Phase 2 DMG implementation is based upon tape unit storage of eight-bit elevation data in a 12.5 meter or 25. meter grid depending on the desired map scale, and geographically covering a *single* 12.8 kilometer block (Figure 2). Each eight-bit data word is decoded into a seven-bit description of the elevation of the associated grid point, the least significant bit being 6 meters or approximately 1/2 the usual contour interval of a 1:50,000 scale map, plus a contour bit. The complete contour line field is computed offline to minimize the SKC-2000 processor burden and then overlayed on the seven-bit elevation data via the contour bit. The eight-bit data are stored in two basic orientations on the tape unit, these being North-up and East-up, and may be displayed on the CRT in any of the four cardinal orientations.

The display memory of the DVC2 equipment consists of five memory planes, each of which can store a 512 by 512 by 1 bit data array. This contrasts the DVC1 capability to store two arrays of 256 by 256 by 1 bit. In response to the desired orientation (i.e., North, South, East, or West) and geographical location of the display area with the available 12.8 kilometer data block, the DMG software loads the precomputed contour field into one memory plane of the DVC2 equipment and a 4 bit *shade* word into the remaining four memory planes. The least significant bit of the shade word is set equal to an integral multiple of the precomputed contour interval. For example, if the contour field is precomputed at a 12 meter interval, the least significant bit of the shade word could be 12 meters, 24 meters, 36 meters, etc.,. The effect of the chosen multiple on the map display is seen in Figure 15 as defining the number of contour lines which appear within any given shade-of-gray. Also shown in Figure 15a is an additional capability incorporated into the DVC2 video processor. Since one's ability to discriminate shades-of-gray in the cockpit environment is limited to approximately eight shades[6], the processor may be commanded to incrementally shift the 3 bit gray scale definition relative to the 4 bit shade word to emphasize certain aspects of the terrain. Multiple contour lines appear within the darkest shade (i.e., the higher ground) of Figure 15a because the processor has been commanded to emphasize the lower terrain. At this point, it is stressed that the need to precompute the contour field and to define a shade word arises solely from the computing speed and display memory capacity limitations of the Phase 2 configuration.

A secondary objective of the Phase 2 configuration is to expand the validation of the control/display architecture begun in Phase 1 to include a *two-dimensional* representation of the stored terrain. Emphasis will be placed upon the interaction of lateral ($\dot{\psi}_E$) maneuvers and the radar altitude control mechanization of Figure 4 [i.e., interaction via the scan vector orientation defined by equation (1)]. Again, the lack of a precision navigation system requires use of simulated radar altitude information based upon the terrain altitude $H_T(\bar{R})$ returned to the SKC-2000 from the display memory of the DVC equipment. The configuration also permits investigation of the utility of the topographic map display as a *direct* visual aid to the reversionary capability. In other words, as the pilot executes the design scenario via the TRANS, LAND and BOB-UP symbology modes, the lack of FLIR information may be *very* partially compensated by the synthetic views of the environment provided by the digitally-generated topographic map display. While it is possible that a digitally-generated *perspective* view of the terrain, in lieu of the navigation-oriented plan view, might be useful in these reversionary circumstances, the question of the *general* utility of a synthetic perspective view remains a subject for considerable future research. It is anticipated that the Phase 2 configuration will be operational in the TASS facility by April,1980 to be followed by a July,1980 flight evaluation in EVAR.

The emphasis of the previous test program was upon the pilot as an isolated element in the aircraft/avionic system. In contrast to the single CRT capability provided by the Phase 1 and 2 configurations, the system shown in Figure 16 provides for two *independent* CRT presentations so that the required interactions between the pilot and copilot may be properly evaluated. The associated hardware/software is a maturation of Phase 2, providing the copilot with an integrated navigation and map display system while retaining the pilotage capability connected with the former configuration. The fundamental hardware difference is the incorporation of a dedicated Digital Map Generator (DMG), the capabilities and general principles of operation of which were previously described in the narrative associated with Figures 1 and 2.

One of the principle topics of investigation relative to the Phase 3 hardware is development of a centralized mode control structure. Although omitted from the diagrams of Figure 13, 14 and 16, the SKC-2000 computer contains a mode control program, actuated by an alpha-numeric and remote switch keyboard. The flexibility incorporated into the Phase 3 hardware and in particular into the DMG, demands an extensive human-factors-engineering type effort to develop an efficient mode control structure. For example, relative to the DMG equipments, the copilot may interactively adjust the map's orientation, geographical location, scale factor, contour interval, contours per shade, shade-of-gray emphasis, and selectively overlay hydrographic, vegetation, cultural and annotation data on the display. Although considerable developmental effort is underway to analyze the the isolated tasks, the pilot/copilot interaction tests are tied to the Phase 3 development schedule.

Responding to the desires of the aircrew, the SKC-2000 computer commands the DMG equipment to produce the appropriate navigational map in an EIA standard RS-170 video format for ingestion by the DVC2 equipment of Phase 2. The DVC2 equipment also accepts similarly formatted video signals from the pilot's DSG and the FLIR(s). Since the DVC2 display memory has been emancipated by the dedicated DMG, it may be used as a ping-pong storage medium for the copilot's navigational symbology, computed and transmitted by the SKC-2000 in the form of a 512 by 512 by 1 bit data array. Again, responding to the aircrew's mode control actions, the SKC-2000 commands the video processor of the DVC2 to configure the two independent CRT presentations. For example, the FLIR presentation overlayed with the TRANS mode may be desired on the pilot's CRT, and the DMG presentation overlayed with the copilot's symbology may be desired on the copilot's CRT. The ability of the pilot to transiently select the DMG presentation to assist his route selection task is retained in this configuration.

With respect to the reversionary TF/landing capability, the hardware configuration affords the first opportunity for testing the complete system concept. The missing ingredient in the previous configurations has been the precision, tactical, navigation system, in evidence in Figure 16 as a terrain-correlation-aided AN/ASN-128 doppler navigator. Although the terrain-correlation concept[1] was originally developed to aid an inertial navigator in a strategic environment, its utilization with a doppler navigator in the *low-speed* NOE environment is very complementary. The tendency of the doppler navigational error to grow with distance traveled rather than time is stabilized by the accumulating terrain elevation measurements. ASD is currently assessing via analysis, simulation and flight-test the viability of this concept in the tactical environment where unanswered questions include; the effects of errors induced by the data compression necessarily associated with the DMG, and the effects of the tendency of a helicopter pilot to follow,rather than cross,drainage patterns in the NOE environment, thereby reducing the terrain signature available for correlation. The system test of the Phase 3 configuration is paced by an FY-80 contractual effort to construct the dedicated DMG equipment. Validation tests of the configuration in the TASS are anticipated to begin in June,1981 followed by an EVAR evaluation in December,1981.

The system of Figure 17 represents an orderly transition of the capabilities of the Phase 3 developmental configuration into a modern avionic equipment architecture based upon the 1553B serial data bus. The centralized mode control structure, developed as part of the Phase 3 test program, has been incorporated into the software associated with the Centralized Mode Control Panel (CMCP) of Figure 17. In response to the desires of the aircrew expressed through the CMCP and the sensed state of the aircraft, both of which are transmitted over the serial data bus, the NNP equipment 1) generates all required symbology, 2) generates the digitally-based topographic map, 3) updates the AN/ASN-128 via terrain-correlation processing techniques, 4) appropriately mixes or insets the symbolic and map results with the video output signal from the FLIR(s), and 5) expels the composite signals for presentation on the aircrew's CRT displays.

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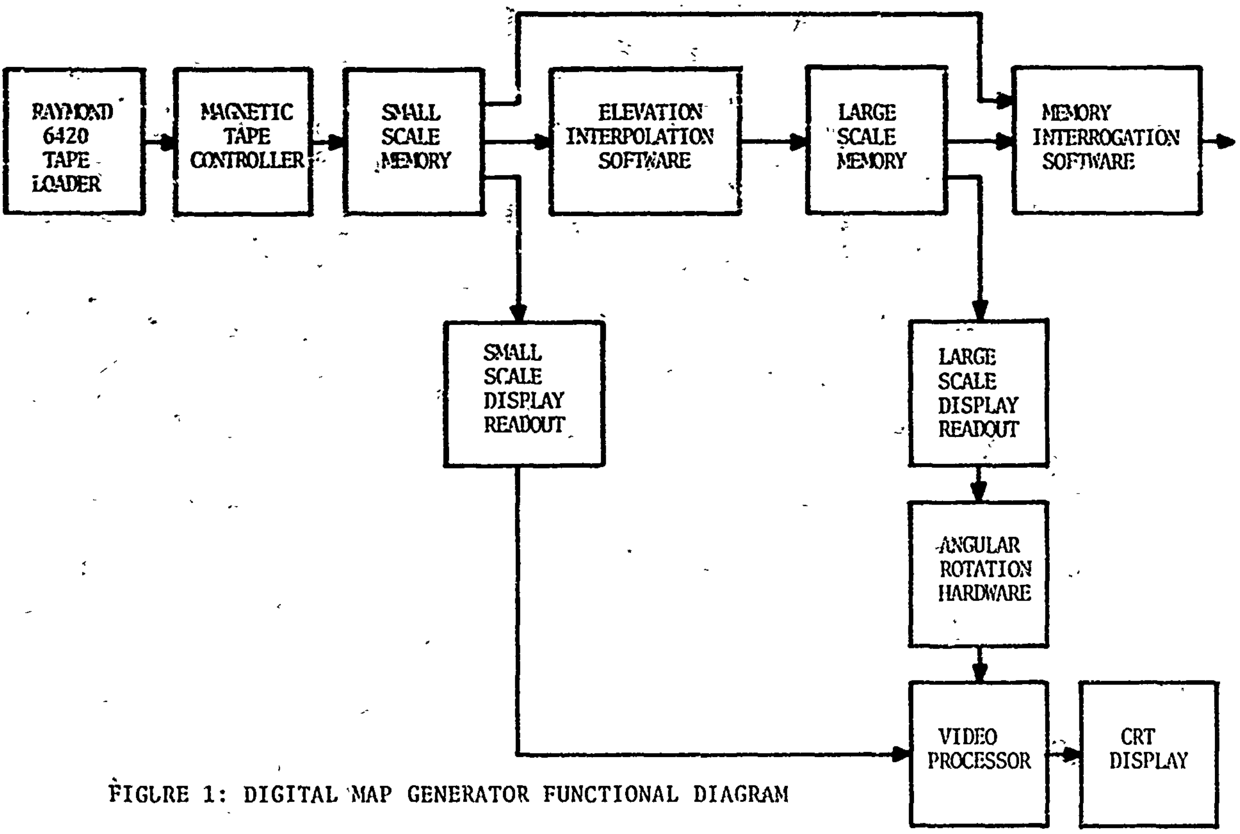

FIGURE 1: DIGITAL MAP GENERATOR FUNCTIONAL DIAGRAM

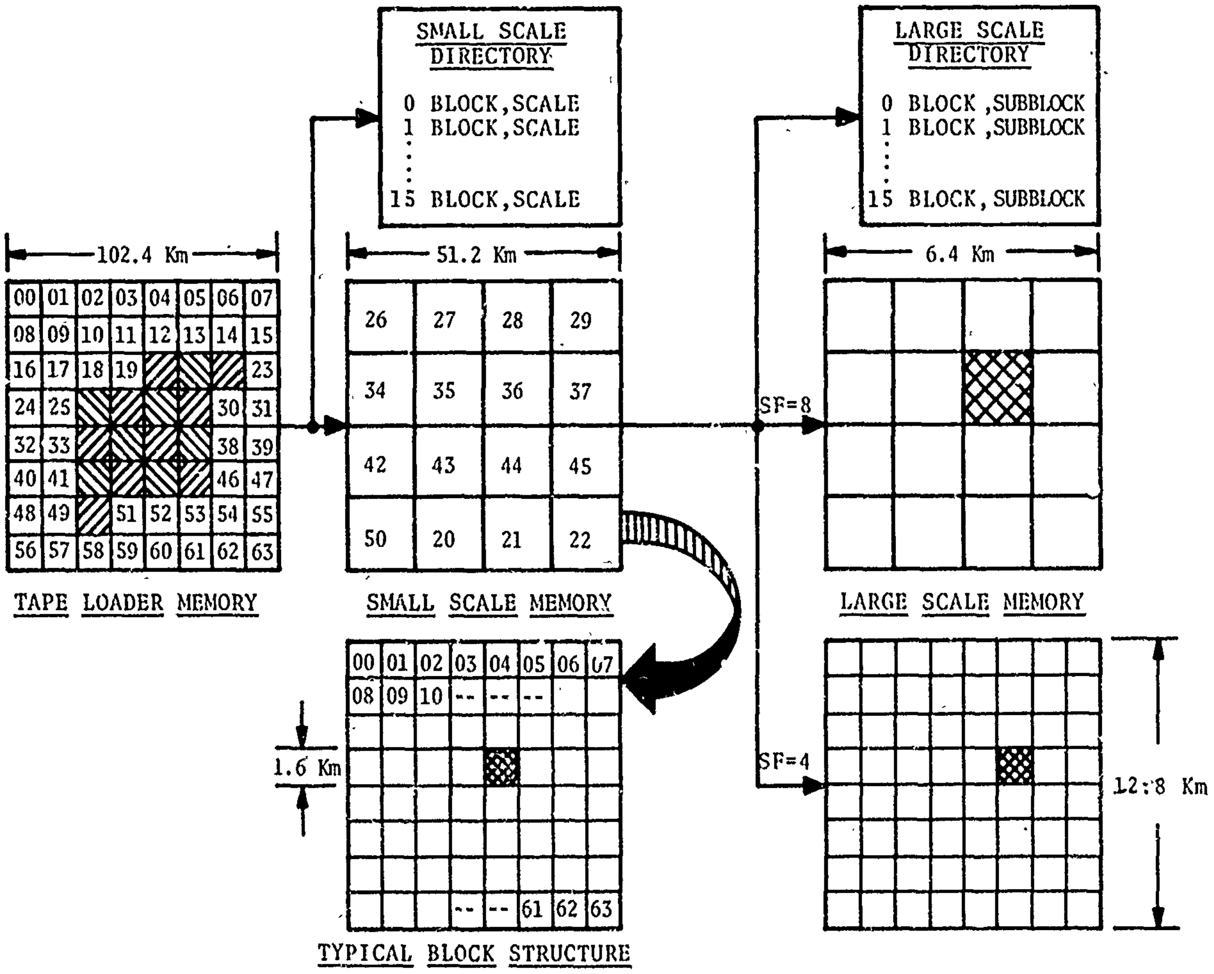

FIGURE 2: DMG ELEVATION DATA MANIPULATION

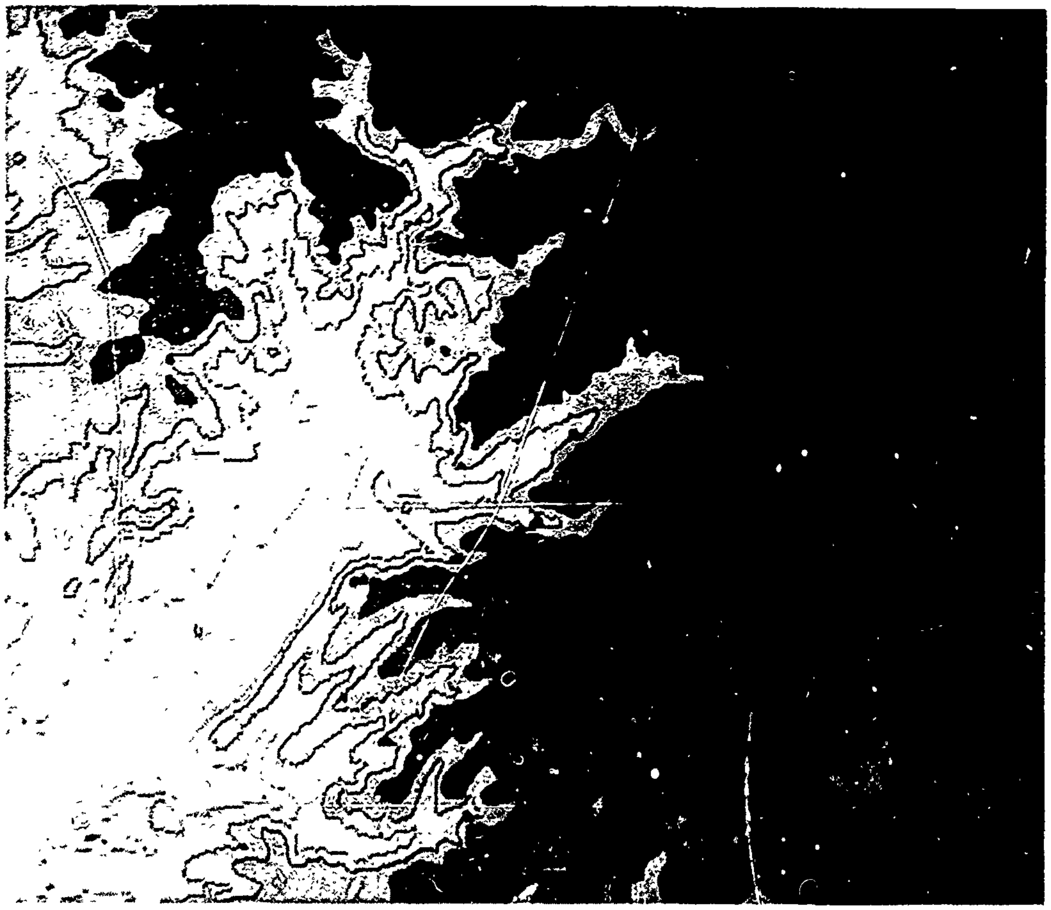

FIGURE 3: DIGITALLY-GENERATED TOPOGRAPHIC MAP- 18 METER CONTOUR INTERVAL

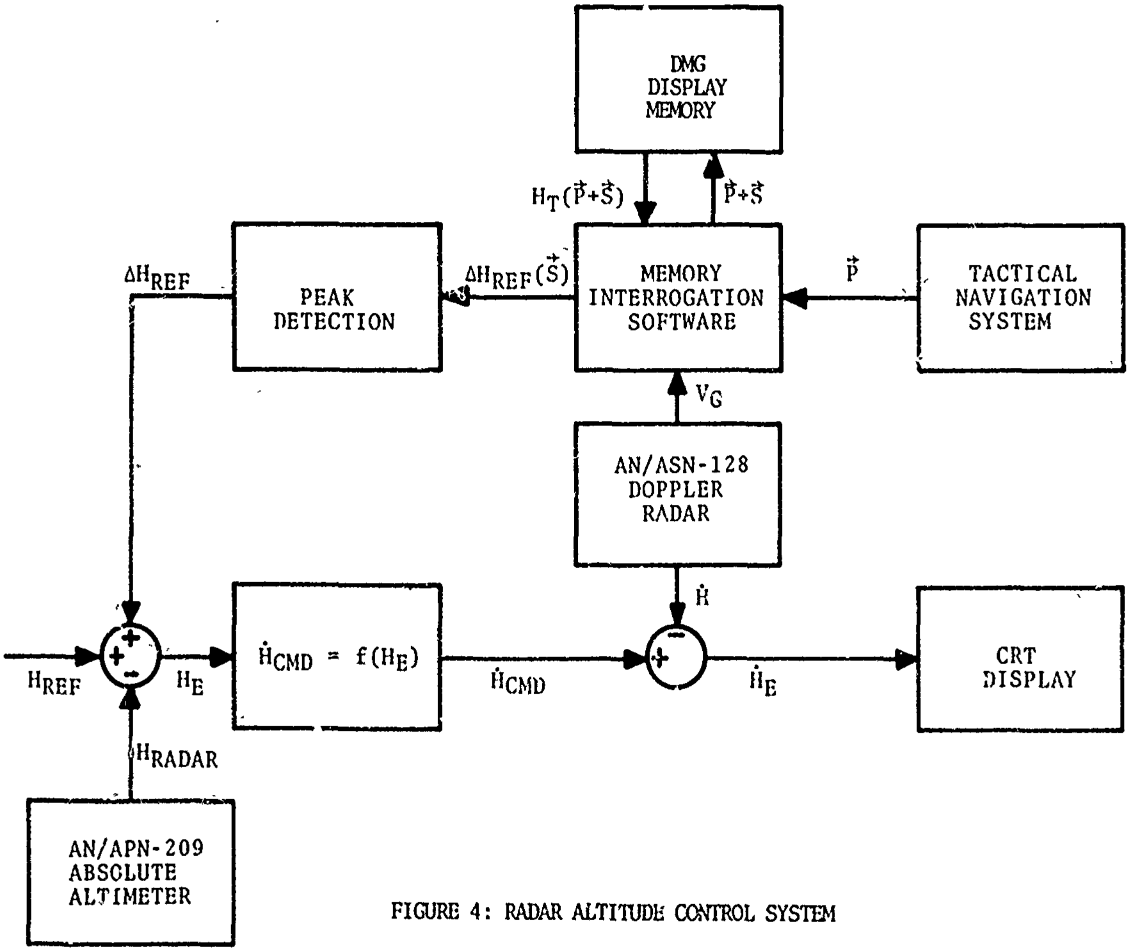

FIGURE 4: RADAR ALTITUDE CONTROL SYSTEM

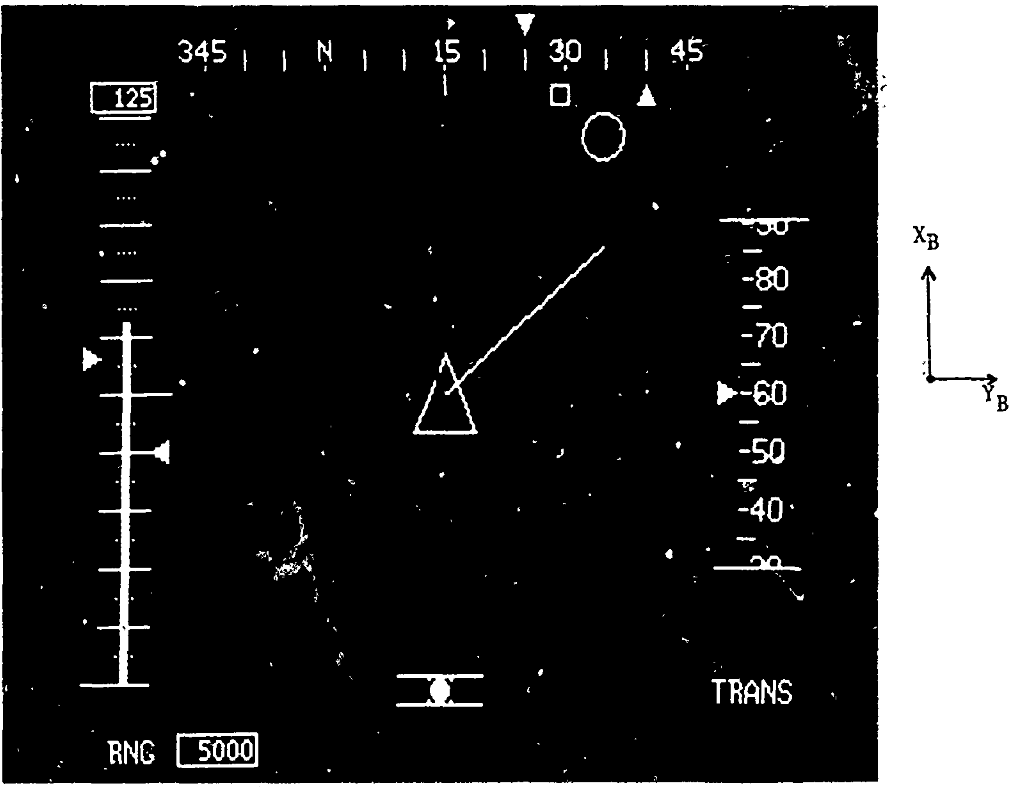

FIGURE 5 : TRANS SYMBOLOGY MODE

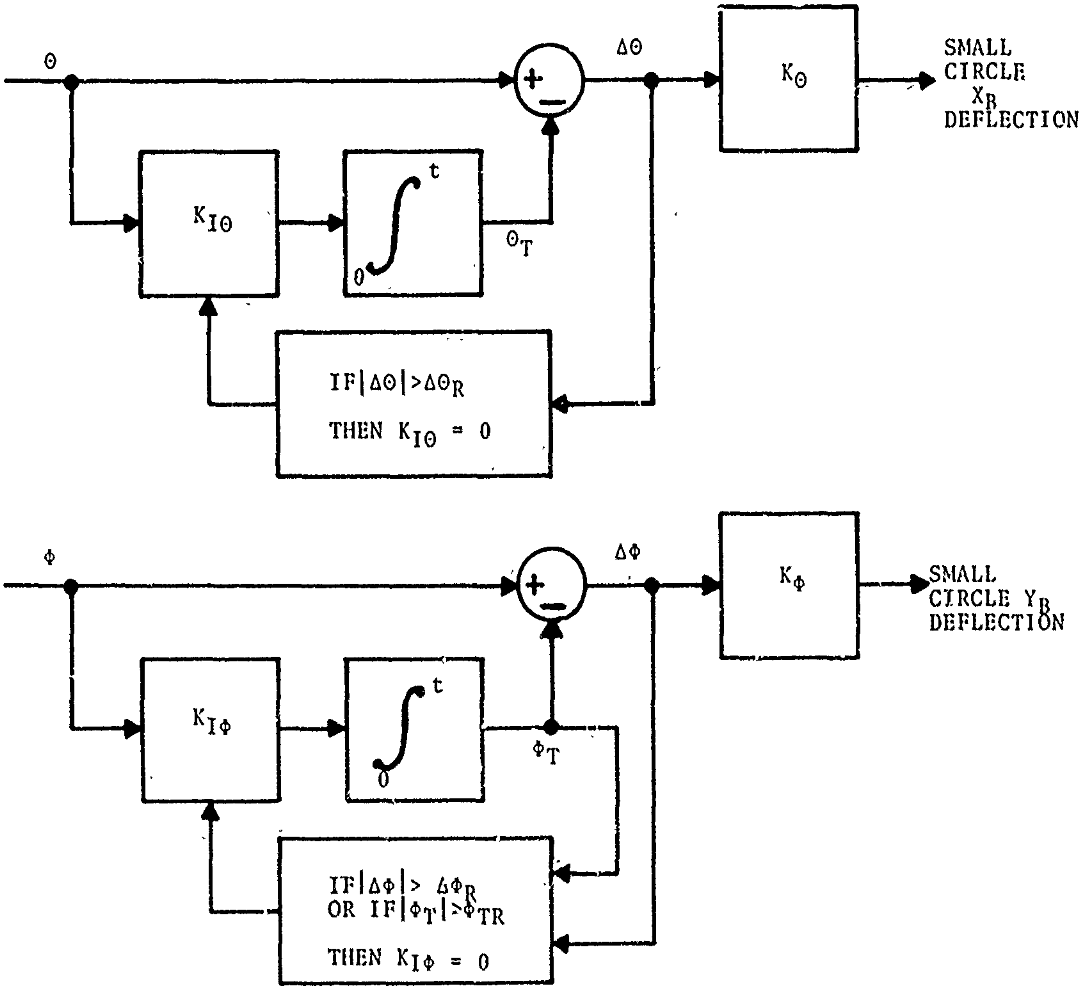

FIGURE 6 : PITCH/ROLL AUTOTRIM MECHANIZATION

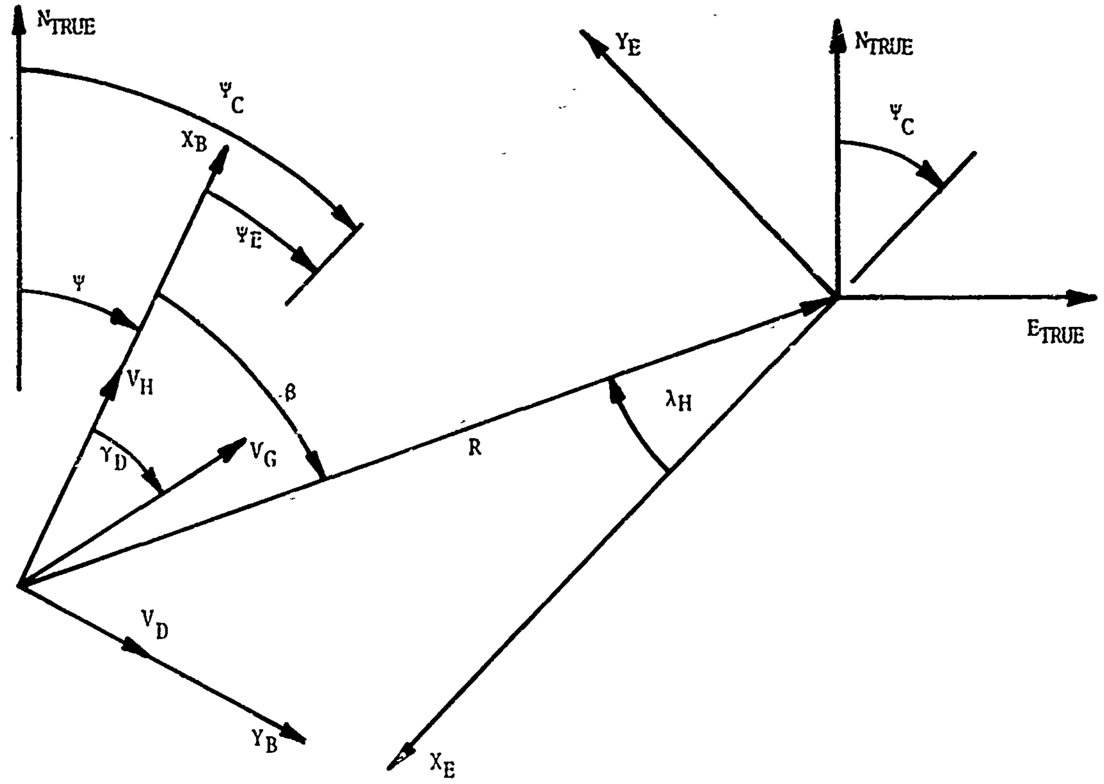

FIGURE 7: NAVIGATIONAL COORDINATE SYSTEM

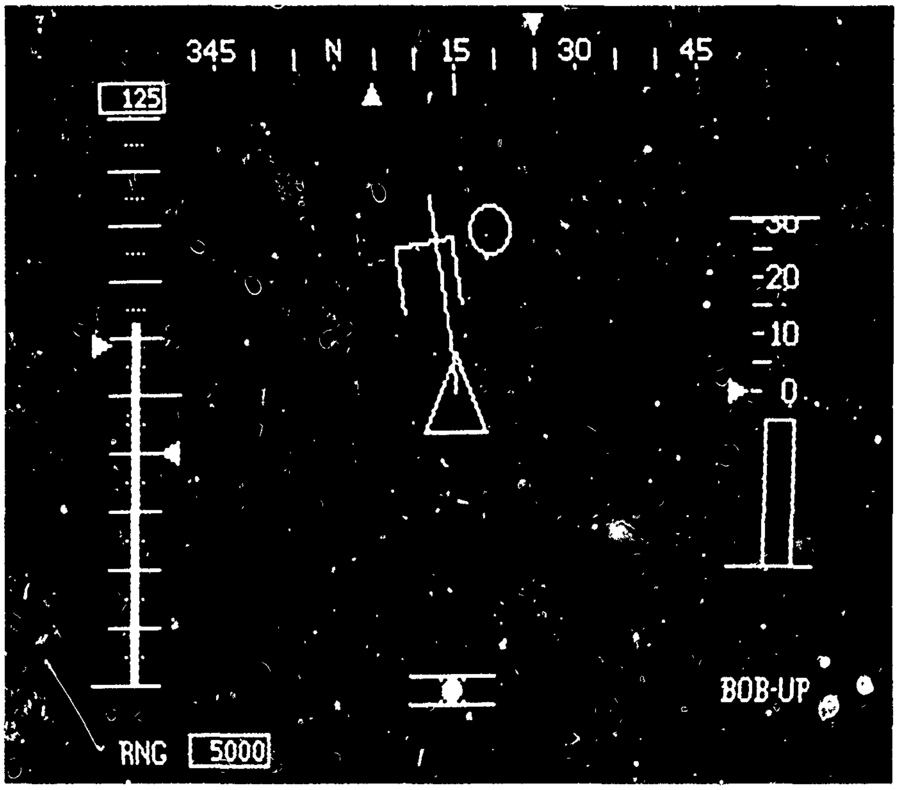

FIGURE 8 : BOB-UP SYMBOLOGY MODE

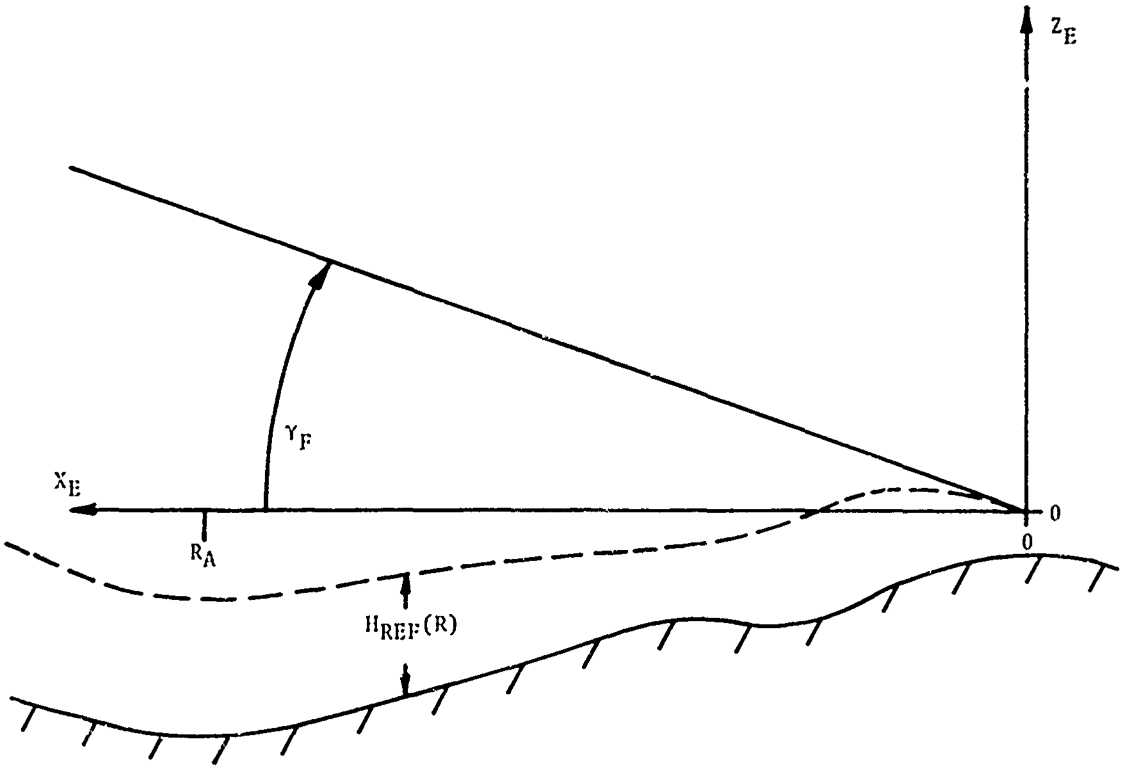

FIGURE 9: TYPICAL TACTICAL ELEVATION APPROACH PATH

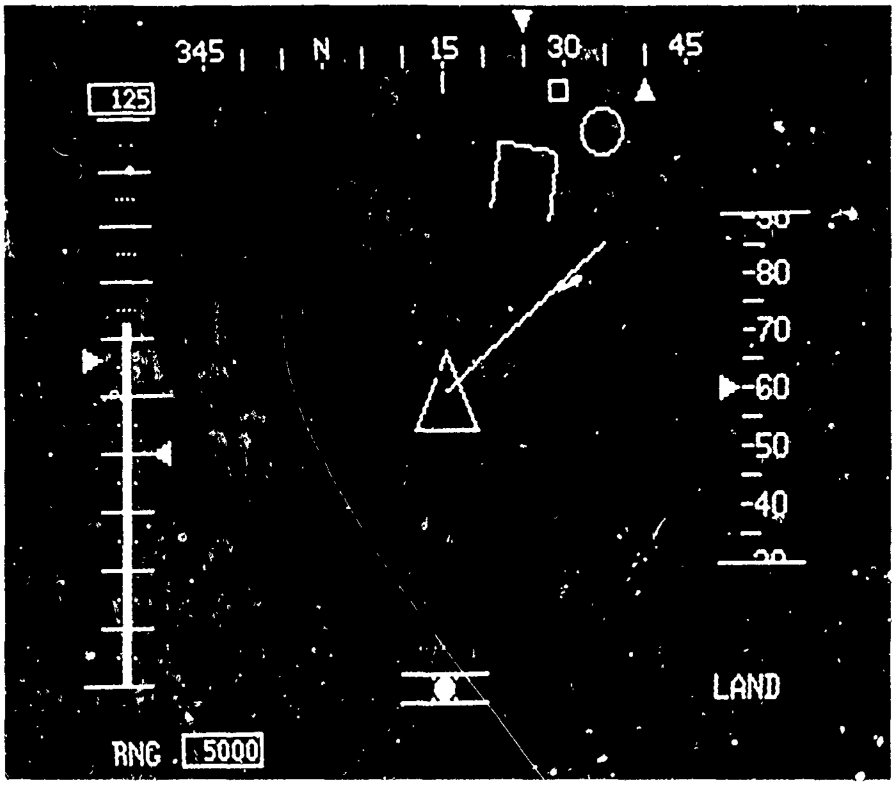

FIGURE 10 : LAND SYMBOLOGY MODE

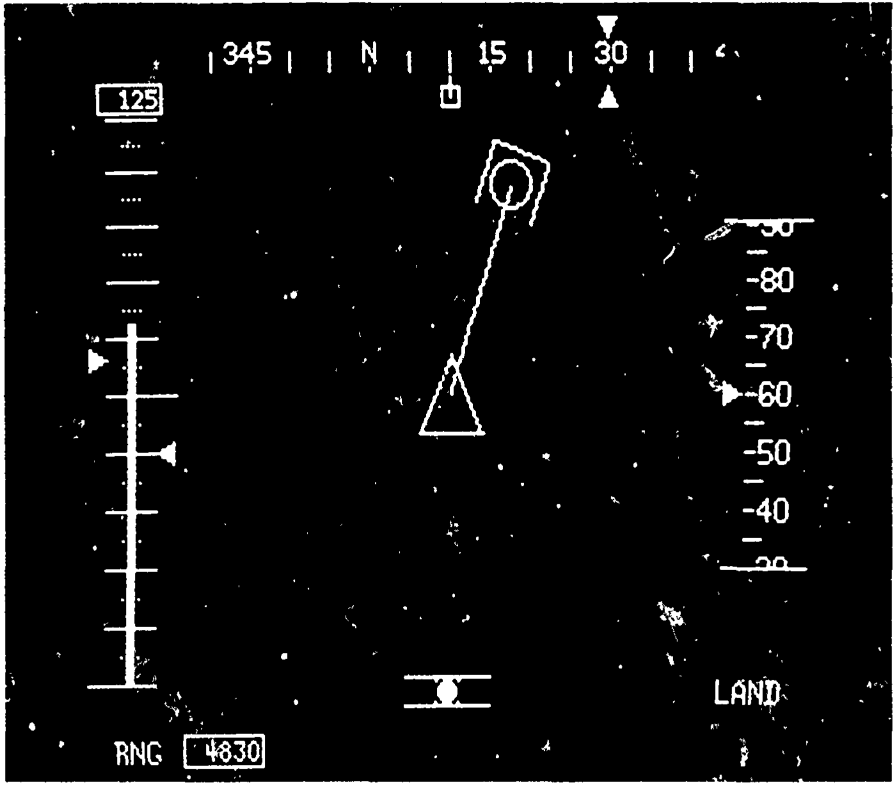

FIGURE 11: IDEALIZED LAND SYMBOLOGY MODE(LINEAR FORMAT)

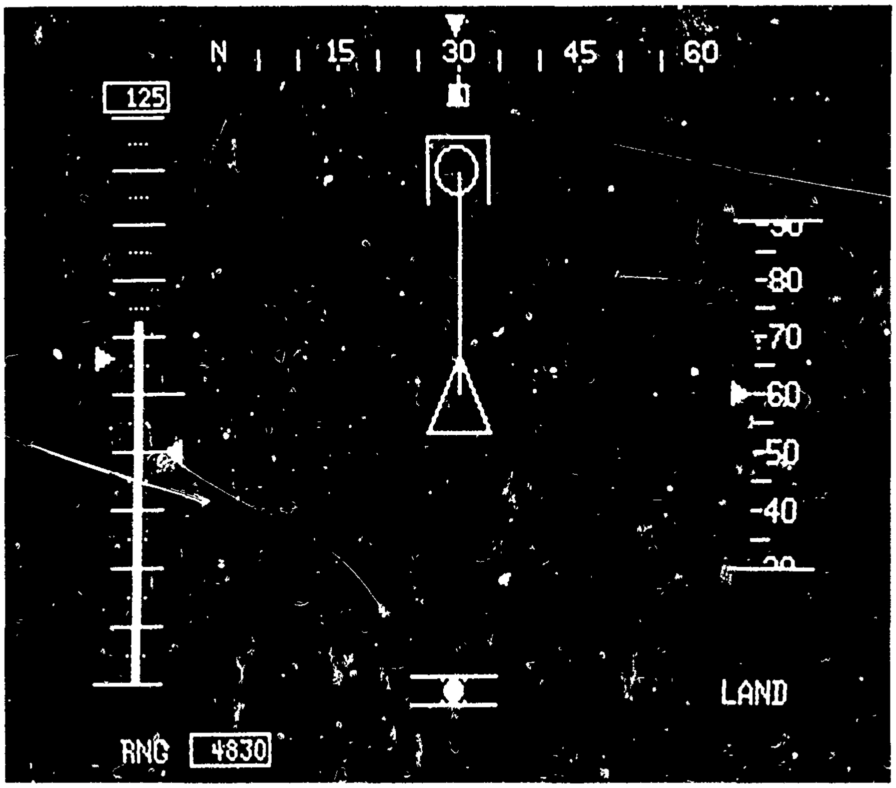

FIGURE 12 : IDEALIZED LAND SYMBOLOGY MODE(POLAR FORMAT)

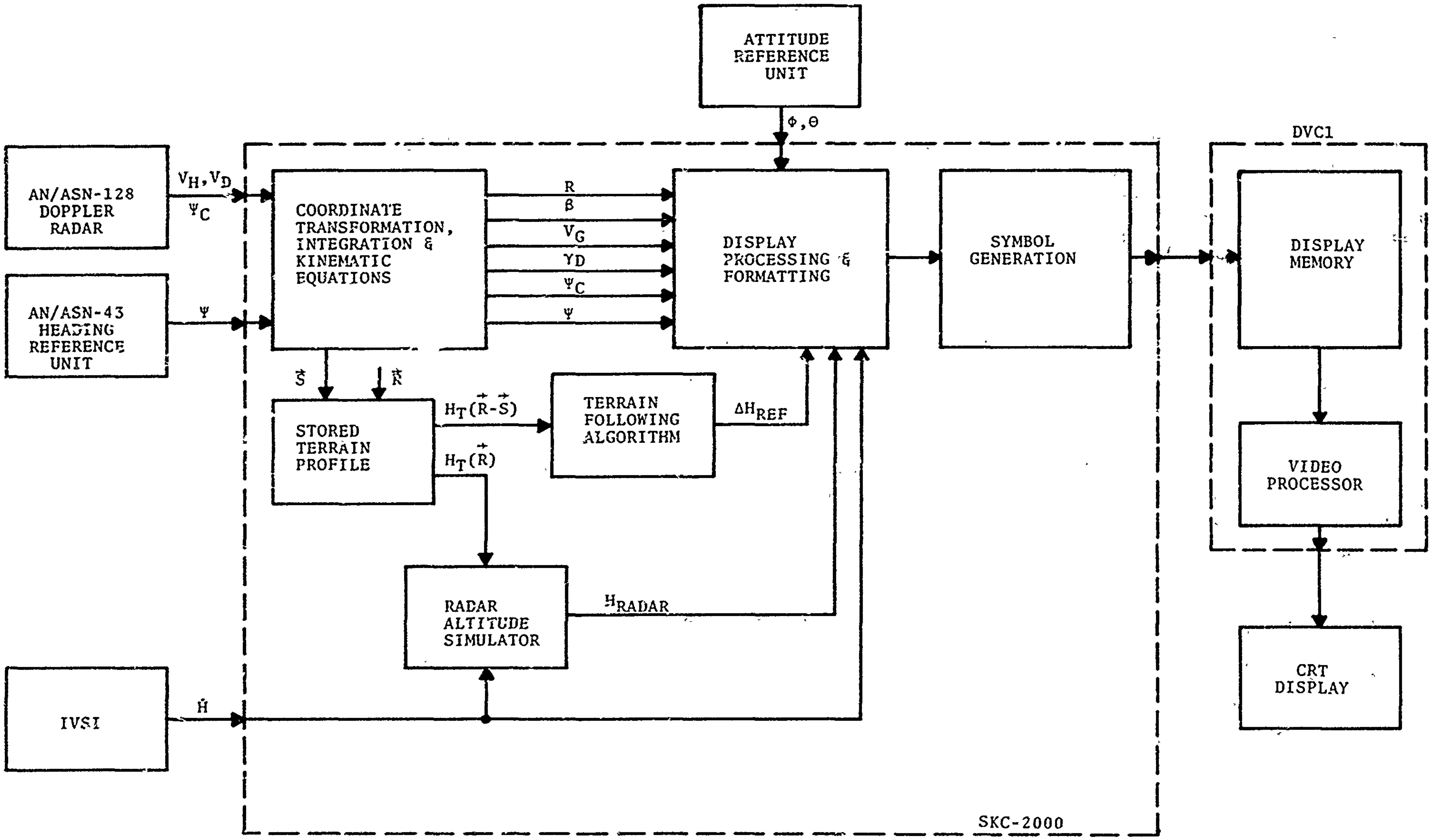

FIGURE 13: PHASE 1 NIGHT NAVIGATION/PILOTAGE SYSTEM

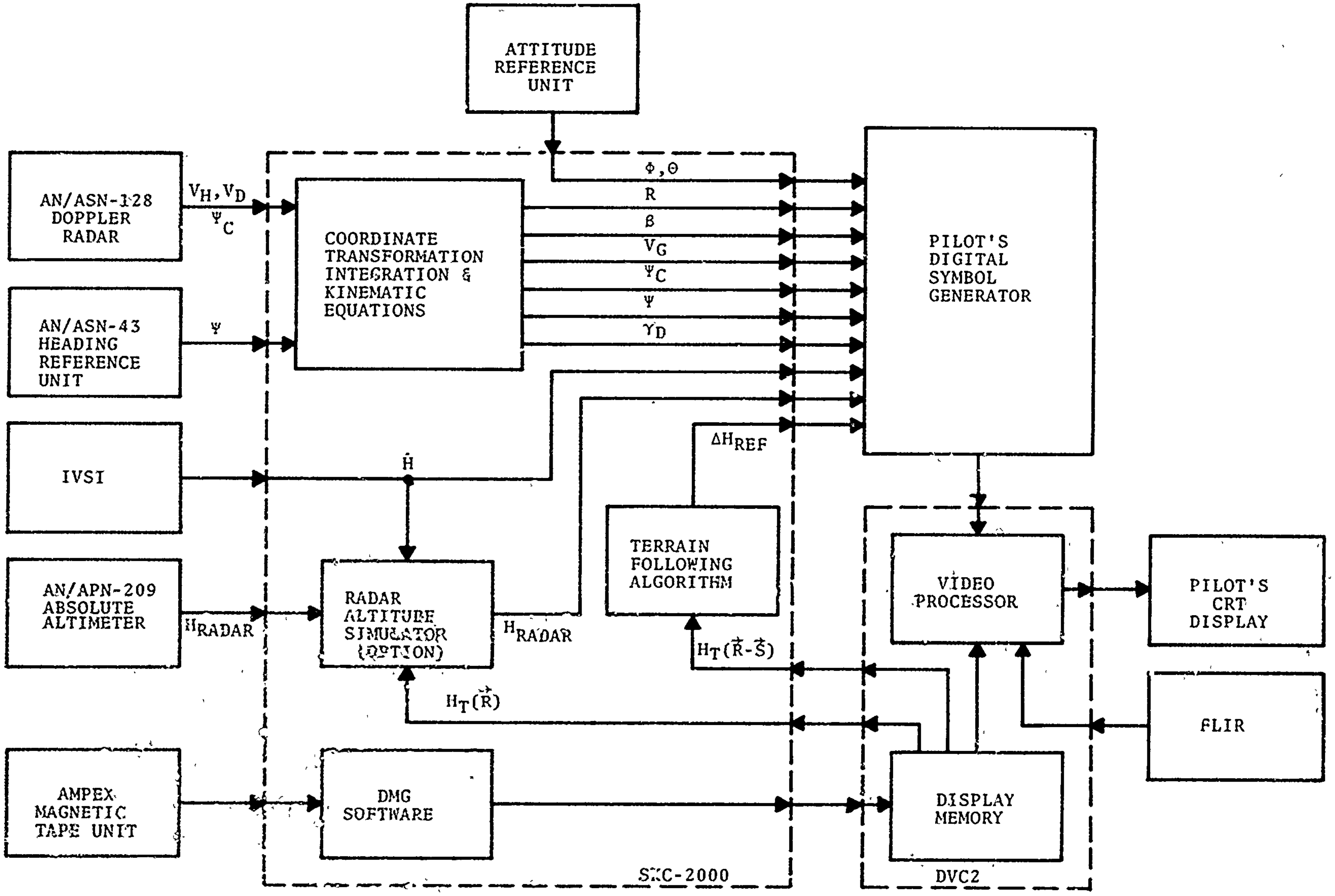

FIGURE 14: PHASE 2 NIGHT NAVIGATION/PILOTAGE SYSTEM

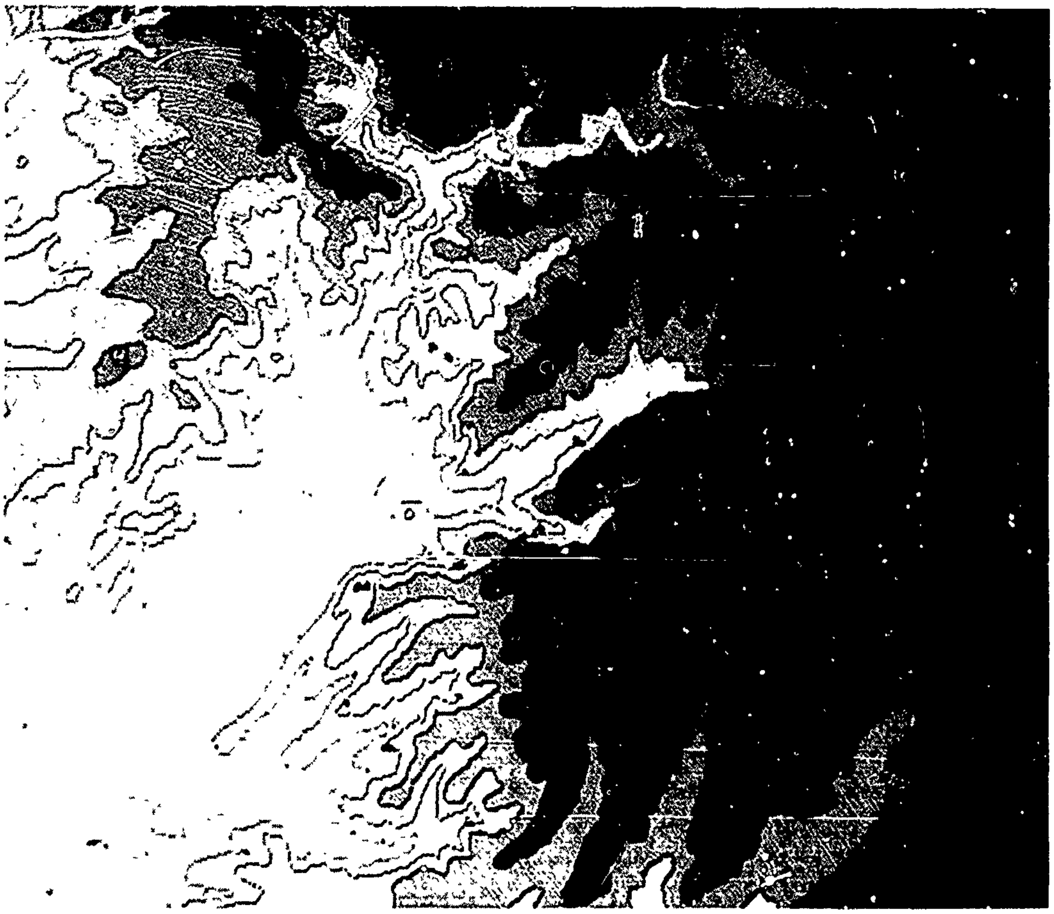

FIGURE 15a: PHASE 2 DIGITALLY-GENERATED MAP(1 CONTOUR PER SHADE)

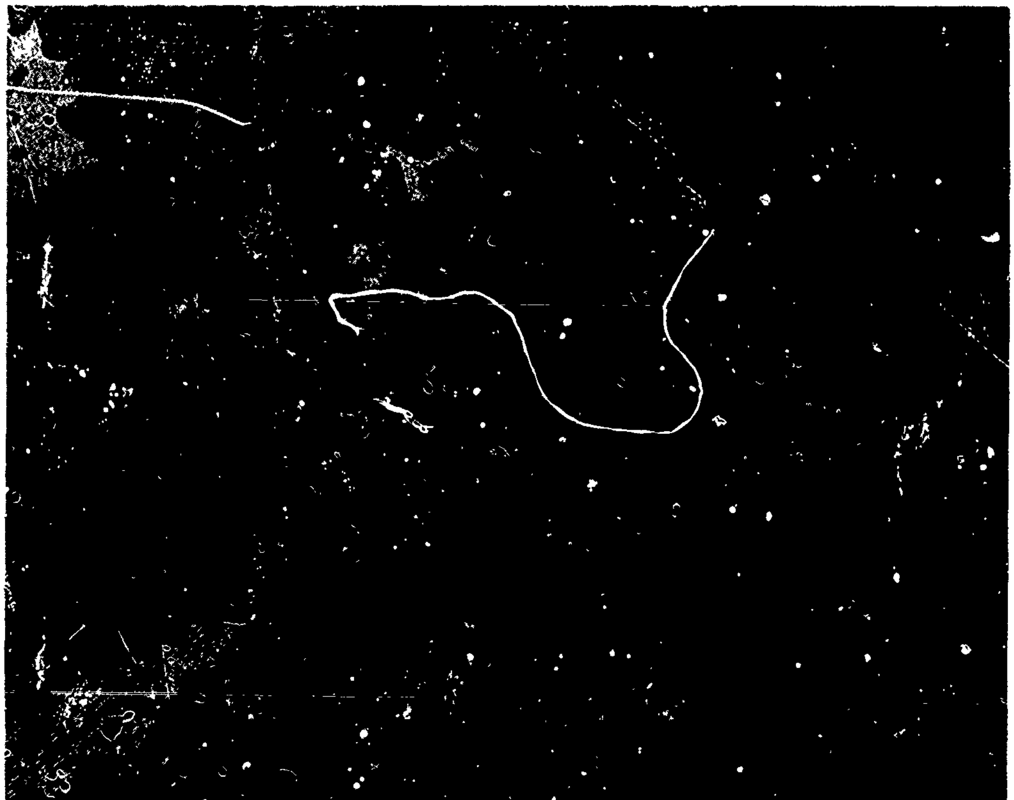

FIGURE 15b: PHASE 2 DIGITALLY-GENERATED MAP(3 CONTOURS PER SHADE)

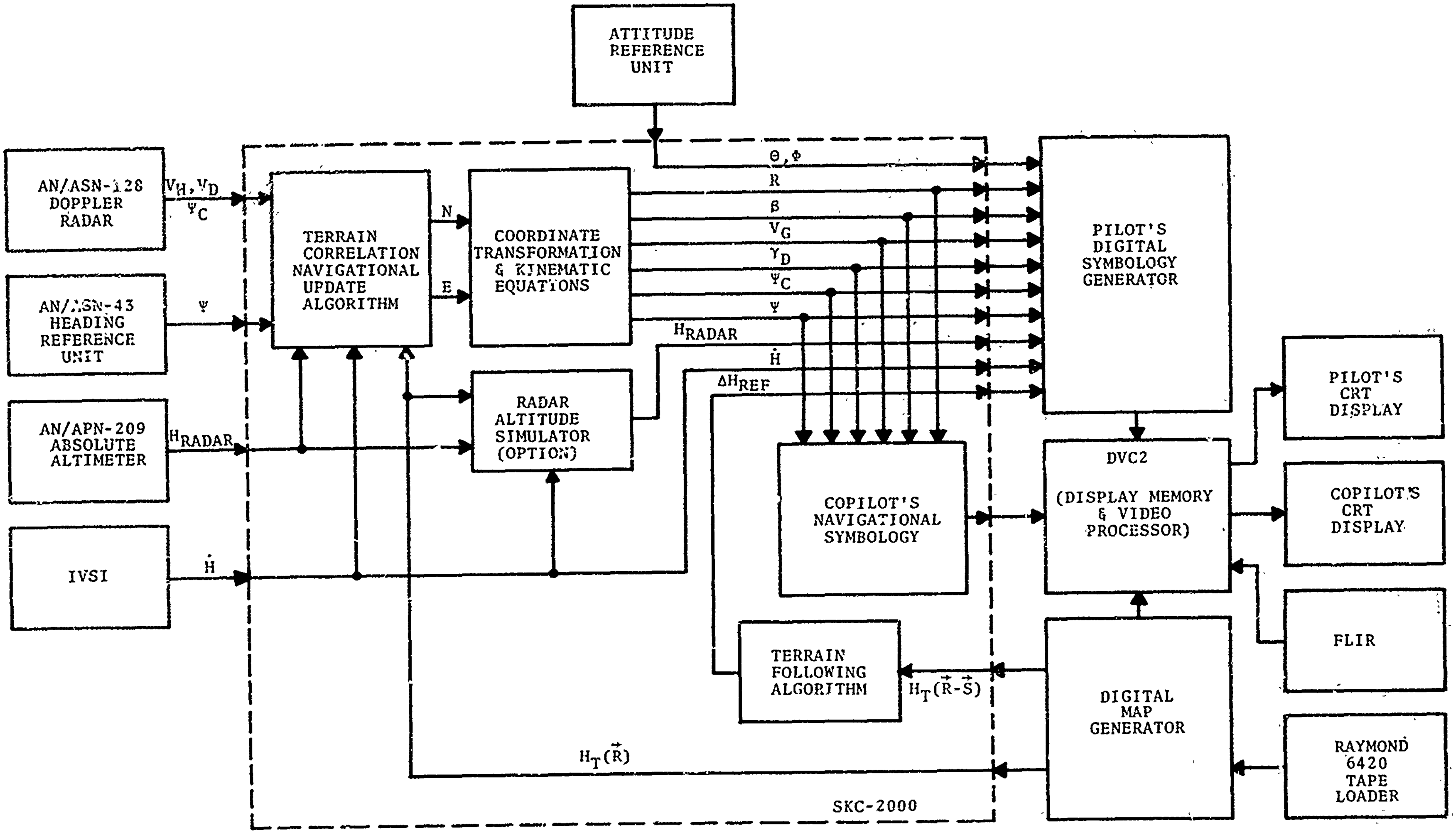

FIGURE 16: PHASE 3 NIGHT NAVIGATION/PILOTAGE SYSTEM

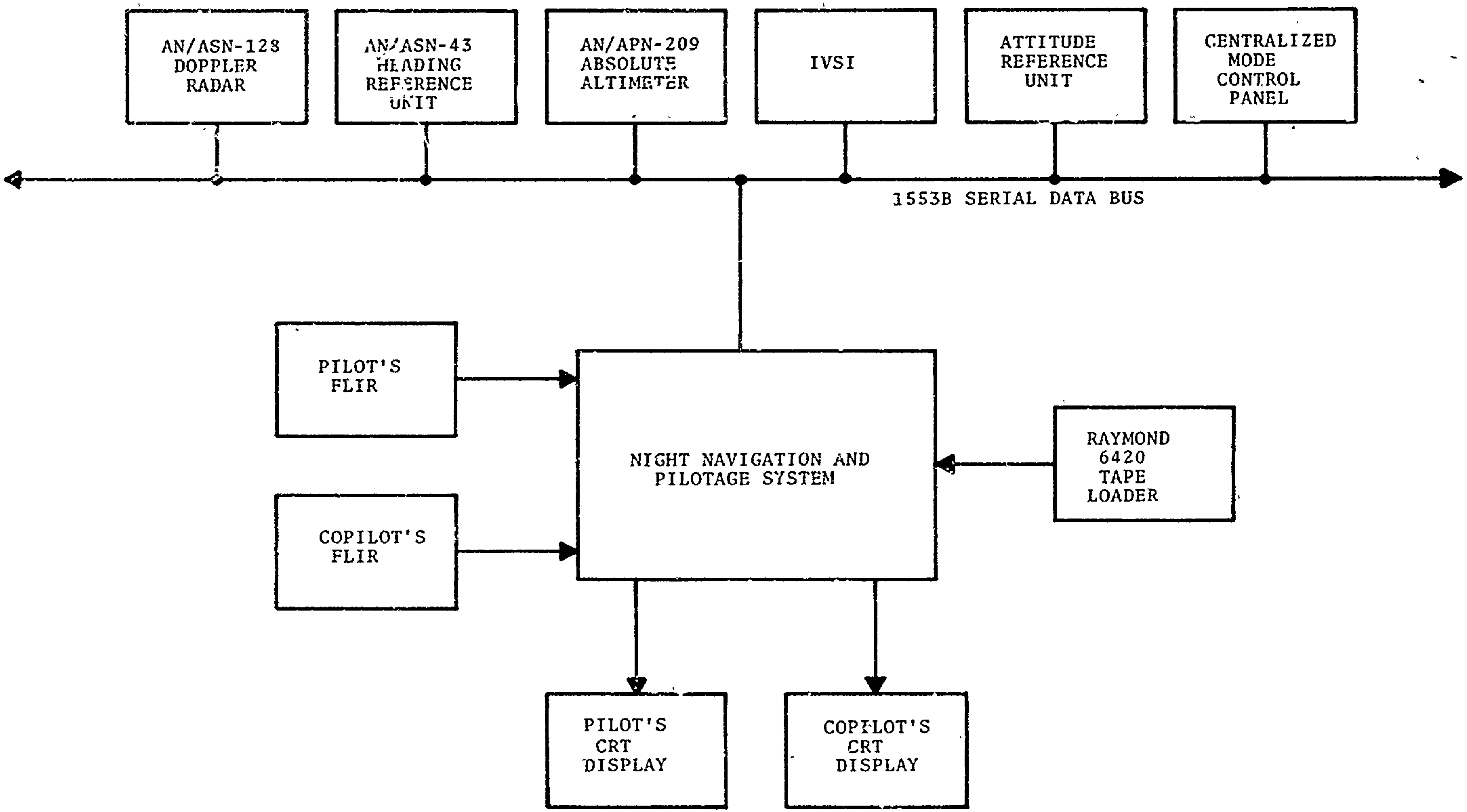

FIGURE 17: PHASE 4 NIGHT NAVIGATION/PILOTAGE SYSTEM

VERY LIGHTWEIGHT AIR TRAFFIC MANAGEMENT SYSTEM USING AN ELECTRONIC SCAN ANTENNA

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SUMMARY

An Electronically Scanned version of a Very Lightweight Air Traffic Management Equipment (VLATME) has been built by The Bendix Corporation's Communications Division under development contract to the U.S. Army Avionics Research and Development Activity. The electronically scanned antenna with all solid-state interrogator, complemented by a Bendix multi-microprocessor driver Tactical Interactive Display, provides a full alphanumeric PPI Air Traffic Management (ATM) system. This system utilizes the standard Mark X/XII ATCRBS/IFF airborne transponder to provide position information on all targets (up to 100) and tracked range, azimuth, and altitude (via mode C) on up to 13 targets.

The two key features of this system are the electronically steered Butler matrix-fed cylindrical array and the microprocessor based intelligent controller. The controller performs search and active track, minimizing interrogator PRF (64-198.5/sec) and electromagnetic interference. The antenna and R/T are physically integrated into a single assembly to minimize set-up time and maximize reliability.

INTRODUCTION

The U.S. Army Avionics Research and Development Activity (AVRADA) is currently investigating concepts for improving Air Traffic Management (ATM) of low flying aircraft near the Forward Edge of Battle Area (FEBA). At the present time, U.S. Army ATM is accomplished through procedural, voice communications, and visual control means. This contrasts with the civil/military, Mark X/XA/XII Air Traffic Control Radar Beacon System (ATCRBS), which provides all-weather real-time aircraft identification and position tracking information. Extending ATCRBS coverage to low altitudes and limited ranges appropriate to the military forward ATM function as an enhancement to mission success is the objective being pursued.

To explore the potential for ATM improvement through the use of ATCRBS, AVRADA had to develop a complement of Very Lightweight Air Traffic Management Equipment (VLATME). This was necessary since inventoried ATCRBS interrogator systems do not provide the sophisticated alphanumeric PPI display capability in a small, lightweight, low power consumption configuration suitable for man portable/transportable operation in the forward area. AVRADA contracted for a family of VLATME modules consisting of handheld and fixed portable interrogators with numeric readout, and a small conventional rotating antenna with PPI display interrogator. Field tests of these equipments in exercises, both in the U.S. and Europe, have successfully demonstrated the ability of the VLATME concept to support the Army ATM function in the forward area. This paper discusses an electronically scanning cylindrical array antenna alternate to the mechanically rotating antenna in the VLATME PPI configuration along with a computing display system which takes advantage of the unique system capabilities available only with electronic scanning.

SYSTEMS REQUIREMENTS

The primary objectives of ATCRBS based VLATME are to provide real-time all-weather aircraft tracking for traffic management. Mission success is enhanced when the ATM operator, through the use of a human engineered traffic situation display, is able to anticipate conflict and quickly alert aircraft concerned. In the event of an emergency, accurate stored position information improves rescue potential.

The Electronic Scan VLATME alternative must meet the basic requirements for a forward ATM system. It should be easily transportable, preferably manportable; hence, it should be small, lightweight, and consume lower power. To be universally useable, it must function interoperably with ATCRBS Mark X/XA/XII(SIF). Use of existing ATCRBS transponders places no additional burden on an aircraft's critical commodities - space, weight, and power. Although not required in every operational scenario, the ATM system should provide a 360-degree azimuth coverage out to a maximum range of 50 km. In many applications, the scan coverage will be limited to a sector of interest to avoid illuminating enemy airspace near the FEBA.

Since it will be used near the FEBA, with a high chance of detection by the enemy, it must have a low RF profile, and a low visible profile. The non-rotating electronic scan cylindrical phased array antenna with a low pseudo-random PRF meets both of these requirements.

A final requirement exists in the flexibility to accept possible VLATME growth features. One of these is the ability to operate in a passive receive only (parasite) mode utilizing one or more friendly interrogators in the vicinity. Electronic scanning is ideally suited to such an application because the monopulse angle measurement capability minimizes the number of cooperating interrogators required. Another growth feature is MLS/ATCRBS crossbanding where each airborne platform determines its position through an air-derived Microwave Landing System (MLS), and telemeters (in a specified time slot) its 3D Positions to the ground ATCRBS unit by use of the transponder's auxiliary data input. Elimination of synchronous garble and greatly increased accuracy in the landing zone are its primary advantages.

All of the above requirements were considered when the system architecture (described below) was evolved.

SYSTEM ARCHITECTURE

The Air Traffic Control Radar Beacon System (ATCRBS) is shared between civil and military users and utilizes common communications channels for both ATC and IFF functions. Control of mutual interference and minimization of ECM vulnerability are both major system design requirements. ECM requirements dictate system coverage, target capacity, update rates, and information output. For the Army's VLATME application, hardware design is further constrained to accomplish the above with a small, lightweight system which is rugged, easily and quickly erected and placed in operation, and consumes low power.

The Electronic Scan VLATME concept developed for this application is depicted in Figure 1. Major functional blocks are similar to the traditional ATCRBS implementation in that it consists of an antenna, interrogator receiver-transmitter (R/T), reply processor, display, and interfaces with an ATC/ATM operator. However, in the traditional ATCRBS, except for the control of interrogation mode, no information or control flows from the operator or display processor to the antenna, interrogator R/T or reply processor. Surveillance information is gathered by this chain of subsystems in a lock-step process which ignores the content of any useful data being passed on. Any reply data being received is processed using antenna angle information and range zero trigger independently output by the antenna and the receiver/transmitter. Antenna rotation rate and PRF are fixed (PRF may be staggered but with a fixed average rate) based on a compromise between worst case required performance and hardware limitations/constraints. PRF is then high (250-450 per second) and independent of the number of targets under surveillance. Software required to acquire/track/display targets must contend with the one-way flow of information, frequently functioning with inadequate update rates, and must smooth-over lost position updates.

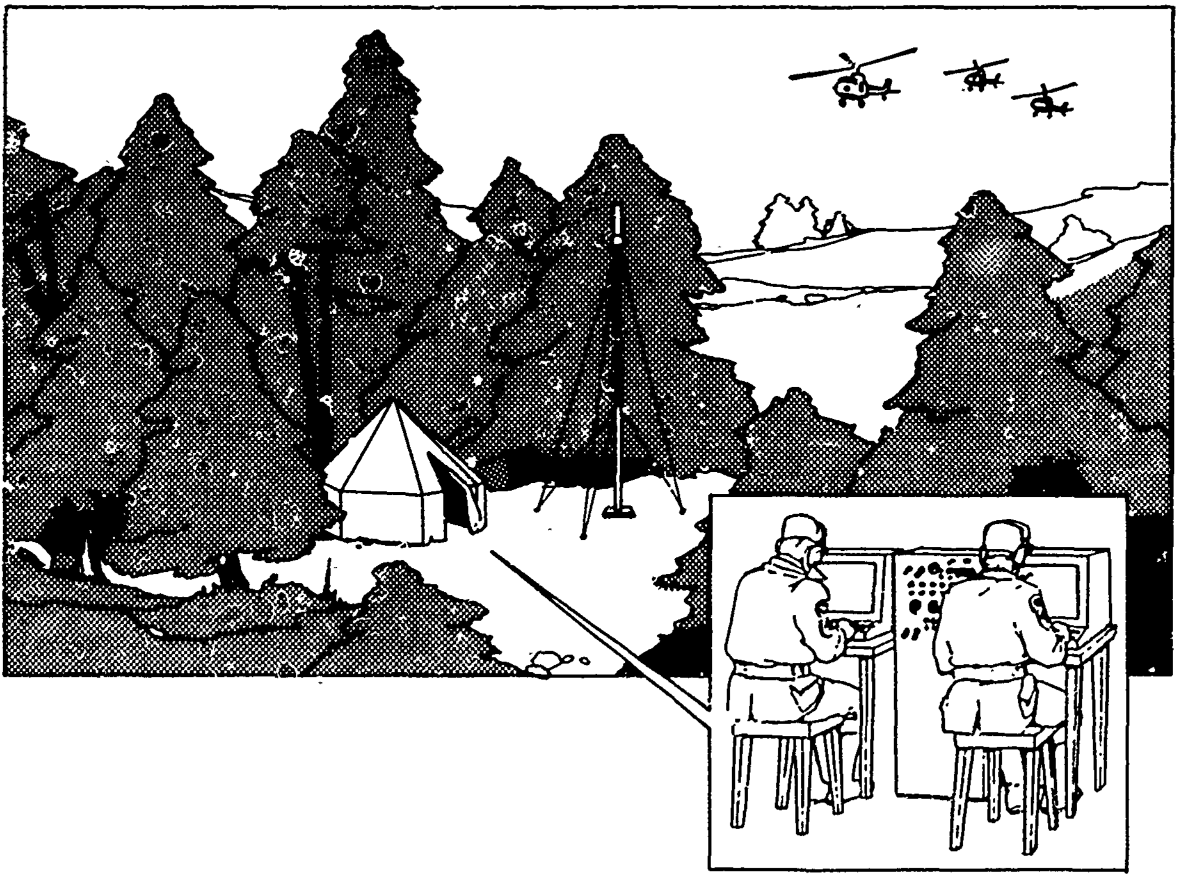


Figure 1. Air Traffic Management System Concealed in Foliage
Near the Forward Edge of Battle Area (FEBA)

The Electronic Scan VLATME shown functionally in Figure 2, was developed to meet the above requirements and to overcome some traditional ATCRBS shortcomings. Major decisions arrived at during the systems engineering effort include:

(a) Replace Mechanically Rotated Antenna with Electronic scanned phased array - must be a circular array for uniform azimuth performance. (Provides low visual profile but no reduction in PRF).

(b) Place interrogator and antenna steering under control of a search/acquire-track algorithm to adaptively schedule interrogations and minimize PRF.

(c) Employ monopulse azimuth measurement on receive to complement (b) above and allows a target report to be developed from a single reply.

(d) Extend array's vertical aperture to increase antenna gain and low angle coverage.

(e) Employ integral interrogation side-lobe suppression (ISLS) to prevent "punch-thru" over 360 degrees through control of azimuth and elevation patterns for both interrogation pulses (P1, P3) and Interrogation Side-Lobe Suppression (ISLS) control (P2) pulses by using a common RF phase center.

(f) Integrate antenna and P/[illegible]ts into single functional assembly with lightweight reliable solid-s[illegible] transmitter/receiver (MIL-E-5400 class II) to eliminate RF cables and [illegible]ated power loss.

(g) Size a beacon [illegible]ly proce[illegible]or with integral monopulse processing to VLATME requirements. [illegible]is requires small, low power consumption data bus system, compatible with subsequent digital processing equipment. Provide additional readout/manual control capability in brassboard model to facilitate development.

(h) System/human engineer a microprocessor based interactive control and display system to meet tactical ATM requirements and interface with E-Scan VLATME.

(i) Provide sector surveillance capability with functional provisions for future passive (listen only, surveillance and cross-connecting landing guidance and ATCRBS (crossbanding).

The design characteristics and rationale for each of the four major functional elements of the E-Scan VLATME is presented below.

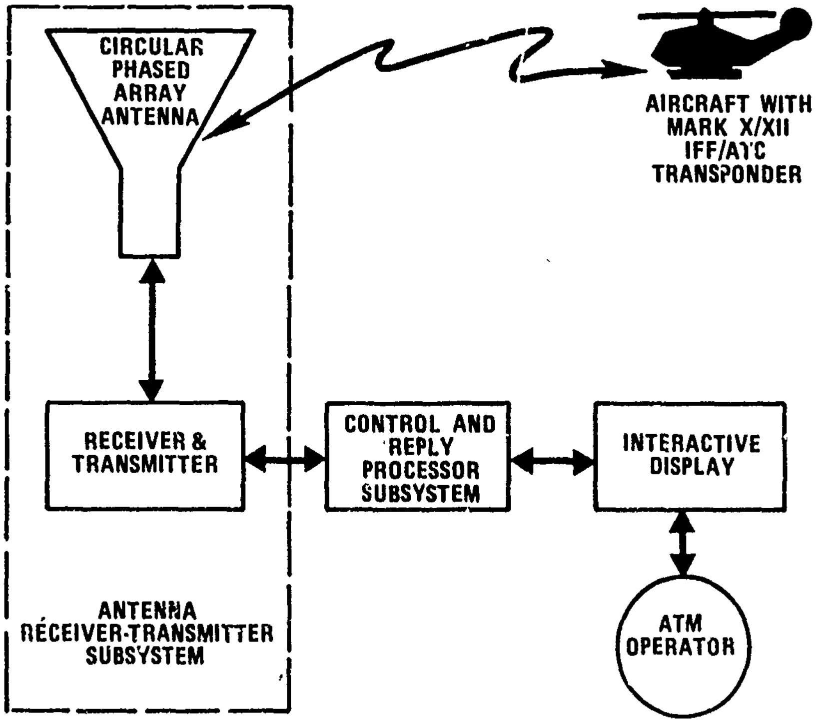


Figure 2. Simplified Diagram of the Electronic Scan Very Lightweight Air Traffic Management System

CYLINDRICAL PHASED ARRAY ANTENNA

The circular phased array antenna was chosen over a set of switched line arrays since it provides a uniform azimuth pattern and a well defined common RF phase center for superior ISLS. Since weight and cost, in addition to size, are proportional to the number of elements in a circular array, a small azimuth (horizontal) aperture is desirable. With a small azimuth dimension, vertical aperture is employed to add gain and low angle coverage without appreciable added weight or cost. Antenna implementation details are discussed following a description of pattern requirements.

Azimuth Pattern Requirements

The general ATCRBS requirement for good target resolution through the use of a large narrow beam antenna is at odds with the tactical requirement for a small, lightweight antenna. Fortunately, the ATCRBS transponder contains ISLS circuitry which may be employed to enhance interrogator resolution through synthetic beamsharpening. This technique is used in many military interrogators where shaped P2 patterns "trick" the transponder into ISLS except for a narrow region in the center of the main beam. The standard technique for this is the use of sum Ω and difference Δ antenna patterns. With appropriate processing hardware, the same sum and difference patterns provide a monopulse measurement on reply.

The operation of the ATCRBS ISLS system is depicted in Figure 3. Normal ATC replies are elicited by the interrogator when the two pulse (P1, P3) pair are received by a transponder carrying aircraft. At greater ranges, this only occurs as the main lobe of the directional interrogation beam passes through the target. However, energy in the main beam side-lobe region may cause false replies from close-in targets. To prevent the resulting false replies, a control pulse (P2) is radiated such that its amplitude exceeds the highest directional side lobe by some safety margin. ISLS, or simply SLS, circuitry in the transponder measures the amplitude of P2 relative to P1 which it follows by two microseconds. Limits established in the Mark X ATCRBS standard require the transponder reply if P1 is more than 9 dB above P2, i.e., in the mainlobe. Likewise, if P1 is equal to or less than P2, the transponder generates a side-lobe suppression (SLS) and replies are preempted for 30 ± 5 microseconds.

The terms "sum and difference" applied to antenna patterns are notations for the two patterns usually employed in monopulse work. They result if an antenna consisting of an even number of elements is separated into two equal halves and each half is driven 180 degrees out of phase. When the drive is applied to the in-phase or sum port on a 180-degree hybrid, both halves of the antenna contribute in-phase components to form a uniform directional pattern. If, however, the hybrid difference port is driven, the two halves of the array are 180 degrees out of phase. This causes a sharp null to develop at boresight where the opposing signals cancel.

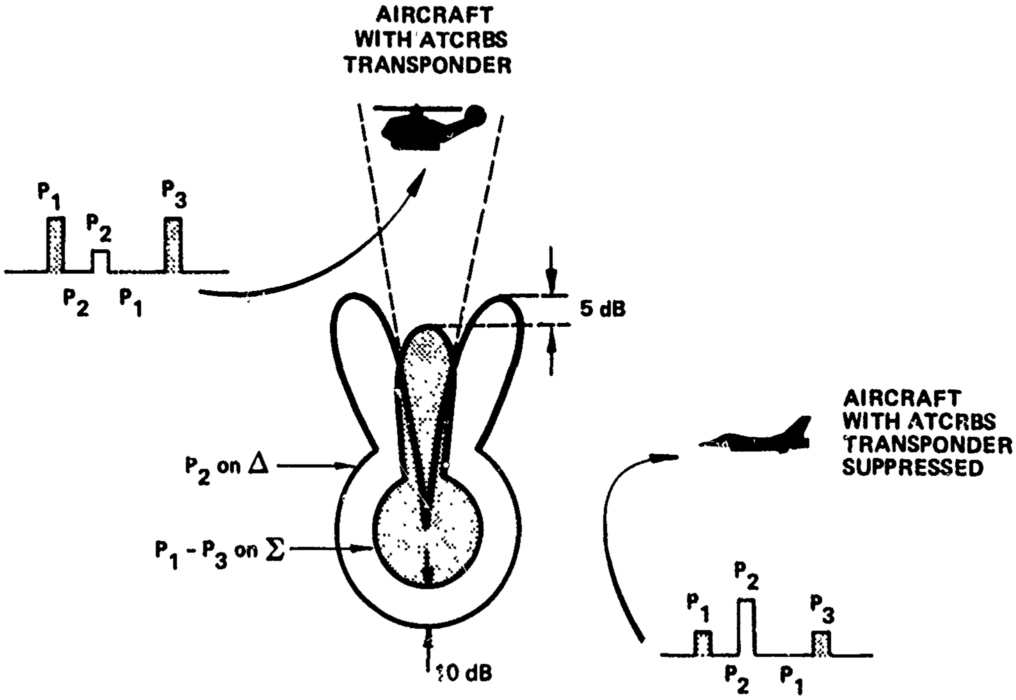


Figure 3. Functional Operation of ATCRBS Interrogation Side-Lobe Suppression System With Standard Mechanically Rotated Interrogator Antenna

Idealized sum and difference patterns are shown in Figure 4. On interrogation, the sum beam signal is attenuated 5 dB relative to the peak difference beam signal. The difference beam signal is then everywhere greater (10 dB in side-lobe region) than the sum beam except in the narrow difference beam null. Transponder SLS circuitry functions to narrow the interrogation beamwidth from a sum beamwidth of 60 degrees to an effective beamwidth of 18 degrees nominal. With monopulse measuring techniques which utilize the inherent sum and difference pattern gains, azimuth resolution of less than 1 degree and accuracy greater than 3 degrees is obtained.

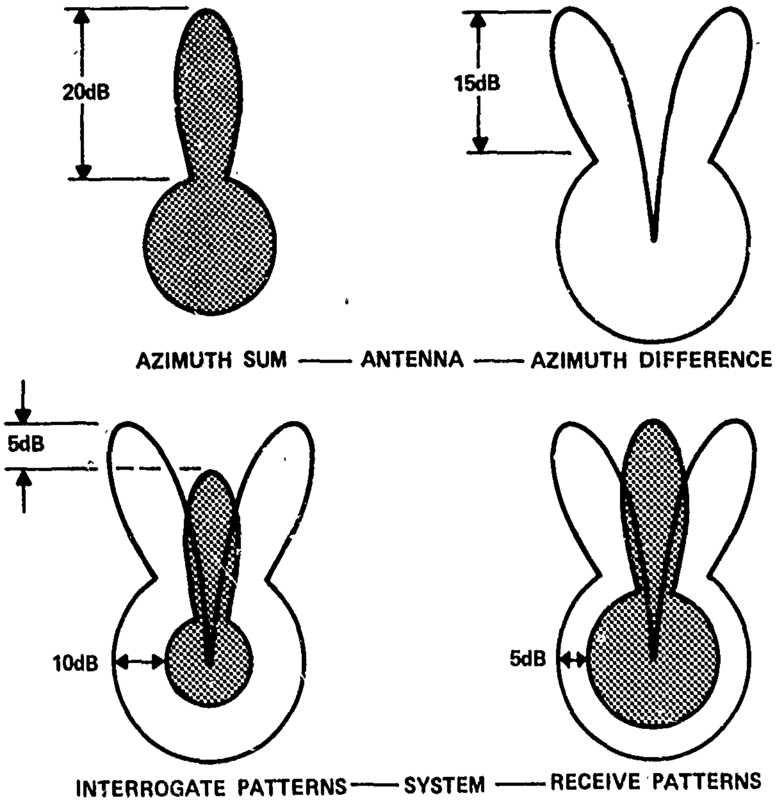


Figure 4. Cylindrical Antenna Azimuth Sum and Difference Pattern Employed for Side-Lobe Suppression on Interrogation and Monopulse on Reply (Sigma and Delta)

Elevation Pattern Requirements

ATCRBS elevation coverage is normally provided from some minimal angle (radio horizon) up to 40 degrees above the horizon. In the case of low flying aircraft, low angle coverage determines maximum system range. Vertical multipath causes low angle signals to be attenuated rapidly ($1/R^4$). For fixed installations, an antenna with sizable vertical aperture (4-8 feet) and a sharp underside cutoff minimizes the energy impinging on and reflected from the ground. This reduces vertical multipath losses proportionally. In tactical situations where the topography is such that this improvement is marginal, the best alternative is to provide maximum antenna gain at the low elevations with a controlled lower gain pattern up to 40 degrees. Unfortunately, with vertical polarization, there will always be a null at the zenith. This is a practical problem that must be handled procedurally as the aircraft passes through the "cone-of-silence".

Antenna Implementation

The E-Scan VLATME antenna developed by Bendix is a type of antenna known as a Butler-matrix fed cylindrical array. Based on a trade study which evaluated 4, 8, and 16 elements as potential array candidates, the 8 element array was selected. Recent work with matrix feeds makes even number non-binary combinations possible but with greatly increased component count and cost.

Figure 5 shows the mechanical arrangement of the integrated antenna and receiver/transmitter unit. In the azimuth (horizontal) plane, the eight etched dipole array elements (referred to as columns) are mounted above an octagonal ground plane and stabilized by low-loss rigid foam; the assembly is covered with epoxy-fiberglass for durability. The unit is coated with low visual/IR detectability paint. The eight dipoles in each column are connected to a simple eight-way weighted power divider below the array to establish the antenna's elevation pattern. All eight columns are identical and the eight column power divider inputs form a circular feed point driven by the Butler matrix (refer to Figure 6).

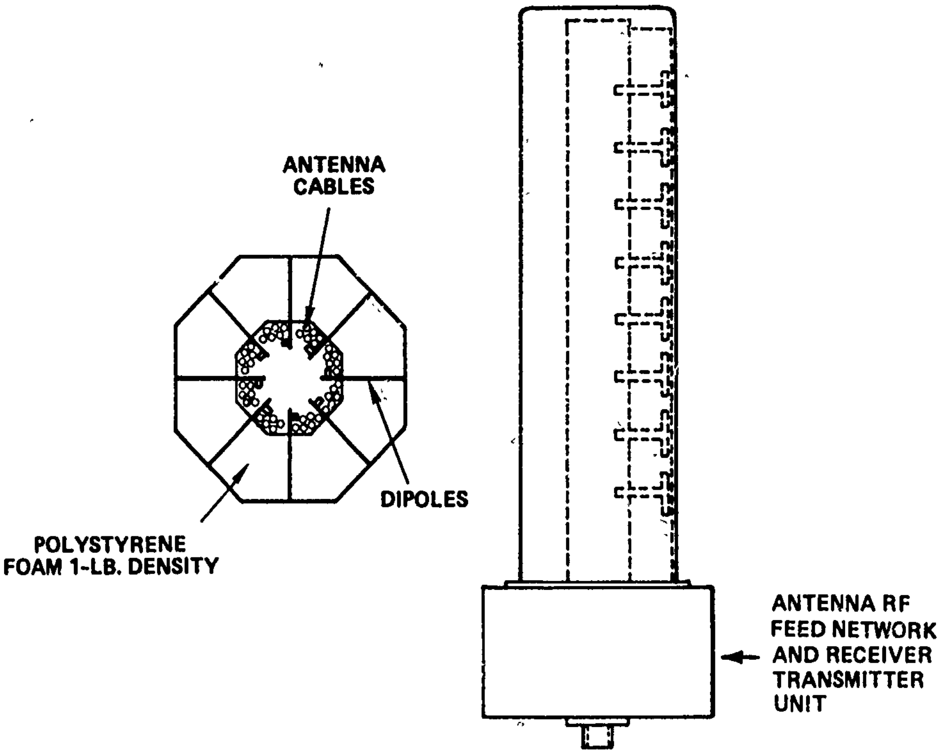


Figure 5. Construction Features of the Cylindrical Phase Array Antenna Showing RF Feed Network and Receiver-Transmitter Location

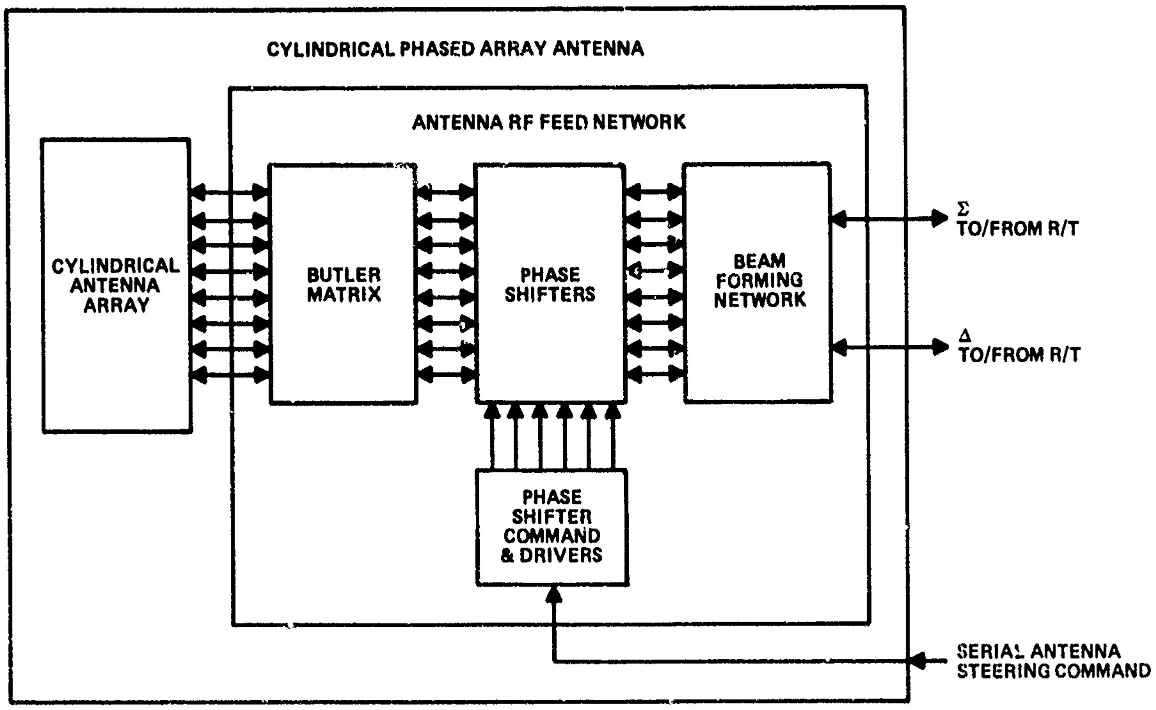


Figure 6. Block Diagram of the Cylindrical Phased Array Antenna Subsystem

The Butler matrix accomplishes an electrical transform by converting a linear array amplitude and phase distribution, steered to some angle at its input, into an amplitude and phase distribution required by a circular array steered to a corresponding angle. Steering over 360 degrees with uniform low side-lobes is accomplished by controlling only the relative phase of the signals at the Butler matrix input. The success of the antenna is primarily attributable to the Bendix developed 8 x 8 Butler matrix.

Seven six-bit diode phase shifters are contained in the antenna feed network. This is one less than the number of elements since the 4th mode input on the Butler (terminal number eight) is terminated. The six-bit shifter provides a 5.625 degree least significant bit (LSB) with peak errors on the order of 1/2 of the LSB.

Phase Shifter Driver

The steering electronics accepts the serial steering command and converts it into commands for the individual shifters. Antenna steering is in binary steps equal to an RF shifter LSB = 5.625 degrees. This provides 64 steps over 360 degrees and greatly simplifies steering command circuitry. Antenna beamwidths are compatible with these increments and the monopulse on reply provides fine grain target resolution.

Significant original work was accomplished in the beam-forming network. Principally, this involved developing the sum and difference networks which functioned at both interrogate and receive frequencies with controlled uniform side lobes. Elimination of the null at 180 degrees off boresight required a unique feed network having a low level directional beam at 180 degrees to fill in this null. Ripple in the side-lobe region was held to less than 3 dB. The feed network is totally passive and reciprocal at both sum and difference input/out ports.

RECEIVER-TRANSMITTER

The R/T subsystem is packaged in the base of the integrated antenna-R/T unit. It consists of the five functional subsystems depicted in Figure 7. The transmitter module is based on the Bendix AN/APX-100 transponder solid-state transmitter, crystal controlled and adjusted for 1030 MHz operation. Peak power output from the module is 450 watts. The RF feed and diplexer accomplishes the ISLS switching function on transmit. This includes attenuating P1, P3 by 5 dB to effect beam sharpening as shown in Figure 4.

On receive, the sum and difference ports are connected through a quadrature hybrid so that the outputs are sum - difference and sum + difference. These signals are then converted to log video in receivers identical to the AN/APX-100 receivers retuned to 1090 MHz. The log video signals provide information necessary to measure angle-off boresight, as well as +/- sense which is not provided in a simple sum - difference monopulse scheme. The local oscillator is crystal-controlled and a separate crystal oscillator pulsed at 1090 MHz during self-test interrogation evaluates receiver sensitivity and balance along with providing test signals to the reply processor subsystem.

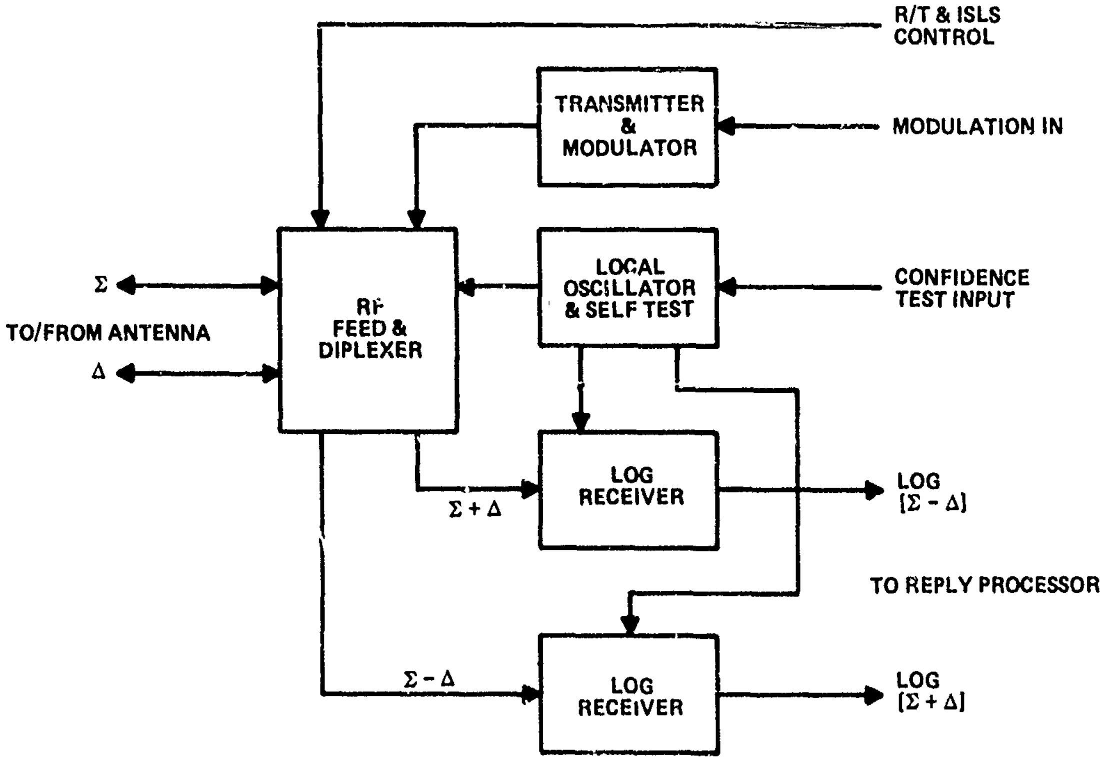


Figure 7. Block Diagram of the All Solid-State Receiver/Transmitter Which is Mounted at the Antenna

CONTROL AND REPLY PROCESSOR SUBSYSTEM

This unit interfaces the Display Processor and the Antenna Receiver/Transmitter unit. It performs the real-time analog and digital conversions to/from the display processor's digital data bus network. Major subsystem functional elements are shown in Figure 8. These are divided functionally into the interrogator control group at the top and the reply processing group at the bottom. The digital data bus and various real time control signals tie the groups together.

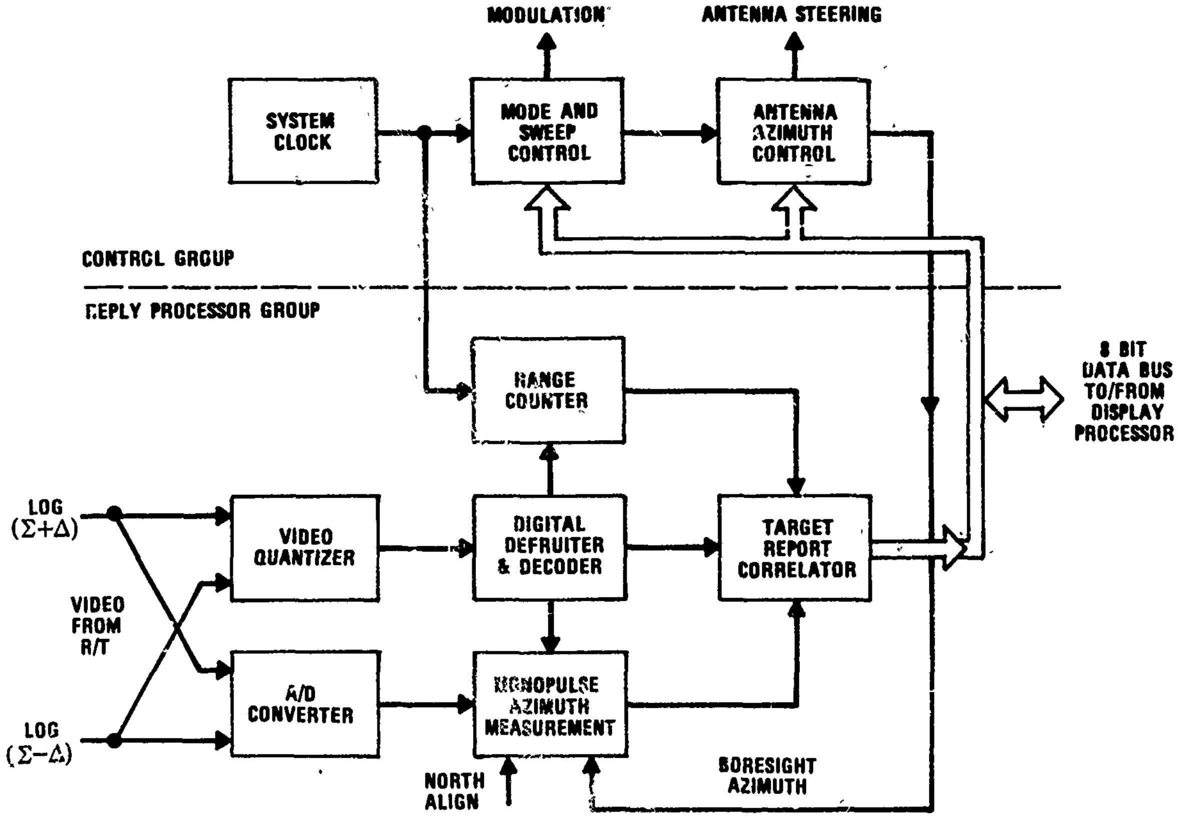


Figure 8. Block Diagram of Interrogator Control and Reply Processor Subsystem

Control Group

The interrogator control group is essentially a programmable interrogator synchronizer. PRF, interrogation mode, and azimuth commands from the display processor are converted into real-time modulation, R/T, and azimuth steering commands which are fed to the antenna-R/T unit. The entire interrogation process is under program control and is totally flexible. In the brassboard model, manual control of the interrogation process and alphanumeric readout on four targets was provided for test and evaluation purposes.

Reply Processing Group

Input Video is processed into a digital target report consisting of target identity (ID) code, range, and azimuth in modes 2 and 3. ID includes the identify position (I/P) reply signal via Special Position Identification pulse when present. In mode C, Gray code altitude data is decoded to numeric in the Bendix display processor.

In operation, the sum beam signal is reconstructed by adding both video inputs. This video is then quantized using an adaptive threshold which slices the video 6 dB below the peak. Digitized reply code data is defruited in a digital defruiter using previous sweep data for reference, then decoded in the digital decoder. Simultaneously, the videos are subtracted to develop the monopulse "S" curve shown in Figure 9. Following leading edge detection in the quantizer, an encode command is passed to the analog-to-digital (A/D) converter. If the monopulse video level is from a target within the desired reply zone, approximately ±8.5 degrees, the video signal is digitized into an angle off boresight measurement. This is added to boresight alignment and north align to give an azimuth report. If, however, the monopulse level is outside the valid range, the azimuth data is deleted. Based on P3 transmit time, the range counter increments and a valid bracket decode is tagged with range and azimuth in the Target Report Correlator.

In mode C, correlation in range and azimuth must be associated with a previous valid ID report to be qualified as acceptable. All bracket decodes which result in a correlated target report are output to the display processor in near real-time, i.e., prior to next sweep.

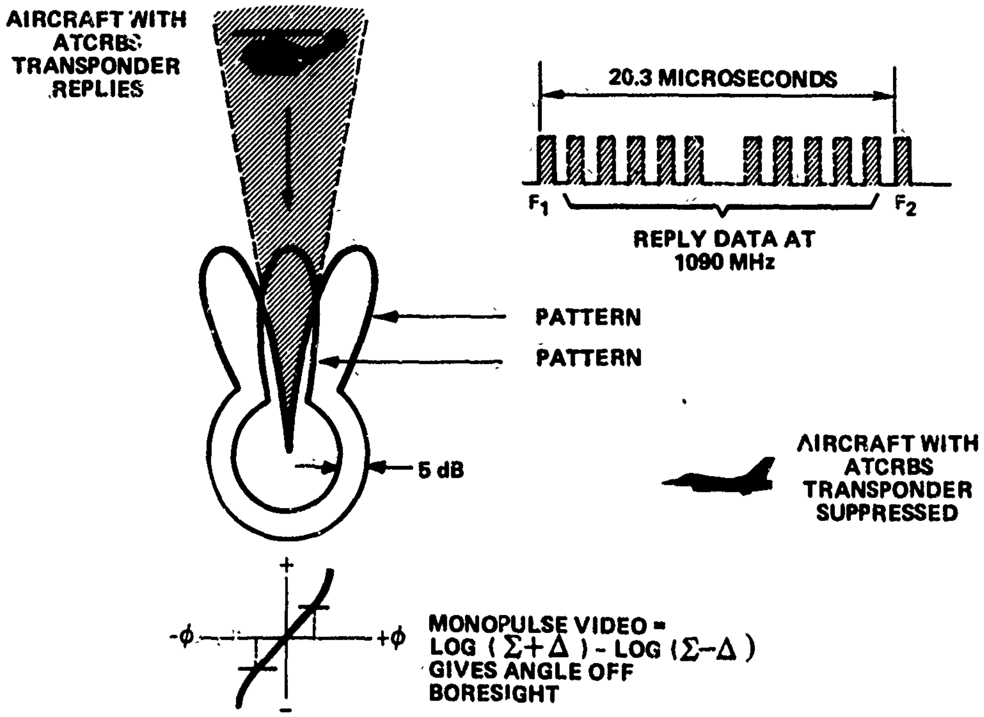


Figure 9. ATCRBS Reply Waveform and Resulting Off-Boresight Monopulse Video Characteristic for Electronic Scan (VLATME)

INTERACTIVE DISPLAY

The initial Army procurement of the Electronic Scan VLATME was for concept evaluation of the antenna system. Operation was in search only with rudimentary reply processing and numeric readout of range, azimuth, and elevation only on selected ID's. Bendix concurrently developed an interactive display on IR&D funds to evaluate the full potential capability of an Electronic Scan VLATME. Subsequently, the Army purchased an improved 100 target display and processing system which was recently completed and is currently undergoing factory test trials.

The display processor subsystem is a multi-microprocessor design driving a plasma discharge panel display. The display with associated operators control panel is shown in Figure 10. Display viewing area is about 8 inches by 8 inches and has a resolution of 64 pixels to the inch. It has sufficient brightness for daylight operation and a map can be mounted behind the transparent viewing face to allow the tracking information to be superimposed onto the map.

The control processor employs three microprocessors in a multiprocessor configuration. One performs search and track functions with shared main memory; another handles I/O and interrupts; and the third performs display interfacing. All programs are in firmware such that the only operator programming interaction is to actuate the power on/off switch. System self-test is performed on all processor subsystems at turn-on, and the antenna-R/T Built-in-Test is monitored continuously with readouts on operators control panel, Figure 11. To provide maximum flexibility in utilizing such maps as may be available for ATM, display scale factor and origin are infinitely variable within system limits (scale factor - 1.00 to 15.00 km/inch). The interrogated region is selectable, either full 360 degrees or any sector where the boundries are formed by two radials on 5.625 degree increments (from north).

Since the interrogator is fully under program control, the search and active track algorithms may be optimized to provide desired target data rates while minimizing PRF. Further, search is accomplished in the ID modes 2 and 3/A (programmable six-step interlace sequence) with altitude data requested via mode C interrogations only on targets under track.

A single ATM operator can handle only a limited number of targets and to minimize display clutter, only priority traffic (operator inserted track list by ID, 13 maximum) is provided with an ID and altitude data block on the PPI. However, all targets (up to 100) are displayed as target symbol only to provide the ATM operation with sufficient information to anticipate potential conflicts. Any target may be identified using the joystick cursor and entered in the priority list if desired. Accurate range, azimuth, elevation and a track status report (current, in search-priority ID track not yet acquired, track coasting, and dropped track -- last reported data shown) is displayed by simply requesting ID (four digits): DATA. Additional features are described as follows.

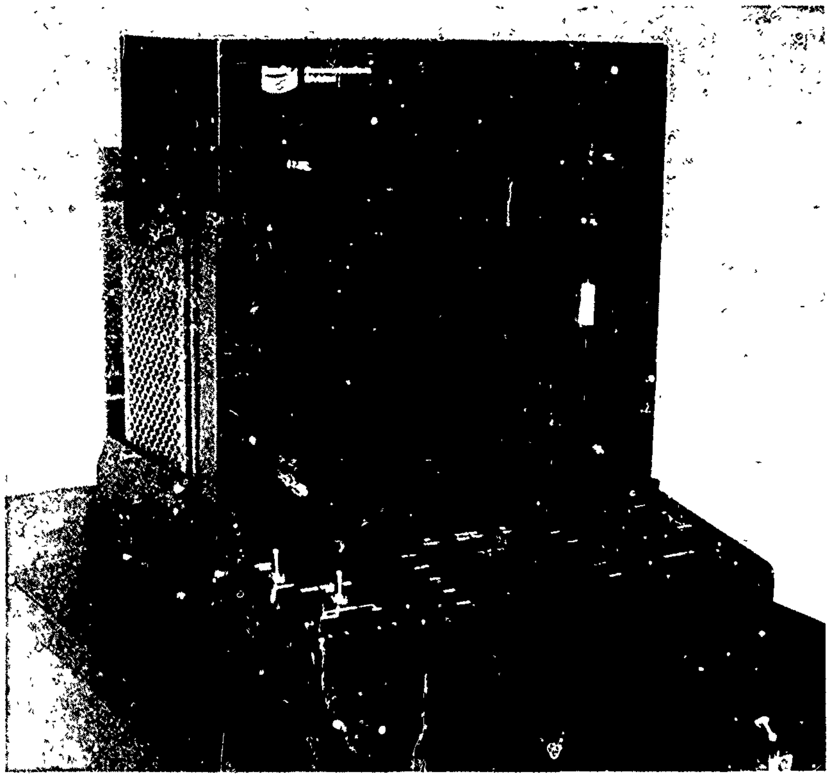


Figure 10. Photograph of the Microprocessor-Driven Plasma Discharge Display and Operator's Control Panel

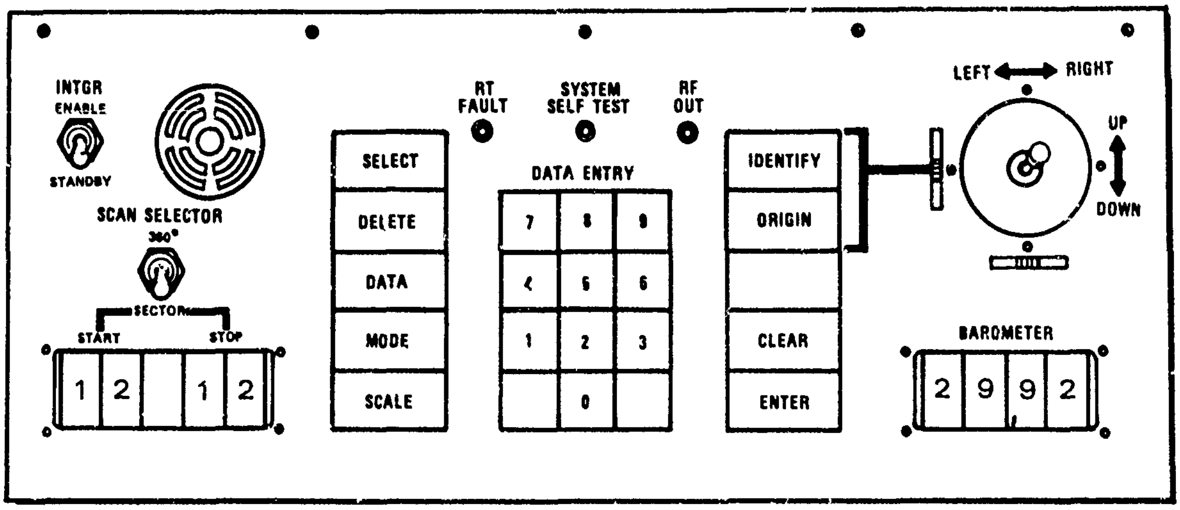


Figure 11. Operator's Control Panel for the Air Traffic Management System Used with the Electronic Scan VLATME

E-SCAN VLATME SYSTEM OPERATION

After the antenna-R/T unit is mounted on an appropriate standard Army crank-up tower, control cables connected between units, antenna erected, and 24 VDC power provided, the system is immediately operable. The antenna may be erected without regard to north alignment which can be accomplished electronically with switches on the Control and Reply Processor unit. North calibration is then accomplished (after ATM operation data is entered) using an aircraft fix on a known location, etc.

Inputting ATM Operational Data

At start-up, site dependent operational data must be input to the display processor if the system is to be used most effectively, particularly if a map (rear projection or overlay) is to be used. Otherwise, a standard set of default values are automatically inserted. In this case the track list is established as the first 13 targets acquired. These data/parameters input via the control panel may be verified on display readout prior to enter command. The start-up sequence is normally:

a. Scale factor: SCALE - four digits 1.00 to 15.00 km/IN - ENTER.

b. Origin positioning: ORIGIN - slew cursor to map location of operating point - ENTER.

c. Sector coverage: 360 degrees or SECTOR - Adjust sector radials using visual cueing from display. Asterisk displayed to indicate active sector.

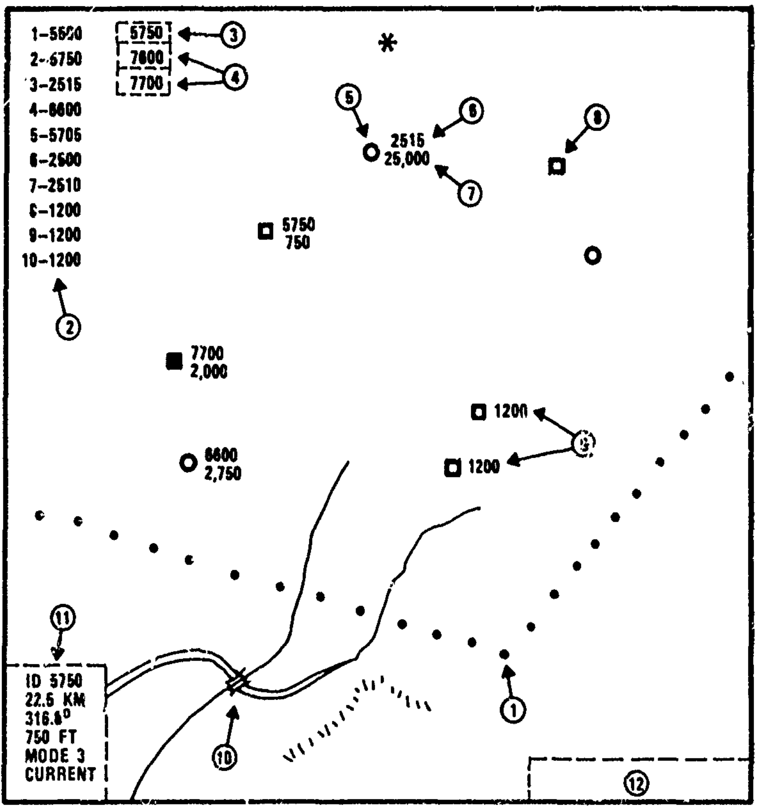
d. Barometer setting: Insert current local sea level pressure - inches of mercury.

e. Mode interlace: six step interlace - 2,3,2,3,2,3 typical.

f. Selected ID to track list: Priority or managed traffic ID (13 max.) from flight plan, etc., SELECT - four digit ID - ENTER.

g. Enable interrogator: ENABLE from STANDBY.

At this point the Electronic Scan VLATME is fully operational. Operation interaction is now limited to monitoring traffic with occasional track list ENTER and DELETE commands as handoffs are effected. Non-track listed targets may be identified if desired using the joystick cursor and IDENTIFY command. A typical operating system display is shown in Figure 12. Aircraft symbols are circles for mode 2 replies and squares for mode 3, Figure 12 note (3). A flashing solid symbol indicates that aircraft is signaling IDENT (Identify/Position). A non-flashing solid symbol is an emergency signal. Emergency replies (including mode 3/A 7600) are automatically inserted in the track list note (4) and an audible alarm sounds until muted. Multiple targets with common ID's are always displayed as target symbol but may be tracked by entering Multiple ID's in track list (13 max).



NOTES:

① ORIGIN AND SECTOR RADIALS (* = ACTIVE)
② TRACK LIST
③ SELECTED ID
④ RESERVED EMERGENCY
⑤ AIRCRAFT SYMBOL
  ○ = MODE 2 } FLASHING = IDENT
  ☐ = MODE 3/A } SOLID = EMERGENCY
⑥ ID CODE
⑦ ALTITUDE-WHEN AVAILABLE
⑧ UNDESIGNATED CODE AIRCRAFT (MODE 3)
⑨ MULTIPLE NON-DISCRETE MODE 3 AIRCRAFT
⑩ MAP (BACKLIGHT OVERLAY)
⑪ DATA BLOCK ON SELECTED ID
⑫ KEYBOARD ENTRY VERIFY BLOCK

Figure 12. Typical Display of An Air Traffic Management Situation

TEST PROGRAM

Initial antenna range system and flight tests of the E-Scan VLATME system which were run in October 1978 in the Baltimore area were very encouraging, and basic systems accuracies were validated.

During 1979 the Electronic Scan VLATME was upgraded to a fully configured VLATME system. The hardware modifications are complete and system tests are underway. Following completion of factory flight test trials, U.S. Army AVRADA is to undertake a validation test program. This is planned to consist of flight tests at the FAA NAFEC test center and subsequent field trials in conjunction with military exercises.

A production version of the Electronic Scan VLATME is expected to have the features described above in the following configuration:

Weight: 39 kg total

Volume: .025 m^3 total

Power Required: 150 watts

Packages: 2 (Antenna-R/T and Processor/Display).

TECHNICAL AND OPERATIONAL FACTORS CONCERNING THE LICENSING AND INTRODUCTION OF A NEW MICROWAVE LANDING SYSTEM FOR CATEGROY II

by

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SUMMARY

The conventional Instrument Landing System (ILS) with its ground components localizer, glide path and marker beacons, limits landing approaches to a straight line with fixed azimuth and elevation. New Microwave Landing Systems (MLS) consisting of the components azimuth, elevation and distance measuring equipment inherently allow a wide variety of approaches within the limits of coverage including curved profiles in the horizontal and vertical coordinates. For the new aircraft Tornado and Alpha-Jet, the new landing system SETAC is now being prepared for category II service at the assigned air bases in Germany. As soon as this system's technical capabilities are to be exploited to the full extent for operational use, all relevant rules and regulations applicable for ILS category II operations must be exhaustively expanded and supplemented. This concerns new concepts for infrastructural measures, such as extension of obstacle clearance limits to the whole area of coverage, calibration and testing of the total radio field, modifications of the approach light pattern, additional training and licensing of ATC staff and pilots etc.

In order to reduce this extensive task to a short-term solution, this paper outlines a stagewise procedure of system introduction. The concept is to utilize SETAC equipment with all the corresponding advantages regarding installation, but to retain in the first stage as closely as possible all regulations, flight procedures and instrumentation pertaining to ILS approach and landing. Only after this first stage of transition has been verified in practice, the more sophisticated possibilities of the new MLS will be envisaged for operational use.

1. USER DEMANDS

1.1 Aerodromes

In connection with the introduction of the new aircraft generations Tornado and Alpha-Jet into the German flying forces the desire for all weather operations down to category II visibility conditions (400 m runway visual range and 30 m decision height) has become urgent. The aerodromes to be equipped with corresponding landing systems are shown in fig. 1: solid disks represent the Tornado wings of the Air Force, while the Navy Tornado wings are marked by circles. The aerodromes of the Alpha-Jet wings are depicted as solid squares.

Installation of new ILS category II performance facilities would be cumbersome and, especially for the military airfields, sometimes impossible. Therefore, the terminal guidance and landing system SETAC, which has been developed since 1970 according to the requirements of NATO Air Force Armaments Group, Section AC 224, Subgroup 7 /1/, is now being prepared for introduction at the aerodromes mentioned so far.

A similar demand exists for the other Air Force wings flying Phantoms, Transalls, and UH-1D helicopters and the remaining Navy wings flying Seaking helicopters and Breguet Atlantic maritime patrol aircraft (solid and transparent triangles in fig. 1). Finally, some supporting units are possibly to be equipped, too (inverted triangles).

1.2 Continuous Distance Information

The conventional ILS provides distance information only at those two or three discrete points where the marker beacons are installed. Fig. 2 indicates the nominal location of the outer marker (OM) at 3.9 NM, the middle marker (MM) at 1050 m and the optional inner marker (IM) at 350 m from the threshold. At the nominal glide path angle of 2.5° these points mark three special values of height above runway, i.e. 1000 ft, 60 m and 30 m, the latter indicating the category I and II decision height respectively.

These markers require installation outside the airfield, and the ideal site is not always available. Therefore, precision distance measuring equipment (PDME) is required by NATO to avoid this problem and to provide the following functions /1/:

1. Continuous indication of distance to threshold or touch down point:
   In fig. 2 it is apparent, that since distance is measured with respect to the azimuth station at the stop end of the runway, the runway length D1 must be subtracted from the measurement to obtain distance to runway threshold. Likewise, the separation D_2 between azimuth and elevation stations must be subtracted to obtain distance to touch down point.

These differences are vector valued, whenever the aircraft is at higher elevation or off the extended runway centerline.

2. Continuous indication of height above runway:
This parameter can be computed on board from the distance to touch down and the measured elevation angle.

Additional functions required by NATO implying precision distance measuring equipment are illustrated in fig. 3. They are:

3. Continuous indication of rollout distance to the stop end of the runway.

4. Coordinate conversion of area navigation type, e.g. to convert the values of azimuth and distance, that are measured with respect to the azimuth station at the stop end of the runway, to equivalent data referenced to a phantom station where an offset straight approach course intercepts the extended runway centerline.

5. More generalized functions of coordinate conversions that are required for curved approaches in three dimensions.

6. Finally, DME is needed to reduce the response senstivity of the aircraft's lateral and vertical control channels to azimuth and elevation deviations. As demonstrated in the lower right hand part of fig. 3, a constant lateral deviation Δx corresponds to growing azimuth deviations as the aircraft closes in. The corresponding rise in gain in the lateral control loop promotes instability and is therefore undesirable. During ILS approaches this effect is barely noticeable since the equivalent characteristic, i.e. the difference in depth of modulation (DDM), saturates beyond the course sector of ±3° in the lateral direction and beyond the glide path half sector in the vertical direction. With MLS however, the destabilizing influence is fully effective due to the pure linearity of the azimuth and elevation characteristic throughout the whole range of coverage. A particular algorithm is necessary to artificially saturate the deviation signals before feeding them to the aircraft's lateral and vertical control loops. This is sometimes called "beam softening".

1.3 Volumetric Coverage

If the landing system is to supply continuous three-dimensional approach guidance information in a given space, all three system components, i.e. azimuth, elevation and distance measuring equipment, should have the corresponding common volume of coverage.

Fig. 4 shows this volume according to the NATO requirement for an advanced approach and landing system /1/. The upper part of the figure is a vertical slice of the approach sector cut along the extended runway centerline. The lower part shows one half of the symmetric projection of the approach sector on the horizontal plane.

The heavily shaded areas represent the minimum level of service: from 1° to 5° in elevation, out to a distance of 10 NM and ±20° in azimuth. The lightly shaded areas indicate the nominal requirements as far as common coverage of all components is considered. The hatched areas show the additional nominal coverage of the azimuth and precision DME components.

Three sets of lines in fig. 4 comprise the coverage provided by the SETAC landing system /2/. Dotted lines designate the coverage of the SETAC azimuth component, dashed lines mark the volume covered by the elevation element and solid lines depict the envelope of PDME availability.

The performance of SETAC lies well above the required minimum level and satisfies all but one parameter of the nominal requirement, i.e. horizontal coverage of precision azimuth. Note, however, that coarse azimuth guidance is served by the short range omnidirectional beacon (SROB) that is collocated with the precision azimuth station and has a 360° horizontal coverage out to 30 NM. The SROB signal has the conventional TACAN format.

2. SYSTEM CAPABILITIES

2.1 Accuracy

In the precision approach sector of the landing system very stringent requirements exist with respect to accuracy. In fig. 5 the specifications set up by the German Military Certification Authority /3/ are compared with the performance of the SETAC system. All accuracies are expressed in terms of 1-sigma values or 68 % probability boundaries.

The shaded boundaries show the maximum allowable tolerances, applicable for landing speeds of 105 kts (Tornado and Alpha-Jet) and glide slopes up to 4°. The same tolerances hold also for higher glide slope angles, but only in conjunction with lower landing speeds /3/.

In azimuth the requirements on the azimuth angle itself and on the deviation angle from a selected landing course are both 0.2° throughout the whole range of distance to touch down point down from 20 NM to 0.2 NM (logarithmic range scale in fig. 5). Note that at 0.2 NM (= 370 m), decision height is reached on a 2.5° glide slope. The corresponding performance of SETAC azimuth is shown by the dotted line, where below 1 NM only noise has been considered, while beyond 1 NM a bias term has been included.

The accuracy performance of SETAC elevation (dashed line) and precision DME (solid line) is evaluated accordingly and shown in the center and lower diagram of fig. 5.

The stated accuracies are available for a system capacity of 50 aircraft in the SROB (or TACAN) mode and of 15 aircraft within the landing sector /3/.

The accuracies are further applicable for approach speeds from 0 up to 250 kts, bank angles between ±45° and pitch angles from -20° (nose down) to +25° (nose up) /1/, /3/ as well as yaw angles between ±10° and pitch and yaw rates up to 2° per sec /3/.

2.2 Operational Aspects Concerning ILS and SETAC

A prominent difference between ILS and SETAC is the much larger angular range of precision guidance and the resulting higher operational flexibility of the latter. ILS allows straight-in guidance on a single fixed glide path only. SETAC provides volumetric coverage over a sector of ±23° in azimuth and 1° to 20° in elevation. A precision DME is collocated with the azimuth ground component forming together the SETAC-A station. The continuous availability of measurements of three independent coordinates allows the aircraft to determine exact three-dimensional position in the given coverage volume /4/.

SETAC also includes a digital data link with a gross rate of 2700 pulses per second, which reduces to a net capacity of 300 bit per second, the rest being used for data security purposes. Information transmitted to the aircraft includes:

- Azimuth of runway centerline referenced to magnetic north
- Distance between SETAC-A and SETAC-E stations
- Angle formed by the runway centerline and the line of sight between SETAC-A and SETAC-E stations
- Lateral distance of SETAC-E station from runway
- Other data such as status of aerodrome, metereological and tactical information etc.

The performance of both localizer (VHF) and glide slope (UHF) of ILS is adversely affected by local terrain irregularities and bad weather conditions, while SETAC, operating at ca. 1 GHz and using different physical principles is insensitive to these factors /5/.

For SETAC the components of ground equipment are more compact, their number is less and antenna sizes are considerably smaller as compared to ILS. Thus, mobility of the landing system is realized.

Since the signal format of the SETAC azimuth and distance information is based on TACAN, the on-board receivers for TACAN and SETAC share the corresponding equipment, the only additional units for SETAC being a control panel and an interface uncluding the elevation circuits and a computing capacity.

2.3 Feasible Approach Patterns

The large volumetric coverage provided by SETAC opens up a vast potential of operational benefits. It permits, for instance, the on-board selection of optimum approach paths for any type of aircraft, see fig. 6. Curved approaches such as in the upper diagram of fig. 6, with only a short straight final leg along the centerline can provide noise abatement, increase airport capacity, and reduce the time of the total approach /6/.

However, the realization of theoretically feasible advanced approach patterns is limited by numerous technical, operational and regulatory constraints, some of which are briefly mentioned here:

Taking into account aircraft performance and cockpit-crew activities, the length of the centerline final approach should be at least 3 NM.

The final glide path angle should be less than 3.5° based on the maximum tolerable rate of descent and the minimum thrust setting with respect to wind-shearing effects and missed approach procedures /7/. Besides that, if the approach lighting systems to be used are of conventional type, the maximum final glide path angle is additionally constrained, because these systems have their 50-per-cent-intensity limits at an elevation angle of 5° according to ICAO Annex 14 /8/.

Moreover, the capacity of airports is inversely proportional to the average longitudinal separation of aircraft, which is most easily optimized under present ATC procedures with a straight-in final approach. A multitude of selectable curved trajectories would require computer aided procedures for approach control.

Finally, fixed obstacle clearance surfaces as well as noise protection zones defined by current regulations confine the variety of new approach procedures considerably. Usually, the construction around an existing airport has already grown in adaptation to the conventional approach patterns, with the minimum of buildings and obstacles essentially along the extended runway centerline. Therefore it is often impossible to find new horizontally curved final approaches that bother the environment less than the old straight ones.

It seems that for existing aerodromes the most promising possibilities for new approach patterns exist in the vertical plane (see fig. 6, lower diagram).

3. CONDITIONS FOR LICENSING THE SYSTEM TO ITS FULL CAPABILITY

3.1 Airworthiness System Requirements

The total approach and landing system consists of interacting ground and airborne components. Furthermore, the on-board components interface with other avionic equipment, especially flight and navigation instruments and possibly the autopilot with or without a flight guidance unit for non-straight-in approaches.

Accordingly there exist two airworthiness requirements: one for the airborne segment /11/ and the other for the total system operation including the characteristics of ground stations and signals in space /3/. The latter requirement has been developed from the NATO AC/224 document and from national Air Force needs while taking into account ICAO specifications and national guidelines with respect to conventional category II landings. The resulting MLS system airworthiness code covers the performance with respect to the following functions:

- 2D coarse guidance with SROB and PDME (TACAN mode)
- 3D precision guidance in the landing sector (APPROACH-mode), distance referenced to touch down point
- Missed approach and rollout guidance with TACAN mode, distance referenced to runway stop end
- On-board selection of glide path angle
- On-board operation of TACAN and APPROACH modes including proper transition back and forth
- On-board warning modes
- Mutual compatibility with other on-board equipment
- Other requirements (ground and on-board environment, reliability, time to readiness for operation etc.)

These characteristics have to be verified during the licensing procedure. While in some cases theoretical proofs are allowed, the main load rests on flight tests including calibration flights for signals in space performance.

3.2 Infrastructural Aspects

Infrastructural requirements for instrument approaches are essentially expressed in terms of obstacle clearance, especially for the final and missed approach area, see e.g. the German Air Traffic Law or ICAO Annex 14 /8/.

For ILS Cat. II the obstacle clearance surface (OCS) is shown in fig. 7 by the hatched areas. It covers horizontally a sector of ca. ±8.5° to both sides of extended runway centerline, see lower part of fig. 7. The sector expands from about the runway threshold out to a distance of 12.8 NM. From here, out to 15 NM the sector is complemented by a rectangular area with a width of ±2.0 NM. Within this total area the terrain may rise with a gradient of 1:50 out to a distance of 10 000 ft and with a gradient of 1:40 beyond /8/, see the upper part of fig. 7.

If the difference area between ILS course sector (±3°) and obstacle clearance sector is considered as a constant tolerance, which carries over to SETAC, one has a way to conceive an OCS for SETAC. Assuming further that the final approach beginning at about 3 NM from the threshold is identical to ILS, the OCS for SETAC in the horizontal plane should then be modified to coincide with that of ILS in this region. The resulting OCS is about 3 times larger for SETAC than for ILS, see lower part of fig. 7.

In the vertical plane the OCS is derived from the lowest assumed descent path which is 0.625 θ for cat. II. Since the lowest admissible value for the nominal glide path angle θ is the same (namely 2°) for ILS and SETAC, the requirements for OCS are assumed to carry over without changes.

3.3 Calibration of the Total Radio Field

For ILS both the course sector and the glide path sector are defined in terms of difference in depth of modulation (DDM). The course sector of the localizer is centered about the course line (DDM = 0) and is bounded in azimuth by the lines where the DDM = ±0.155. The glide path is the line in the vertical plane containing the runway centerline where the DDM is zero, while the glide path sector is given by DDM = ±0,175.

Linearity of the DDM-function is specified for the localizer in the full course sector and for the glide path in the half sector (defined by DDM = 0.0875). For a typical configuration these linearity ranges correspond to ±3° in azimuth and between 2.2° and 2.8° in elevation /9/, /10/, see fig. 8. For the calibration of these linear parts 7 measuring points on each curve seem to be adequate: for the course sector in steps of 1° and for the glide path half sector in steps of 0.1°. This results in a total number of 7 x 7 = 49 different straight-in approaches for flight inspection.

For SETAC the variety of operational approach paths depends essentially on the on-board equipment. The prototypes for Tornado feature selectable approach courses between 0° and 359° in steps of 1° and glide paths between 2.0° and 19.5° in steps of 0.1°.

Considering the azimuth sector of ±23° and subtracting from this a tolerance of ±3° this results in a total number of 41 x 175 = 7175 operational nominal straight-in approach paths for SETAC as compared with the single glide path of ILS. The necessary number of calibration flights is slightly larger, since the tolerance areas have to be covered, too. The resulting number of flight inspection paths is 47 x 190 = 8930. This calibration effort would be about 200 times larger than for ILS, although it is anticipated, that the inspection procedure is necessary only once at the initial commissioning of the facility.

4. STAGES OF SYSTEM INTRODUCTION

The problems of existing infrastructure, limitations of calibration expense, reluctance to install more than the minimum amount of additional on-bord equipment and the missing experience with flight operations using unconventional approaches have led to the philosophy of system introduction in successive stages of ascending complexity:

1. Copy as closely as possible the conventional ILS cat. II approach while utilizing SETAC equipment instead of ILS equipment. In particular, retain the straight glide path at nominal 2.5° along the extended runway centerline.

   This first stage reflects the priority of immediate cat. II operational capability above more complex approaches.

2. Generalize in the vertical plane by admitting straight glide paths at variable angles, which in case of SETAC are selectable on board the aircraft and which may be different depending on aircraft type.
   Particular points to be considered are:

   - Vertical speed
   - Vertical angular range of approach lights
   - Relation between threshold height and touch down point
   - Relation between decision height and runway visual range.

   For glide path angles higher than 4° it is probable that new definitions for landing minima and other parameters have to be elaborated.

3. Generalization in the horizontal plane is expected to be more cumbersome due to the existing infrastructure which has grown according to the valid législation tailored to ILS. A possibility would be to admit offset straight approaches which intercept the extended runway centerline at a point outside the equivalent position of the present outer marker. Piecewise linear flight paths and a centered final approach leg from outer marker distance to threshold are deemed necessary if the approaches are to be flown manually.

4. The next stage would be to allow curved profiles in azimuth and elevation in the whole range of the three-dimensional landing sector. This class of approaches cannot be flown without an approach guidance computer unit.

5. The last and final stage covers the complete potential use of the mobile version of the system during approaches to tactical landing sites such as highways or temporal runways.

5. OUTLINE OF LICENSING PROCEDURE FOR STAGE 1

For Stage 1, i.e. approximation of conventional approach and landing, the licensing requirements can be deduced and extrapolated from ICAO and German civil requirements for ILS category II operations. This way, an exhaustive set of licensing requirements has been established by the Commissioner of Type Testing of the Procurement Office /3/, /11/.

5.1 System Segments at Stage 1

In the licensing process, the three basic system segments are:

- Aerodromes with SETAC ground facilities and other necessary components such as approach and runway lighting, meteorological sensors etc.

- Aircraft with SETAC on-board equipment and complementing avionics and

- Air crew.

These segments have to be certified for cat. II performance first separately, and then in conjunction (fig. 9).

According to the airworthiness code /11/, at least three different ground facilities are required for system licensing.

A minimum of 300 approaches down to 30 m decision height have to be flown for each aircraft type to be rated for category II. Since not more than 60 % of the flights may be performed by the same aircraft, it follows that at least two aircraft of the type in question are needed.

Similarly, an individual pilot must not fly more than 15 % of the approaches, so that at least 7 pilots with category II rating are involved.

5.2 Contributing Agencies

The arising tasks are accomplished in cooperation by a number of interacting agencies in government and industry (fig. 10).

The Air Force Staff of the Defense Ministry represents the user and formulates their demands in the form of tactical requirements.

The Air Fleet Command operates the aircraft wings and the associated aerodromes and is the primary unit to determine the sequence of bringing the system into operational service.

The Armed Forces' Office of Flight Safety establishes rules and regulations in correspondence with its civil counterpart, while their common Flight Inspection Agency in Landsberg is in charge of periodic re-inspection of the system after the first commissioning of the facility.

The Procurement Office issues the development and procurement contracts for the landing system hardware and associated equipment.

An important responsibility rests on the Commissioner of the Procurement Office for Type Testing of Aviation Equipment. This agency issues the airworthiness codes for the ground and airborne segments of the landing system and the specifications for the initial commissioning of aerodromes, aircraft type and complete system operation for the category II rating.

The Test Center Manching of the Procurement Office is engaged in the installation and testing of the necessary on-board avionic equipment in the test aircraft.

The main contribution by industry is due to Standard Elektrik Lorenz, the producer of the SETAC system. Auxiliary on-board equipment such as interface/adapter units and modifications of indicators are delivered by various other companies.

ESG has been charged by the Procurement Office with the coordination of the total effort.

5.3 Tentative Concept for Stage 1

Before elaborating the licensing program for stage 1, two important questions must be answered:

- Where to chose the three necessary aerodromes?
- Which type of aircraft is to be used for the first step of stage 1, the basic licensing of the system?

In principle, these two questions are interrelated in the sense that each operational aircraft wing flies a uniform aircraft type and is - with one exception (MFG 5 with Seaking) - stationed at one single home base. Another factor is the problem of simultaneous availability of the aircraft types and SETAC ground facilities. Furthermore it can be troublesome to execute the vast testing effort at an operational air base in parallel with the daily flight routine, especially when the wing is fully occupied with switching from, say F-104 to Tornado.

Therefore it was decided to decouple the procedure for basic system licensing from the introduction into operational service at the various wings. As test aircraft the C-160 Transall transport aircraft has been chosen for reasons of immediate availablity and suitability as carrier for additional registration equipment. Furthermore, the C-160 pilots are familiar with ILS category I operations and need only relatively little additional training for cat. II. The fighter pilots on the other hand, have to switch to the new landing aid from ground controlled approach (GCA) procedures.

A tentative concept for the first three steps of stage 1 is outlined in fig. 11. The candidate aerodromes that are being considered for basic system licensing (step 1) are primarily (solid lines in fig. 11):

- Test Center E61 in Manching
- C-160 Pilot's School at Wunstorf
- F-104/Tornado Weapon System School at Jever

The Weapon System School for Close Air Support, which has been in Fürstenfeldbruck for the G-91 aircraft, will probably be transferred to Béja, Portugal for Alpha-Jet training and is therefore not favored for test and calibration activities.

After basic SETAC certification has been reached with the test aircraft, the next two steps of stage 1 are the licensing of the operational aircraft types Tornado and Alpha-Jet. For this goal the procedure has to be repeated with two aircraft of each type and three suitable aerodromes.

Usually trainer versions of the new aircraft types are the first ones to be supplied.

In the case of Alpha-Jet, the first units are being delivered this year to Fighter Wing 49 in Fürstenfeldbruck. One possibility for step 2 would therefore be to equip this base with SETAC and use it for licensing, together with two of the aerodromes of step 1, e.g. Manching and Wunstorf (dashed lines in fig. 11). An alternative is to use directly the bases of Husum and Oldenburg of Fighter Wings 41 and 43, that will get Alpha-Jet from 1981 on.

The first Tornado series aircraft for Germany will be trainers for Navy Wing 1 at Schleswig-Jagel in mid 1980. From 1982 [illegible] fighter-bombers are scheduled for this wing and for Navy Wing 2 in Eggebeck. Step 3 of the licensing program could therefore consist of using the Schleswig base in conjunction with Manching and Jever from step 1 (dotted lines in fig. 11).

Various other possibilities and aerodrome combinations are possible and the final choice can only be made after extensive consultations among the parties involved.

After these 3 steps, system licensing for cat. II landings with SETAC and type ratings for Alpha-Jet and Tornado will be realized.

The further steps are straight forward and consist mainly of one for one licensing of the bases in question. This holds, for instance, for the 4 fighter-bomber wings of the Air Force, of which wing Nr. 31 in Nörvenich will be the first to be supplied with Tornados in 1983.

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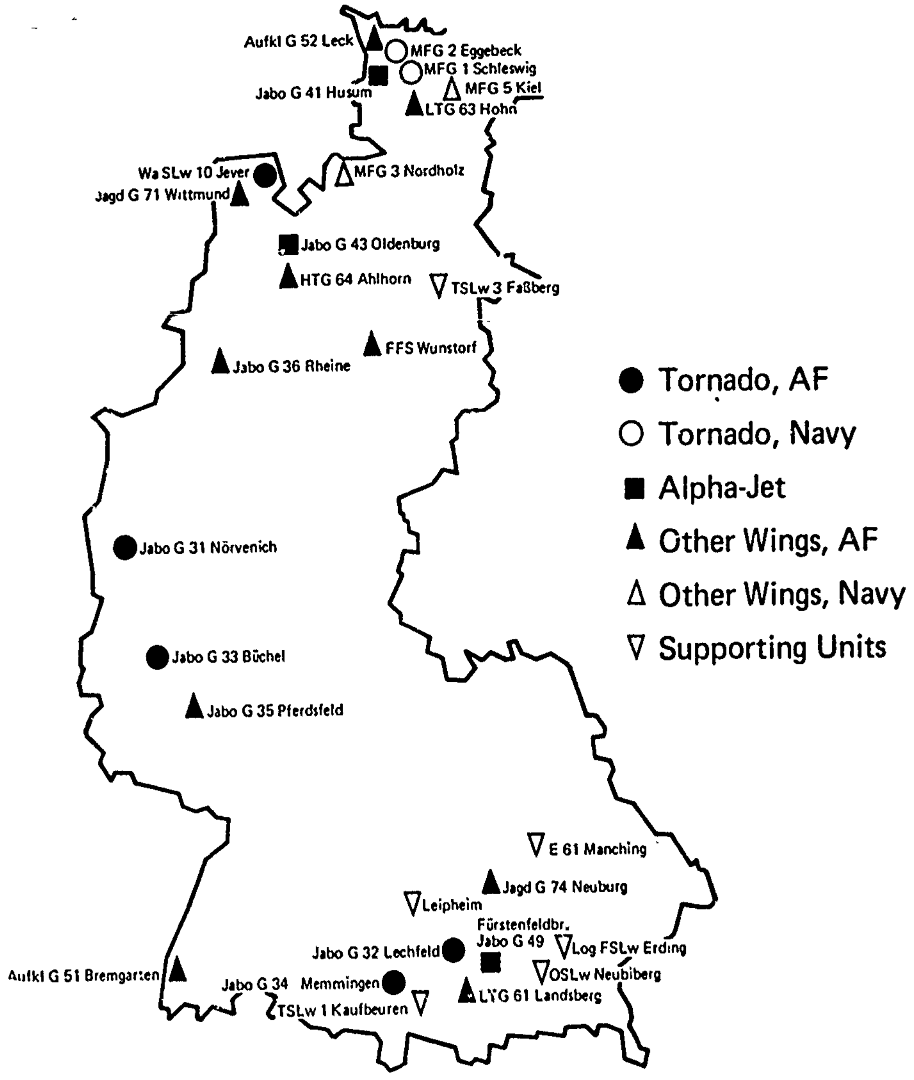


Fig. 1: Aerodromes

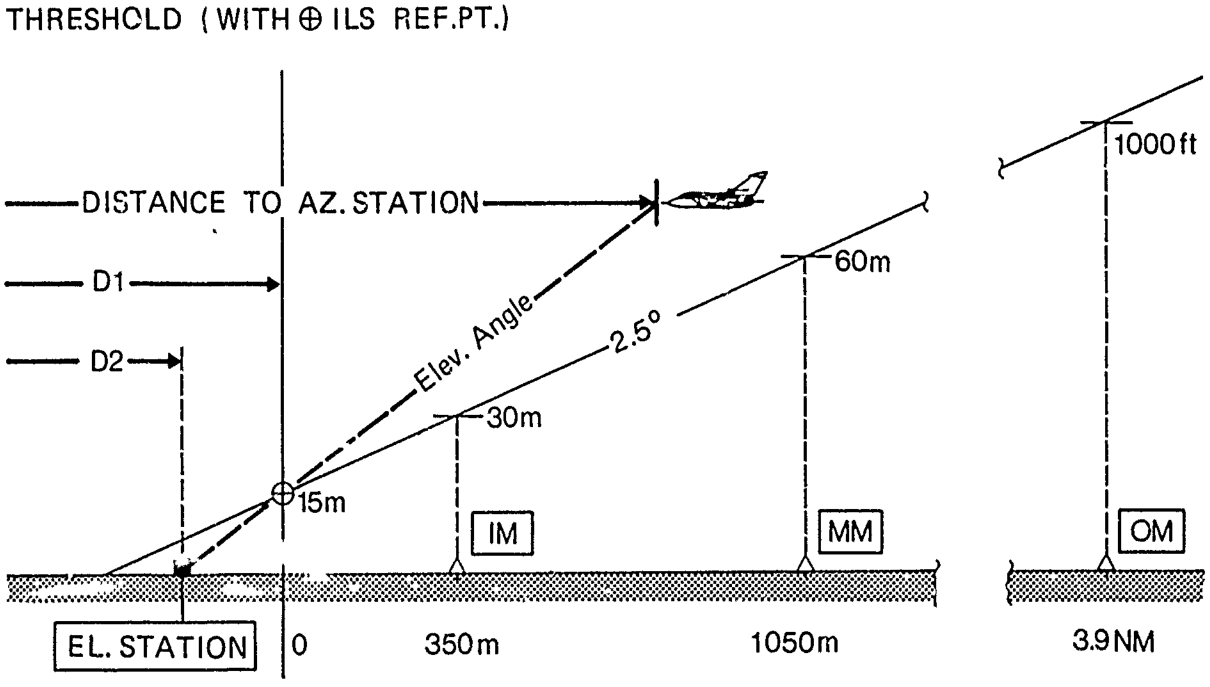


Fig. 2: Distance to Touch Down and Height Above Runway

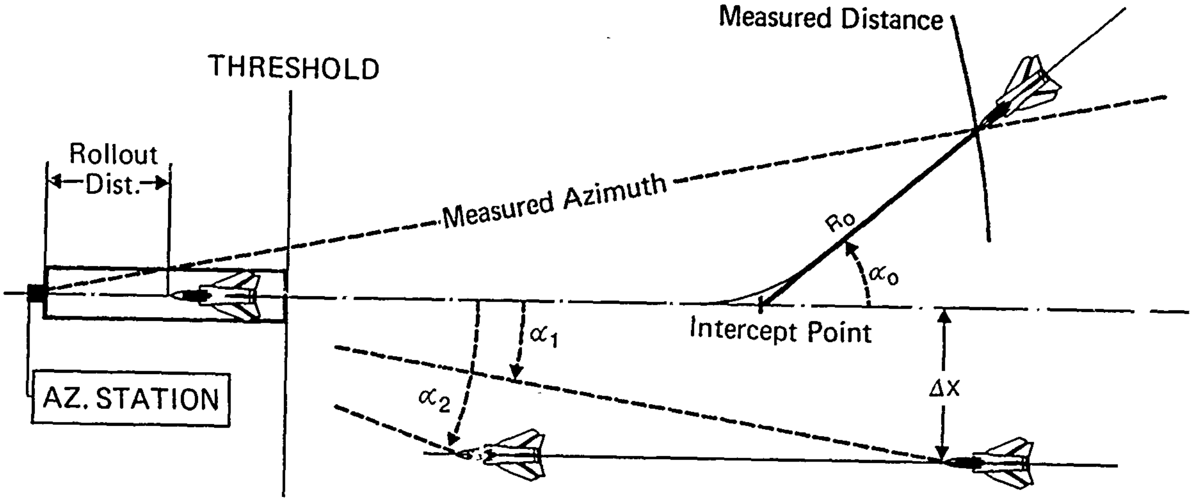


Fig. 3: Further Functions of PDME

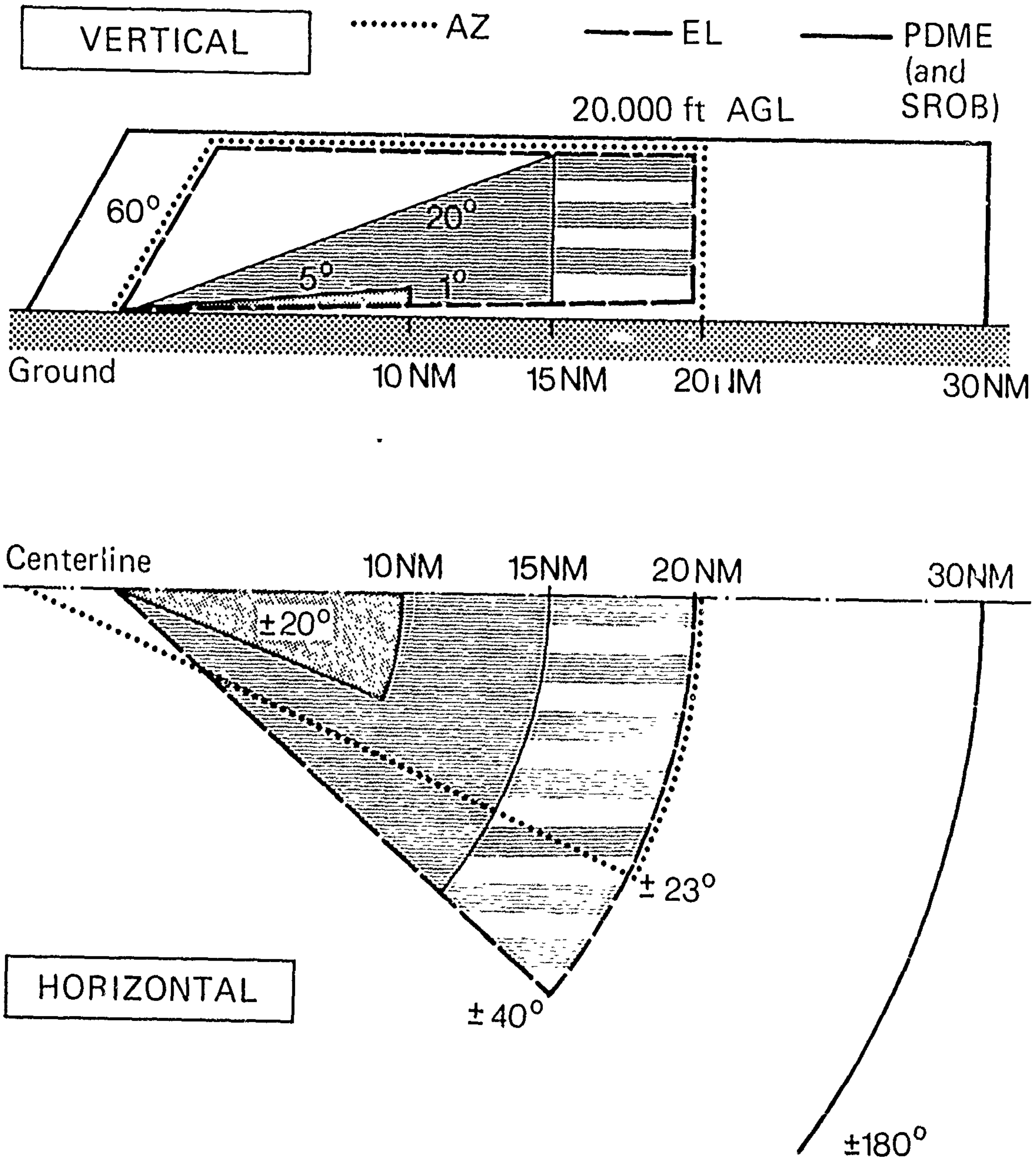


Fig. 4: Coverage

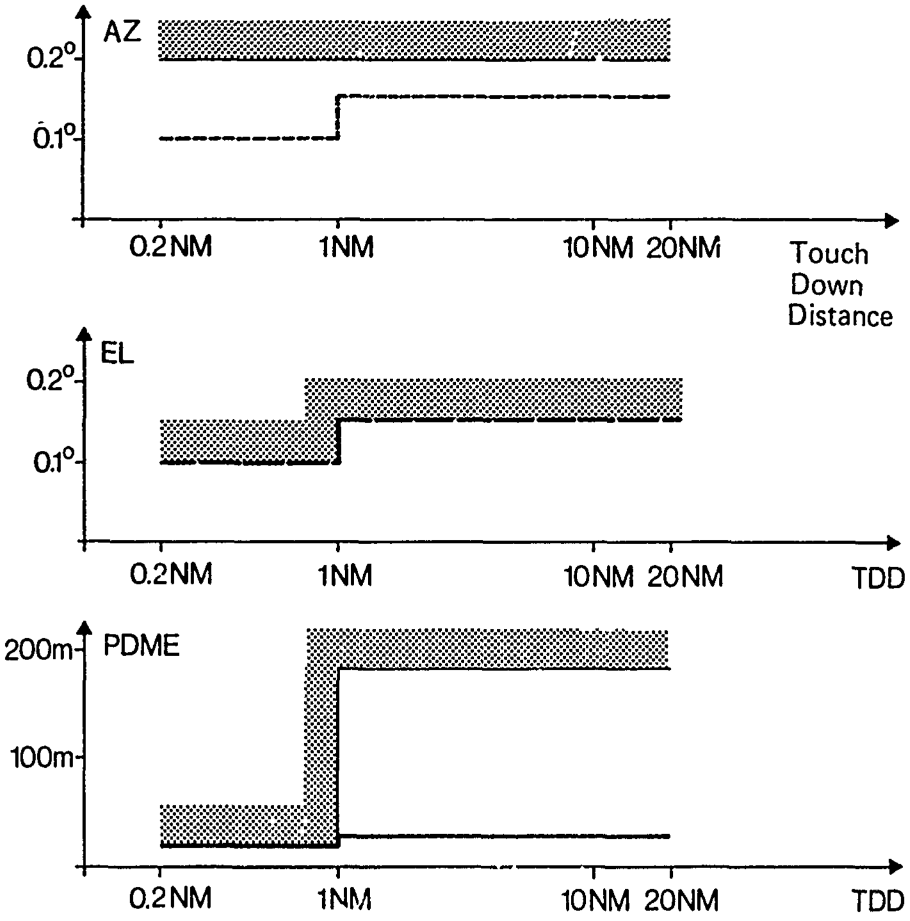


Fig. 5: Accuracy

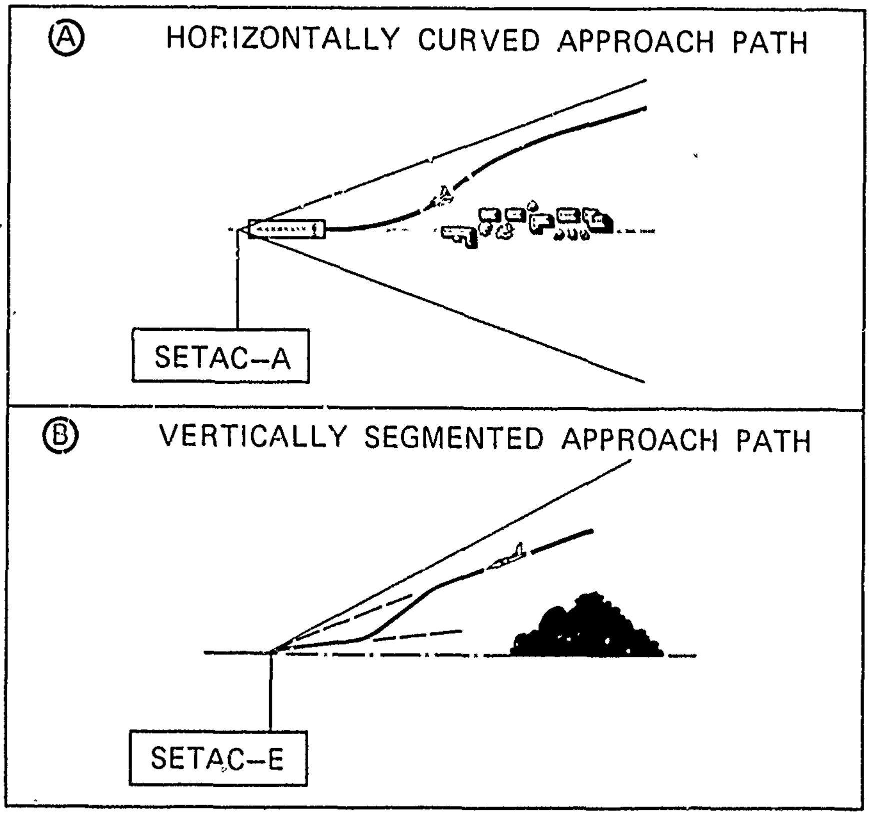
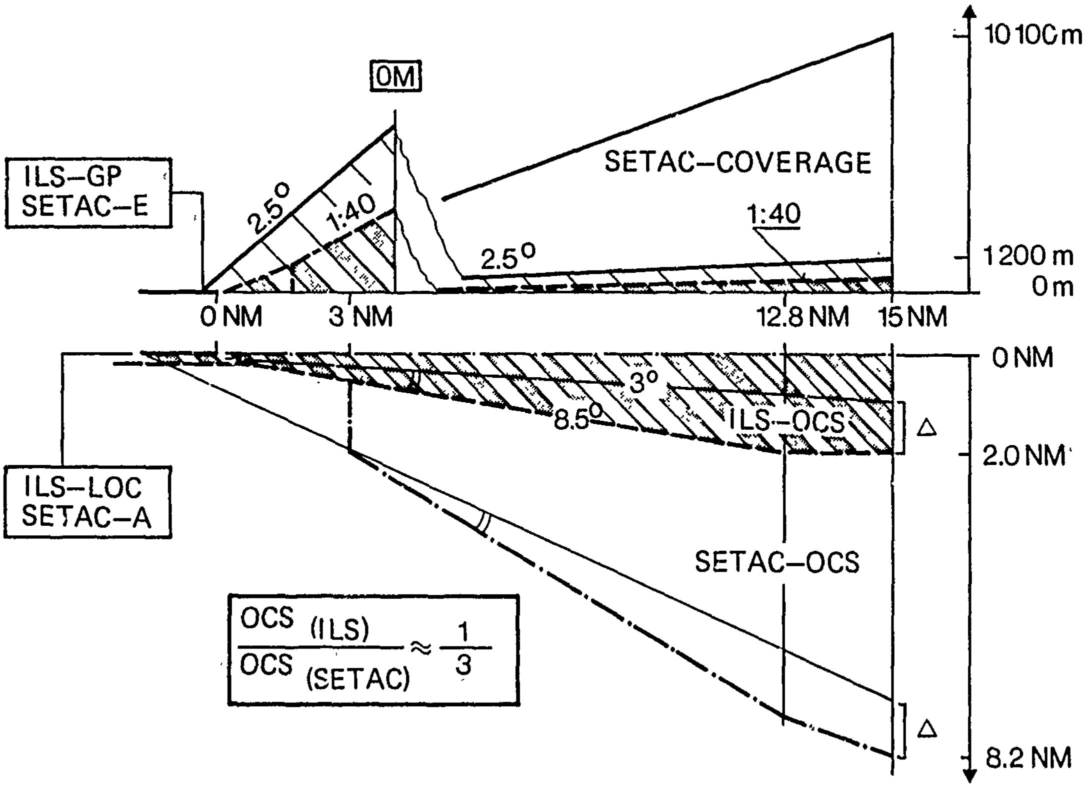
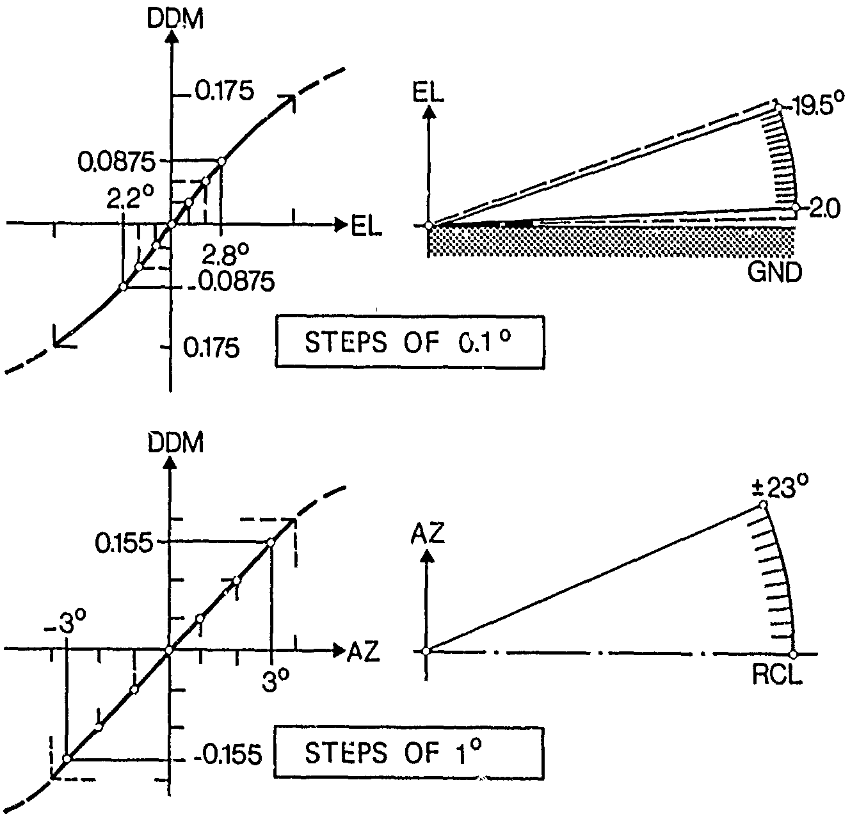


Fig. 6: Feasible Approach Patterns



$$\frac{\text{OCS (ILS)}}{\text{OCS (SETAC)}} \approx \frac{1}{3}$$

Fig. 7: Infrastructural Aspects



STEPS OF 0.1°

STEPS OF 1°

MEASURING PATHS: $\sum$ ILS = 7 x 7 = 49
$\sum$ SETAC = 47 x 190 = 8930

Fig. 8: Calibration of Total Radio Field

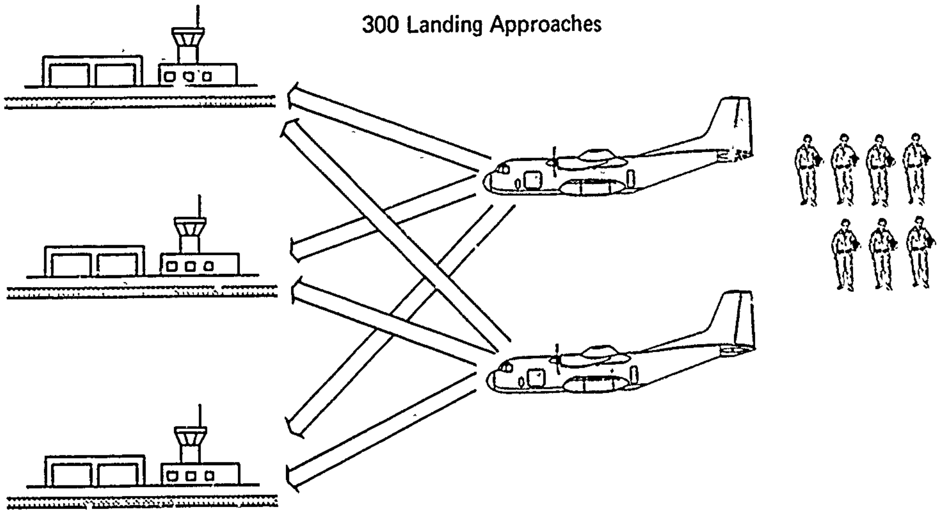


Fig. 9: System Segments at Stage 1

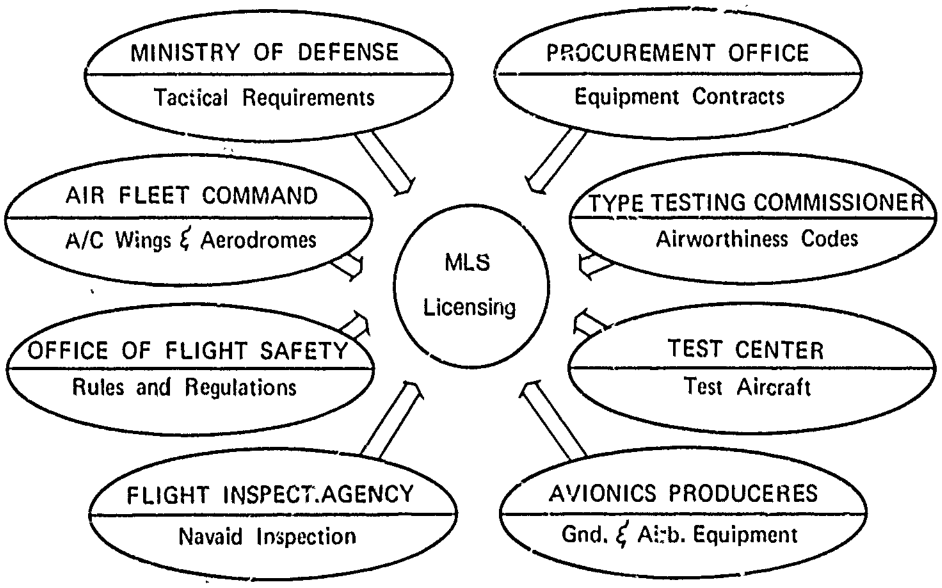


Fig. 10: Contributing Agencies

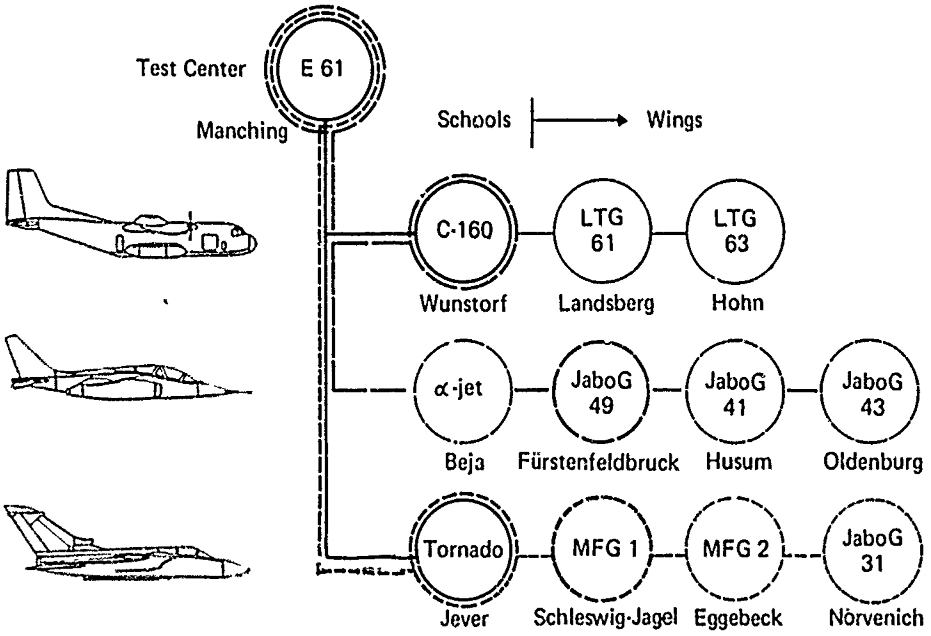


Fig. 11: Tentative Concept for Stage 1

THE INTEGRATION OF AREA NAVIGATION AND THE MICROWAVE LANDING SYSTEM

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SUMMARY

RNAV and MLS are non-competitive complementary navigation/landing systems that, working together, can markedly enhance the safety and efficiency of terminal area operations while at the same time impacting the overall concept of terminal airspace management. Primarily, these systems afford the opportunity, which has been debated so vigorously for many years, of converting to a distributed management philosophy of ATC system design and operation in which much of the navigation function is transferred from the radar vectors issued by the ground controller to the flight crew, aided by increasingly available, low cost, multifunction avionics systems. This paper has attempted to introduce some of these concepts and to indicate some activities on the part of the United States Federal Aviation Administration to develop and integrate these complementary capabilities into the terminal area airspace system.

I. INTRODUCTION

Recent advances in airborne and ground based hardware and software technology have opened the door to the potential for substantial improvements in the efficiency and safety of terminal airspace operations. The capabilities afforded by these new systems will allow for major restructuring of our current airspace management concepts to not only permit aircraft to operate over lateral routes and vertical profiles that are optimum in time and fuel for their particular configuration, but also to markedly reduce the overall cost of operation of the ATC system as regards controller staffing and productivity. This paper deals with some aspects of this situation as regards two major and interrelated recent developments, namely area navigation (RNAV) and the microwave landing system (MLS), from primarily the operational point of view. Current and projected programs to integrate each, and both, of these systems into the terminal area ATC will be described.

RNAV

The basic capability of Area Navigation is to provide course guidance along arbitrary, pre-defined routes without constraints, such as flying toward or over navigation stations, etc. The classic benefits attributed to RNAV are that, 1) it can provide more direct routings from one airport to another since it operates with fewer constraints, and 2) it can improve the efficiency of terminal procedures by virtue of the fact that radar vector procedures may be supplanted by published RNAV arrival and departure routes, which would be self-navigated. The end result is more efficient operations and reduced ATC controller workload.

RNAV provides the ability to program an arbitrary route. This can range in complexity from specifying a single waypoint over an airport and flying to it, all the way to preprogramming a departure route, the enroute phase, a terminal arrival route and an RNAV instrument approach procedure. This freedom and diversity brings with it a price which must be paid in terms of avionics cost, cockpit workload and data input blunder potential. RNAV operational problems and flight crew performance interact, in that higher avionics cost brings lower cockpit workload, etc., and so the system can be matched to the requirement and to the expected economic payoff.

To the ATC system, RNAV, on the surface, appears to complicate matters since new route structures will overlay existing routes (in the high altitude environment the existing structure would eventually be eliminated), and a "mix" of RNAV and conventional traffic will have to be tolerated. However, RNAV provides the potential for significant reductions in ATC controller workload, particularly in the terminal environment, through the substitution of self-navigated procedures for radar vector procedures, thereby reducing that aspect of the radar controllers' workload associated with providing navigational guidance.

The primary applications of RNAV to the terminal area are that it 1) allows airspace to be allocated to the various arrival and departure routings more efficiently, and 2) promotes self-navigation of the routes, therefore reducing controller workload by a considerable extent. In addition, the terminal controller's set of control options is further enhanced by such procedures as the delay fan and base-leg extension techniques, as well as the parallel offset and direct-to procedures. One of the advantages of the reduction to workload, besides the eventual impact on staffing requirements, is that the controllers are free to more carefully sequence the arrival traffic, resulting in improved capacity and reduced delays.

The usage of RNAV terminal routes also allows special routes to be designated to satellite airports in major hub areas. This reduces workload and may guarantee conflict-free paths to these minor airports. RNAV can also be used for defining IFR noise-abatement routes. These would avoid noise sensitive areas and would be designed to intercept the ILS (or narrow-beam MLS) approach course. Departure noise-abatement routes can also be implemented.

RNAV capability may also be used for conducting non-precision instrument approach procedures. Primary candidates for RNAV procedures are non-ILS runways at major airports, particularly when they are used extensively for GA and STOL operations, and primary runways at the many smaller airports which do not have ILS capacity.

MLS

Basically, the MLS is an air derived system, that is, ground stations will generate and transmit coded signals which will enable an airborne receiver/processor unit to derive its precise azimuth angle, elevation angle and range data. This data will be suitable for display to the pilot or for use by an automatic flight control system. In addition, provision is made for the ground-to-air transmission of auxiliary data providing runway identification, the condition of the runway, the operational status of the guidance system, and weather data.

An important feature of the MLS design is that of modularity whereby configurations having different levels of performance capabilities and costs can be adapted to satisfy the diverse requirements of various users. Because of this performance modularity, all airframe and ground based components of the system will be fully compatible with each other. This implies that in any particular operational situation, the service provided by any combination of a ground facility and an airborne unit is limited only by the capability of the less sophisticated of the two.

The coverage volume provided by the MLS is shown in Figure 1.1. Current plans dictate that azimuth coverage be provided within a 120° sector symmetric about the extended runway centerline (specific installations may offset the MLS axis of symmetry). The elevation angle ranges from 1.5° to 22° and the maximum DME range is 20 nm. The maximum altitude for MLS coverage is expected to be 20,000 feet. This coverage is adequate to support a wide variety of approach trajectories.

MLS position coordinates are defined with respect to a runway centered reference frame rather than the 360° north referenced bearing system of RNAV. Slant range measurement is similar to the slant range available from DME. The additional measurement, elevation angle, is a substitute for the altimeter. However, unlike the barometric altimeter, the MLS derived altitude is computed with respect to the ground independent of the local barometric pressure setting. The overall similarities in the types of measurements insures that a common form is appropriate for the basic guidance computations required of both RNAV and MLS. Both of the equation sets can be defined in terms of a waypoint referenced system.

Though similar in form, RNAV and MLS systems are not similar in function. MLS is primarily intended as a precision landing system to serve the guidance requirements of a high density terminal area. RNAV was conceived as a means to provide point-to-point navigation capabilities. RNAV is intended to serve the enroute navigation function and also will be utilized in the terminal area to acquire the precision landing aid, or to facilitate approach procedures where such aids are unavailable.

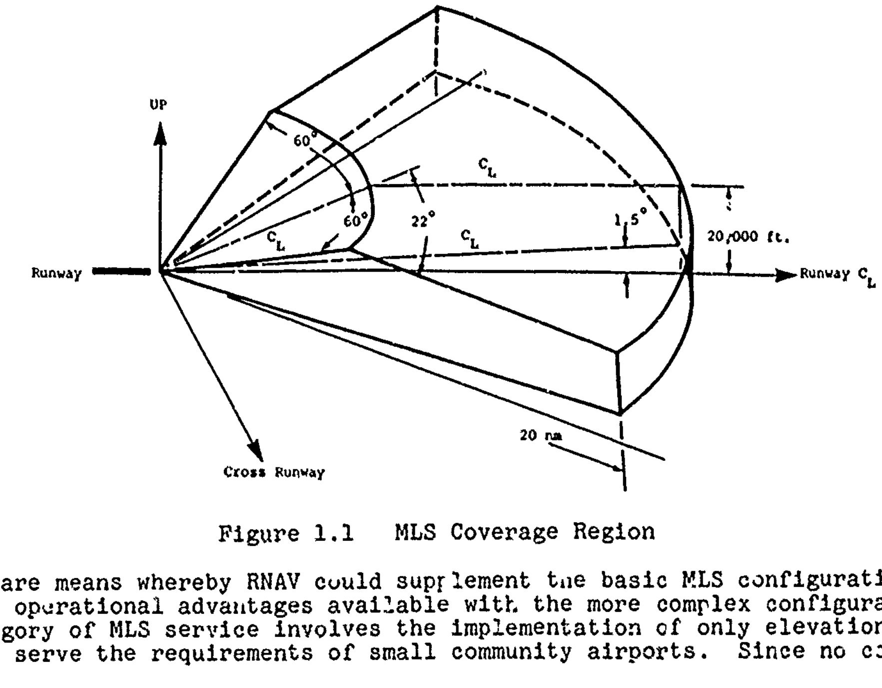


Figure 1.1 MLS Coverage Region

There are means whereby RNAV could supplement the basic MLS configurations to achieve some of the operational advantages available with the more complex configurations. The lowest category of MLS service involves the implementation of only elevation and azimuth elements to serve the requirements of small community airports. Since no collocated DME is provided with this lowest category MLS, the obvious application of RNAV to this configuration is the addition of range to touchdown information. A waypoint located at the airport would indicate this data and aid in the final approach guidance. Also, the lower capability MLS ground configurations (Cat I and Cat I/II) may not have a back azimuth element for guidance on missed approach. In this respect, RNAV could supplement these configurations by providing the basis for missed approach guidance. Further, the early introduction of RNAV to accomplish this objective would also ease the later transition to MLS missed approach guidance for those implementations including a back azimuth element. Another potential application for RNAV supplementing MLS involves the small angle coverage implementations. MLS with only a 20° azimuth scan would not permit many of the curved approach paths possible with the broader coverage conflexibility of curved approach paths to intercept the narrow coverage MLS guidance for precise control along the final approach leg.

As each of these systems (RNAV and MLS) progressed through their individual development cycles, it became increasingly obvious that their characteristics uniquely complemented each other as regards an approach to an optimum concept of terminal area airspace management. Both systems are essentially cockpit managed, thus subscribing to the philosophy of distributed management of an ATC system. RNAV, of itself, is an all-area navigation system, providing unlimited access to all airspace regardless of currently defined routes or specific radio navigation facilities, but not possessing sufficient accuracy to permit precision landing approach capability to low weather minimums. MLS, on the other hand, is an extremely accurate precision landing aid, relatively unaffected by historical siting problems of previous precision landing aid systems, and while offering markedly expanded coverage volume capability, still limited in range and azimuth coverage to a finite area in the vicinity of the airport(s) it serves. Logic dictated that these two systems should be integrated into one potential terminal area navigation, approach and landing concept. The remainder of this paper discusses both the philosophy and specific actions concerned with bringing this concept closer to operational reality.

II. RNAV AND MLS TERMINAL AREA AIRSPACE MANAGEMENT CONCEPTS

Too often RNAV and MLS are interpreted as independent, and sometimes competing, functional objectives within the framework of future ATC system goals. This unfortunate disassociation of the two programs is probably due in part to the fact that RNAV and MLS are identified as separate program objectives of any advanced ATC system configuration. Basically, RNAV is an operationally oriented objective providing the basis for a more flexible point-to-point navigation capability than that available with current procedures where flight paths coincide with VOR radials. On the other hand, MLS is principally a hardware oriented program providing the signal source to enable guidance a long more flexible approach paths than the current straight-in approaches coincident with the ILS localizer and glideslope beams. Thus the point-to-point navigation concepts afforded by RNAV are essential to the MLS concept. In fact, MLS could be considered as a sub-category of RNAV in the same sense as RNAV systems are classified according to the nature of the signal source (i.e., VOR/DME, DME/DME, inertial, Loran, Omega, etc.). In light of this interpretation, it should not be surprising that the two subjects share common areas of concern.

MLS/RNAV procedures can be used in the terminal area to enhance the pilot and ATC interaction. In busy terminal areas controllers apply radar vectors to separate and sequence arriving and departing aircraft. Simulations at the FAA NAFEC facility have shown the use of RNAV procedures instead of radar vectors can significantly reduce controller workload. On the other hand, using RNAV the pilot is in charge of his aircraft's navigation and he continues to have aircraft derived guidance throughout the terminal area phase of flight. The use of MLS with RNAV procedures adds to the overall operation by providing highly accurate navigation and guidance.

The Radio Technical Commission for Aeronautics (RTCA) has undertaken the task of developing industry standards for both area navigation and MLS avionics systems. Included in this effort has been the identification of the postulated operating environments in which these advanced systems will operate. In great measure the functional design and performance characteristics of these systems are directly configured by the character of these environments and the airspace management concepts they represent. A brief summary of these environments is presented in the following paragraphs.

AREA NAVIGATION

The current ATC environment is predominantly VOR radial and radar vector oriented. The use of area navigation is most prevalent for VFR as opposed to IFR operations. The degree of use of IFR area navigation today varies considerably with such factors as geographic areas, phase of flight, and controller workload.

IFR area navigation operations are conducted along charted and uncharted high altitude routes as well as low altitude non-public and non-regulatory area navigation routes and for non-precision approach procedures. Other IFR area navigation equipped flights operate on jet high altitude routes, VOR airways, and direct point-to-point (when controller workload permits).

The following paragraphs present a reasonable postulated future environment in which it can be anticipated that area navigation will be more fully used. This future environment has been developed by the RTCA in conjunction with its work on area navigation avionics standards.

Fundamental to this future RNAV airspace environment is a basic assumption that, given an airborne capability that will adequately comply with ATC RNAV maneuver instructions, the ATC system will use RNAV capabilities in the control of traffic. This basic assumption, and the following listed assumptions, allow for the evolution of RNAV utilization in a mixed environment in which initially the RNAV user represents a minority group of the total ATC system users, progressing to an environment wherein the RNAV equipped traffic may represent a majority. It is anticipated that as the number of RNAV equipped operations increases, controller familiarity with the use of RNAV in the ATC system will also increase. This, in turn, will increase the use of RNAV maneuver capabilities and assignment of RNAV routes (both charted and uncharted).

Assumptions

1. The ATC system accommodates both RNAV and radial navigation flight operations.
2. Non-precision area navigation approaches are defined and approved for use.
3. Area navigation maneuvers are used by ATC to accomplish deviations from established or previously cleared routes or direct flight paths in the control of area navigation flights.
4. VNAV is used as a pilot aid for enroute and SID/STAR navigation in that control clearances and route structure designs are not predicated on its use. When applicable, pilots are presently using and will use VNAV guidance for economic comfort to adhere to clearances.
5. All area navigation charted routes are defined by waypoints based on range and radial from VORTAC stations and latitude and longitude. Noncharted waypoints (not published) designated by an air traffic controller will be defined reference to VORTAC facilities only.
6. Area navigation will continue to be used for the conduct of both IFR and VFR operations.
7. Helicopters as well as fixed-wing aircraft will use RNAV systems.
8. Current route widths will be used as defined in:
    a. Federal Aviation Regulations, Parts 71, 73 and 75, revised as of 1 January 1977.
    b. FAA Handbook 7400.2B, printed 1 August 1976.
    c. Advisory Circular AC 90-45A, dated 21 February 1975.
    d. FAA Order 7130.2, dated 14 October 1965.
    e. FAA Handbook 7110.18, dated 27 February 1970.

Included in the overall philosophy of RNAV terminal area airspace design is the concept of a standardized terminal area route structure, with alternating arrival and departure sectors aligned with the dominant traffic flow. Figure 2.1 illustrates the nominal traffic pattern, in this case aligned with a predominant North-South traffic demand operating on runway 36. Further discussions in this paper will indicate the relationship of these standard RNAV traffic patterns with MLS coverage and proposed combined RNAV/MLS terminal area operating procedures.

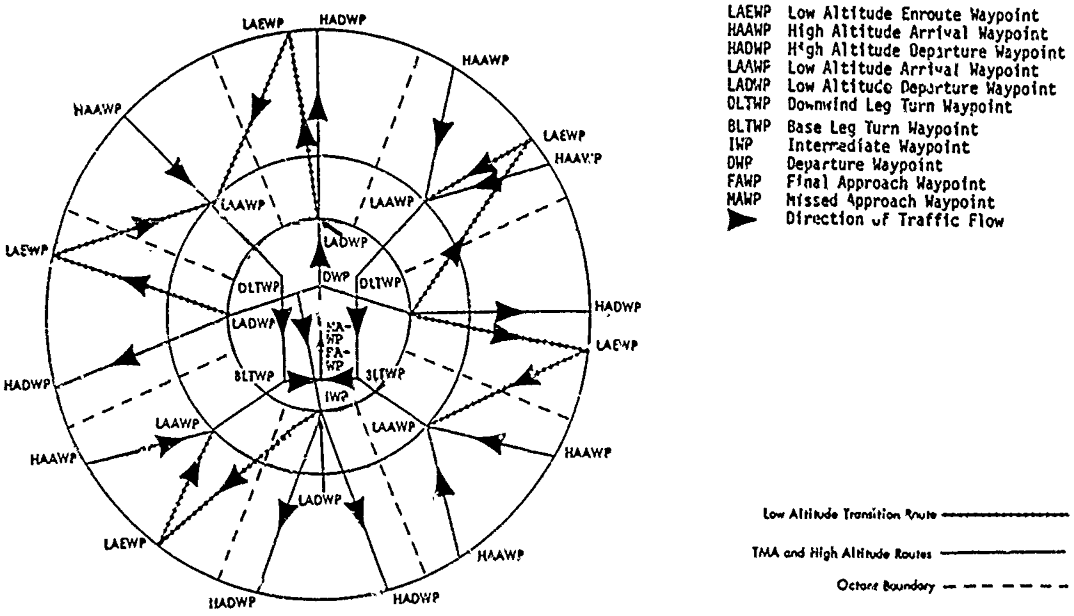


Figure 2.1 Task Force Terminal Area Design

The MLS system can meet the needs of a variety of users in the transition, approach, landing, missed approach and departure phases of flight. Typical applications are described in the following paragraphs. It should be noted here that these illustrative examples are presented primarily as a means for establishing the range of applications of the MLS system, both the ground and airborne aspects included, that may be encountered as MLS becomes an operational element of the National Airspace System. Specific operational requirements and required features of the avionics system could thus evolve from subsequent detailed consideration of these applications.

Low Density or Small Community Airports --

At these airports, using aircraft can vary from business jets, commuter aircraft, and helicopters, single or twin engine piston aircraft. The range of possible glidepath angles available with MLS will encompass the requirements and capabilities of all these aircraft.

The initial approach segment may use an enroute navigation aid or procedure turn. The intermediate and final approach paths are normally aligned with the extended runway centerline. In certain situations, MLS approach procedures may be used to solve or lessen terminal area problems involving noise and/or terrain. Approaches designed to avoid noise sensitive areas or to avoid obstructions can be flown using straight paths (offset azimuth, airborne selectable) that may not be aligned with the runway centerline.

Medium and High Density Terminals --

Air carrier, military and general aviation aircraft need to operate in high density terminal areas. At these airports many operators have a need to make precision approaches and some have an additional need for specialized profiles in the terminal area and for efficient interface with the enroute environment. Wide area MLS proportional guidance coverage may be needed in some terminal areas. Aircraft must be equipped to respond to tactical ATC instructions for separation, metering, etc.

Operators who require or possess only minimum guidance equipment will use straight-in approach paths. Curved paths or segmented paths, or paths between MLS defined waypoints within the proportional MLS coverage area may be used by aircraft with more sophisticated MLS equipment, including the possible integration with RNAV computer systems. Figures 2.2, 2.3 and 2.4 illustrate typical examples of such MLS/RNAV procedures. In addition to using MLS guidance to avoid noise sensitive areas or to avoid obstructions, approach paths with differing vertical gradients or paths containing two or more glide path angles may be used both for terrain avoidance or to keep aircraft at the highest practical altitude for the longest period of time for noise reductions.

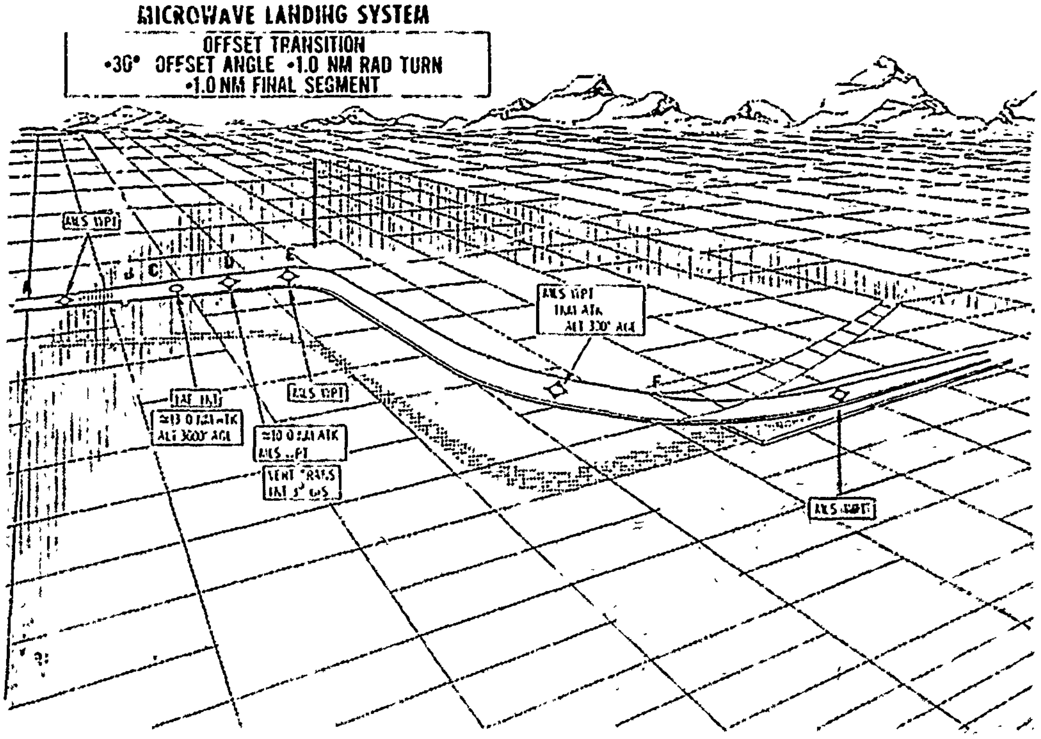


Figure 2.2 MLS 30° Offset Transition

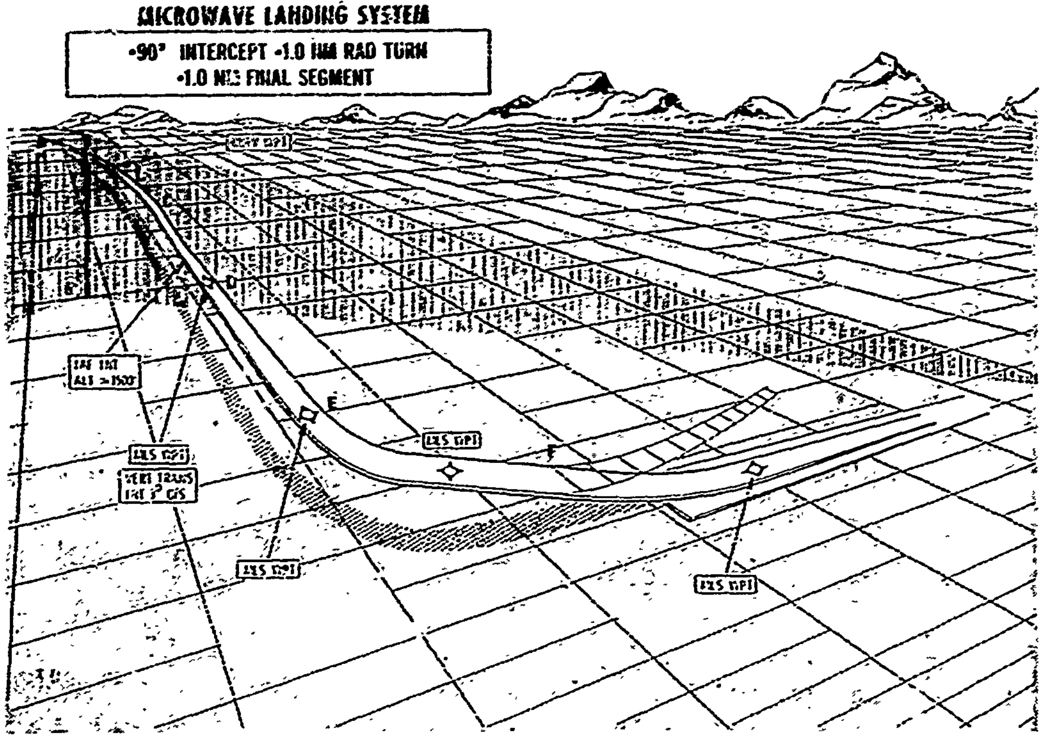


Figure 2.3 MLS 90° Intercept

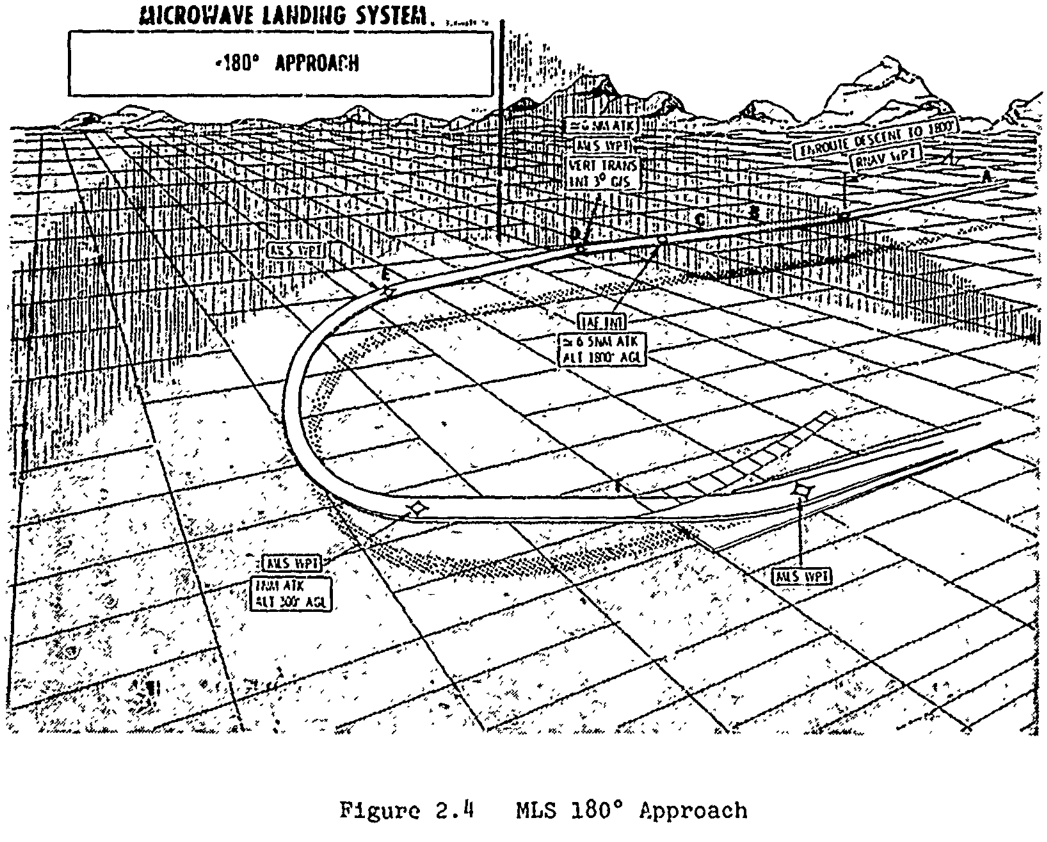


Figure 2.4 MLS 180° Approach

Missed Approach and Departure --

MLS may be used to provide missed approach or departure guidance for obstruction clearance, noise abatement or ATC purposes. The application is similar to the approach procedures for noise abatement requiring segmented or curved paths.

The missed approach or departure path may be the continuation of the runway heading, a selected MLS missed approach or departure azimuth, or a segmented/curved path using MLS defined waypoints.

Special Operational Applications --

MLS guidance may be used for several special purpose applications. In some cases, approaches may be made to non-instrumented runways that are near MLS instrumented runways by using offset azimuth angles or segmented paths between MLS defined waypoints. This technique may be used for approaches to STOL runways and airport helicopter landing areas. Without appropriate airborne computation, proper vertical guidance may not be available for some or all portions of the approaches, depending on the location of the elevation antenna on the instrumented runway.

MLS azimuth and elevation guidance may be used to provide approach capability to helipads, remote areas, offshore oil exploration rigs and moving platforms such as ships. In addition, MLS portable transmitters may be set up at emergency sites in disaster relief, medical evacuation and in other emergencies. Typically, co-located azimuth and elevation antennas will be used to provide a straight-in approach. Approach glide path angles utilized will vary depending on the characteristics of the aircraft.

Automatic Landing and Rollout Guidance --

MLS azimuth, elevation, flare and DME signals may be used for aircraft equipped for automatic landing and rollout. The MLS inputs, and those from other available systems such as radar altimeter and/or inertial sensors may be used to define a lateral and vertical path that will smoothly intercept the runway surface and provide guidance along the runway for rollout.

III. USER REQUIREMENTS

As discussed previously, in the civil aviation arena in the United States, the Radio Technical Commission for Aeronautics (RTCA) is the focal point for the development of documents called "Minimum Operational Performance Standards" (MOPS) for avionics systems considered to be of interest to the aviation community. Combining the operational/functional aspects of previous RTCA documents called "Minimum Operational Characteristics" (MOC) and technical performance aspects of "Minimum Performance Standards" (MPS), the new MOPS documents are expected to be used, by reference, by the FAA as one portion of a certification procedure for pertinent avionics systems.

Special Committees (SCs) are created by the RTCA with a charter to generate a MOPS for a particular category of equipment. SC-137 (Airborne Area Navigation Systems) and SC-139 (Time Reference Scanning Beacon Microwave Landing System Airborne Receiving Equipment) are each in the process of defining functional/operational requirements for their respective equipments. Each of these Special Committees is giving attention to the needs of coordinating their activities, particularly since MLS may become an RNAV sensor on the one hand, and RNAV computational capability may be required in order to realize the full potential of the MLS system. The following paragraphs summarize the early findings of these two RTCA Special Committees as regards a consensus of user requirements, based in large measure on the airspace management concepts developed by each Special Committee and outlined in previous sections of this paper.

SC-137 -- AREA NAVIGATION

The following set of functional requirements presented in Table 3.1 are those which are currently being considered by SC-137 as being required for a 2D RNAV system, as a minimum, in order to safely and efficiently operate in the U.S. National Airspace system. All of the RNAV system requirements must be considered in the context of the postulated area navigation operational environment presented in Section II of this paper. A necessary corollary requirement to this set of minimum requirements is the need to ensure like maneuvering over the ground in response to like controller instructions regardless of RNAV system type.

Table 3.1 SC-137 Preliminary System Functional Requirements - (2D RNAV)

- Position Determination
- Position Display
- Waypoint Entry*
- Distance To/From Waypoint*
- Waypoint Storage*
- Waypoint Sequencing
- Course Selection
- Cross Track Deviation
- Direct-To Function
- Parallel Offset*
- Slant Range Error Correction*
- Input Data Verification
- Mode Annunciation/Selection
- Failure Warning
- Control/Display Capability

*Quantitative values of input and/or output of these quantities are in the process of being defined by SC-137

Additional optional 2D functions as well as required and optional 3D and 4D functions are still being developed by SC-137. Quantitative accuracy criteria for both 2D and 3D RNAV are also being developed, again based on the postulated future area navigation operational environment. A complete 2D/3D RNAV MOPS, including both functional and accuracy criteria, based primarily on VOR/DME sensors, is projected to be submitted to the RTCA Executive Committee for approval and final release by early Spring 1980. As mentioned elsewhere in this paper, SC-137 has considered the MLS sensor as one possible candidate for future RNAV operations in the terminal area environment, subject, of course, to the RNAV/MLS system meeting all applicable accuracy criteria.

SC-139 -- MLS

During the development of MLS, certain principles have been adopted as fundamental to the design of the future landing system for widespread international use. These design principles are derived from operational goals for achieving improved capabilities for future aircraft approach and landing operations in all weather conditions at a wide variety of airports and for the full range of aircraft types. SC-139 has developed a set of typical information requirements and functional capabilities related to the spectrum operational applications set forth in Section II of this paper. Table 3.2 summarizes these capability requirements as they represent the current status of the deliberations of SC-139. In some cases, a minimum capability MLS avionics suite can provide complete functional performance capability for the specified application. In other cases, the "minimum" system can provide reduced capability, while advanced or optional features will be required to provide full capability. It should be pointed out that the computational capability called out for certain system applications (i.e., segmented or curved paths) is functionally identical to that contained in RNAV systems of the same relative complexity.

Table 3.2 Typical MLS Information/Functional Capabilities

		REQUIREMENTS (R = REQUIRED, O = OPTIONAL)													
		INFORMATION								FUNCTIONAL					
APPLICATION	APPROACH PATH	AZIMUTH	ELEVATION	BASIC DATA	DISTANCE INFORMATION	DPE/M (PRECISION)	COMPUTED DEVIATION FROM SELECTED PATH	AUXILIARY DATA	MLS FLARE	MLS CHANNEL SELECT	AZIMUTH (OFFSET) SELECT	GLIDE SLOPE SELECT	WAYPOINT/FLIGHT PATH ENTRY	COMPUTATIONAL CAPABILITY	REVERSE SENSING
LOW DENSITY OR SMALL COMMUNITY AIRPORTS	STRAIGHT-IN ALIGNED WITH RUNWAY CENTERLINE	R	R	R	R	O				R		O			
	OFFSET AZIMUTH	R	R	R	R	O	R			R	R	O			
MEDIUM AND HIGH DENSITY AIRPORTS	STRAIGHT-IN ALIGNED WITH RUNWAY CENTERLINE	R	R	R	R	O				R		O			
	ABOVE PLUS SEGMENTED/ CURVED PATHS	R	R	R		R	R	R		R	R	O	R	R	
MISSED APPROACH AND DEPARTURE	MLS RUNWAY CENTERLINE EXTENDED	R		R		O				R					O
	SELECTED MLS MISSED APPROACH AZIMUTH	R		R		O	R			R	R				O
	ABOVE PLUS SEGMENTED PATHS	R		R		R	R	R		R	R		R	R	
SPECIAL APPLICATIONS: NON-INSTRUMENTED RUNWAYS	OFFSET AZIMUTH	R	R	R	R	O	R			R	R	O			
	ABOVE PLUS SEGMENTED PATHS	R	R	R		R	R	R		R	R	O	R	R	
SPECIAL APPLICATIONS: REMOTE AREAS	STRAIGHT-IN	R	R	R	R	O				R		O			
AUTOMATIC LANDING AND ROLLOUT GUIDANCE		R	R	R		R		R	O	R		R		R	

*I.E., MARKER BEACONS, DME/M, OR OTHER POSITION FIX

The deliberations of SC-139 are planned to result in a MOPS document describing early MLS applications by early Spring 1980.

IV. CURRENT TEST PROGRAMS

The current status of technological and operational research and development is such that the basic feasibility of terminal area airspace management utilizing either MLS or RNAV concepts has been proven. What is required now is a more comprehensive formulation of how these concepts can be integrated into an already existing ATC system. Our present arrival and departure procedures are based, for the most part, on a combination of controller-initiated radar vectors, VOR-based navigation, and finally either ILS or PAR precision approach procedures. While this terminal area airspace management concept has developed as an evolutionary process based on technology advances and traffic demands, both MLS and RNAV represent a fairly drastic transition towards an emerging concept of cockpit-managed navigation, monitored and strategically controlled from the ground. As such, there still remains a significant amount of proof-of-concept tests to be performed in order to sort out the proper balance of airborne vs ground control, operational and communication procedures, and airspace design techniques. To this end an integrated series of test programs have been proposed and are currently in various stages of implementation in the United States under the overall jurisdiction of the FAA. Integration of both the MLS and RNAV programs and systems into the air traffic control system of themselves, as well as with each other, is the stated goal of these efforts. It is the purpose of the following discussion to briefly introduce each of these test programs as regards scope, objective and current status.

MLS SERVICE TEST AND EVALUATION PROGRAM

The majority of the MLS flight tests performed by the FAA up to the present time have been conducted at the FAA's National Aviation Facilities Experimental Center (NAFEC), although short term demonstration flights were made at twelve airports around the world in connection with the ICAO landing system selection process. While the NAFEC tests were adequate for the engineering activities then being conducted, they furnished little opportunity to develop the longer term operational experience needed by those who will face implementation decisions in the future. Therefore, the next logical step to be taken in the MLS program is to extend the scope of test and evaluation work to operational field facilities and in that way provide a transition from the research and development phase to the operational phase. For this purpose the Service Test and Evaluation Program (STEP) has been developed to meet these general goals.

In general terms the STEP plan provides for the procurement of a limited number of TRSB MLS ground and avionics hardware systems and the deployment of those systems in a way that will foster the obtaining of "real world" operational experience. The operational tests of these systems will focus on the development, validation, and refinement of operational, technical and support concepts which use the unique attributes of MLS to optimize user benefits and minimize costs. Additionally, it is anticipated that these tests will instill confidence in the performance and capabilities of the MLS among all program participants, and encourage them to support the transition from ILS to MLS and the associated procurement and implementation of production units.

A phased program has been planned. The first phase will use existing R&D prototype ground systems (together with some newly procured avionics) so as to permit an early start. Phase II involves the procurement of new hardware systems which are better suited to demonstrate its high quality performance in difficult airport environments. These procurements will consist of the simpler MLS configurations (Small Community and Basic Narrow) in which there is high technical confidence in design specifications and performance capabilities. In addition, field evaluation of these systems represents a logical extension of work already accomplished. In the case of the expanded configuration, where Category II and III performances will be evaluated, additional development work is required. Upon completion of the initial development effort, field evaluations will be conducted to demonstrate these capabilities.

The basic purpose of STEP is to facilitate the transition from MLS research and development to MLS implementation. This can best be accomplished by: 1) conducting an operational evaluation of the system with user participation at locations typical of those which will be encountered in full implementation; 2) demonstrating that TRSB MLS will satisfy the total spectrum of user requirements; and 3) developing operational procedures including those for instrument approach and landing, flight inspection and hardware maintenance.

In order to translate these general objectives into specific evaluation factors a survey of the aviation community was conducted. An analysis was made of the responses received and this resulted in a list of technical and operational program objectives which should be obtained during STEP. They fall into the following categories:

- Prove the system technically in challenging environments
- Demonstrate the operational and economic benefits of TRSB MLS

Tables 4.1 and 4.2 list the specific technical and operational program objectives identified in the survey and indicate in which phase of STEP the objectives should be obtained.

Table 4.1 Technical Program Objectives

Output	Phase 1*	Phase 2
• Experience W/Actual Airport Environments	X	X
• Experience W/Difficult Multipath Conditions/ Shadowing		X
• Demonstration of Performance in WX Extremes		X
• Determine Environmental Sensitivity/Stability		X
• Determine Reliability Strengths/Weaknesses		X
• Determine Installation Requirements	X	
• Develop Production Technical Data Package (TDP)	X	X
• Develop Maintenance Procedures/Requirements	X	X
• Prove Compatibility W/Colocated ILS		X
• Demonstrate Simultaneous MLS Operations		X
• Evaluate Cost/Performance Tradeoff		X
• Prove Integrity of Monitoring System	X	X
• Assess Flight Inspection Requirements	X	X
• Assess Remote Monitor Concept		X

* Although certain outputs are indicated as being applicable principally to Phase 2, to the extent practicable all outputs will be developed and/or refined in both phases.

The benefits expected from STEP are numerous and they will ultimately affect all segments of the aviation community. In general, STEP will facilitate the orderly transition from research and development to an operation/implementation phase, and will address questions and uncertainties regarding performance characteristics and cost/benefit tradeoffs. Specific benefits to major segments of the aviation community are summarized in Table 4.3.

At the present time the STEP activity is concentrating on the detailed analysis and selection of sites to be used for ground installations and operating bases for both the Phase I and Phase II portions of the program. One of the primary guidelines for the selection of test locations is the consideration of the deployment of the ground systems in networks whenever possible to maximize operational benefits for user participants.

The networks will be chosen for maximum coincidence with the route structures of the user participants and, where practical, the network will include a major hub airport to broaden the operational base for system exposure and data collection.

Table 4.2 Operational Program Objectives

Output	Phase 1	Phase 2
• Verify Technical Qualities for System Refinement	X	X
• Develop Obstruction Clearance Criteria	X	X
• Determine Procedural Uses of MLS	X	X
• Verify Specific User Operational Benefits	X	X
• Verify Govt. and User Economic Benefits	X	X
• Provide Initial Training Capability	X	X
• Verify Installation Criteria	X	
• Obtain Experience W/Avionics Interface	X	X
• Small Community		
– Determine Suitability of Coverage for AZ & EL	X	X
– Determine Operational Advantages as Compared With Cat 1 ILS	X	X
• Basic System		
– Determine Suitability and Benefits of Selectable Glide Path	X	X
– Determine Benefits of Wide Coverage Other Than Curved Approaches	X	X
– Determine Suitability and Benefits of Curved Approaches		X
– Determine Operational Advantages as Compared With Cat 1 ILS	X	X
• Determine Suitability of MLS Flare Guidance		X
• Determine Benefits of Missed Approach Guidance		X
• Verify improved automatic landing capability	X	X

Table 4.3 Benefits of STEP

Benefit	Major Beneficiary		
	User	Industry	Govt.
• Acquire Operational Experience	X		X
• Aid Domestic Technology Transfer	X	X	
• Ease Initial Implementation of MLS	X		
• Discourage Further Establishment of Nonstandard Systems	X		X
• Expand U.S. Technology	X	X	X
• Aid in ICAO SARPS Development			X
• Sustain Program Continuity	X		
• Expand Opportunity for Hardware Sales		X	
• Build Confidence in System	X		
• Improve Public Awareness of MLS	X	X	X

MLS INSTALLATION AT WASHINGTON NATIONAL AIRPORT

In concert with the previously described STEP activity, a "Basic Narrow" MLS ground system has been installed at Washington National Airport with the azimuth antenna located just south of the approach end of runway 36, basically serving runway 18. This system, with its precision DME, will provide the capability to demonstrate, among other things, the ability of MLS to provide guidance for relatively complex flight paths, particularly for noise abatement procedures. In this regard Washington National Airport has a unique problem coupled with the necessity for the avoidance of several prohibited areas which lie in the nominal instrument approach path. Figure 4.1 illustrates the classical Washington National "River Approach" which is often used to illustrate the applicability of MLS to the solution of real world operational problems.

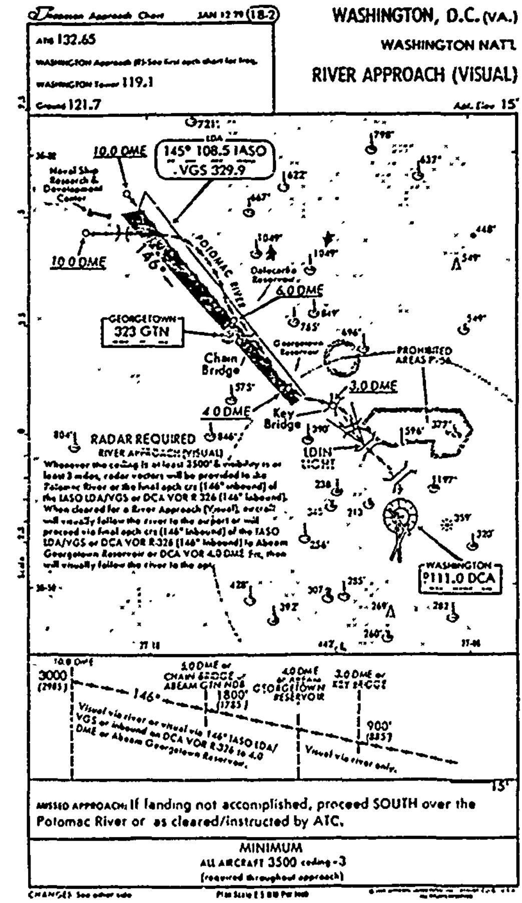


Figure 4.1 Washington National "River Approach"

The "Basic Narrow" MLS is designed to provide operationally useable glide paths between the angles of 2.5 degrees and 8.0 degrees with azimuth guidance provided throughout a sector ±40 degrees of the runway centerline. To assure that there is adequate signal in space in the MLS coverage sector and to prepare for the eventual operational application of complex approach procedures, such as the "River Approach", a series of flight profiles have been designed to be flown during the MLS flight checkout period. Table 4.4 defines the series of flight check profiles that will be flown as part of the initial commissioning process.

The flight inspection aircraft shall fly level radial flights inbound at 3000 feet above the elevation site from 15 nm (from the elevation site) until the aircraft passes out of the MLS coverage sector. This type of profile permits the aircraft to pass through all of the transmitted elevation angles from approximately 1.75 degrees up through the maximum elevation angle as the aircraft passes out of elevation coverage passing the elevation site. Five radials shall be flown at this altitude. The five radials are; 0 degrees, ±20 degrees, and ±40 degrees (with respect to the azimuth site). These radials should provide an adequate data sample to confirm the presence of all the elevation angles and a partial sample of the azimuth data coverage. Figures 4.2 and 4.3 illustrate typical level radial flight profiles.

The Basic Narrow MLS configuration is designed for a minimum selectable glide path angle of 2.5 degrees in operational use and elevation coverage is provided for a glide path guidance width of 0.25 Ø degrees at low angles (up through 4.5 degrees). It is desirable to observe the signal in space near the lower limit of guidance (1.875 degrees). Since glide path angles are only selectable in one half degree increments in the present airborne receiver hardware, the flight check pilot shall select an elevation angle of 2.0 degrees and fly both a clockwise and a counter clockwise partial orbit (±50 degrees) while maintaining a constant elevation angle (approximately 11.78 nm from the elevation site at an altitude of 2500 feet). These orbits will provide data equivalent to near full needle displacement below glide path for a 2.5 degree approach. Since 3 degrees is the nominal conventional glide path angle, another set of partial orbits will be flown to observe the data at this prime elevation angle. A third set of partial orbits shall be flown in the STOL region of coverage (6 degrees). For 6 degrees these orbits shall be flown at 5000 feet at a distance of approximately 7.82 nm. Figures 4.4 and 4.5 illustrate typical orbital flight profiles.

It has been common in past MLS flight checks to fly centerline approaches also. Accordingly five 3.0 degree and three 6.0 degree centerline approaches shall be flown during this checkout period as typified by Figures 4.6 and 4.7. The purpose of the additional runs at each glide path is to confirm the data repeatability. For the Washington National installation it is considered essential to reconfirm the advertised MLS coverage limits. This can be accomplished by flying ±40 degree radials inbound from 20 nm at an altitude of 20,000 feet and partial orbits (±50 degrees) both clockwise and counter clockwise at a distance of 20 nm from the sites at an altitude of 2000'. As the operational data base is expanded, it is expected that these orbits will be flown in the 5 nm to 10 nm region and the recorded signal strength data will be extrapolated to determine the coverage limits of the installation. At the present time data flights corresponding to runs 1-17 have been completed and the data is undergoing detailed processing and analysis. Runs 18-25 are awaiting pertinent airborne equipment installation.

Table 4.4 Washington National Flight Check Profiles

RUN	DESCRIPTION	DME	
		DCA*	MRXQ**
1	40° left @ 3000' MSL from 15 nm		
2	20° left @ 3000' MSL from 15 nm		
3	0° @ 3000' MSL from 15 nm		
4	20° right @ 3000' MSL from 15 nm		
5	40° right @ 3000' MSL from 15 nm		
6	Partial orbit (6° elevation), CW, 5000' MSL	7.8	8.9
7	Partial orbit (6° elevation), CCW, 5000' MSL	7.8	8.9
8	Partial orbit (3° elevation), CW, 3000' MSL	9.4	10.5
9	Partial orbit (3° elevation), CCW, 3000' MSL	9.4	10.5
10	Partial orbit (2° elevation), CW, 2500' MSL	11.7	12.8
11	Partial orbit (2° elevation), CCW 2500' MSL	11.7	12.8
12	Partial orbit (1° elevation), CW, 2000' MSL	20.0	21.1
13	Partial orbit (1° elevation), CCW 2000' MSL	20.0	21.1
14	Partial orbit (5° elevation), CW 10,000' MSL	20.0	21.1
15	Partial orbit (5° elevation), CCW 10,000' MSL	20.0	21.1
16	Centerline approach (3° G/P) from 15 nm @ 3000' MSL		
17	Centerline approach (6° G/P) from 15 nm @ 3000' MSL		
18	MLS/RNAV 1 runway 18		
19	MLS/RNAV 2 runway 18		
20	MLS/RNAV 3 runway 18		
21	MLS/runway 15		
22	MLS/Copter runway 15		
23	MLS runway 21/33		
24	MLS/Copter 1 Point-in-Space 223°		
25	MLS/Copter 2 Point-in-Space 223°		

*DCA VORTAC located at the center of the field

**MLS DME located at the south end of the field at the approach end of runway 36

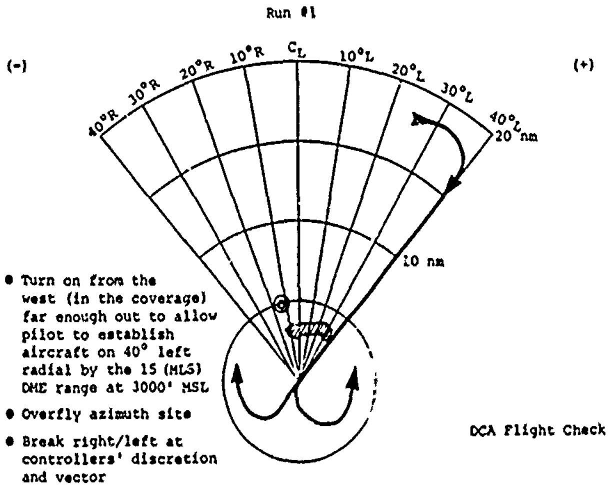


Figure 4.2 Level Radial Approach (40° Left Radial)

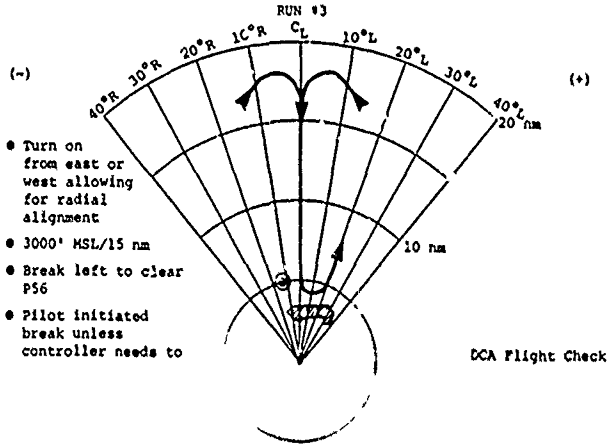


Figure 4.3 Level Radial Approach (Center Radial)

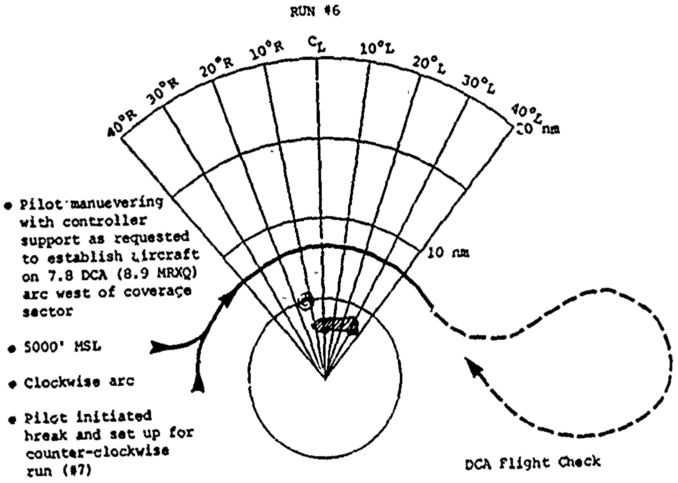


Figure 4.4

7.8 Mile Orbital Profile

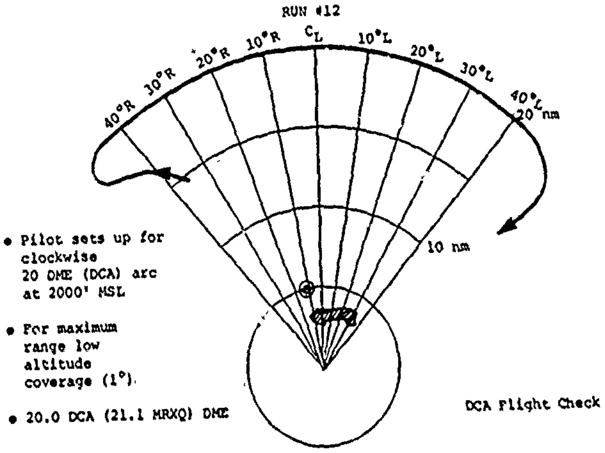


Figure 4.5

20 Mile Orbital Profile

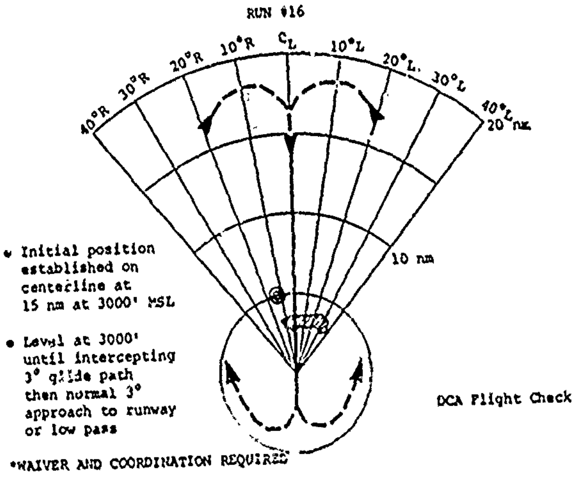


Figure 4.6

3° Glideslope Centerline Approach

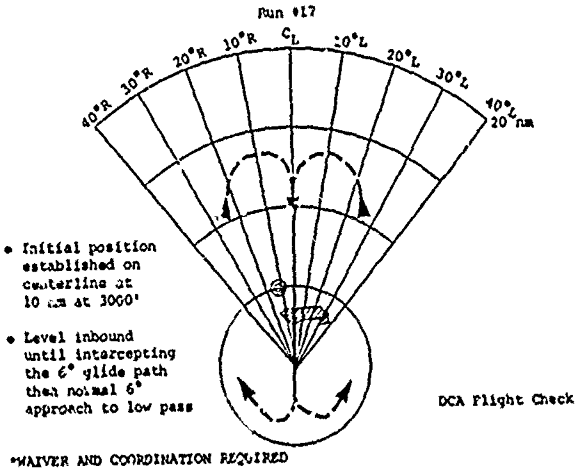


Figure 4.7

6° Glideslope Centerline Approach

MLS/RNAV INTEGRATION

Considerable emphasis has been placed in preceding sections of this paper on the operational and economic benefits of area navigation in the terminal area. In actuality the basic concept of RNAV does not define the navigation sensor to be uniquely VOR/DME, MLS/DME-M, or any other sensor system. If the general RNAV Standard Terminal Arrival Routes (STARs) can be flown by a properly equipped aircraft (which covers both accuracy and functional performance criteria), then the fuel and time benefits ascribed to RNAV will be realized. However, for the most part these RNAV profiles involve adhering to cockpit-navigated carefully defined routes in three dimensions.

Early developments of MLS avionics did not include the capability to perform RNAV maneuvers utilizing waypoint insertion functions and lateral/vertical steering guidance relative to three dimensional STARs. Most complex maneuvers were performed using procedural techniques combined with angle receivers. In order to more fully exploit the wide coverage and improved accuracy of MLS, it was decided to develop and flight test a combined RNAV/MLS system, in which a basic VOR/DME based RNAV computer was married with an MLS receiver. In this way the RNAV computer would aid in the initiation of the RNAV STAR, using VOR/DME sensor inputs until the aircraft was located within the MLS azimuth and elevation coverage. Once the valid MLS signals are received the RNAV computer will automatically switch to MLS sensor inputs (azimuth, elevation and DME/M), perform a preprogrammed transition to accommodate any position fix differences between VOR/DME and MLS, and continue to navigate along the RNAV waypoint defined route using MLS guidance signals.

The flight test system has been configured around an existing production version VOR/DME RNAV system shown in Figure 4.8. The control/display unit (CDU) is identical to that shown. The existing operational software has been reconfigured to perform the switching from VOR/DME to MLS inputs as well as to smoothly handle any position transient which might occur at the time of sensor switching. The RNAV computer hardware has been similarly modified to interface with an airborne MLS angle receiver and DME/M.

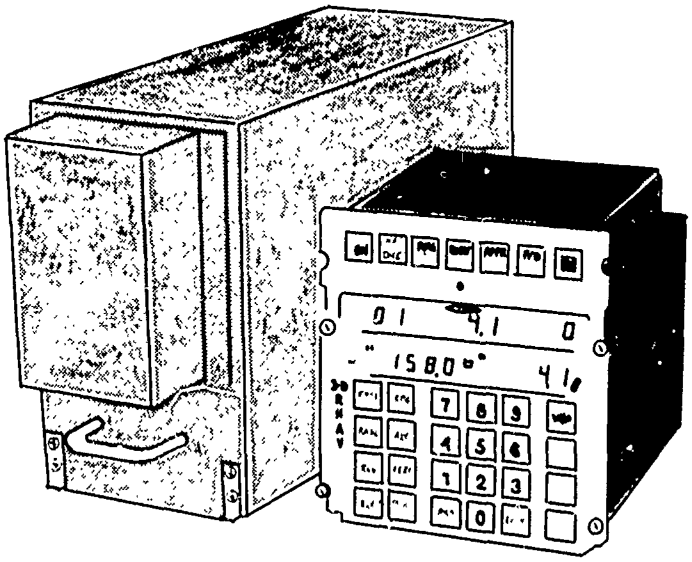


Figure 4.8 3D RNAV Digital Airborne Computer System

The primary objectives of this RNAV/MLS flight test are two-fold, first to demonstrate the ability of the combined systems to perform a variety of approach procedures representative of real world operational situations, and second, to develop cockpit and ATC procedures that will allow a smooth integration of such equipped aircraft into the current and future ATC system, particularly in congested areas. To this end a series of flight tests have been designed to be flown at the FAA NAFEC flight test facility. Table 4.5 indicates a preliminary estimate of the flight test matrix. Figure 4.9 illustrates the location of the MLS "Basic Wide" ±60 azimuth system that is installed at runway 31 at NAFEC and which will be used in this test program.

Table 4.5 A Preliminary Estimate of the Flight Test Matrix

3 Pilots/3 Flights Each -- Autopilot Coupled/3 Flights *Total Flights: 12 Per Procedure*

FLIGHT TEST PROFILE	CIRCUIT TIME (min)	TOTAL FLIGHT (hrs)	FLIGHT TEST PROFILE	CIRCUIT TIME (min)	TOTAL FLIGHT (hrs)
RNAV #1	36	7.3	JFK Canarsie 13L	20	4.0
RNAV #2	46	9.2	JFK Canarsie 13R	20	4.0
DCA River 3 Segment	20	4.0	Multi-Gradient	30	6.0
DCA River 5 Segment	20	4.0	St-In Non-Inst. Runway	30	6.0
LGA Expressway	20	4.0	DCA 3 Segment Multi-Gradient	20	4.0

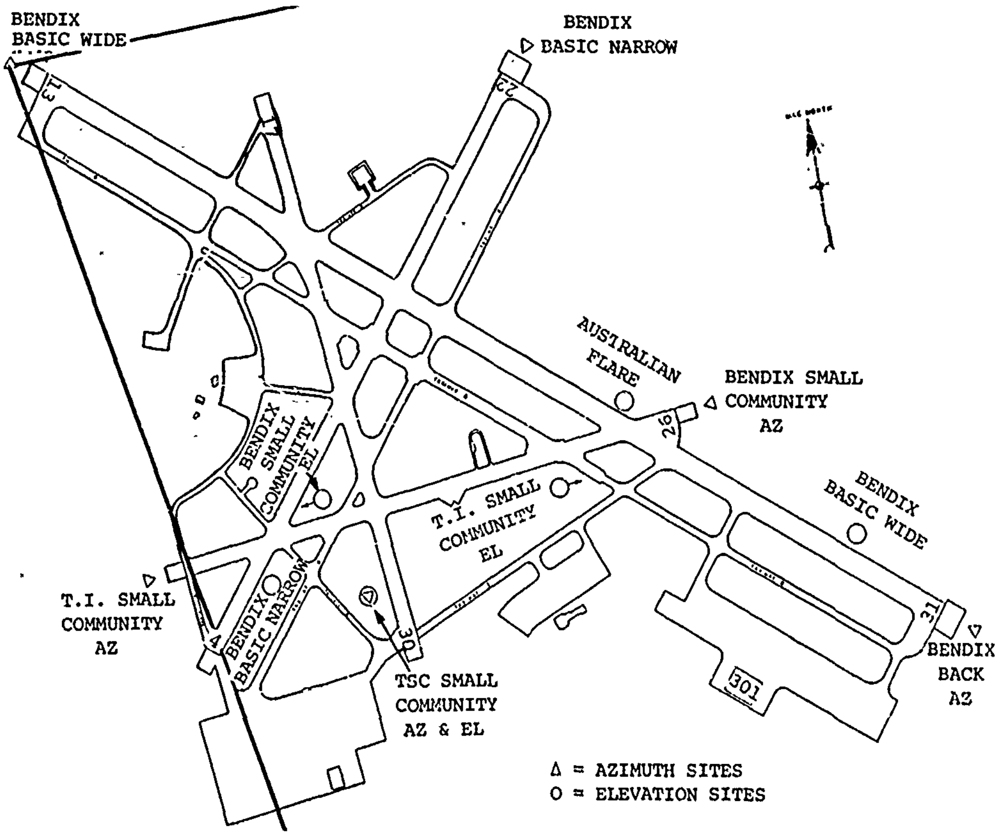


Figure 4.9 NAFEC Airport Diagram

The NAFEC RNAV/MLS test program will be flown in an FAA B-727 aircraft, both manually and autopilot coupled, as shown on Table 4.5. While several of the procedures shown on Table 4.5 have been designated as special case procedures designed to investigate unique parameters, additional tests have been assigned to evaluate the ability of the RNAV/MLS system to perform existing noise abatement procedures that are currently flown only under visual conditions. The waypoints defining these procedures have been translated from their particular geography to their respective locations with respect to runway 31 at NAFEC. Figure 4.10 illustrates a five segment RNAV/MLS approach which approximates the Washington National River Approach previously shown on Figure 4.1. The existing approach procedures for the La Guardia Expressway and Kennedy Canarsie Approaches shown on Figures 4.11 and 4.12. The corollary NAFEC RNAV/MLS procedures are shown on Figures 4.13 and 4.14.

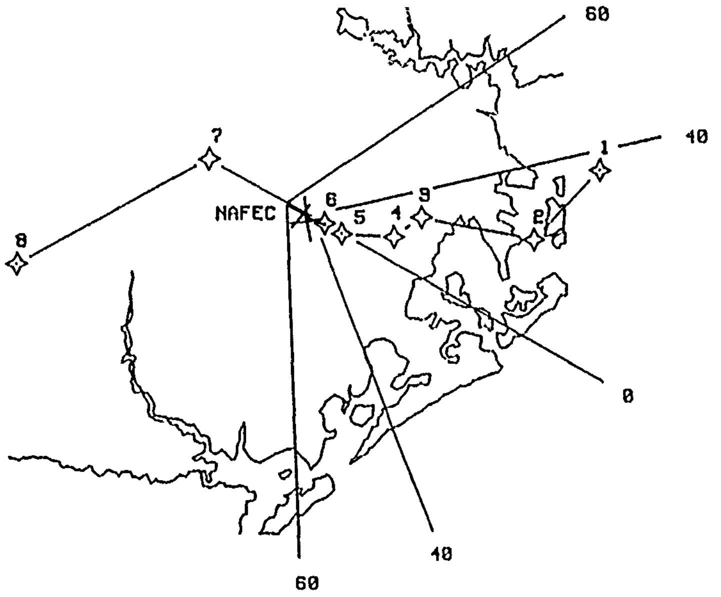
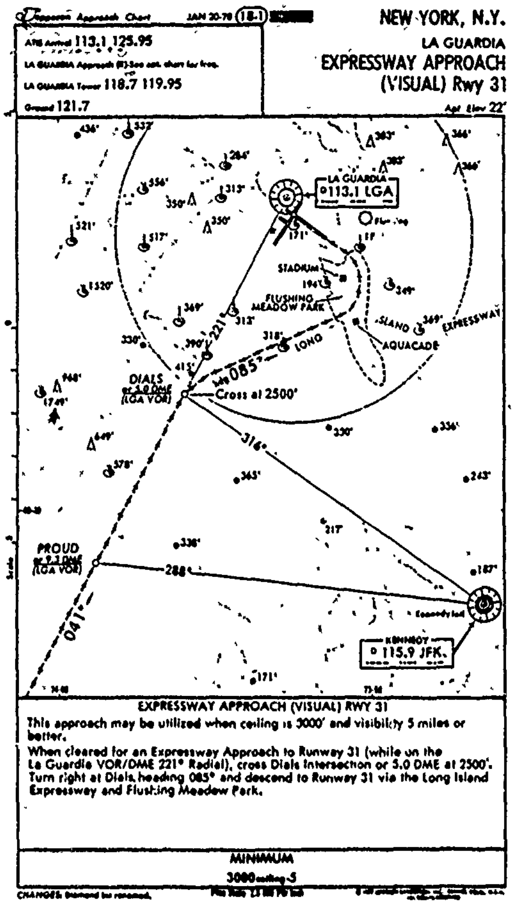


Figure 4.10 DCA 5 Segment RNAV/MLS River Approach
NAFEC Runway 31



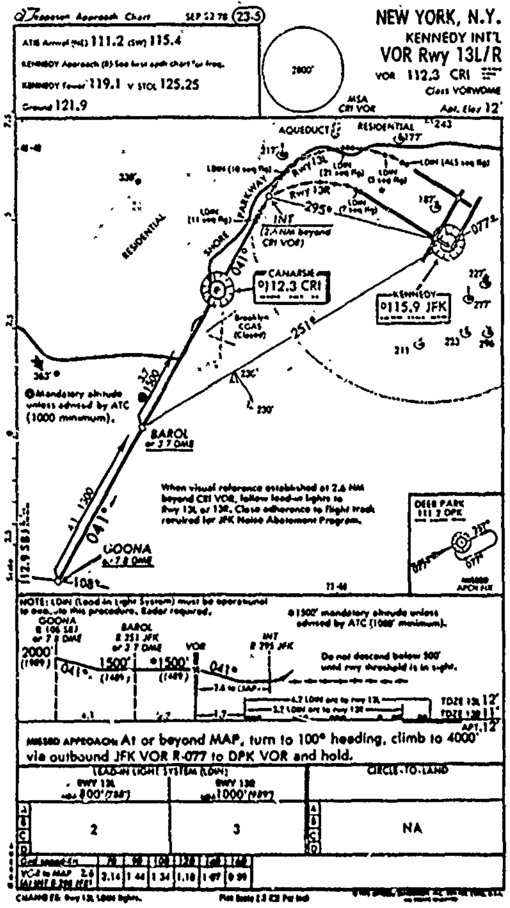
EXPRESSWAY APPROACH (VISUAL) RWY 31

This approach may be utilized when ceiling is 3000' and visibility 5 miles or better.

When cleared for an Expressway Approach to Runway 31 (while on the La Guardia VOR/DME 221° Radial), cross Dials Intersection or 5.0 DME at 2500'. Turn right at Dials heading 085° and descend to Runway 31 via the Long Island Expressway and Flushing Meadow Park.

MINIMUM

3000 ceiling-5



Mandatory altitude unless advised by ATC (1000 minimum).

When visual reference established at 2.6 NM beyond CRI VOR, follow lead-in lights to Rwy 13L or 13R. Close adherence to flight track required for JFK Noise Abatement Program.

NOTE: LDIN (Lead-in Light System) must be operational to execute this procedure. Radar required.

1500' mandatory altitude unless advised by ATC (1000' minimum).

Do not descend below 500' until rwy threshold is in sight.

MISSED APPROACH: At or beyond MAP, turn to 100° heading, climb to 4000' via outbound JFK VOR R-077 to DPK VOR and hold.

LEAD-IN LIGHT SYSTEM (LDIN) RWY 13L 800' (788')	RWY 13R 1000' (989')	CIRCLE-TO-LAND
2	3	NA

Figure 4.11 La Guardia Expressway Approach (New York, N.Y.)

Figure 4.12 Kennedy Canarsie Approach (New York, N.Y.)

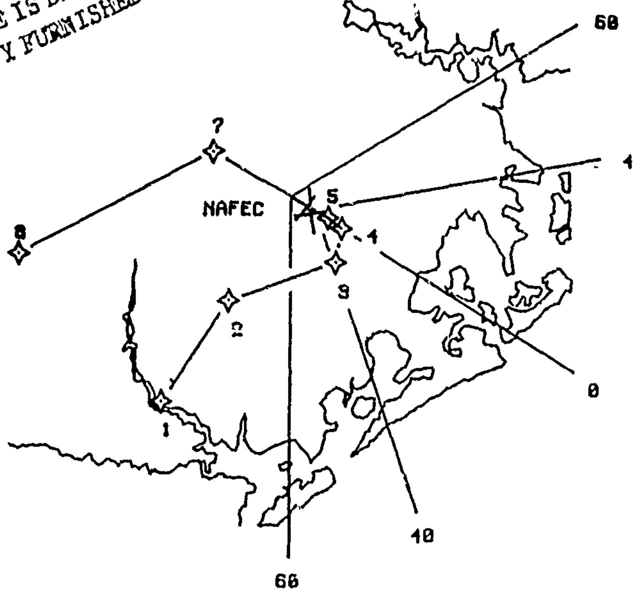


Figure 4.13 LGA Expressway RNAV/MLS Approach NAFEC Runway 13

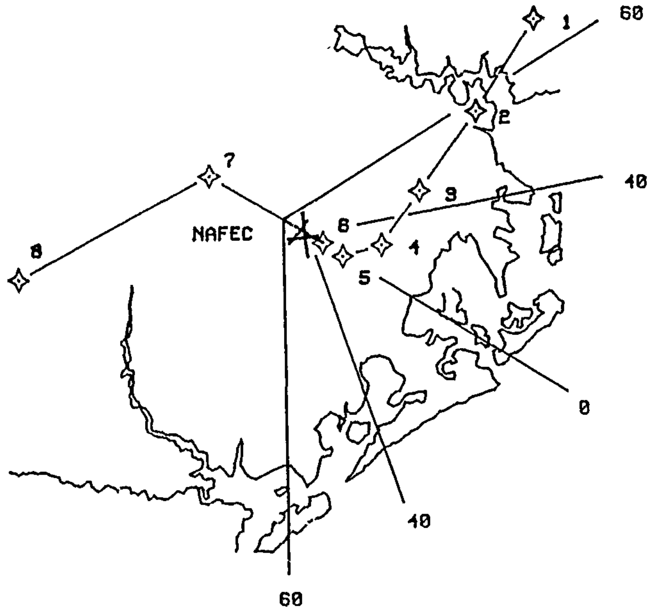


Figure 4.14 JFK Canarsie 13R RNAV/MLS Approach
NAFEC Runway 31

At the present time the RNAV/MLS system is undergoing initial acceptance tests at NAFEC in the contractor's aircraft. Upon successful completion of these tests the equipment will be installed in the FAA B-727 and the flight test plan of Table 4.5 will be initiated during the late fall of 1979.

SUMMARY

Two other supplemental activities in this general area are worthy of passing note. Negotiations are currently underway to extend the basic STEP MLS program to include the installation of a combined RNAV/MLS avionics system in an air carrier's wide body jet aircraft in the test and evaluation of ATC procedures and approach procedure certification pertinent to an aircraft of that type. In a related effort, an RNAV/MLS system similar to that described previously and shown in Figure 4.8 will be installed in an FAA helicopter to be tested at both NAFEC and Washington National Airport as a means of expanding the data base on system performance and ATC procedures relative to helicopter operations in an RNAV/MLS environment.

RNAV and MLS are non-competitive navigation/landing systems that, working together, can markedly enhance the safety and efficiency of terminal area operations while at the same time impacting the overall concept of terminal airspace management. Primarily, these systems afford the opportunity, which has been debated so vigorously for many years, of converting to a distributed management philosophy of ATC system design and operation in which much of the navigation function is transferred from the radar vectors issued by the ground controller to the flight crew, aided by increasingly available, low cost, multifunction avionics systems. This paper has attempted to introduce some of these concepts and to indicate some activities on the part of the United States Federal Aviation Administration to develop and integrate these complementary capabilities into the terminal area airspace system.

This technical paper was prepared by Systems Control, Inc. (Vt) (SCI) for the Systems Research and Development Service (SRDS), Federal Aviation Administration (FAA). The contents reflect the views of the authors who are solely responsible for the facts and accuracy of the information presented herein.

SINTAC-C T.M.A.

APPLICATION OF SINTAC-C IN THE TERMINAL AREA, DURING LANDING AND GROUND TAXIING

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SUMMARY

SINTAC is an integrated navigation, traffic control, collision avoidance and communication system.

Its various functions are performed according to the flight phase or ground rolling : en route ; TMA ; landing, take off and ground taxiing.

In the terminal area (TMA), the system performs Navigation, Surveillance with Identification, data link, voice communication functions with a very satisfactory localization accuracy and communication capacity.

In the final approach and landing phase, it may be used alone or with the MLS.

- It is used alone when visibility is sufficient for elevation guidance operations (category 1 landings), the accuracy of SINTAC being more than sufficient to perform the azimuth guidance during final approach and landing.
- SINTAC is used with MLS for category 2 and 3 landings. In this case, SINTAC performs the precision DME and data link functions.

In the landing phases, SINTAC carries out also the TMA functions, in conjunction with the landing functions.

In the case of an MLS failure, SINTAC can replace MLS for azimuth guidance purposes and, jointly with redundant elevation guidance systems, SINTAC can provide for landing functions.

- After landing, SINTAC performs the ground taxiing functions,
- During take off, SINTAC performs all the flight control and navigation functions.
- If a landing aborts and the flight resumes, SINTAC performs continously the navigation and flight control functions, as the TMA procedures have not been interrupted.

Due to SINTAC high capacity in the TMA, SINTAC can control between 200 and 1000 aircrafts according to the number of runways (or airports) included in the TMA.

During final approach and landing, the system controls 16 aircraft, the maximum which can be considered in the MLS beam, with a 30 second landing rate.

According to the required control capacity, the system uses one, two or three time-shared nets for all the functions and for all the in flight and ground phases.

The navigation transmission rates are very high (32-16 Hz) thus ensuring a pratically continuous navigation function.

The surveillance and synchronization frequency depend of the area : a maximum of 4 seconds in the terminal area and a 1 second maximum at landing time.

Three types of SINTAC ground stations are considered :

1 - SINTAC-TMA : 100-150 km range covering the TMA area with three or four stations.

2 - SINTAC-landing : located at the far-end of the runway (precision DME), range and antenna beam aperture same as MLS.

3 - SINTAC-ground taxiing : airport area coverage by three stations : station range : 5 to 10km.

The difference between stations lies in their range and measurement accuracy as well in their transmission organization.

A single airborne SINTAC terminal is used for all the flight phases : the terminal consists of a transceiver with the MLS interface.

Redundancy can be provided according to the landing category and the type of liaison.

USE OF SINTAC IN THE TMA
FOR LANDING AND GROUND TAXIING

I - GENERAL PRESENTATION

1 - SYSTEM DESIGN

SINTAC is a multifunction system including navigation, traffic control, collision avoidance and communications.

Its performance characteristics on one hand : range, accuracy, discrimination power, communication capacity ; and on the other hand its modular design makes it adaptable to the different functions and to different operational configurations : identification, direct and indirect tactical links, traffic control and navigation : en route, in the TMA, during landing and ground taxiing.

Due to the operational requirement of protecting the system against hostile jamming, SINTAC exhibits spread spectrum modulation, fast frequency hops in a wide band, time-division organized synchronous transmissions.

The use of pseudo-random laws for the pulse codes and frequency hops and transmission redundancy allow the multinet operation of the system with simultaneous transmissions in a given space.

2 - INTEGRATED SYSTEM VERSUS TO SPECIFIC SYSTEMS

These factors give the opportunity of integrating the functions listed previously in a multifunction system and give major benefits to the new system with respect to the specialized systems ; this is both from an operational viewpoint and from an overall cost viewpoint.

This is a feature of the various integrated systems and not only of SINTAC ; however, there is always a certain amount of reluctance to the systems.

Considering only the civil systems, it appears that the idea of the integrated system seems out of favor or, in fact, is practically no longer mentioned.

- The DABS and BCAS are developed to replace the SSR and also to carry out part of the DATA LINK and air-to-air collision avoidance functions.
- ICAO has selected the MLS to replace the ILS as the future landing system,
- Currently under consideration to complete the MLS is the solution to be adopted for the future precision DME, on one hand and, on the other hand larger capacity DME as an extension of the current DME.

On this last item, there is however a trend toward system integration starting with the DME. But, overall, the fondamental trend still remains toward specialized systems by function and by operational configuration.

3 - RESISTANCE TO THE INTEGRATED SYSTEM

There are several reasons which would take too long to explain here but one reason which seems to have a major impact is the difficulty to comprehend the integrated system :

- the operational characteristics in the various configurations for each function of the system,
- its operating safety,
- its insertion with respect to the existing systems,
- its total cost in the final stage as well as in the transition period.

Also, it is often said that the system is interesting in a long term perspective but that, in the present, we must remain in line with current systems or, at least, in the philosophy of specialized systems.

This may be explained on one hand by the fact that it is very difficult to proceed to the overall study of the system under real operating conditions and, on the other hand, by the current evolutive status of the system and by the lack of practical achievements to carry out the real-scale testing of the system for all its functions, in the various operational configurations.

4 - OUR STUDY OF THE INTEGRATED SYSTEM

We have ourselves tried to carry out such studies on a relatively modest scale but which has seemed sufficient to us to state ranges meaningful of system validity for the following :
- functions which can be performed by the system,
  operational performance characteristics for the various functions,
- total cost of system in the final stage and during the transition period.
These studies show the validity of the integrated system and demonstrate that system validity increases with the integration level.

5 - OUR CURRENT POSITION ON THE INTEGRATED SYSTEM

We believe that technological progress as well as future economic and operational requirements and constraints put the integrated system in a favourable position with respect to the specialized systems and that, despite the change it represents, the integrated system has the best chance of becoming the electronic navigation aid system of the future.

In this perspective, we continue our SINTAC development effort and we examine all the system possibilities to be able to carry out an overall real-scale experiment.
The basic assumptions we use are as follows :

- the multifunction synchronous transmission spread-spectrum military system will become operational between 1985 and 1990 and progressively, all military aircraft and ground stations will be fitted with the new system.
- Still not clearly understood now, the operational and economic value of the system will become clear at that time and we can believe that the future civil system will also derive from the multifunction military integrated system.
- Compatibility between the two systems - civil and military - should not result in problems ; the military system being encrypted, the problem of indiscretion or voluntary jamming will be no more important than if the system was only military.
- Transition between the current civil systems and the future civil integrated system will only occur after 1990, overlapping to year 2000.
- This time period is not as remote as it may seem at first sight so as not to act now, accounting for the time required for the definition, adoption and development of a new system, in particular when the change is so drastic.

Among the various functions of the integrated system, the landing phase which is closely associated with the TMA navigation and ground taxiing phase is not currently examined ; it does not seem possible for the integrated system not to be used in these phases.

Thus, for the design of the integrated system and for its overall validity as a system, it is important that it is considered also in these phases.

6 - ADVANTAGES OF THE INTEGRATED SYSTEM IN THE TMA AND FOR LANDING

The use of SINTAC in the terminal area and for landing has the following benefits :

- In the aircraft :
  - a single terminal is used for all the in flight and ground taxiing phases - landing requires no additional equipment.
- On the ground, the stations are adapted to each flight and ground taxiing phase - the adaptation process involves mainly the station range and coverage as well as its operating mode.
- The navigation and control procedure in the terminal area, during the landing phase, is superimposed to the latter - time-interleaving - thus ensuring a perfect operation continuity and added safety in case of an MLS failure or of an aborted landing (flight resumed).

7 - SYSTEM VERSIONS

Ground stations can comprize only an omnidirectional antenna, the position is obtained by the 3 R process. This organization use the simplest stations and gives the system a maximum surveillance capacity and continuous navigation as a result of a high transmission rate.

However, the procedures can be adapted to the use of a directional antenna in addition to the omnidirectional antenna and with a single station to obtain aircraft localization in the ($\rho\theta$) coordinates.

The directional antenna can be used for transmission and reception or only for reception.

Procedure selection can be effected by a programm change according to the configurations and station types in each area.

8 - PRESENTED SYSTEM

With respect to the presentation which took place in 1975 at the AGARD congress, the current presentation accounts for the evolution of SINTAC into the SINTAC 2 interoperable with JTIDS and, also, we have modified the navigation is now performed by the SINTAC operating alone.

We do not consider this presentation as a final solution ; this would be premature, we consider it as a contribution to the definition of the integrated system and we hope that it will help to demonstrate the value and benefits of the integrated system.

II - SYSTEM DESCRIPTION

The operation of the SINTAC-C in the terminal area will be reviewed successively in three cases :
- independent airport with one or several runways,
- several airports with one common terminal area,
- several adjacent terminal areas.

These three configurations cover the major possible organizations and their description is required to understand the job performed by SINTAC-C in the terminal area.

The case of the independent airport will be described in the most detail as it constitutes the base of the general organization.

The other configurations will be infered from the first and will be described more briefly.

1 - ORGANIZATION OF TRANSMISSIONS

1.1. - Time division

The various SINTAC-C functions (navigation, surveillance, data link, voice communications, landing aid) are performed on a single net by time sharing of the various functions.

This time division of the functions is the base of the organization of the SINTAC-C transmissions (and receptions).

The functions are distributed over a 125 ms interval (1/8 th of a second) called a cycle.

Each cycle is divided in 16 time-slots (7.8125 msec each) and each time-slot is subdivided in 16 sub-slots (0.4882813 msec each).

The latter represent the duration of the shortest possible transmission, reception or guard time.

The time division structure is illustrated on figure 1.1.1.

1.2. - Composition of a message

The SINTAC-C transmission consists of transmitting 6,4 μs duration MSK-coded in 32 0,2 μs chips pulses in "transmission" sub-slots.

Due to the MSK m-aire modulation, each pulse carries a 5 bit information ($2^5 = 32$).

The interval between pulses is 6,6 μs and this determines the pulse transmission period :
$T = 6{,}4 + 6{,}6 = 13$ μs (figure 1.2.1.).

Three successive pulses provide for the transmission of 15 bits, i.e. a word (B.C.H. 15/11).

The composition of a SINTAC-C message is given on figure 1.2.2.

The message consists of :

- a preamble, consisting of 6 6,4 μs pulses,
  i.e. $t_1 = 6 \times 13 = 78$ μs
- a pre-synchronization, consisting of 4 6,4 μs pulses,
  i.e. $t_2 = 4 \times 13 = 52$ μs
- a text consisting of 9 x 13 = 351 μs
  i.e. $t_3 = 3 \times 9 \times 13 = 351$ μs

Total transmission time :
$T = t_1 + t_2 + t_3 = 78 + 52 + 351 = 481$ μs

This time is 7 μs shorter than the duration of a sub-slot (T = 488 μs).

- The preamble is for message coding purposes.
  Thus, reception can only occur on receivers set on the adequate code.
- The pre-synchronization provides for the correct decoding of the text by synchronizing the receiver decoder clock.
- The text contains information concerning :
  - the nature of the message (data link, voice com., navigation, surveillance, etc...),
  - sender adress,
  - receiver adress, and the message proper.
- The measurement of distance is made possible by the fact that the "ground" and "air" time-slots (transmissions-receptions) are strictly synchronized ; thus, the transmission time being known by the receiving station, the arrival time can be used to compute the distance between the two stations (with a very high accuracy).

2 - ORGANIZATION OF THE SINTAC-C TMA FUNCTIONS

2.1. - Independent airport

2.1.1. - Equipment required

An independent airport, i.e. an airport with no other neighbouring airports, consitutes an autonomous terminal area which must perform all the functions required to guide the aircraft in the various phases of air navigation as well as on the ground.

The various functions required can be performed by SINTAC-C which offers the following services :

- Navigation : localization by each aircraft of its own position with respect to the geographically known ground stations (aircraft flying or on the ground).
- Landing and take off : measurement of the distance which is the complement to the MLS system.

- Data link : bilateral liaison between ground and aircraft (flying or on the ground).
- Random access : entry in the SINTAC net by an aircraft initiative for an urgent communication.

With the exception of landing, these various functions are obtained by means of 6 stations :

- three ground stations covering the air space of the airport,
- and three small stations covering the ground area of the airport (i.e. runways, taxiways, parking areas).

Note : In some cases, particulary favourable ground configuration (flat land), three stations only located 5 to 7 km apart can perform the simultaneous coverage : air and ground.

The landing function (DME function with DL and voice communications) will be performed by a number of SINTAC-landing type stations equal to the number of runways used.

The coverage of these stations is the same that the coverage of the MLS beam used.

Note : The number of stations must be doubled when the runways are used in the two directions.

Transmission coordination and data processing - transmission, reception, computations, etc - is carried out by a management and computation center.

This center is permanently linked with the regional "SINTAC-C en route" type computation center which handles the traffic on the air routes heading toward the terminal area of the airport.

On the "airborne" side, all the SINTAC functions are performed by a single transceiver.

The airborne equipment can be made redundant for safety considerations.

Figure 2.1.1. illustrates an example of the ground layout of the ground stations of a three runway airport.

2.1.2. - Time organization of the SINTAC-C functions within a 125 msec cycle

The various air and ground time-slots are synchronized by the periodic restting of the aircraft central clock with respect to the high stability (10^{-12}) central clock on the ground.

The synchronization is performed by ground-air-ground information exchange and is part of the "navigation-surveillance" sequences.

Based on the time division, the distribution of the various functions is shown on figure 2.1.2.

The time occupation of each function is given in the following table for a 125 msec cycle (The repetition rate is 8 times per second).

Table 1

Distribution of the SINTAC functions in a 125 msec cycle.

FUNCTION	NUMBER OF TIME-SLOTS (7.8125 msec)
Navigation - surveillance (air)	4
Navigation - surveillance (ground)	4
Landing	2
Data Link	2 (or 1) *
Voice communications	4
Random access	0 (or 1) *

The total number of time-slots is 16 (16 x 7,8125 = 125 msec).

* Every other cycle of the last time-slot is DL or AA.

2.1.3. - Navigation - surveillance - synchronization

A navigation-surveillance sequence consists of two connected time-slots.

Figure 2.1.3. illustrates the distribution of Ground transmissions and Air replies.

The operation mode is the same for TMA transmission (flying aircraft) and GA transmissions (aircraft on ground), only the time-slots are diffgrent.

The navigation function is performed either by the successive transmission of three ground station (S_1 ,S_2 , S_3) whose transmissions are aimed at all aircraft flying in the terminal area (TMA time-slots) or by the three S'_1 , S'_2 , S'_3 , stations whose transmissions are aimed at all the aircraft on the ground (GA time-slots).

The aircraft use these transmissions to determine their respective position with respect to the ground stations (by performing three distance measurements).

There are two navigation transmissions (S_1, S_2, S_3,) for each 125 msec cycle, i.e. 2 x 8 = 16 transmissions per second.

Each aircraft determines its position 16 times per second and thus performs a continuous navigation.

Note : When three ground stations can cover simutaneously the TMA air space and the airport ground area, the number of stations decrease from 6 to 3 ; in this case, there are 4 navigation transmissions for each 125 msec cycle i.e. 32 transmissions per second and the aircraft measurement rate is 32.

For this function, the number of aircraft is unlimited.

This "unlimited" capacity of the navigation function is a feature specific of systems like the SINTAC in which distance measurement is performed with no bilateral exchange (one way measurement) as a result of the airborne synchronized clock.

The "navigation" transmission is performed for all the aircraft with no particular difference and ensures onboard each aircraft a localization rate of 16 (or 32) per second.

Surveillance

The purpose of the surveillance function is to determine the position of the aircraft from the ground.
It is obtained by a cyclical transmission of the aircraft, upon designation by the ground station S1.

Before the three navigation transmissions S_3, S_2, S_1, station S1 designates 8 aircrafts which will perform their surveillance time-slot (the minimum time required to reply is 6,84 ms).

Air aircraft surveillance transmission always contains its identification number, the last distance measured with respect to station S1, its altitude, speed and direction and possible other data.

Each ground station (S_1, S_2, S^3) measures the distance to the transmitting aircraft and, using this measurement and the data contained in the aircraft message, the central computer (on the ground) computes the position of the aircraft.

One time-slot contains 8 surveillance transmissions, 2 x 8 = 16 in a cycle and 8 x 16 = 128 aircraft per second.
System capacity is 128 aircraft per second.
Station S1 calls cyclically all the aircraft within the TMA, thus, the surveillance transmission period will depend on the number of interrogated aircraft. With a 128 aircraft per second capacity, the surveillance period per aircraft is :

0,5 sec. for 64 aircraft
1.0 sec. for 128 aircraft
2.0 sec. for 256 aircraft
3.0 sec. for 384 aircraft
4.0 sec. for 526 aircraft, etc...

System capacity is large and largely sufficient to meet the requirements of an airport. In most cases, the number of aircraft will be lower than 526 and the surveillance period will not be higher than 4 sec. In fact, a longer period would make it difficult for the ground to follow the aircraft. (e.g. in 4 seconds, an aircraft flying at 900 km/H travels ower 1000 meters).

The ground taxiing function (ground navigation and surveillance) is performed by the three specialized stations (S'_1, S'_2, S'_3), as illustrated on figure 2.1.3., in the GA sub-slots.

The navigation capacity of the system is unlimited, while the surveillance capacity is 128 aircraft per second.

As the number of aircraft on ground will seldom exceed 128, the surveillance period of ground aircraft will generally be lower than 1.0 sec.

2.1.4. - Synchronization

Synchronization consists in the cyclical resetting of the aircraft master clock with respect to the ground central clock.
The synchronization procedure is as follows :
The S1 ground station which has received successively the surveillance messages of 8 aircraft computes, for each aircraft, the "corrected" distance.
With DA = distance measured by the aircraft (the value of this distance is retransmitted in the surveillance message).
DS = distance measured by the S1 ground station
DC, the corrected distance, is :

$$Dc = \frac{DA + DS}{2}$$

Dc is the distance with no synchronization error (figure 2.1.4.).

The S1 transmitter retransmits to the aircraft the computed values of the Dc distance in the following navigation time-slot (62,5 msec later) and the aircraft use this information to reset their master clock.

In the same time-slot, S1 specifies 8 new aircraft (by their respective addresses) which will make their surveillance transmission in the next surveillance time-slot. Thus, via cyclical process, each aircraft performs its surveillance transmission and receives the information required to synchronize its own airborne clock.

The time interval between the two distance measurements DA and DS is between 7,8 and 11 msec.

The maximum difference between the 2 measurements is in the range of 3 m (with an aircraft flying at 900 km/H (Δ t = 10 ns). The error is very low and it is not necessary to provide for its correction to perform the resetting of the aircraft clock. The correction can however be performed with respect to the speed and direction of the aircraft.

In the described procedure, the synchronization period is equal to the surveillance period. N = 128 aircraft are synchronized each second.

After a synchronization period T = 4 sec and with a 10^{-8} accuracy airborne clock, the error resulting from the maximum clock deviation with respect to a 10^{-12} ground clock will not exceed t = 40 msec.

2.1.5. - Navigation

For the navigation function. the resulting error of the distance measurement therefore becomes negligible (Δ d = 12 m). For ground taxiing, the synchronization period is approximately 1 sec and the maximum error affecting the distance measurement and due to synchronization will not exceed Δ d = 3 m (Δ t = 10 ns).

The accuracy of localization depends of the distance between the three ground stations (S_1, S_2 , S_3) which are assumed to be located on a circle with a d radius and of the distance X between the aircraft and the center of the circle (Figure 2.1.5.).

For X = 40 km and d = 10 km, the localization error will be in the area of 120 m.
If X = 10, the error is lower than 50 m.
For stations located at a shorter distance (S_1 , S_2 , S_3), e.g. for d = 5 km, the localization error will be approximately 50 m for X = 7 km.

2.1.6. - Landing (take off)

The system performs the distance measurement function during the "landing" and "take off" phases. For the sake of simplicity, only the term landing will be used in the following description.

During the landing phase, angular guidance is performed by the MLS and distance measurement by the SINTAC ; however, aircraft localization by the navigation and surveillance functions is still carried out in the navigation/surveillance time-slots during the complete landing phase and during ground taxiing.

The "landing" MLS + SINTAC procedure completes the SINTAC Navigation/surveillance and provides a better localization accuracy during the final landing phase.

The SINTAC-landing station consists of a ground transceiver located at the end of the runway, on the MLS side.

The station performs essentially the function of a precision DME (measure of distance by pulses obtained by a τ = 200 msec. pulse compression).

By comparison with a precision DME, the SINTAC has additional functions : Data link and voice communications.

The station transmits in the "landing" time-slots (figure 2.1.6.).

In the time organization of the transmissions, two 7.8125 msec time-slots are reserved for this function.

Each landing time-slot is organized as illustrated by figure 2.1.6. and serves four landing runways simultaneously with 16 aircraft per runway (surveillance, synchronization rate : 16 aircraft second).

Services performed are :
- distance measurement (ground-to-air) by each aircraft, 16 times per second.
- distance measurement (air-to-ground) by the ground, once per second, for each aircraft.

Once per second, resynchronization of the master clock of each aircraft.
For less than 16 aircraft in the MLS beam in their landing phase, the rates will be proportionately higher.

For the overall TMA, the maximum number of aircraft in the MLS beam is 64 (4 runways, 16 aircraft per runway).

Note : Should the need arise, it is possible to increase the number of active runways in the TMA by generating parallel nets in the same landing time-slots (e.g. on different frequencies).

Description of the procedure

The ground station transmission contains on one hand the request of a given aircraft (N) (designated by the ground station) and on the other hand the corrected distance information for the synchronization of the aircraft (N -1) which has made its surveillance transmission in the previous time-slot.

The aircraft (N) designated in the "ground" message will reply in the "air" section of the time-slot. Its message contains the last distance measured with respect to the ground station.

This transmission allows the ground station to compute the "ground-aircraft" distance and to compute the corrected distance (required to synchronize the aircraft clock ; see "Navigation-Surveillance).

The time interval between the distance measurement by the aircraft and by the ground is 3,9 msec maximum. In 3,9 msec, an aircraft flying at 100 m/sec (200 knots) travels 0,4 m. This difference between the two measurements is negligible.

The following table illustrates the procedure to be followed for the interrogations and answer (see also figure 2.1.5.).

GROUND TRANSMISSION		AIRBORNE TRANSMISSIONS	
aircraft transmission request	gives the corrected distance for the aircraft	gives the measured distance	correction of the master clock
N - 1	N - 2	N - 1	N - 2
N	N - 1	N	N - 1
N + 1	N	N + 1	N
N + 2	N + 1	N + 2	N + 1

2.1.7. - Data link

In the time-division organization of the functions, 1 or 2 time-slots are alternatively reserved for the Data Link (DL) function in each 125 msec cycle (4 time-slots with 2 DL, 4 times-slots with 1 DL + 1 A.A.).

A 7.8125 msec time-slot provides for 4 two-way DL links - figure 2.1.7. The total number of DL links per second is :

N = (4 x 2) + (4 x 1) x 4 = 48 DL/sec

Output capacity of a DL :

9 x 15 bit words

(+ preamble and pre-synchronization)

DL capacity can be increased by performing simultaneous transmissions in the same DL time-slot, on different nets for the "airport" and "landing" transmitters.

Each transmitter will communicate with the adjacent aircraft.
Table 2.1.7. shows the various possible solutions which can be used to organize the DL nets.

2.1.8. - Voice communication time-slots

On figure 2.1.2. the time division of a 125 msec contains 4 time-slots of 7.8125 msec reserved for the transmission of digitalized voice information.
Using a transcoding system with a 9,6 kbits/sec rate, it is possible to create a voice channel by time-slot, thus a total of 4 voice channels for the 4 time-slots desired.

Figure 2.1.8. shows the organization of the voice transmission in a 125 msec cycle and within a 7.8125 msec time-slot.
A time-slot is divided in two equal sections and a 3.419 msec transmission is performed in each half time-slot.

3,419 msec → 263 symbols of 13 µs
→ (preamble + synchro + message) =
(6 x 13 µs + 4 x 13 µs + 253 x 13 µs)
253 symbols → 5 x 253 = 1265 bits = 1,265 kbits

A second contains 16 voice half-slots ; thus, the rate capacity of a channel is :
1,265 x 16 = 20,24 kbits
(thus, messages can be easily transmitted with 9,6 kbits/sec).

Note : The number of voice channels can be increased by carrying tout simultaneous transmissions in the same voice time-slot on the particular nets of the SINTAC functions or for each ground transmitter.
In the latter case, each transmitter will only communicate with the aircraft which are the closest to it.
For example, with the S_1, S_2, S_3 transmitters, it is possible to create 3 x 4 = 12 voice channels.

The following table gives the mean time between two voice messages, for the same aircraft (voice period).
- accounting that the mean duration of an exchange is 10 seconds (more than sufficient as the existence of the DL in the system results in a significant decrease of the need to use a voice link),
- and considering that the aircraft load of each function is maximum (which is pessimistic considering the large capacity of the system).

The following table gives the voice period with respect to the number of nets used.

A) One net for all areas

N/S (TMA) : 2 channels 512 : 2 = 26 aircraft/channel T = 2560 s
N/S (GA) : 1 channel 128 : 1 = 128 aircraft/channel T = 1280 s
Landing (4 RW) : 1 channel 16 x 4 = 64 aircraft/channel T = 640 s

B) One voice net per area

(voice transmission in parallel, in the same time-slot)
N/S (TMA) : 4 channels 512 : 4 = 128 aircraft/channel T = 1280 s
N/S (GA) : 4 channels 128 : 4 = 32 aircraft/channel T = 320 s
Landing (4 RW) : 4 channels 16 : 1 = 16 aircraft/channel T = 160 s

C) One voice net per ground transmitter

(voice transmission in parallel in the same time-slot)
N/S (TMA) : 4 x 3 = 12 channels 512 : 12 = 43 aircraft/channel T = 430 s
N/S (GA) : 4 x 3 = 12 channels 128 : 12 = 10,6 aircraft/channel T = 106 s
Landing (4 RW) : 4 x 4 = 16 channels 16 : 4 = 4 aircraft/channel T = 40 s

2.1.9. - Random access

Each other 125 msec cycle contains a 7.8125 msec time-slot reserved for random access (RA). Thus, there are four RA time-slots per second - Each time-slot gives 16 possible entries, i.e. ; a total of 64 entries per second.

Allowing that during each hour 100 aircraft request a random access, each request will be at a 36 seconds interval. Under these assumptions, the probability of the requesting aircraft being alone in one of the (36 x 64 = 2304) RA sub-slots is very high and the random access will take place in less than one second.

Once the ground has received the request, the ground enters in a DL communication with the requesting aircraft (in the following DL time-slot).

Random access is used at the initiative of the aircraft when an urgent communication (less than 1 sec) must take place with the ground.

2.1.10. - Example - The following example shows the capacity of the system for a medium-size airport

Terminal area : 256 aircraft
Ground taxiing : 64 aircraft
Landing : 8 aircraft

Total number of aircraft : 328 aircraft

Surveillance/synchronization period :

Terminal area : 2 sec (256/128)
Ground taxiing : 0,5 sec (64/128)
Landing : 0,5 sec (8/ 16)

Data link : (meantime)	One net	Several nets
Terminal area :		1,25 sec (4 nets)
Ground taxiing :	≈ 6,8 s	1,5 sec (1 net)
Landing	(328/48)	1/6 sec (1 net/runway)

Voice communications * Distribution period	Several nets
Terminal area : (12 channels/3 nets)	21 aircraft/channel T ≈ 3'
Ground taxiing : (4 channels/1 net)	16 aircraft/channel T ≈ 3'
Landing : (4 channels/1 net per runway)	2 aircraft/channel T ≈ 20 s

* 1 two-way communication ≈ 10 seconds.

2.2. - Several airports with a common terminal area

In heavy air traffic areas where several airports are close to each other (large cities) air navigation traffic in the area common to the various airports can be performed by the SINTAC-TMA multi-airport service.

Figure 2.2.1. shows six airports within a large terminal area.

The organization of each airport is identical to the organization of an isolated airport - This organization has been previously described. Each airport operates on a specific net (with 3 ground stations only). However, aircraft guidance beyoud the area close to the airports is performed by 3 or 4 ground stations carrying out the following functions :

- Navigation,
- Surveillance,
- Data link,
- Voice communication,
- Random access,

The multi-airport SINTAC-TMA has its own net ; its coverage is approximately a 50 Nmi radius and 7600 m high cylinder.
The time division organization of the various functions is illustrated on figure 2.2.(the ATT time-slots are replaced by the DL time-slots).
The internal organization of the time-slots is identical to the organization described for an isolated airport.
Distribution of time-slots : 7,8125 msec in 125 msec.

FUNCTION	NUMBER OF TIME-SLOTS
Navigation	4
Surveillance	4
Voice communications	4
Data link	4 (or 3) *
Random access	0 (or 1) *

* last DL or AA time-slot, every other cycle.
With this distribution, the capacity of the system is :

- Navigation : 32 measurements/sec/aircraft
  Number of aircraft : unlimited (continuous navigation)
- Surveillance : 256 aircraft/sec
  (synchro)
- Data link : 112 DL/sec
  rate (preamble + synchro + 9 words of 15 bits)
- Voice communications : 4 channels
  rate 9,6 kbits/sec

Note : The voice and DL capacity can be increased by the simultaneous use of 4 SINTAC-TMA transmitters, each operating on a specific net, in the same DL or voice time-slot.

Each transmitter communicates with the aircraft in its close neighbourdhood. In this case, the number of DL/sec increases from 112 to 448 and to 16 from 4 voice channels.

System capacity is very large :
for a T = 4 sec surveillance period, the number of aircraft monitored is : 1024.
Management of the 4 ground stations is performed by a data computing and processing center connected with airport own computing centers.

2.3. - Adjacent terminal areas

As the locations of the various airports is such that coverage by a single multi-airport SINTAC-TMA net is not feasible, other stations of the SINTAC-TMA type must be added to the 4 stations of a single net. There are two basic solutions to the coverage extension problem.

The first is to keep the single net and to add the required number of stations(figure 2.3.1.) to achieve continuity in the required area. The system operates according to the time division principle and transmissions are performed with three stations which are in the best location to communicate with a given aircraft.

Management of the overall system is carried out by a single computing center and system expansion is only effected by means of additional stations(RX - TX).

The surveillance/navigation capacity of the expanded system is identical to the case of a 4 station net, i.e. 256 aircraft/sec. That is to say a surveillance/synchronization capacity of 1024 aircraft for a 4 sec period (complete net).

This aircraft capacity is sufficient for most cases.
DL and voice capacity increase in relation with the number of stations added using the same number of nets than stations for these functions.

Theoretically, the navigation capacity remains unlimited, due to the principle of the system. However, in pratical conditions, when the ground transmitters operating do not see some aircraft these one loose the navigation data, (during some N/S slot).

To offset this drawback, ground transmitters will be cyclically exchanged, to cover periodically the TMA coverage.
The other solution to effect the general coverage of a very large terminal area where traffic density is too large for a single net, is to use several separate nets (figure 3.2.).

In this case, each net operates autonomously with its own computing and processing center.

The centers are interconnected to transfer aircraft from one area to the other.
In addition to the additional ground stations, this solution requires a computing center, thus it is more costly than the first solution ; however, this is compensated by a larger capacity as each net keeps its maximum capacity.

3 - AIRBORNE SINTAC EQUIPMENT

All SINTAC-C functions will be performed by a single airborne transceiver.
The antenna will be an omnidirectional DME band L type antenna.
For safety reasons, the airborne equipment will be redundant.

4 - POWER OF GROUND TRANSMITTERS

(all figures stated are to be considered as undications)
TMA ground transmitter (R ≈ 100 km) p = 30 - 100 W
GA ground transmitter (R ≈ 10 km) p = 1 - 3 W
Landing ground transmitter (R ≈ 35 km) p = 5 - 15 W

The ATT transmission and in many cases the GA transmission are directional, thus the required transmitter power will be a function of the antenna gain to provide a given coverage.

ABBREVIATIONS USED

TMA : Terminal movement area (ZT)
AA : Random access
N/S : Navigation/surveillance
GA : Ground area (RS)
S : Ground station
B : Airborne station
Ph : Voice communications
DL : Data Link
CCT : Terminal computer center
TC : Control tower
CCR : Regional control center

SINTAC : Integrated Navigation, traffic control, collision avoidance and communication system.

SINTAC C : Civilian SINTAC.

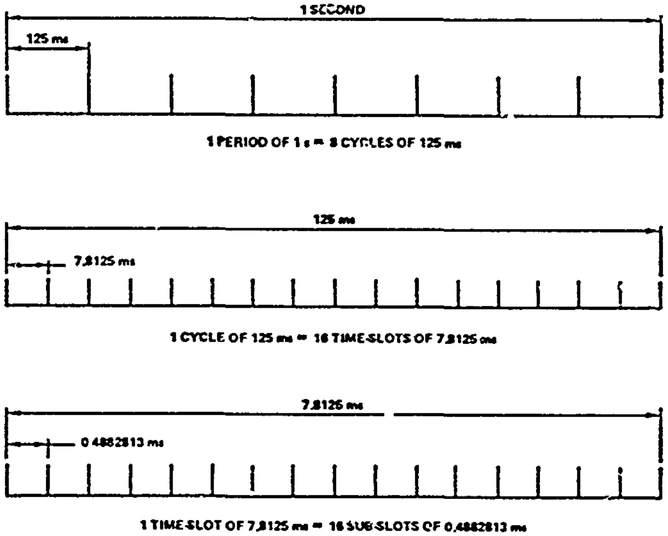
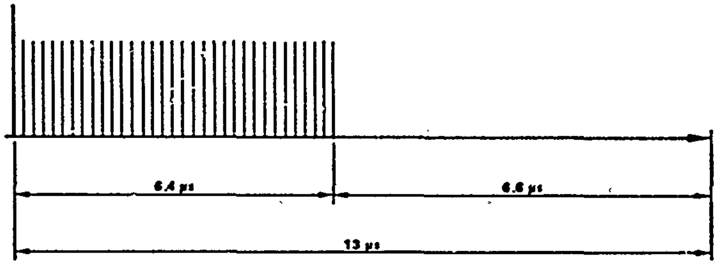


FIGURE 1-1 1 - SINTAC-C TMA TIME DIVISION



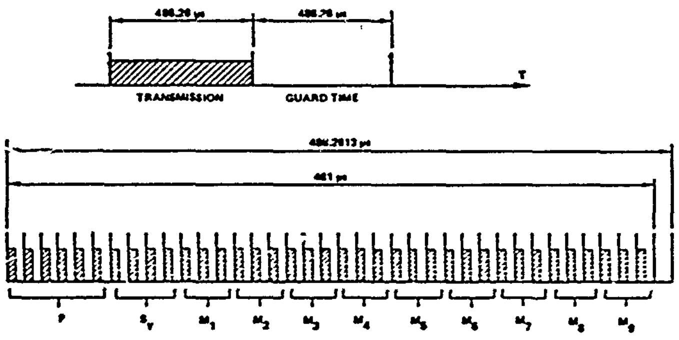
- 32 CHIPS OF 0,2 µs → 6,4 µs

  MODULATION : MSK

  1 SYMBOL → 5 BITS (2^5 = 32)

- 6,6 µs GUARD TIME
- LENGHT OF A SYMBOL : (6,4 + 6,6) = 13 µs

FIGURE 1-2-1 - SINTAC-C TMA TRANSMISSION SYMBOL



P = PREAMBLE 6 x 13 = 78 µs

S_y = SYNCHRONIZATION 4 x 13 = 52 µs

M = MESSAGE 9 x 3 x 13 = 351 µs

481 µs

MESSAGE = 9 WORDS OF 15 BITS

FIGURE 1-2-2 - SINTAC-C TMA MESSAGE

SYSTEM CAPACITY (SUMMARY)

NAVIGATION (TMA)

- Number of aircraft : non limiting (∞).
- Aircraft localization rate : 16/sec. or 32 sec.
- Function : continuous navigation.

SURVEILLANCE (TMA)

- Number of aircraft : 128 sec.
- Capacity for $T \leq 4$ sec. : 512 aircraft

NAVIGATION (SURFACE)

- Number of aircraft : non limiting (∞).
- Aircraft localization rate 16/sec. or 32/sec.
- Function : continuous navigation.

SURVEILLANCE (SURFACE)

- Number of aircraft : 128/sec.

SYNCHRONIZATION OF AIRCRAFT'S MASTER CLOCK :

- Number of aircraft : 128/sec.

DATA LINK :

- Bidirectional DL/net : 48/sec.
- One DL capacity : 9 words of 15 bits.

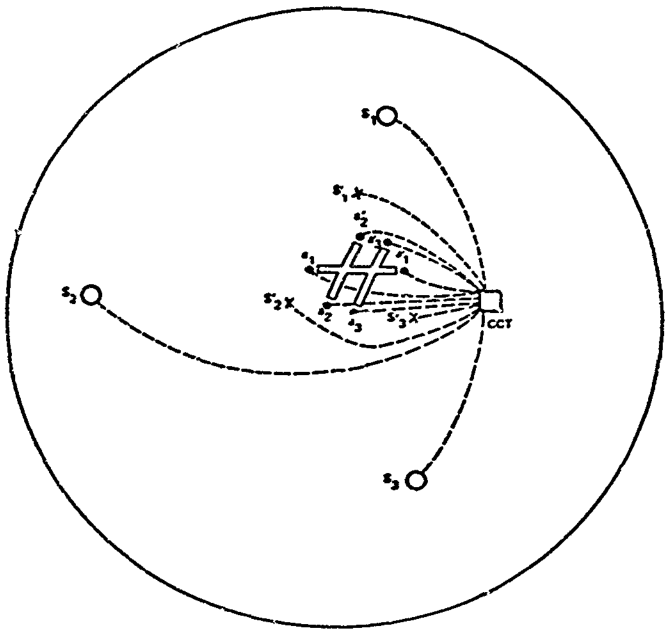
VOICE COMMUNICATIONS :

- Number of channels : 4.
- Rate : 9.6 k bits.

LANDING :

- Airborne measuring period : 1/16 sec.
- Ground capacity : 10 aircrafts/runway/sec.

TABLE 2-1



S_1 S_2 S_3 GROUND STATIONS TYPE : TMA (≃ 60 Nm)

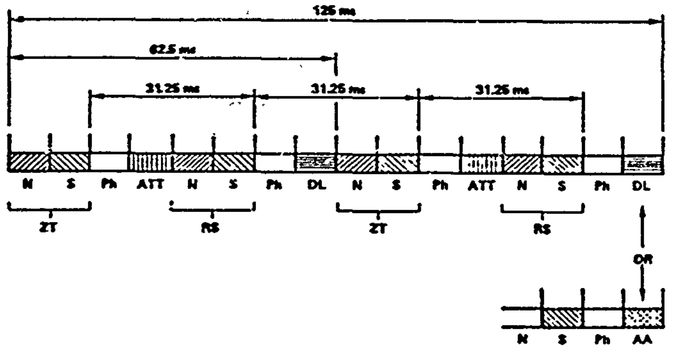
S'_1 S'_2 S'_3 GROUND STATIONS TYPE : R.S.* (≃ 7 Nm)

a_1 a_2 a_3 + (a'_1 a'_2 a'_3) GROUND STATIONS TYPE : «LANDING» (≃ 25 Nm)

C.C.T TERMINAL COMPUTER CENTER

* R.S. GROUND NAVIGATION

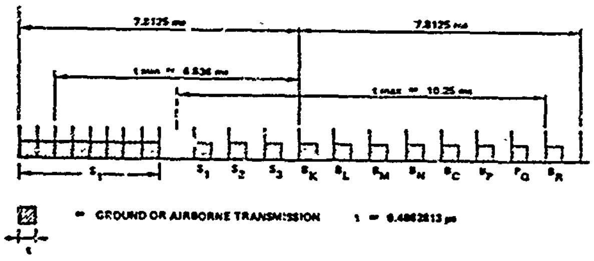
FIGURE 2-1-1 - SINTAC INSTALLATION IN AN AIRPORT



	FUNCTIONS	NUMBER OF TIME-SLOTS
N/S	NAVIGATION/GROUND SURVEILLANCE-TMA	4
Ph	VOICE-FREQUENCY	4
ATT	LANDING	2
N/S - RS	SURFACE NAVIGATION AND SURVEILLANCE	4
DL	DATA LINK	2 * (OR 1)*
AA	RANDOM ACCESS	8 * (OR 1)*
		16

* 1 CYCLE OF 2, LAST TIME-SLOT : DL OR AA.

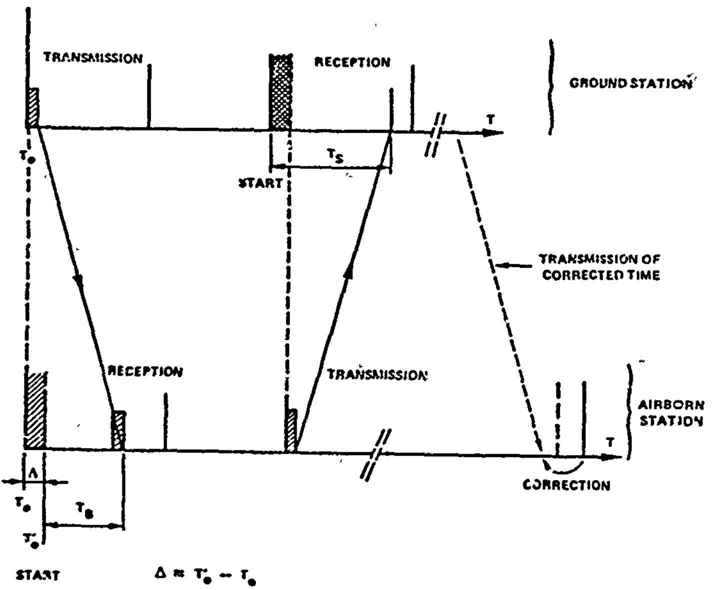
FIGURE 2-1-2 - ORGANIZATION OF THE TIME-SLOTS OF A SINTAC-C TMA CYCLE



= GROUND OR AIRBORNE TRANSMISSION $\tau = 0.4882813\ \mu s$

S_1 S_2 S_3	GROUND STATIONS
B_K to B_R	8 DIFFERENT AIRCRAFT TRANSMISSIONS
NAVIGATION	: 16 (OR 32) LOCALIZATION MEASUREMENTS PER SECOND FOR ALL AIRCRAFTS.
SURVEILLANCE (GROUND SIDE)	: 128 (2 x 8 x 8) AIRCRAFTS/sec.
SYNCHRONIZATION	: 128 AIRCRAFTS/sec.

FIGURE 2-1-3 - TIME DIVISION OF "GROUND" AND "AIRBORNE" TRANSMISSIONS, NAV. AND SURV. FUNCTIONS



$$\Delta = T'_e - T_e$$

$$T_C = \frac{T_B + T_S}{2}$$

$$\Delta = \frac{T_S - T_B}{2}$$

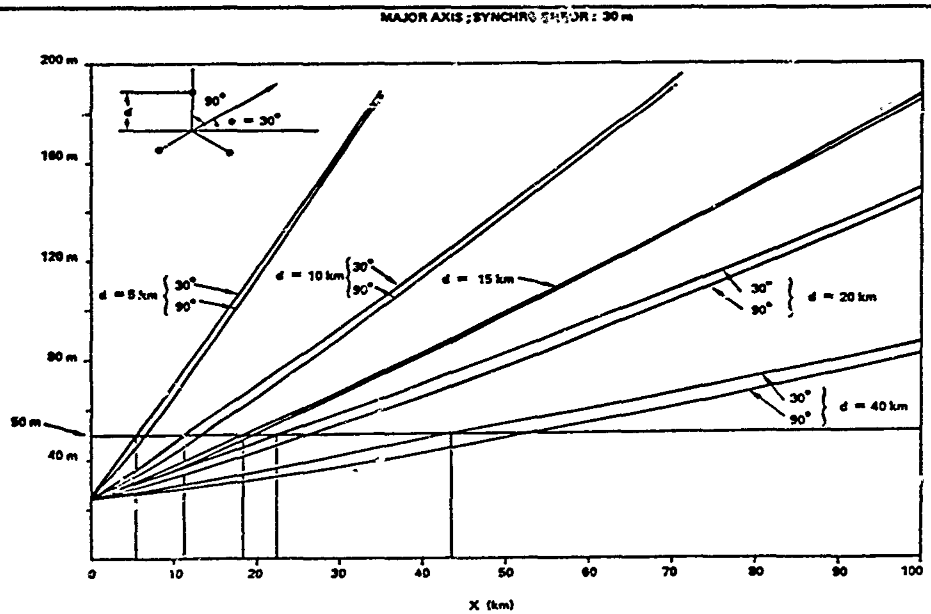
EXAMPLE $T_B = 54\ \mu s$

$T_S = 60\ \mu s$

THE CORRECTED TIME IS $T_C = \frac{60 + 54}{2} = 57\ \mu s$

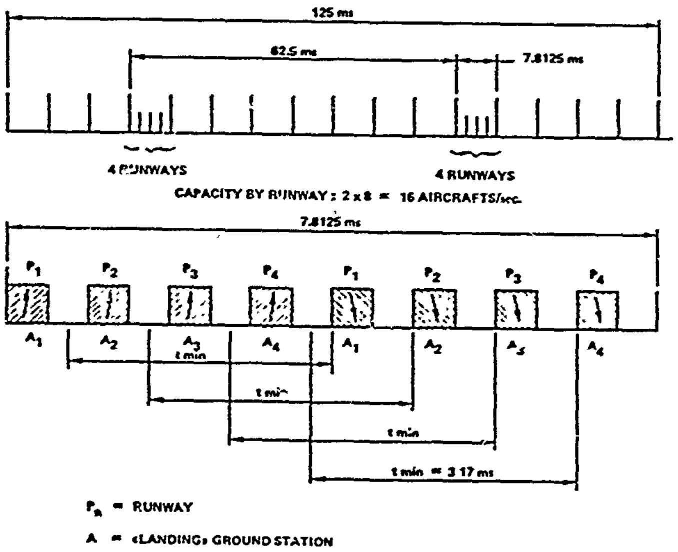
CORRECTION $\Delta = 3\ \mu s$

FIGURE 2-1-4 - SYNCHRONIZATION PROCEDURE



MAJOR AXIS ; SYNCHRO ERROR : 30 m

FIGURE 2-1-5 - NAVIGATION ERROR OF MOVING TARGETS WITH THE SINTAC-C TMA SYSTEM



«GROUND» STATION		«AIRBORNE» STATION	
AIRCRAFT TRANSMISSION REQUEST	GIVES THE CORRECTED DISTANCE FOR AIRCRAFT :	GIVES THE MEASURED DISTANCE	CORRECTION OF THE CENTRAL CLOCK
(N - 1)	(N - 2)	(N - 1)	(N - 2)
N	(N - 1)	N	(N - 1)
(N + 1)	N	(N + 1)	N

62.5 ms

62.5 ms

FIGURE 2-1-6 - TIME DIVISION OF "GROUND" AND "AIRBORNE" TRANSMISSIONS IN A "LANDING" TIME-SLOT (4 RUNWAYS CAPACITY)

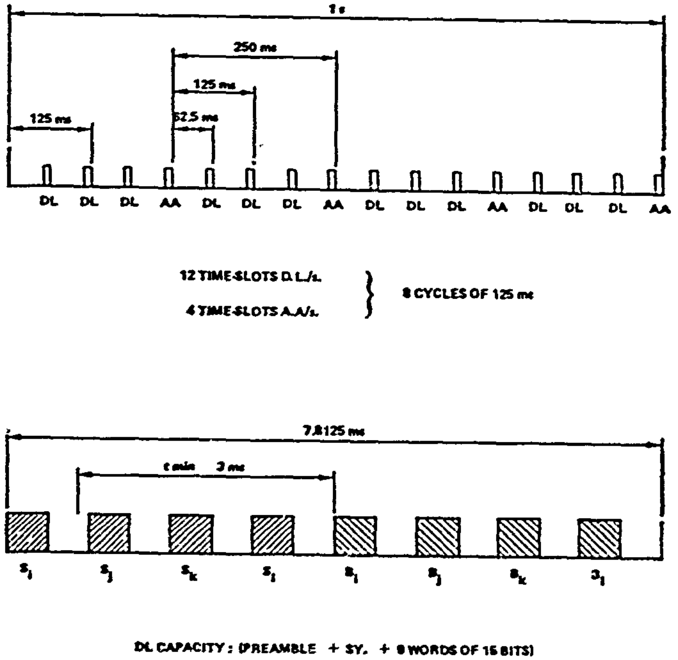


FIGURE 2-1-7 - DATA LINK : FUNCTION ORGANIZATION OF CYCLES AND TIME-SLOTS

DL NET (CAPACITY)

A — ONE DL NET FOR ALL THE AREAS

AREA	NUMBER OF TIME SLOTS	DL/TIME-SLOT	DL/s.	DL PERIOD (MAX)
N/S TMA	8	4	32	512/32 = 16 s
N/S GA	2	4	8	128/8 = 16 s
ATT	2	4	8 *	16/2 * = 2 s

B — ONE DL NET PER FUNCTION

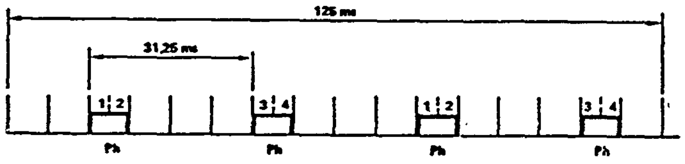
AREA	NUMBER OF TIME SLOTS	DL/TIME SLOT	DL/s.	DL PERIOD (MAX)
N/S TMA	12	4	48	512/48 = 10,66 s
N/S GA	12	4	48	128/48 = 2,56 s
ATT	12	4	48 *	16/12 * = 1,33 s

C — ONE DL NET FOR EACH GROUND TRANSMITTER

AREA	NUMBER OF TIME SLOTS	DL/TIME SLOT	DL/s.	DL PERIOD (MAX)
N/S TMA	12	4	48 x 3 = 144	512/144 = 3,55 s
N/S GA	12	4	48 x 3 = 144	128/144 = 0,888 s
ATT	12	4	48	16/48 = 0,333 s

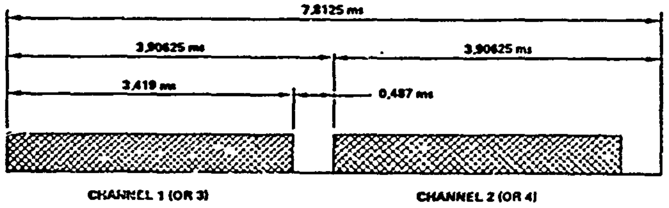
* DURING LANDING, THE DL ARE SHARED BETWEEN 4 RUNWAYS.

TABLE 2-1-7 - DL PERIOD / AIRCRAFT



125 ms → 4 TIME-SLOTS Ph

1 s → 8 x 4 = 32 TIME-SLOTS Ph



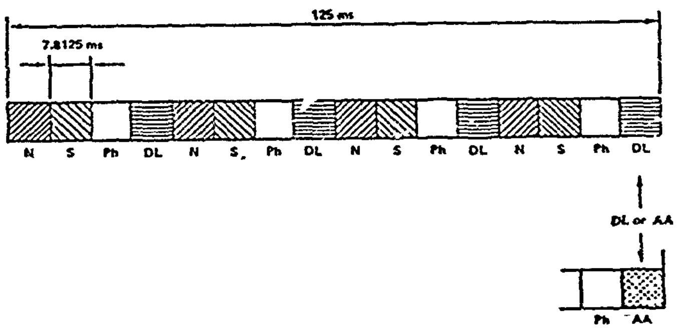
3,410 ms → 263 SYMBOLS OF 13 µs

→ (PREAMBLE + SY. + 1.265 k BITS)

ONE CHANNEL, CAPACITY/sec. : (1,265 x 16) = 20.24 k BITS

VOICE FREQUENCY RATE : 9.6 k BITS/sec.

FIGURE 2-1-8 - ORGANIZATION OF VOICE FREQUENCY TIME-SLOTS



FUNCTIONS		NUMBER OF TIME SLOTS/125 msec.	
NAVIGATION	(N)	4	
SURVEILLANCE	(S)	4	
VOICE COMMUNICATIONS	(Ph)	4	
DATA LINK	(DL)	4 (or 3) *	ALTERNATELY
RANDOM ACCESS	(AA)	0 (or 1) *	

CAPACITY WITH ONE NET *

NAVIGATION	– 32 LOCALIZATIONS/AIRCRAFT/sec – NUMBER OF AIRCRAFTS : NON LIMITING (∞)
SURVEILLANCE (+ SY)	– 256 AIRCRAFTS/sec.
VOICE	– 4 CHANNELS RATE : 9 6 k BITS
DATA LINK	– 112 DL/s USEFUL CAPACITY : 5 WORDS OF 15 BITS
RANDOM ACCESS	– 64 POSSIBLE ENTRIES/sec (16 x 4)

(REMARK : DL ⟶ DOUBLE DL GROUND ⟶ AIR)

FIGURE 2-2 - TIME SHARING OF FUNCTIONS FOR TMA COVERAGE

ARTIST VIEW OF A SINTAC-C TMA, WITH 6 AIRPORTS AND 15 RUNWAYS

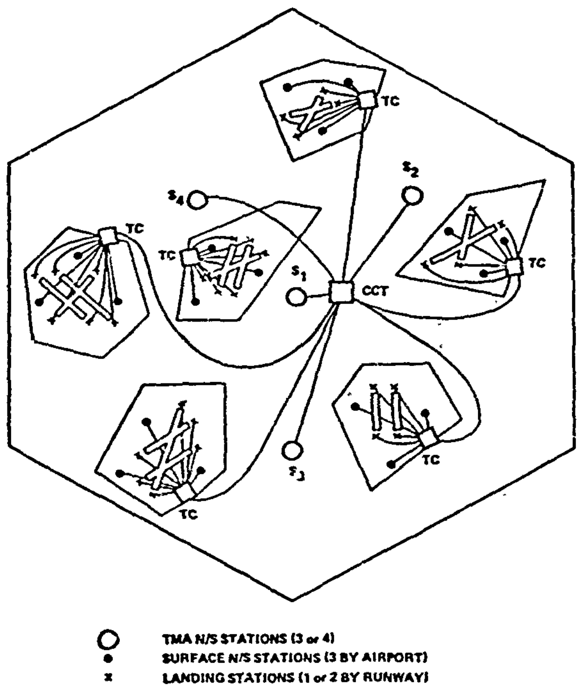


FIGURE 2-2-1 - TMA WITH SEVERAL AIRPORTS

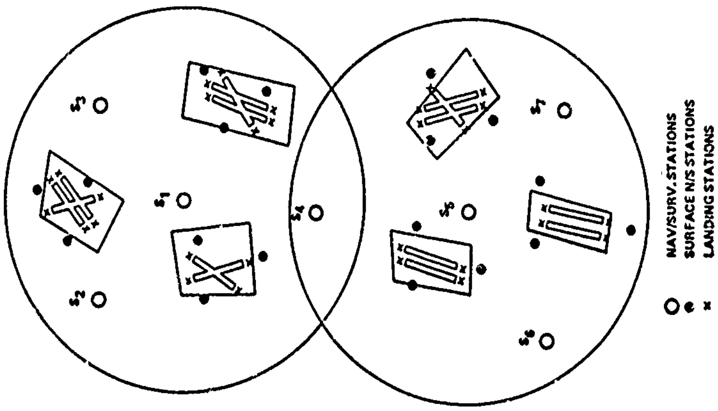


FIGURE 2-3-1 - EXTENSION OF THE TMA

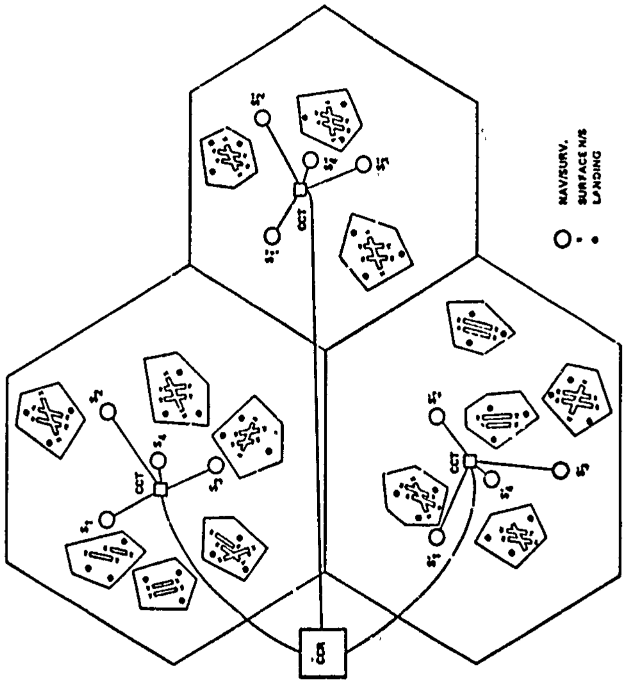


FIGURE 3-2 - MULTIPLE TMA-S

EVOLUTION AND TRANSITION OF TODAY'S MILITARY LANDING SYSTEM TO COMPATIBILITY WITH PRESENT AND FUTURE CIVIL/MILITARY SYSTEMS

by

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SUMMARY

The operational need for a single avionics system to operate with the present Instrument Landing System (ILS), the future ICAO approved Microwave Landing System (MLS), and the Marine Remote Area Approach Landing System (MRAALS), is discussed. The operational solution developed in response to a U.S. Navy/Marine requirement is a Multimode Receiver (MMR) that is capable of operating with any of the systems mentioned above. The evolutionary process involved in progressing from a single to a multiple mode system capability is reviewed with emphasis on the technological advances leading to a most cost and volume effective solution.

THE NEED FOR INTEROPERABILITY

The current ILS, operating at 110 MHz and 330 MHz, has served well for over 30 years, however, it has remained relatively unchanged over that period. During this time the requirements for landing systems and the characteristics of aircraft have changed, leading to the development of the MLS system to meet present and future needs. In addition, the military have special requirements peculiar to the tactical environment. Faced with having to operate in both the changing civil as well as the tactical environments, military aircraft must be provided with all three capabilities. To provide separate avionics for each, namely the ILS which will probably not be phased out for many years, the MLS which will be phased in over the next decade, and the tactical landing systems currently in production, would pose an unacceptable burden on the aircraft. Hence, the need for a military interoperable airborne landing system receiver which is volume interchangeable with the current single capability receiving set.

The recently issued U.S. Navy Requirement Document No. N00019-79-Q-0065, Attachment 1, defines an interoperable Multimode Receiver (MMR). The key requirements called for are:

- ILS operation to the requirements of RTCA Documents Nos. DO-131 (Glideslope) and DO-132 (Localizer)
- Marker Beacon Operation per RTCA Document No. DO-143
- MLS operation per FAA-ER-700-08C
- Pulse Coded Scanning Beam capability with the MRAALS (AN/TPN-30), AN/SPN-41 or AN/TPN-28 systems.
- Range information in conjunction with on-board TACAN or DME per MIL-STD-291B

The operation in all modes listed above must encompass the features of that mode, i.e., flare-out, course softening, use of back course, precision range and range rate, and pilot selectable glideslope.

DESCRIPTION OF RELEVANT LANDING SYSTEMS

The standard ILS system is familiar to everyone. It is a fixed-beam system which provides a single path to touchdown by means of a Localizer (110 MHz) and a Glideslope (330 MHz) set of equipments. The Localizer and Glideslope frequencies are paired to provide twenty operational channels. The desired path is defined by an equisignal condition of the 90 Hz and 150 Hz radiated antenna beam modulations. Decision positions along the approach path are designated by 75 MHz marker beacons placed on the approach centerline. This system is deployed world-wide in the civil environment.

The MLS is a C-Band system (200 channels at 5 GHz) defined in FAA-ER-700-08C which provides Category III landing capability utilizing a Time Referenced Scanning Beam (TRSB) providing azimuth and elevation guidance. Accompanying auxiliary data is transmitted to permit offset siting, course softening and conical beam geometry corrections to be computed by the airborne receiver. The angle guidance information is provided by the scanning of the azimuth (or elevation) beam back and forth (TO and FRO) across the approach region. The time interval between successive crossings of the beam detected by the airborne receiver provides the measure of angular position. The guidance function being transmitted is identified by a preamble which is applied on the signal using differential phase shift keying (DPSK). This method of keying is also used to transmit ground system status, volume coverage, station identification, safety of flight data, ground system configuration, deployment geometry and meteorological data.

The tactical system of interest, the U.S. Navy/Marine Corps. Remote Area Approach and Landing System (MRAALS) which was developed and is being produced by The Singer Company represents the third type of system.

The MRAALS system, consisting of an AN/TPN-30 Ground Station and the AN/ARN-128 airborne set, is probably the least familiar of the systems mentioned so far. Because it is the antecedent of the specific equipment which has evolved as the answer to interoperability and because it is one of the systems with which interoperability is required, it will be described in some detail.

MRAALS SYSTEM DESCRIPTION

The MRAALS tactical landing system provides azimuth, elevation, range and range rate information of a quality suitable for Category II operation. Figure 1 shows the signal flow between the ground and airborne elements of the system. The salient system characteristics are summarized in Figure 2. Two pulse coded scanning fan shaped beams are provided by the ground station, one sweeping vertically to provide elevation angle data and the other sweeping horizontally to provide azimuth angle data. Figure 3 shows the approach coverage of the angle guidance signals, as well as the total DME coverage. The beams are pulse coded with a stream of pulse pairs wherein the separation between pulses of a pair denotes the function (AZ and EL) and the separation between pulse pairs denotes the instantaneous angle data. The pulse pairs are also modulated with an additional 0.5 microsecond increment to indicate a zero or one's bit so that auxiliary data including Morse Code can be identified.

MRAALS GROUND STATION (AN/TPN-30) DESCRIPTION

The ground station shown in Figure 4 is a single unit packaged so that, when it is folded up into its transport configuration, it can be man portable without any additional carrying case. The entire ground station weighs 52 kg (115 lbs.) and is 97 cm X 104 cm X 66 cm (38 in. X 41 in. X 26 in.) including the DME station. This single unit is capable of providing all of the functions required for a Category II landing capability. If one unit is used, then of necessity, the Glideslope and the Localizer signals would originate from that unit. However, two ground stations may be tied together via an interconnecting cable or via a radio link so as to provide split-site operation wherein the Glideslope information originates from the station offset at the Glidepath Intercept Point and the Localizer from the station at the stop end of the runway. The fan beams in either configuration (Figure 3) scan the entire approach corridor up to ±20 degrees horizontally and 0-20 degrees vertically and to a distance in excess of 10 nautical miles in 25 mm/hr. rainfall. All aircraft in this volume receive guidance information simultaneously. Among the special features provided by the ground station are rapid set up (10 minutes), remote control, self-contained test and monitoring of the radiated signals, integral precision DME, built in optical alignment and obstacle determination and provision for radio linked split site synchronization and control.

Figure 5 is an exploded view of the TPN-30. The scanning beams are generated by the rotation of a set of lightweight feed waveguides arranged like the spokes of a wheel. Half of the spokes are for the vertically scanned beams (Glideslope) and the other half for the horizontally scanned beams (Localizer). These feed guides receive microwave energy at the hub of the wheel as they move past a non-contacting coupling and, one at a time, they illuminate a folded pillbox radiator from which the shaped beam emanates and scans as the feedguide moves through the pillbox. It is obvious that a conventional feed impinging upon the circular reflector would produce unsatisfactory beam shapes. To provide high quality scan patterns across the circular reflector a correction lens is employed at the exit of each feed assembly.

This technique for generating the scanning beams has several unique features:

- The intermittent scan is produced by a continuously rotating mechanism.
- The rotating feed system is very light.
- The rotating feed system is entirely enclosed and protected from external wind loads.
- The required drive power is very low (6 watt - Size 11 Motor).

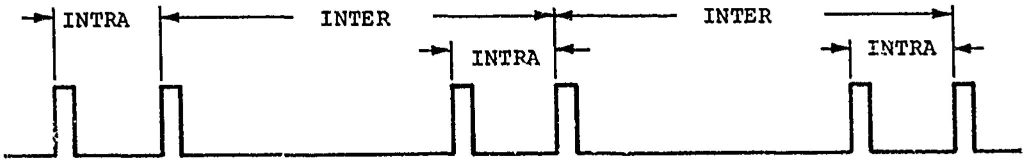
- The rotational speed is one fourth of the scan rate due to the multiplicity of feed spokes.
- The same rotating structure produces both azimuth and elevation scanning beams mechanically synchronized to each other.

In addition to radiating the angle guidance information, the TPN-30 provides DME out to greater than 40 nautical miles, with precision DME furnished within 3 nautical miles. The DME elements are shown in Figure 5.

In order to align the ground station during initial set-up, an optical sight permanently mounted to the antenna structure aligned to the zero reference direction of the antenna beams is provided. The operator typically sees the image depicted in Figure 4, which projects a calibrated reticle into the approach space and allows determination of obstacle locations as well as course alignment. Observed obstacle warning limits are encoded on the transmitted beams using this visual determination and the control panel.

The radiated signal modulation format, which consists of a stream of paired pulses, is displayed below.

AZ/EL SIGNAL FORMAT



The intra pulse spacing identifies the type of beam being transmitted. This spacing is nominally 12 microseconds during elevation transmission and 14 microseconds during azimuth transmission. These spacings are increased by 1 microsecond to provide an additional channel at each RF frequency. In addition to identifying the angle function, the intra pulse spacing is used to provide auxiliary data such as ground system configuration (split site/co-located), Morse code station identification and operating channel identification by incrementing the intra pulse interval by 0.5 microsecond to form a zero or one's bit.

The inter pulse spacing provides Glideslope or Localizer angle information. As the antenna scans, interpulse-pair spacing changes by 2 microseconds per degree of antenna rotation.

In the case of elevation, the interpulse spacing begins at 60 microseconds corresponding to zero degrees of elevation and increases at 2 microseconds per degree up to 100 microseconds corresponding to 20 degrees of elevation. For azimuth the interpulse spacing begins at 100 microseconds corresponding to 20 degrees left of center, decreases to 60 microseconds at zero degrees and increases again to 100 microseconds at 20 degrees to the right of center. The right or left of center information is transmitted as information on the intrapulse spacing.

MRAALS AIRBORNE EQUIPMENT (AN/ARN-128) DESCRIPTION

The AN/ARN-128 is the baseline configuration and point of departure for our interoperable discussions. It is comprised of the five boxes shown in Figure 6. The Control Unit provides for the selection of Power On/Off, Channel, Glideslope Angle, Built-In-Test and Course Softening.

The AN/ARA-63 Receiver and Modified Decoder assemblies receive and process the angle signals from the MRAALS TPN-30, the shipborne SPN-41 or the ground-based TRN-28. To accommodate MRAALS, the decoder unit was modified to permit automatic course softening which required ±18° linear range in azimuth and ±5° linear range in elevation. Previous limits were ±6° and ±1.4°, respectively. These assemblies working in conjunction with the three remaining units of the ARN-128 system provide pilot selectable Glideslope and obstacle avoidance (for helicopter use) as well as range and range rate when coupled to a TACAN receiver such as the AN/ARN-52, -84 or -118. The Navigational Computer employes an 8 bit, 2 MHz microprocessor (Intel-8080). It accepts either the SPN-41, TRN-28 or MRAALS signals and provides landing angle guidance on one of 10 pilot selectable Glideslopes (3°-12°). When used with the TPN-30 it provides course softening. An obstacle warning is generated when the aircraft descends to within 0.5 degrees of the obstacle limit transmitted by the ground station. The angular location of the obstacle is also provided on a third needle of a Cross Pointer Indicator which is positioned relative to the horizontal needle.

The Functional Block Diagram of Figure 7 shows the relationship of the ARN-128 components and details functions of the Navigation Computer. The microprocessor performs the DME signal processing function. It utilizes this range information to provide course softening which is a proportional reduction of the fly left/right signal sensitivity at ranges less than 3/4 mile from touchdown. Without "softening" the course becomes too "tight" to fly at very close range. A separate circuit performs the decoding function for the auxiliary data. Because the microprocessor is used to provide only the range function, it is very lightly time-loaded. Computer loading is illustrated in Figure 8 and identifies the fraction of available time used by the DME as being less than 20%. The unused capacity of the microprocessor was fully utilized in the next phase of evolution toward interoperability.

PCAS (PERFORMANCE COMPATIBLE AVIONICS SYSTEM) DESCRIPTION

In 1976 the U.S. Navy issued a requirement to make the AN/ARN-128 compatible with the civil MLS Specification #FAA-ER-700-08. In evaluating the means available to perform this added task it was recognized that the excess capacity of the 8080 microprocessor in the ARN-128, as mentioned above, could be programmed to decode and process both the angle signals and the range signal by the addition of four memory flatpacks.

The microprocessor could further be used to decode the auxiliary data and provide the AGC. Placing the angle processing in the computer eliminated the need for the AN/ARA-63 Decoder unit, thus reducing the total number of boxes from 5 to 4. The resultant configuration is shown in the functional block diagram of Figure 9. The microprocessor now receives the outputs of the Time of Arrival Detectors (TOAD) in the DME and angle guidance channels and performs the DME acquisition and tracking functions as before, plus the angle measurement, auxiliary data decoding and AGC functions. A dual band frequency synthesizer was developed to replace the local oscillators of the ARA-63 receiver and provide 200 channel tuning at C-Band and 10 channels at K-Band without increasing the outline dimensions of the receiver unit. The Navigational Computer in addition converts the MLS Time Referenced Scanning Beam (TRSB) angle data to a planar coordinate system. This function is initiated based on auxiliary data sent from the fixed, broad coverage antenna of the azimuth ground station. Moreover, the computer provides computed height over the DME site based on elevation angle and range, computes an offset approach course if required and provides automatic course width adjustment. The PCAS receiver decodes the auxiliary data which has been encoded using FAA specified Differential Phase Shift Keying (DPSK). The DPSK signal uses "soft switching" during the phase shift transitions to minimize bandwidth. A PCAS receiver (modified AN/ARN-128 was built by The Singer Company and tested in early 1979 at the National Air Facility Experimental Center (NAFEC). It operated successfully against the DPSK format without losing phase lock during the DPSK transitions. Currently, the Navy is conducting flight tests of the PCAS in an A-7 aircraft at the Naval Air Test Center at Patuxent River, Maryland, using FAA MLS ground stations.

MULTIMODE RECEIVER

In June of 1979 the U.S. Navy issued a Requirement Document No. N00019-79-Q-0065, Attachment 1, for a receiver that would provide complete operability with any of the following:

- Current VHF Civil ILS (90 Hz/150 Hz fixed course)
- Civil MLS (C-Band, Time Referenced Scanning Beams)
- MRAALS (Ku-Band, Pulse-Coded Scanning Beams)
- TPN-28/SPN-41 (Ku-Band, Pulse-Coded Scanning Beams)
- Standard and Precision DME (L-Band)
- Civil Approach Marker Beacons (75 MHz)

The Receiver is required to provide outputs in both analog and digital form, the latter to be compatible with the MIL-STD-1553 Multiplex Data Bus format. In addition, there are many subsidiary requirements specified such as automatic antenna switching, self-test, computation of vertical velocity and retention of all operational features of each of the ground systems.

As already mentioned, the key to having been able to achieve two-system operability in PCAS, while at the same time reducing the system size by eliminating one box, was the use of available microprocessor capability to decode the angle information as well as the range information. In order to extend this technology to the MMR, the use of multiple microprocessors versus a more powerful unit had to be explored, since the 8080 was now fully loaded by the PCAS functions. (See Figure 8). This study led to the selection of a dual sourced Zilog Z-8000, a 16 bit high speed (5 MHz) microprocessor having built-in hardware multiply that provides significant improvement in the time load margin over the -8080. Whereas the -8080 was fully time loaded in the PCAS, the Z-8000 will be approximately 80% time loaded in the MMR.

Because the bulk of the processing logic is in software, the transition from PCAS to the fully interoperable Multimode Receiver can be accomplished within a smaller volume than that required by PCAS. IC logic which is used in the ARN-128 and PCAS to drive the range/range rate displays will also be replaced by a microprocessor (Intel-8748) which will reduce the display circuit complexity by 60%.

The desired MMR Receiver frequency and mode of operation (ILS, PCSB, TRSB) can be selected via the console mounted control panel or from an external control source via the MUX bus. Receiver tuning is accomplished by a single knob on the control panel which selects any of the 200 MLS C-Band channels, the 20 MRAALS channels or the 20 UHF/VHF ILS paired channels. The selected inputs, Mode, Glideslope Angle and Channel, are transmitted to the data processor by means of a serial data word. These signals are used to program the receiver's synthesized local oscillator and initialize the data processor to accommodate the ground system format. It is noteworthy that the accuracy with which ILS signals can be processed is greater in the MMR than in existing analog receivers because problems such as accurate control of filter Q's and center frequencies are avoided, as are effects of AGC or carrier level changes and circuit gain changes. This is true because an algorithm representing the exact solution to derive angular displacement can be executed digitally in the microprocessor.

The MMR hardware configuration is composed of the following boxes pictured in Figure 10.

- A synthesized four band MMR Receiver (K-Band, C-Band, UHF and VHF) with self-contained power supply, DPSK Decoder and internal BITE. The Receiver has the same outline dimensions as the single channel AN/ARA-63 receiver.

- A compact MMR Control Panel having the same outline dimensions as that for the AN/ARN-128 and providing all the required controls for MMR.

- A digital Range/Height Display of the same size as that employed on the AN/ARN-128 and PCAS. This display has been modified to replace 60% of the discrete logic with a self-contained -8748 Microcomputer. It provides a continuous display of range and a rotary switch to display: Range Rate, Height or Vertical Velocity on the second window.

- A MMR Navigation Computer that provides PCSB, MLS, ILS and DME processing in a form factor equal to that of the AN/ARA-63 Decoder making it physically interchangeable.

- A Coupler/Calibrator which in addition to providing the normal DME time-of-launch determination will also generate a test pulse on each L-Band TACAN channel. This pulse which determines the delay in the TACAN Receiver permits subsequent elimination of the range error caused by this delay.

- An optional small self-contained broadband C-Band RF Head which can be placed near the antenna. This amplifier is used to overcome aircraft cable losses arising from lengthy cable runs.

The complement of equipment identified in Figure 10 will weigh less than 20 pounds and will consume less than 130 watts of input power.

The system outputs as mentioned earlier will be both analog (Cross Pointer indications, voice, aural tone warnings and Morse Code) and digital (Range/Height Displays, -1553 MUX). Electromagnetic interference is reduced by having all interbox communications via single low frequency (15 KHz) serial data coax cables thus reducing the possibility of spurious radiation usually encountered with fast rise time digital transmissions.

CONCLUSION

In a span of five years the AN/ARN-128 technology has evolved from a single purpose landing system airborne set to the Multimode Receiver. This evolution is depicted in Figure 11 and clearly shows a realistic trend toward increased operational capability accompanied by decreased hardware complexity. The short time taken to achieve the MMR concept was made possible by the rapid development and application of powerful microprocessor and software architecture technology that benefited from the ten fold increase in devices/chip every three to four years. The MMR configuration is a software dominated, multi-usage airborne system which can be expanded to meet changing requirements with software thereby minimizing hardware modifications. This promises to be an economical way to extend the life of avionic equipment in the face of events which might otherwise render them obsolete. In addition to the flexibility and versatility inherent in this technology, avionics designed using microprocessors will provide increased reliability, accuracy and significant reductions in size, weight and cost.

MRAALS SIGNAL FLOW DIAGRAM
(CO-LOCATED)

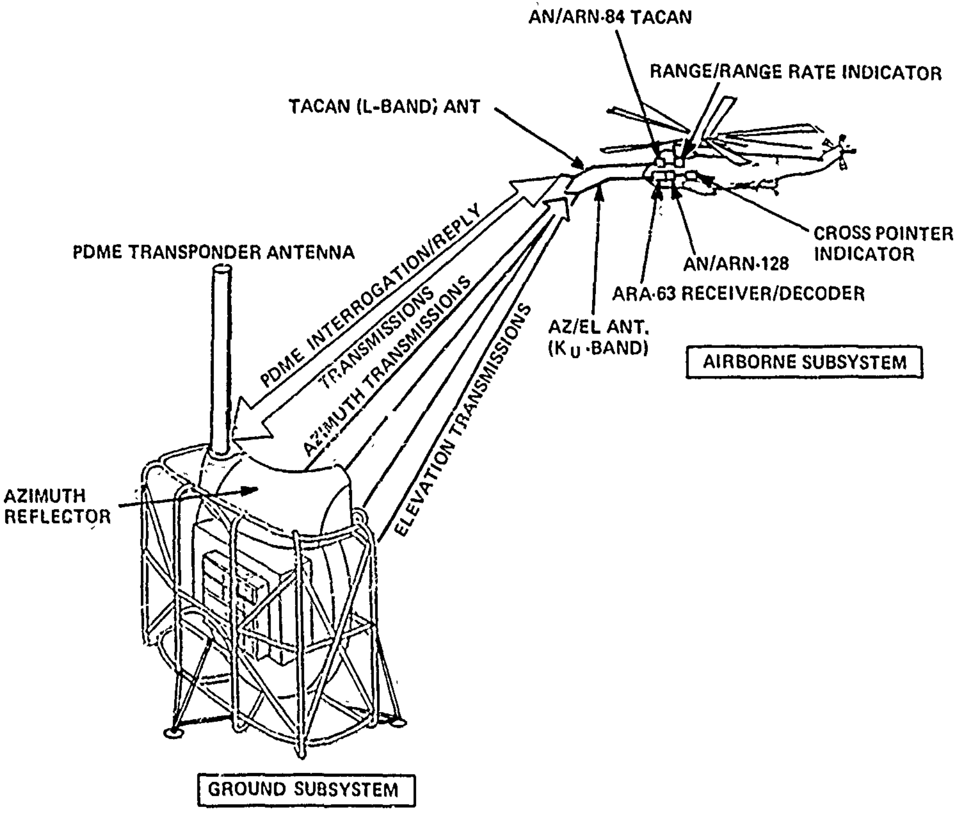
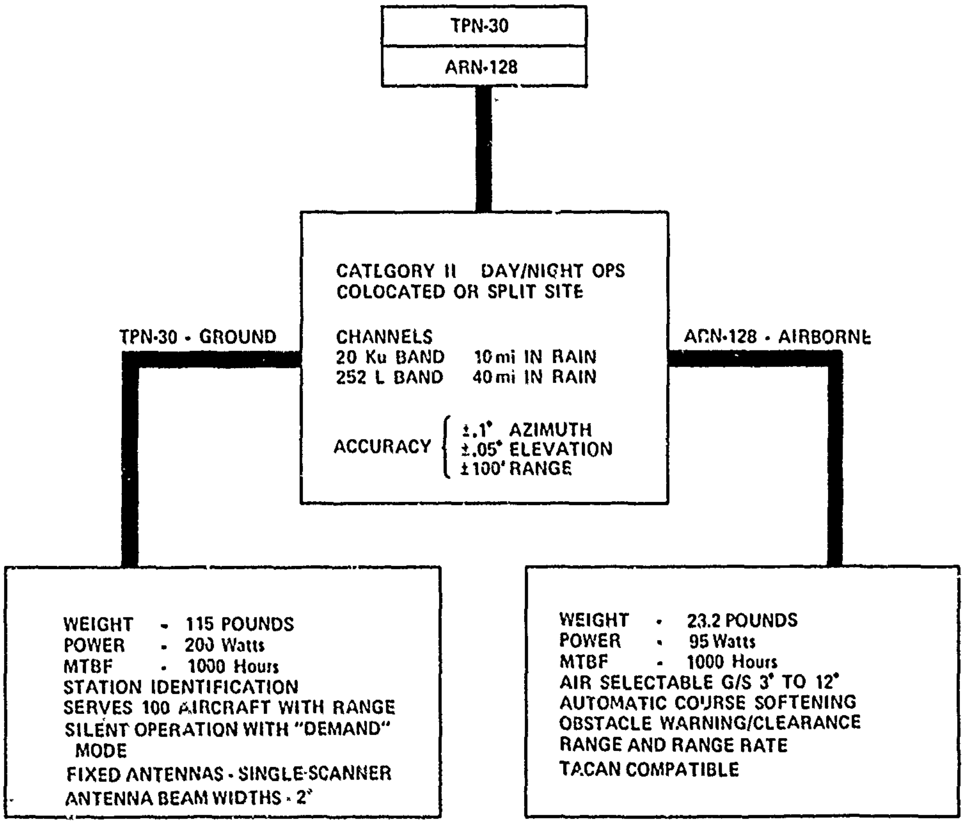


Figure 1

TPN-30/ARN-128 LANDING SYSTEM PERFORMANCE



CATEGORY II DAY/NIGHT OPS
COLOCATED OR SPLIT SITE

CHANNELS
20 Ku BAND 10 mi IN RAIN
252 L BAND 40 mi IN RAIN

ACCURACY ±.1° AZIMUTH
±.05° ELEVATION
±100' RANGE

WEIGHT - 115 POUNDS
POWER - 200 Watts
MTBF - 1000 Hours
STATION IDENTIFICATION
SERVES 100 AIRCRAFT WITH RANGE
SILENT OPERATION WITH "DEMAND" MODE
FIXED ANTENNAS - SINGLE-SCANNER
ANTENNA BEAM WIDTHS - 2°

WEIGHT - 23.2 POUNDS
POWER - 95 Watts
MTBF - 1000 Hours
AIR SELECTABLE G/S 3° TO 12°
AUTOMATIC COURSE SOFTENING
OBSTACLE WARNING/CLEARANCE
RANGE AND RANGE RATE
TACAN COMPATIBLE

Figure 2

COVERAGE VOLUME FOR MRAALS AZ/EL AND DME

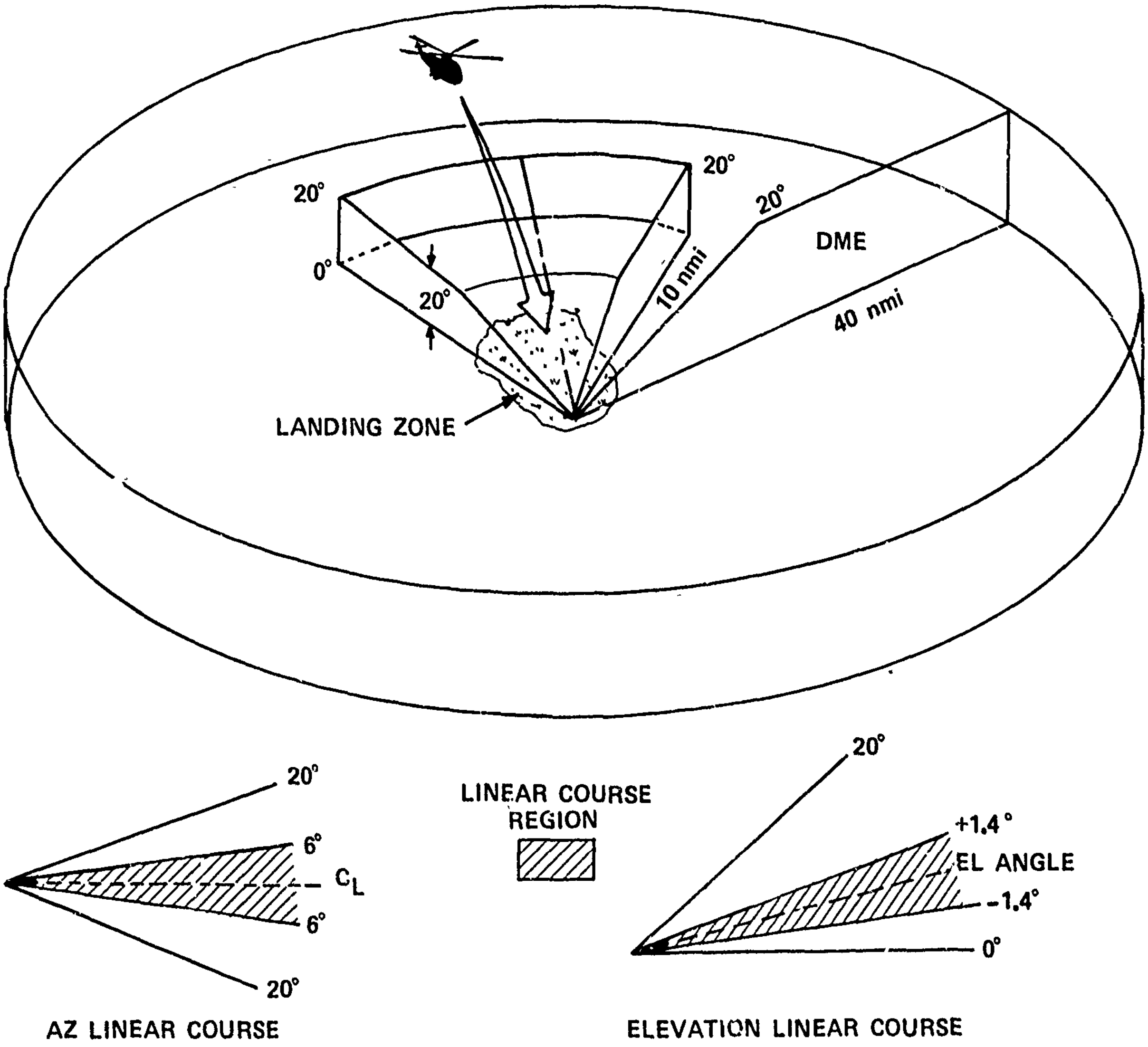
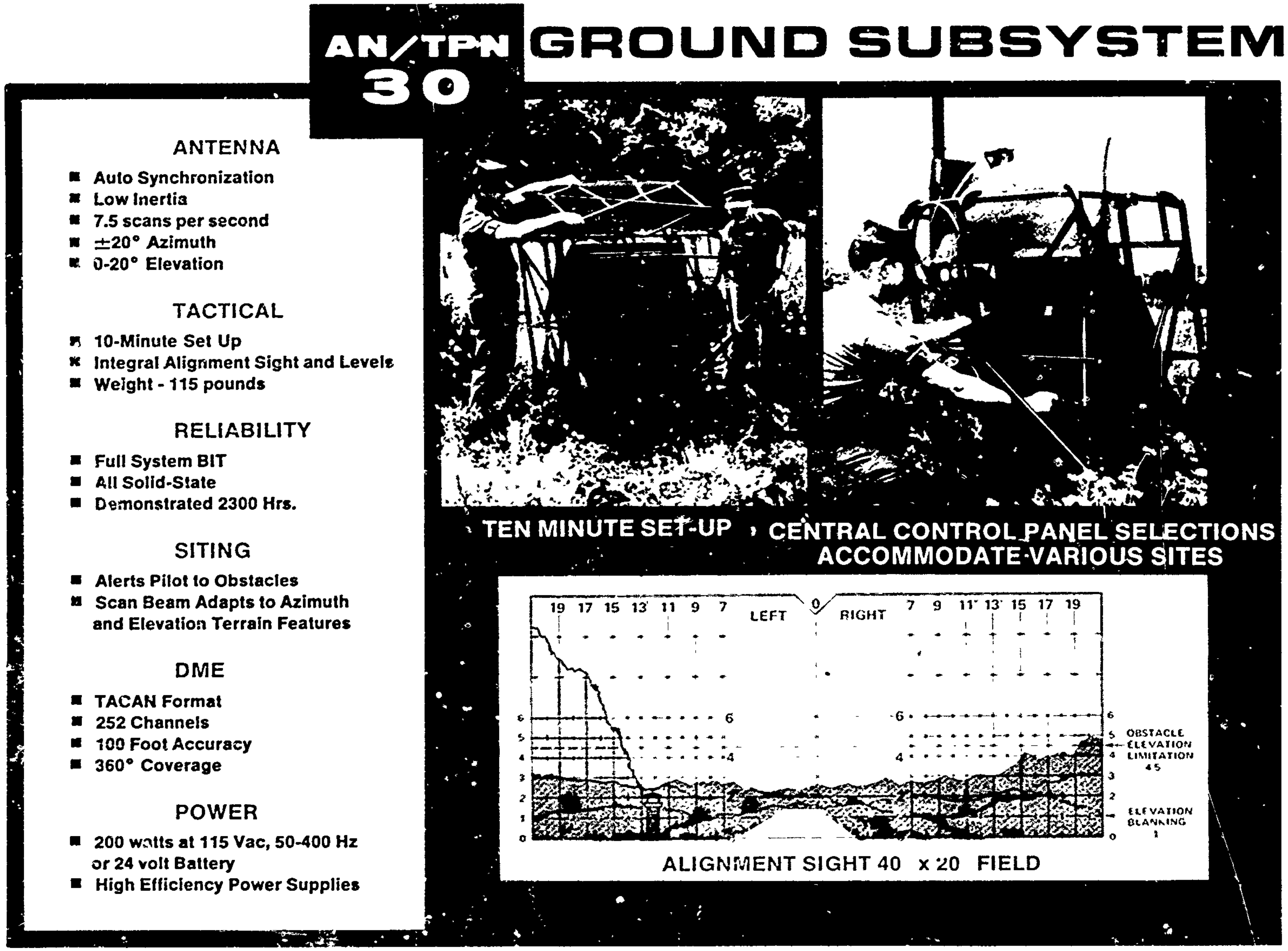


Figure 3



AN/TPN 30 GROUND SUBSYSTEM

ANTENNA

- Auto Synchronization
- Low Inertia
- 7.5 scans per second
- ±20° Azimuth
- 0-20° Elevation

TACTICAL

- 10-Minute Set Up
- Integral Alignment Sight and Levels
- Weight - 115 pounds

RELIABILITY

- Full System BIT
- All Solid-State
- Demonstrated 2300 Hrs.

SITING

- Alerts Pilot to Obstacles
- Scan Beam Adapts to Azimuth and Elevation Terrain Features

DME

- TACAN Format
- 252 Channels
- 100 Foot Accuracy
- 360° Coverage

POWER

- 200 watts at 115 Vac, 50-400 Hz or 24 volt Battery
- High Efficiency Power Supplies

TEN MINUTE SET-UP

CENTRAL CONTROL PANEL SELECTIONS ACCOMMODATE VARIOUS SITES

ALIGNMENT SIGHT 40 x 20 FIELD

Figure 4

TPN-30 GROUND SUBSYSTEM COMPONENT LOCATION

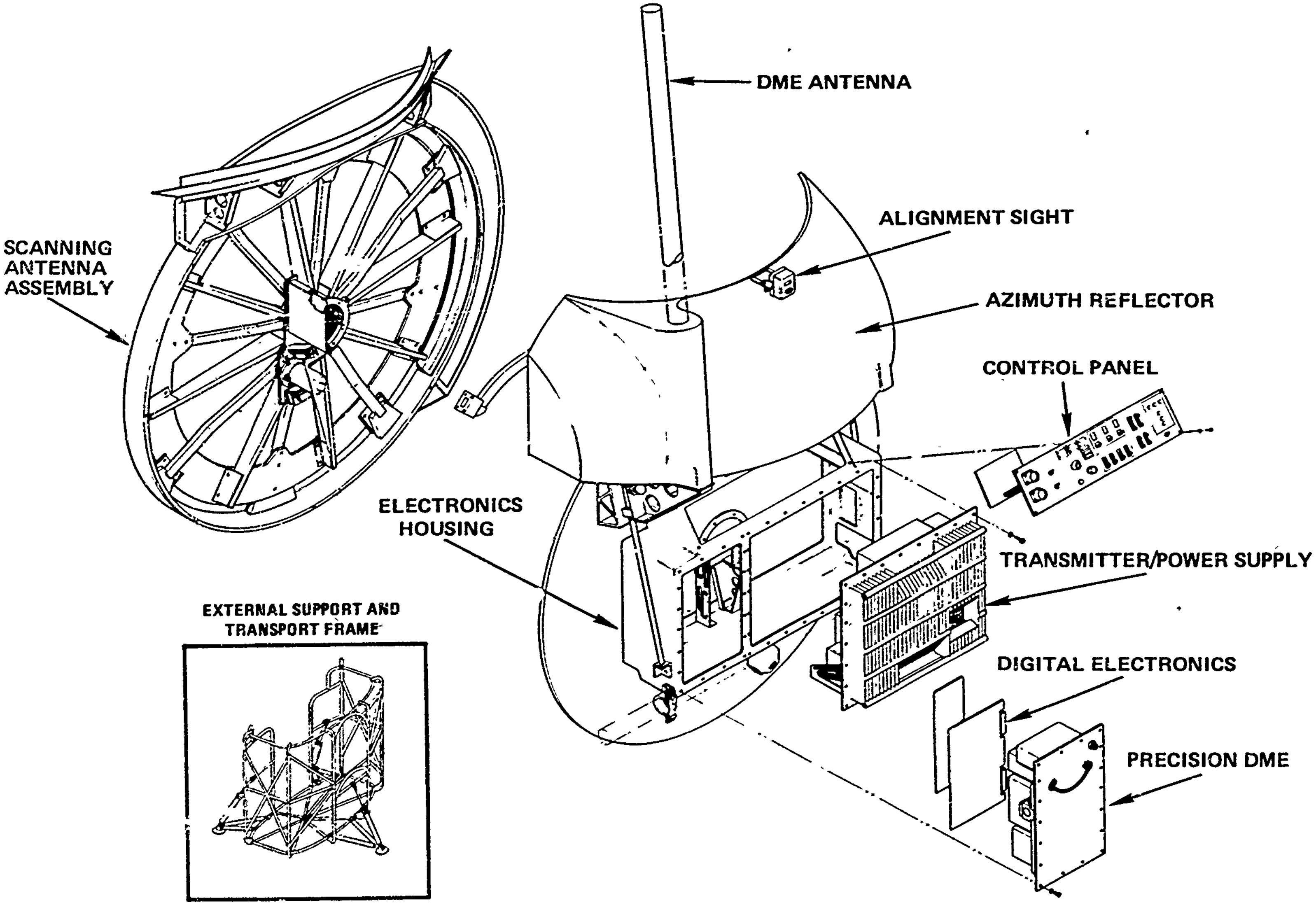
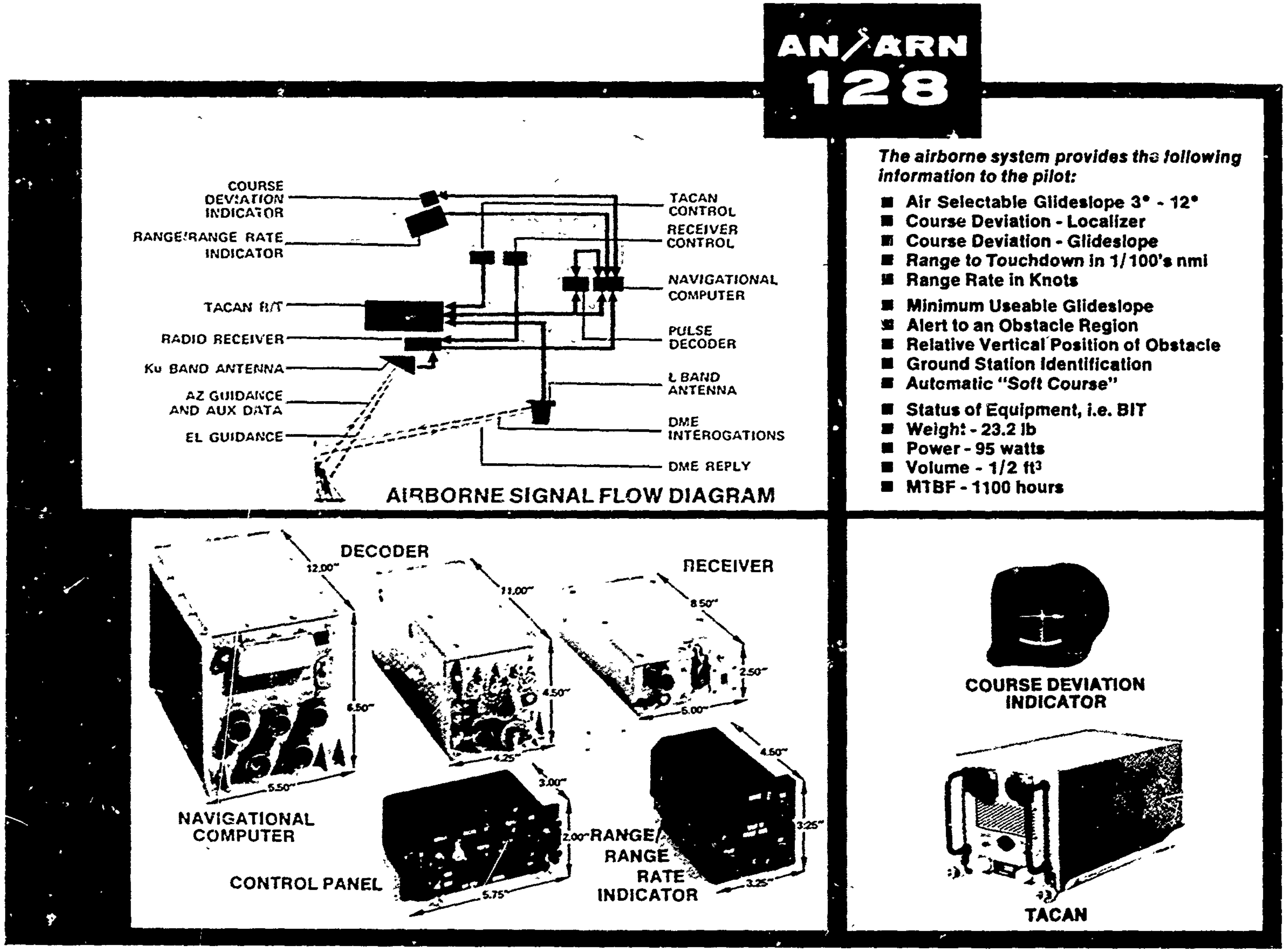


Figure 5

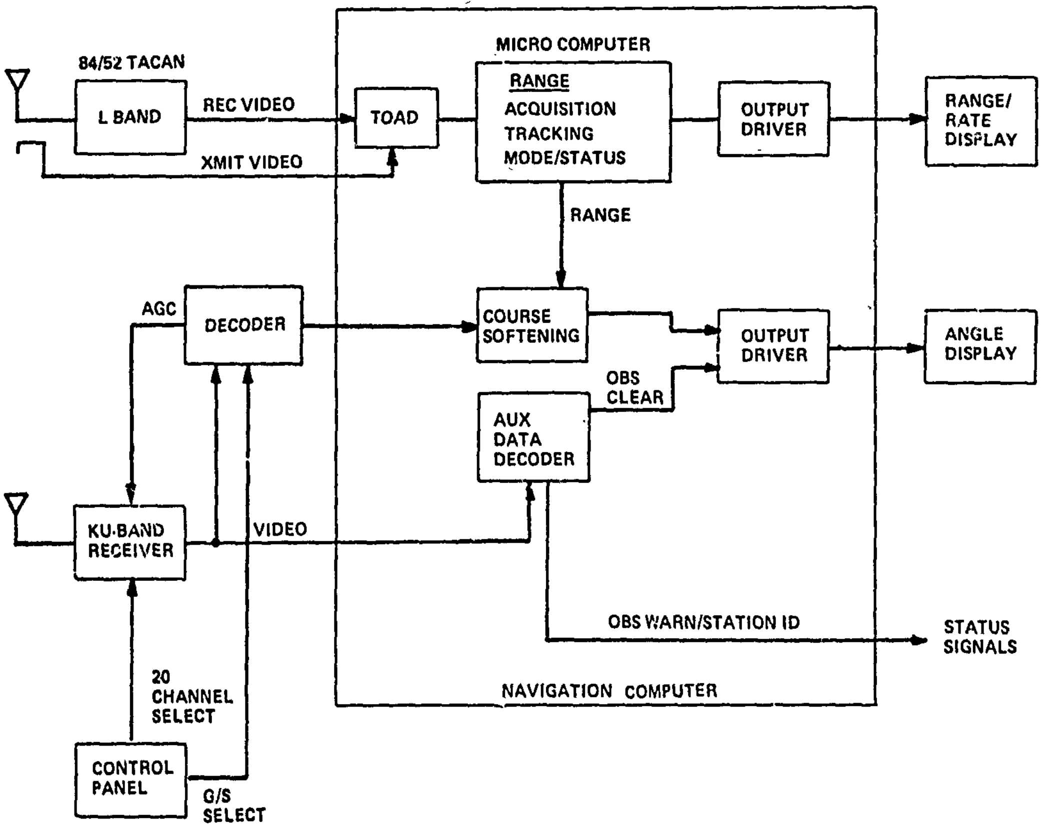


AN/ARN 128

The airborne system provides the following information to the pilot:

- Air Selectable Glideslope 3° - 12°
- Course Deviation - Localizer
- Course Deviation - Glideslope
- Range to Touchdown in 1/100's nmi
- Range Rate in Knots
- Minimum Useable Glideslope
- Alert to an Obstacle Region
- Relative Vertical Position of Obstacle
- Ground Station Identification
- Automatic "Soft Course"
- Status of Equipment, i.e. BIT
- Weight - 23.2 lb
- Power - 95 watts
- Volume - 1/2 ft³
- MTBF - 1100 hours

Figure 6



MRAALS AIRBORNE FUNCTIONAL BLOCK DIAGRAM

Figure 7

MICROPROCESSOR TIME UTILIZATION
TRSB/PDME MODE

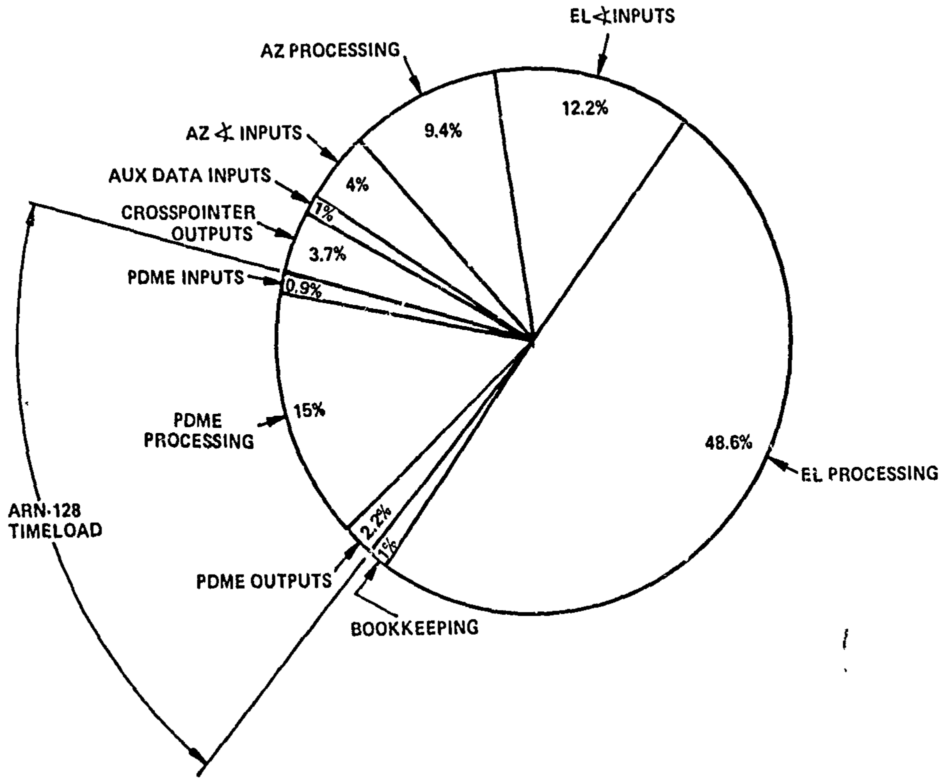


Figure 8

PCAS AIRBORNE FUNCTIONAL BLOCK DIAGRAM

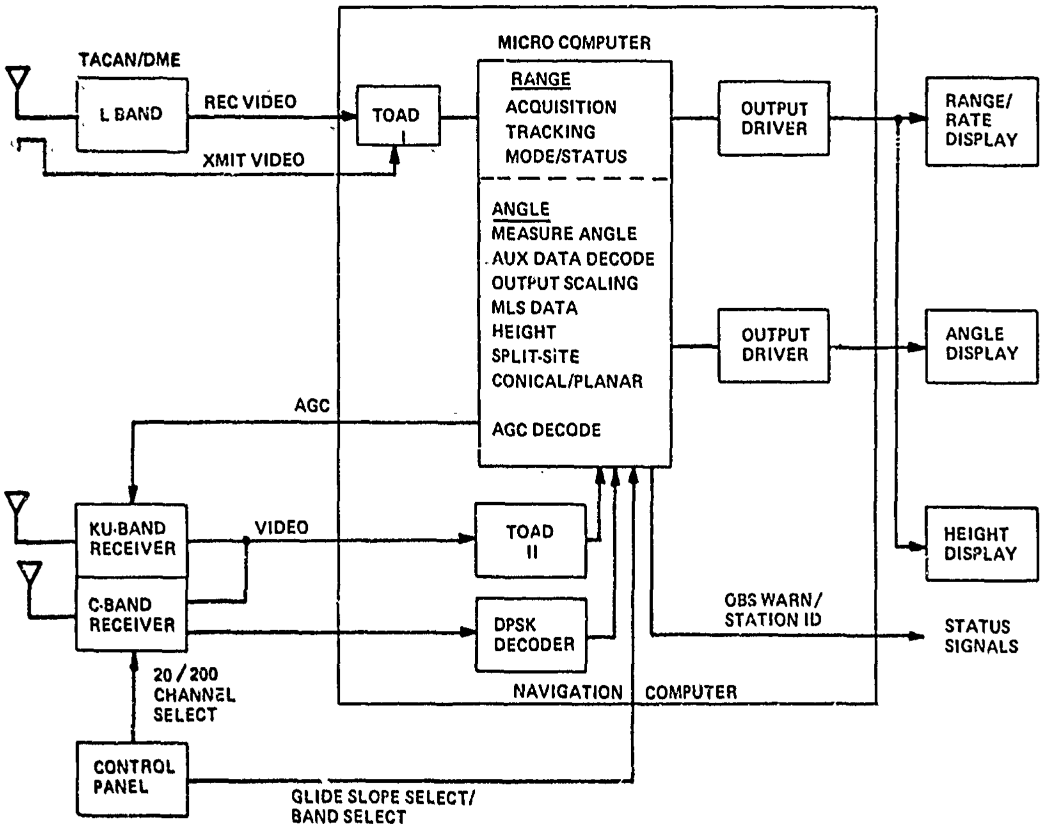


Figure 9

MULTIMODE RECEIVER (MMR) AVIONICS

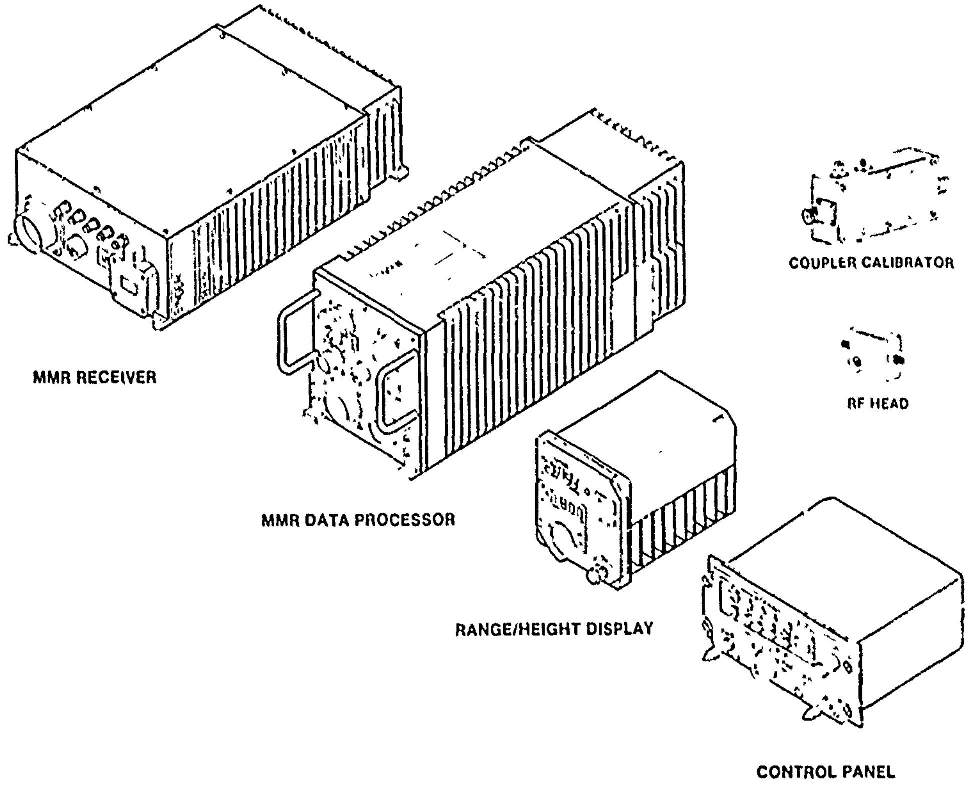


Figure 10

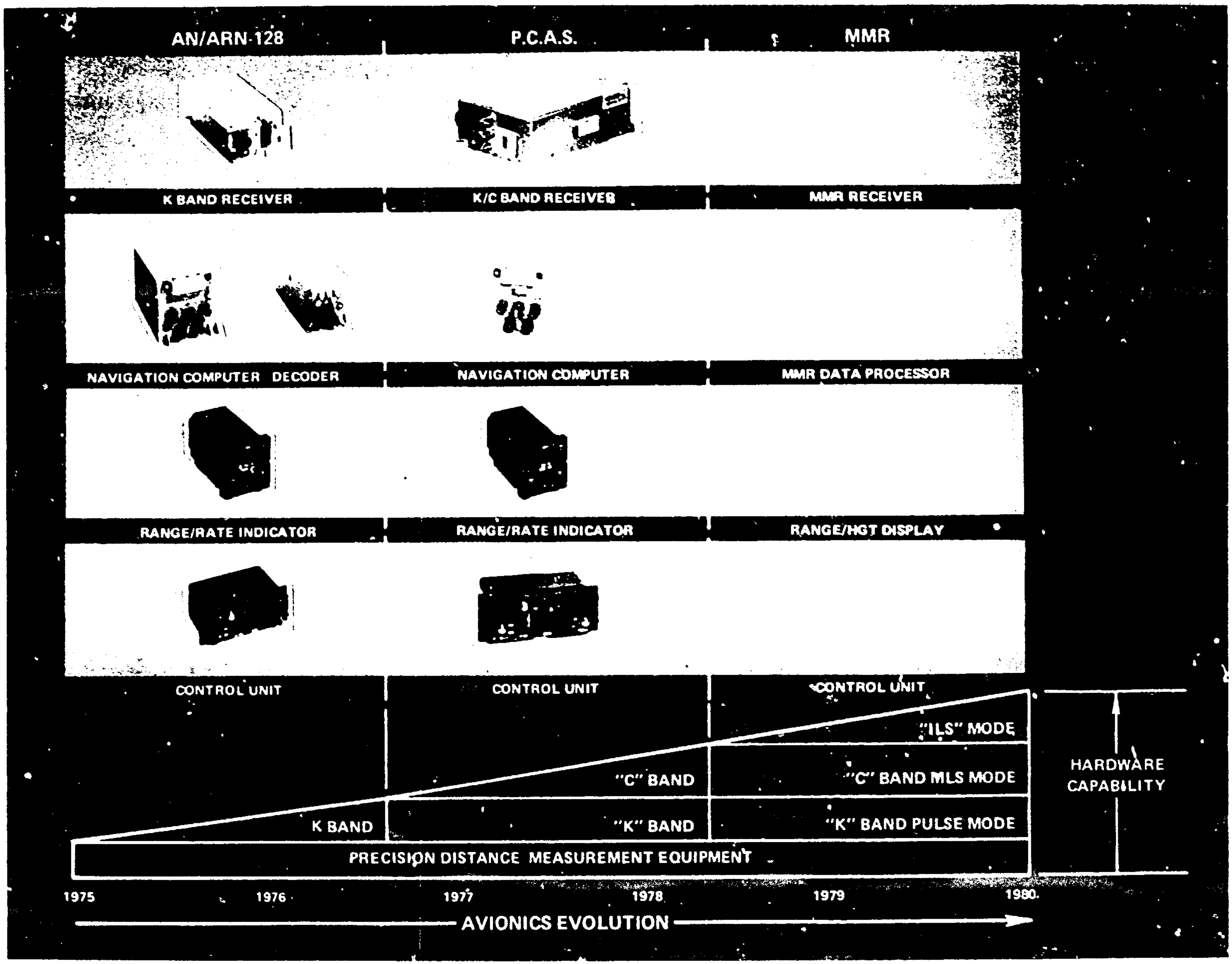

AN/ARN-128
P.C.A.S.
MMR
K BAND RECEIVER
K/C BAND RECEIVER
MMR RECEIVER
NAVIGATION COMPUTER DECODER
NAVIGATION COMPUTER
MMR DATA PROCESSOR
RANGE/RATE INDICATOR
RANGE/RATE INDICATOR
RANGE/HGT DISPLAY
CONTROL UNIT
CONTROL UNIT
CONTROL UNIT
"ILS" MODE
"C" BAND
"C" BAND MLS MODE
K BAND
"K" BAND
"K" BAND PULSE MODE
PRECISION DISTANCE MEASUREMENT EQUIPMENT
HARDWARE CAPABILITY
1975
1976
1977
1978
1979
1980
AVIONICS EVOLUTION

Figure 11

Paper 61

Title: Introduction on LORADS and ASDE

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LIST OF ABBREVIATIONS

ASDE	AIRPORT SURFACE DETECTION EQUIPMENT
ATC	AIR TRAFFIC CONTROL
APP	APPROACH
ACC	AREA CONTROL
ACR	APPROACH CONTROL RADAR
ADNC	AIR DEFENCE NOTIFICATION CENTRE
ATS	AIR TRAFFIC SERVICE
AIS	AERONAUTICAL INFORMATION SERVICE
ATIS	AUTOMATIC TERMINAL INFORMATION SERVICE
AFC	AUTOMATIC FREQUENCY CONTROL
DISCO	DIGITAL SCAN CONVERTER
EDD-F	FLIGHT DATA ELECTRONIC DATA DISPLAY
EDD-S	STATIC DATA ELECTRONIC DATA DISPLAY
EMER. OPS	EMERGENCY OPERATIONS
FIR	FLIGHT INFORMATION REGION
FIS	FLIGHT INFORMATION SERVICE
FT	FEET
FPDP	FLIGHT PLAN DATA PROCESSOR
FPE	FLIGHT PLAN PROCESSOR EXTENSION
FDL	FERRITE DIODE LIMITER
GMP	GROUND MOVEMENT PLANNER
GMC	GROUND MOVEMENT CONTROLLER
HF-RTF	HIGH FREQUENCY RADIO TELEPHONY
ICAO	INTERNATIONAL CIVIL AVIATION ORGANIZATION
IOCS	INPUT/OUTPUT CONTROL SYSTEM
LORADS	LONG RANGE RADAR AND DISPLAY SYSTEM
LAR II	LONG RANGE RADAR TYPE II
MET-OFFICE	METEOROLOGICAL OFFICE
MTI	MOVING TARGET INDICATION
MOP	MONITOR PANEL
MUCROS	MULTI COMPUTER OPERATING SYSTEM
MTBF	MEAN TIME BETWEEN FAILURE
NM	NAUTICAL MILE
NS	NANO SECOND
PEC	PLAN EXECUTIVE CONTROL
PVDM	PLAN VIEW DISPLAY MIXED
PRF	PULSE REPETITION FREQUENCY
RCC	RESCUE COORDINATION CENTRE
RDP	RADAR DATA PROCESSOR
SSR	SECONDARY SURVEILLANCE RADAR
SID	STANDARD INSTRUMENT DEPARTURE
STAR	STANDARD APPROACH ROUTE
STC	SENSITIVITY TIME CONTROL
TMA	TERMINAL AREA
TV	TELEVISION
TWR	TOWER
VOLMET	METEO INFORMATION FOR AIRCRAFT IN FLIGHT

SLIDE

①

1. Introduction on Lorads and ASDE Systems

My company, Hollandse Signaalapparaten B.V., is honoured by the AGARD Guidance and Control Panel to take part in its International Air Traffic Management Symposium.
In considering the substance of this paper, I have a broad treatment rather than a single subject in depth, hoping thereby to appeal to the widest audience.

② The aim of this paper "Introduction on LORADS and ASDE", Lorads standing for long range radar and display system and ASDE for airport surface detection equipment, is to give a panoramic view of both systems, its functional and operational requirements, the system architecture of both the hardware and software and, where applicable, pointing out the highlights.

SLIDE

First the Lorads system will be presented, followed by the ASDE system.

Both systems are intended for the new international airport at Changi-Singapore.

The Department of Civil Aviation has chosen these systems because they are among the most sophisticated in the world and of a well proven design.

③ Moreover, the Lorads system is a typical sample of an integrated civil-military ATC system.

Both the Civil Aviation Authorities and the military ATC organisation are to share one and the same ATC system.

The long range radar system provides information to both organisations.

By means of centralized computer processing of radar and flight plan data, it is possible to make use of a central source of information. Both organisations can retrieve information from this common source and can easily and rapidly exchange information of different natures through the computer complex.

④ 2. What has Lorads to do?

Basically, any ATC radar system has to provide the air traffic controller with "a three dimensional" picture of the air space around him.

What did change in recent years, however, is the much higher level of precision demanded from the equipment.

There is a number of reasons for this. Aircraft in flight maintain separation, that is they avoid conflicting courses, by flying carefully defined air routes at a set height according to ICAO recommendations.

In the vicinity of an airport, simple rules will not do, making the separation the continuous responsibility of the controller on the ground.

In recent years, traffic at all international airports has grown and along with this growth have come powerful pressures to keep aircraft on the move. Procedures like stacking or keeping aircraft circuiting must be avoided.

Airline operators need a maximum utilisation of their aircraft to stay in business.

This means that the physical separation of aircraft in flight must be reduced to a minimum still satisfying safety regulations.

These then are the important facets of the problem.

A compromise has to be set, that is on the one hand the efficient flow of traffic to and from an airport has to be increased, accommodating overflying traffic at the same time, and on the other hand a high standard of safety has to be maintained.

The Lorads system does this in two fundamental ways.

⑤ First by the high standard of precision and reliability of information, thus being capable to provide:

- adequate radar coverage (in range, azimuth and height),
- high reliability (24 hours around the clock, every day),
- operation in the worst weather conditions,
- high definition.

Second, it aids the air traffic controller in computer processing the vast amount of incoming data and in presenting these data to him in the most suitable form.

⑥ 3. Operational Aspects

Lorads together with the approach control radar system provides the facility for the control and management of all air traffic (civil and military) in the controlled airspace of the FIR.

Military air traffic control mainly operates outside the controlled airspace.

Advisory services are given in non-controlled airspace.

The Singapore FIR is divided into four airway sectors, a TMA being situated around Changi Airport.

Danger and restricted areas are located in various places within the FIR. Lorads provides ATC-services to five airports.

The Singapore air traffic control center is organised as a joint ATC center consisting of a civil and a military element.

⑦ Within the civil element, three main operational ATC units are distinguished:

- Aerodrome Control (TWR),
- Approach Control (APP),
- Area Control (ACC).

⑧ Aerodrome Control is responsible for air traffic services on and in the vicinity of the Changi aerodrome.

It includes the following operational positions:

- Tower supervision,
- Runway control (R/W1, R/W2),
- Ground movement plan control (GMP),
- Ground movement control (GMC),
- Master apron.

These positions are located in the control tower and are equipped with tabular electronic data displays (EDD) and associated keyboards. The displays show flight data (EDD-F) and ancillary (static) data (EDD-S). The keyboards enable adequate function requests and data inputs. The information for the tower is completed with printed flight progress strips.

Approach Control provides a radar-based control within the Terminal Control Area (TMA), which is covered by the Approach Control Radar (ACR). The actual control is done by executive radar controllers.

Functionally, Approach Control is subdivided into three operational positions:

- Departure Control (ACR 1),
- Arrival Control (ACR 2),
- Final Control (ACR 3).

SLIDE

Each position is supplied with radar data and computer-generated data presented on a mixed radar display (PVDM), flight data on an electronic data display (EDD-F) and static data on an electronic data display (EDD-S). Moreover, use is made of printed flight progress strips.

Area Control is based upon "the PEC-principle", plan-executive control. The air route structure learns us that area control makes use of a four-sector organisation.

Almost three sectors are covered by the Long Range Radar and therefore radar executive control is performed by:

- Sector 1 controller (C1),
- Sector 2 controller (C2),
- Sector 3 controller (C3).

Each sector is supplied with radar data and computer-generated data presented on a mixed radar display, flight data on an EDD and static data on an EDD.

For the fourth sector, procedural control is applied. For this control, use is made of the High Frequency Radio telephone operations (HF-RTF). Spare position C4 serves as a back-up for C1, C2 and C3, but can also be employed either to share the load of sector C3 or to reconstitute recorded data in a play-back mode of operation.

Coordination with adjacent centres is done by the ATC-coordinator position.

All approach control and area control operations are monitored by the Civil Watch Supervisor, utilising a flight data EDD and a static EDD. Radar-based information is at his disposal via a Conference Display.

The military ATC element is responsible for the control of military air traffic flying in the non-controlled airspace and for the approach control to and from the military airfields.

Military aircraft using civil airways, however, are handled by the civil ATC element.

Four operational working positions perform radar based control of military air traffic.

Rack position is similarly equipped as the civil working positions and is manned by two persons.

Printed flight progress strips are not used for these positions.

Other working positions perform various specialised tasks and their consoles are equipped according to their particular requirements.

All military ATC activities are monitored by a military watch supervisor whose working position is identical to his civil counter part.

The joint Lorads air traffic control system is completed by a number of Air Traffic Services (ATS), all equipped with electronic data displays and can be summarized as follows:

- Aeronautical Information Services (AIS),
- Automatic Terminal Information Service (ATIS),
- Meteorological Office (MET-OFFICE),
- Meteo information for aircraft in flight (VOLMET),
- Rescue Coordination Centre (RCC),
- Emergency Operations (EMER. OPS).

4. Basic Components

Basically, the Lorads system comprises the following components:

- ⑨ the LAR II L-band long-range primary radar,
- ⑩ the en-route secondary surveillance radar,
- ⑪ the approach control S-band primary radar,
- ⑫ the approach control secondary surveillance radar,
- ⑬ video processing equipment,
- ⑭ flight plan processing and storage equipment,
- ⑮ display equipment,
- ⑯ intercom, interphone and R/T equipment,
- ⑰ non-interrupted power supply system.

⑱ The LAR II radar has an outstanding performance. The design of this radar is based upon the following criteria:

- long range (over 200 NM, height over 80,000 ft) resulting from a high mean power,
- short minimum range (approx. 0.5 NM) resulting from multi-pulse operation,
- ⑲ improved signal-to-clutter ratio by the use of:
  - . dual antenna beam arrangement,
  - . small resolution cell,
  - . sharp cut-off at lower edge of the beam,
- optimum performance of MTI and cancellation of second time around and diplex clutter by using a crystal-controlled coherent amplifier chain,
- extended reliability and availability through a low peak power,
- optimum performance of radar resulting from dynamic video processing,
- excellent resolution and accuracy.

The en-route secondary surveillance radar is on-mounted and operates according to the ICAO recommendations.

The primary and secondary approach control radars are in this particular case not of SIGNAAL make. The Lorads system accepts information from these radars for further processing and display.

⑳ The video processing equipment contains primary and secondary video extractors for processing radar data from both radar sensors. Decoding, degarbling and defruiting functions are also performed by the secondary extractor systems. Each primary and secondary video extractor is linked to a plot processor.

SLIDE

The tasks attributed to a plot processor can be summarized as follows:
- acceptance of digital radar plot information,
- primary plot filtering,
- primary radar tracking,
- secondary radar tracking,
- correlation of the primary and secondary radar tracks,
- formatting,
- producing output.

㉑ The flight plan processing and storage equipment makes the nucleus of the Lorads system. The main function of this equipment is to process, to update, to distribute and to display positional and tabular information at controllers positions, either automatically or upon request.
To perform this function, the system is capable:
- to accept and process radar data from two sensors,
- to accept and process manual inputs,
- to manage a data base,
- to monitor and control the system configuration,
- to accept and process inputs from computer peripherals.

The data base in the form of the storage equipment mainly contains:
- flight-related data,
- non-flight-related data,
- system data.

Some of the additional main system functions are:
- paper strip printing,
- stored flight plan processing,
- flight path calculation,
- ATC-clearance processing,
- SSR-code assignment,
- SID/STAR assignment,
- legal recording and playback,
- hard copy recording,
- static data processing.

The display equipment is of a different nature.
There are four types of displays used in the system.
㉒ On the mixed 23-inch radar display, processed digital radar data and condensed flight plan
and map data are presented together with raw primary video.
The controller can select either a long-range radar picture or an approach control radar
picture. This display is the executive and military controllers' primary source of informa-
㉓ tion. In addition, they have an electronic data display (EDD) on which flight plan details
of aircraft movements are presented in a tabular form at their disposal. A second EDD shows
static information like weather reports and status of services.
Finally, the system produces printed flight progress strips for the civil ATC element only.
㉔ All the display and communication equipment is housed in consoles.
The uninterrupted power supply system forms the back-up power system for all the data handling and display equipment.
The radar units have their own no-break power system which is delivered by the customer.

㉕ 5. System Architecture

The Lorads system is divided into a number of subsystems:
- the radar subsystem,
- the video extractor subsystem,
- the main computer subsystem,
- the magnetic tape subsystem,
- the strip printer subsystem,
- the radar display subsystem,
- the EDD subsystem,
- the communication subsystem.

㉖ The radar subsystem consists of the long-range primary radar LAR II and the secondary radar SSR. They are considered as the main system sensors.
The analogue video of the LAR II radar, together with the video of the Approach Control Radar, is passed on to the video extractor subsystem and to the radar display subsystem.
The transponders of approaching aircraft react to SSR interrogations, and the coded replies are also passed on to the video extractor subsystem.
The primary video extractor converts the video into digitised primary plots which contain positional information of aircraft.
The secondary video extractor decodes the SSR replies and generates secondary plots containing position, identity and height information of aircraft. Both types of plots are passed on to a plot processor which performs plot filtering and independent tracking for primary and secondary aircraft, and combines primary and secondary tracks in case of correlation. The combined tracks - dotted to indicate the flight path of the aircraft - are passed on for correlation with flight plan data to the main computer subsystem. Flight plan data is input as stored flight plans originating from magnetic tapes or as basic inputs via the keyboards of the EDD-subsystem. To avoid loss of this data in case of a system reconfiguration, flight plans are stored in drum memories.
The object of the EDD-subsystem is to display flight plan data and ancillary data in a tabular form.

SLIDE

The subsystem consists of 62 TV-type EDD's. Each has its own memory, retaining the display data until it is updated by the main computer subsystem.
Three strip printers forming the strip printer subsystem provide the controllers with printed paper "flight progress strips", which are mainly used by the planning controllers for procedural routines.
Print actions are initiated by the main computer subsystem.
The magnetic tape subsystem - consisting of six tape units - provides bulk storage for:
- programs for initial loading,
- flight plan data,
- recordings.

The tape units are connected to the main computer subsystem.
The tasks of the radar display subsystem are as follows:
- displaying synthetic radar data and condensed flight data on the Mixed Plan View Display (PVDM),
- displaying raw primary video on the PVDM as background information,
- displaying flight data and ancillary data on EDD's,
- processing inputs made by the controllers.

The subsystem consists of 14 autonomous display positions, each consisting of a display computer which controls a PVDM and two EDD's with associated control devices. If a display computer fails, the operator shifts his control position to another position not in use by making a reconfiguration procedure input.
The displays, keyboards, control devices (light pens and handwheels) and display computer are combined in a console designed for easy operation and minimum fatigue to the operator.
The communication subsystem consists of intercom, interphone and radio communication equipment. Though it has no direct interface with the Lorads, it is integrated for convenience into each display console.

㉗ Modes of Operation

The main computer subsystem consists of a duplicated main computer chain, each chain comprising:
- a flight plan data processor (FPDP),
- a flight plan processor extension (FPE),
- a radar data processor (RDP).

The main computer chains are identified as main computer chain I and II respectively.
Depending on the availability of both main computer chains or the processors operating on an individual basis in the main computer subsystem, the following modes of operation are distinguished:

㉘ Mode 0 : Duplicated Main Computer System

The inputs from and outputs to other subsystems are handled by main computer chain I, while main computer chain II operates in a hot standby mode. The standby chain does not receive inputs from other subsystems, but is continuously updated by the main chain I via a direct connection between the flight plan data processors. In parallel with the main chain I, the standby chain performs the same tasks without outputting to other subsystems.
The performance of main and standby chains is monitored by the Monitor Panel (MOP) connected to both flight plan data processors. This MOP receives quality messages, from which the MOP derives the degree of availability of each chain and determines whether an automatic change-over has to be initiated.
This automatic fault detection is based on a hierarchical relationship between relevant units of the system. This relationship is as follows:
the plot processors monitor their video extractors; the display processors monitor the display circuitry and EDD connection; the main radar data processors monitor the connections to the plot processors and the connections to the display processors; the flight plan data processors monitor the radar data processors and connections to the electronic data displays, strip printers, tape units, drums, line printer and monitor typewriters; the monitor panel monitors both flight plan data processors.
An automatic change-over from main to standby mode of operation may occur in two ways:
- the controlled change-over takes place when both main processor chains operate correctly, but when for instance an interface in the main processor fails. This change-over does not affect system operation except during a short time for the peripheral connected to the failing interface. The actual change-over takes place after running autonomous data transfers between processors and peripherals are concluded. It implies that the controlled change-over requires a certain period of time.
- the non-controlled change-over takes place in case a main radar data processor, flight plan processor extension and/or flight plan data processor spontaneously ceases to operate. The standby processors are immediately ordered by the MOP to act as main units. All relevant units of other subsystems and flight plan data processor peripherals are switched over simultaneously without waiting for normal data transfer terminations.
  The appropriate software routines are informed about interrupted data transfers, resulting in repetition of output actions and failure indication of input actions.
  Prior to giving a repaired radar data processor, flight plan processor extension or flight plan data processor the function of standby unit, the main flight plan data processor must be informed. During a few seconds, the main flight plan data processor updates the standby unit, during which procedure the operational system is in an idle status.

Mode 1 : Single Main Computer System

In this mode of operation, main computer chain I with peripherals performs the operational tasks as described under mode 0. Main computer chain II with peripherals is used in an off-line mode enabling the user to perform maintenance, replay of recorded data or generation/

modification of software programs.
It is emphasized that in this mode of operation the system availability in comparison with mode 0 is decreased. Whenever the performance of the on-line operational system gives rise to a change-over, the off-line units have to be made operational, which is to be realised via a system restart from scratch (start-up).
Putting the system in an off-line configuration is done by means of manual control of the switches in the system. To this end the MOP not only contains status indicators but also the controls (next to the indicators) to handle these switches.
The disconnection of an operational unit by means of the MOP switches is not considered by the operational system to be a failure.

Mode 2 : Back-up System

In case both main computer chains break down, radar-based control can be continued in a back-up mode.
This is possible since track data (aircraft position and SSR-code) will be updated each antenna revolution and passed on to the radar displays. Flight plan data and static data, however, are not updated, so the alphanumeric information on the radar displays and the tabular electronic data displays becomes obsolete.
In this situation, strip printing is disabled.
The system will change over automatically to this back-up mode starting from mode 0 or mode 1. Return from this mode back to mode 0 or mode 1 is realised by means of a system start-over or start-up action.

Mode 3 : Minimum System

The worst situation is the breakdown of both radar data processors or even all processors.
In this situation the complete system is declared down.
Air traffic control is then only possible by means of making use of raw primary video presentation and already printed flight progress strips.

6. Software Architecture

(29a) The software package for this system consists of three parts:
- the operational software,
- the test software,
- the support software.

(29b) The Operational Software

The operational software is split up into two main programs:
- one overall operational program is running in the flight plan data processor with associated flight plan extension processor, the radar data processor and the display processor,
- one operational program per plot processor for radar data processing and tracking.

The overall operational program in turn is subdivided into:
- the application program,
- the multicomputer operating system program (MUCROS).

The application program is built up of fragments to allow easy storage, each having a dedicated function in the various processors.
The following fragments can be distinguished:
- flight plan processing,
- data base management,
- periodic investigation,
- general inputs (EDD, magnetic tape unit),
- EDD page handling and reconfiguration,
- radar data inputs,
- radar display inputs,
- display outputs,
- semi-permanent data handling.

The MUCROS part is to be considered as an overall supervisory program. It deals with job assignment, fault registration, system loading and peripheral handling.
The operational program per plot processor is subdivided into two parts:
- application program,
- input/output control system program (IOCS).

The application program comprises modules for primary radar tracking and secondary radar tracking, correlating primary and secondary radar tracks and primary radar plot filtering.
The IOCS program is to be considered as a supervisory program in a similar way as pointed out for the MUCROS program.
The operational programs are written in the high level RTL-2 compiler language, the supervisory programs in the Assembler language.

(29c) The Test Software

The test software consists of a package for testing parts of the system (system proving programs) and a package for testing peripherals with their computer connection (hardware proving programs).
The system proving programs can be used to test all the connections between the various processors, the correct central load facility and the video extractor performance.
The hardware proving programs are available for testing all the peripherals on an individual basis.

The Support Software

The support software is provided in order to assist the programmer in writing, executing and debugging his application programs. The design of the support software is based on closed-shop principles and comprises two parts:

- programming support software with the several language compilers and programs to assemble and sequence program parts,
- operating support software for debugging, input/output control and job control of an application module.

SLIDE

① 1. Introduction on the Singapore Airport Surface Detection Equipment (ASDE) System

The number of ground movements scheduled for the new international airport Changi, together
with the clutter of buildings, necessitates a very efficient control, not only of aircraft
② taking off and landing, but also of the movements of aircraft and other vehicles on the
ground. It is therefore justified to introduce an ASDE system with an associated daylight
③ display system providing tower controllers with an excellent tool for ground movements
guidance.

④ The main functions of an ASDE system are:

- to provide accurate information on moving aircraft and vehicles as well as stationary objects at and around runways, taxiways and aprons of an airport,
- to present this information under high ambient lighting conditions to the users.

⑤ 2. What has ASDE to do?

To perform these functions, the design of the ASDE is based on the following primary requirements:

- presentation of the radar video under high ambient lighting conditions,
- high radar resolution and display resolution,
- satisfactory performance of the radar under adverse weather conditions.

⑥ 3. Operational and Technical Considerations

These primary operational/technical requirements can only be met if careful attention is paid to the choice of the most important parameters defining the performance of the ASDE system:

- the transmitter frequency band,
- the rotational speed of the antenna,
- the pulse repetition frequency,
- the antenna,
- the operator display.

The Transmitter Frequency Band

The choice of the transmitter frequency is based on the high resolution and performance required. To obtain a high resolution, the horizontal beamwidth has been fixed at 0.25°. The antenna dimensions are to remain within reasonable limits to realise the tangential resolution. A Ku-band frequency (new designation J-band) has been chosen to guarantee a satisfactory performance under all weather conditions, taking into account the application of circular polarisation.

The Rotational Speed of the Antenna

The rotational speed of the antenna is based on the permitted maximum displacement of an object between two successive scans, assuming that a fast moving object, such as an alighting aircraft, produces an almost uninterrupted track on the display.
To meet this condition, a rotational speed of 60 rpm has been chosen.

The Pulse Repetition Frequency

The prf must be high enough so that at the rotational speed of the antenna chosen, a sufficient number of hits is obtained to show the contours of a medium-sized target on the display.
On the other hand, the prf must be low enough to prevent occurrence of second trace targets.
As a last item regarding the choice of the prf, precautions were taken to avoid that a scan-to-scan jitter of displayed radar information takes place. To this end the radar transmitter is linked directly to the "bearing transmission unit".

⑦ The Antenna

The requirements set for the antenna are critical and can be summarized as follows:

- a small beamwidth of approx. 0.25°,
- a vertical antenna pattern having an inverted cosec shape to -15° and a vertical beamwidth of approx. 3°,
- a fixed circular polarisation.

SLIDE

⑧ The Operator Display

The operator display must be sufficiently bright to permit surveillance to take place by means of direct viewing under the high ambient lighting conditions normally obtained in the control tower during the daytime.

In addition, the display must give a complete presentation of the airfield and its immediate surrounding area at surface level, with the outlines of runways, taxiways, buildings and objects clearly and accurately shown, together with the real-time presentation of all the moving objects of commensurate size.

To satisfy the above conditions, the "digital scan converter" (DISCO) is introduced.

The DISCO's with their solid-state electronic circuitry and memory refresh the radar information, which has a rather low data rate, to give it a high repetition rate, thus enabling its presentation under high ambient lighting conditions. In addition, the DISCO's accept video from the Lorads approach control radar and have the facility for supplying synthetic video maps. As the radar information and the synthetic video are both contained in the same memory, this presentation is always in proper registration and free from drift.

4. System Architecture

⑨ Basically, the ASDE system consists of the following main units:
- an antenna,
- a duplicated radar transmitter/receiver,
- a duplicated digital scan converter,
- three operator displays,
- a maintenance display.

The Antenna

The antenna has a rigid, light-weight aluminium construction. The reflector has a parabolic cylindrical shape and is illuminated by a slotted waveguide equipped with a circular polarisation device.

⑩ The Radar Transmitter/Receiver

The transmitter is equipped with a tunable magnetron, which operates within a frequency band of 16.0 - 16.5 GHz. The magnetron is pulsed by a line-type modulator containing a ceramic thyratron.

The generated transmitter pulse has a length of 50 ns.

Part of the transmitter energy is used for Automatic Frequency Control (AFC).

A built-in safety circuit prevents the transmitter from being switched on during the preheating time of the magnetron.

This unit also protects the modulator against overload.

The receiver is, on RF basis, protected by a Ferrite Diode Limiter (FDL), which blocks the receiver input during transmission and after that adapts the receiver sensitivity according to the Sensitivity Time Control (STC) setting.

The STC can be adapted to local circumstances by adjustment of the amplitude and the slope, thus determining the effect of the STC control voltage.

The radar linear video is routed via the video distribution circuit and is distributed among the maintenance display, the AGC circuit and the video processor. The latter transfers the video on a sampled basis to the digital scan converter.

⑪ The Duplicated Digital Scan Converter

The all solid-state digital scan converter (DISCO) transforms a radar picture with a specific scan format and data rate into a picture of identical contents, though having a different scan format and/or data rate, which are more convenient for the ATC-operator. The DISCO as designed by SIGNAAL excels in resolution, accuracy, stability and MTBF. Moreover, it offers much latitude in the admixture of synthetics, and facilitates control over and processing of the entire radar picture contents.

Of course there are system limitations in respect of relative and absolute accuracy and resolution, but these only depend on the display monitor used.

The converting medium is constituted by a dynamic MOS-memory of 16K modules.

It is built up from 1024 x 1024 topography-related storage cells, each having a capacity of 5 bits, the total being 5M bits. Such a random access memory can deal with a square topographical area measuring 1024 cell sizes in each direction. Thus, a cell is made to represent an area of 7 x 7 meters, and the area which can be covered is 7268 x 7268 meters.

The radar information per cell is distinguished in various grey levels.

The facility to present an artificial afterglow on the display monitor is incorporated in the DISCO.

It represents a process which preserves radar data in the DISCO memory for a certain length of time, according to its validity, and then causes it to decay gradually.

Another mode of operation is the "freeze" mode.

In this mode the accumulated memory contents remain displayed.

⑫ Apart from the radar data processed by the DISCO, it is also possible to insert computer-generated data. In this application use is made of a cassette recorder on which video map data is stored.

SLIDE

(13)

The Operator Display Monitor

Use is made of a monitor-type 875-line TV tube applying conventional line scanning. A maximum of 6 display monitors can be connected to a scan converter, and if use is made of more than one output section in the scan converter, it is possible to retrieve simultaneously different pictures from the memory. In other words, a number of operators is permitted to work with independent pictures differing in contents of topographic relevance.
Scaling and off-centring can be done with the display monitors.
An additional feature called "zoom" allows the operator to request for display a picture fragment occupying one quarter of the display area to be magnified to cover the entire monitor screen surface, and the geographical "specimen" thus obtained can be shifted throughout the DISCO area. This off-centring method is superior to the method of radar origin off-centring in that it is instantaneous and does not involve picture erase or disturbance.
The display monitors are housed in the same tower consoles as used for the Lorads equipment.

Conclusion

It is hoped that this paper has provided an insight into a possible application of an advanced air traffic control management system with supplementary aerodrome control facilities for a busy air traffic control environment.

(14) My company not only claims having produced air traffic control systems which are in operational use, but is also eager to fulfil modern requirements, thinking in this particular case of the application of multicolour displays in ATC systems, and continues to pay full attention to the operational aspects of air traffic control, with the conviction that the design and production of costly air traffic control management systems require thorough knowledge of the operational and the technical problems involved.

LORADS

long range radar and display system

ASDE

airport surface detection equipment

LORADS

integrated civil/military
air traffic control system

LORADS

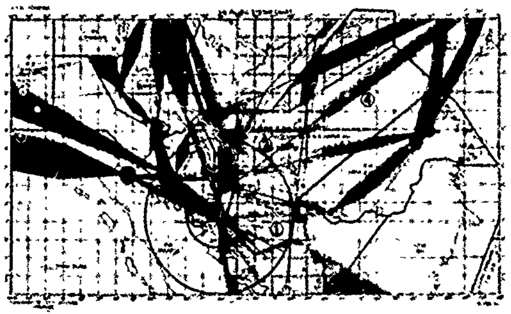
- what has lorads to do ?
  - handling fast and efficient flow of traffic
  - maintaining high standard of safety

LORADS

aim

- high standard of precision and reliability of information
- centralized computer processing of vast amount of data

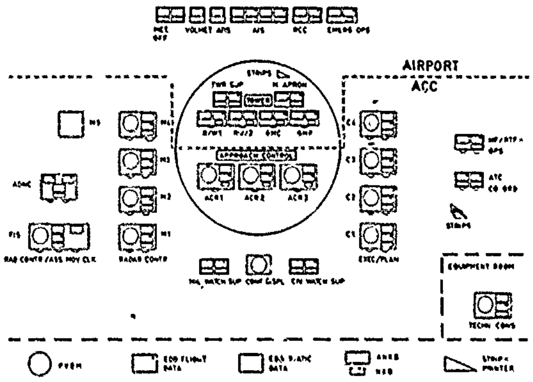
SINGAPORE FIR LAY-OUT



LORADS

- aerodrome control
- approach control
- area control

LORADS
atc organisation



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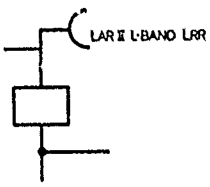

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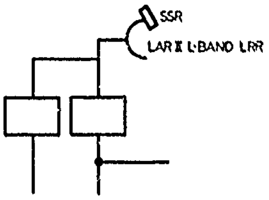

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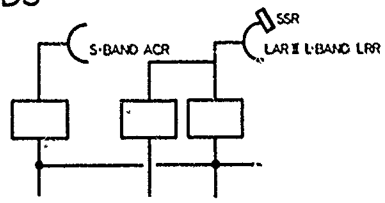

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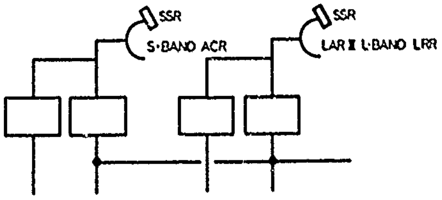

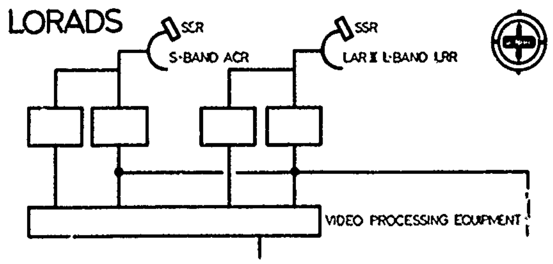

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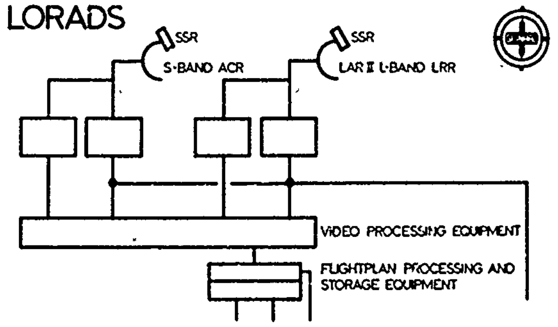

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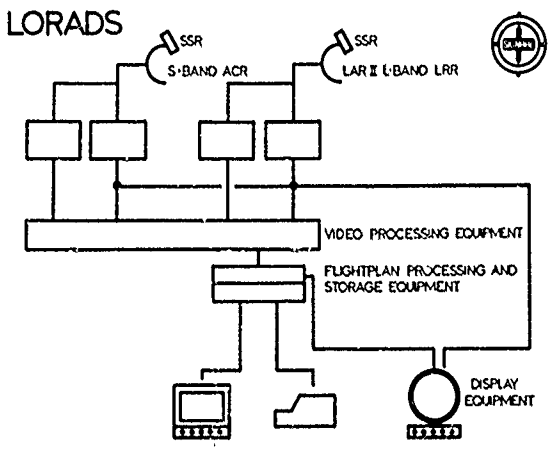

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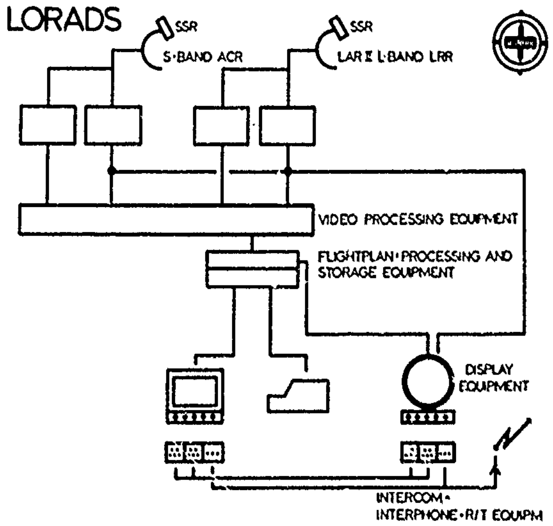

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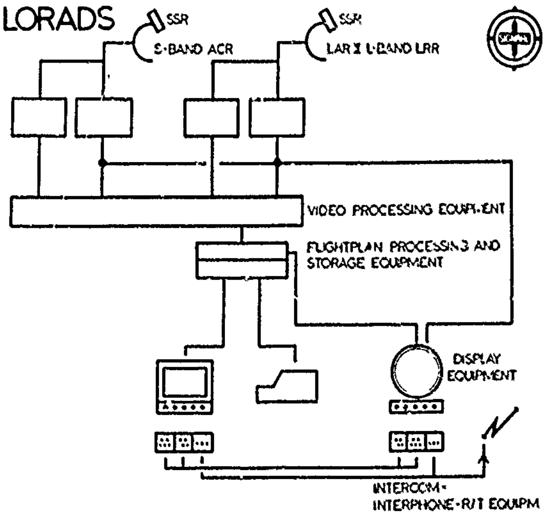
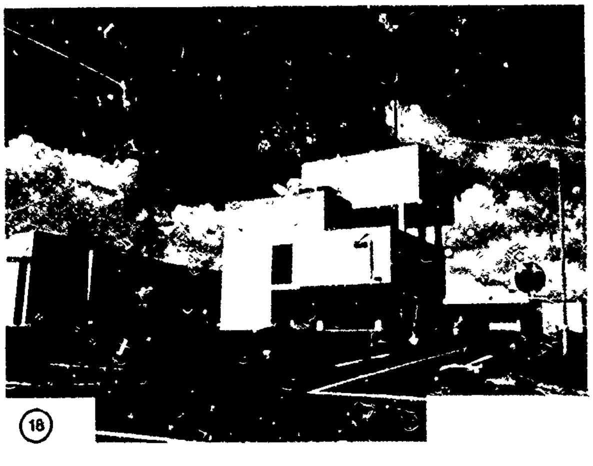


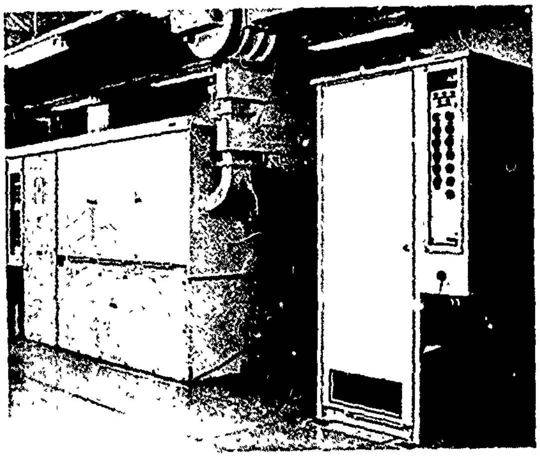
⑰

LORADS
larII l band antenna



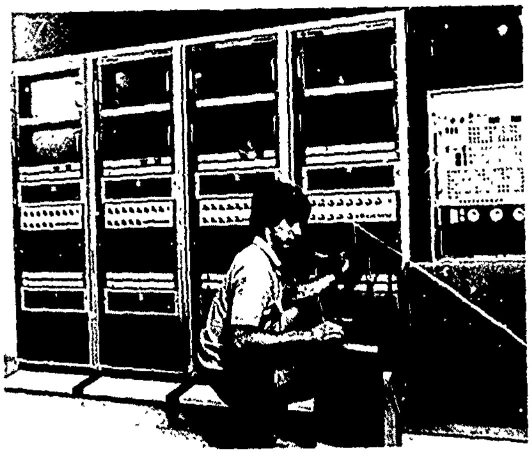
⑱

LORADS
lar II transmitter



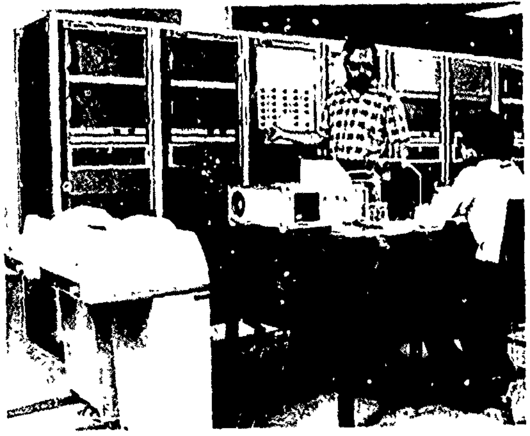
⑲

LORADS
video extractors



⑳

LORADS
flight-plan processing & storage equipment

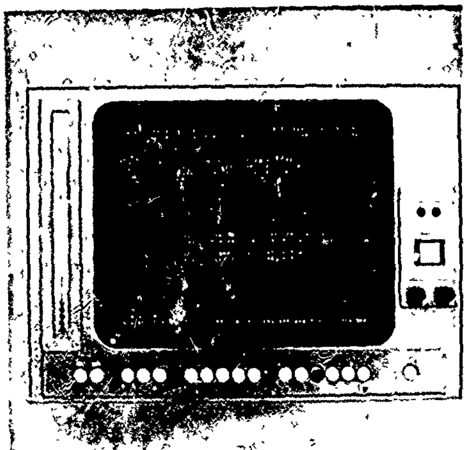


㉑

LORADS
mixed display

㉒

LORADS
tabular electronic data display



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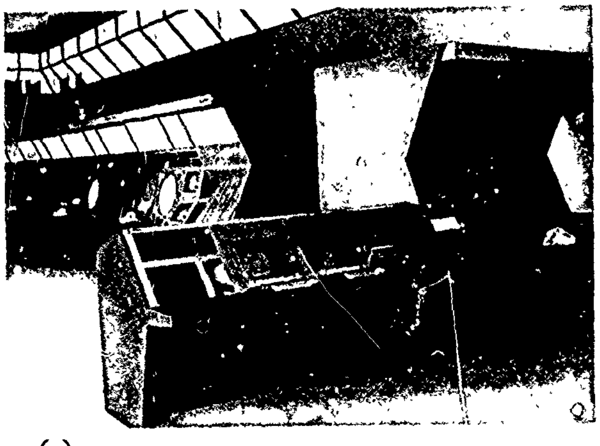
LORADS
operator console



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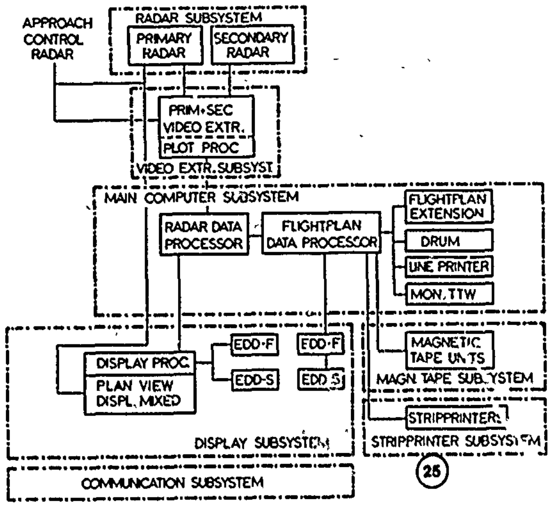
LORADS
system architecture



APPROACH CONTROL RADAR

RADAR SUBSYSTEM

PRIMARY RADAR

SECONDARY RADAR

PRIM+SEC VIDEO EXTR.

PLOT PROC

VIDEO EXTR. SUBSYST.

MAIN COMPUTER SUBSYSTEM

RADAR DATA PROCESSOR

FLIGHTPLAN DATA PROCESSOR

FLIGHTPLAN EXTENSION

DRUM

LINE PRINTER

MON. TTW

DISPLAY PROC.

PLAN VIEW DISPL. MIXED

EDD-F

EDD-S

EDD-F

EDD-S

MAGNETIC TAPE UNITS

MAGN TAPE SUBSYSTEM

STRIPPRINTERS

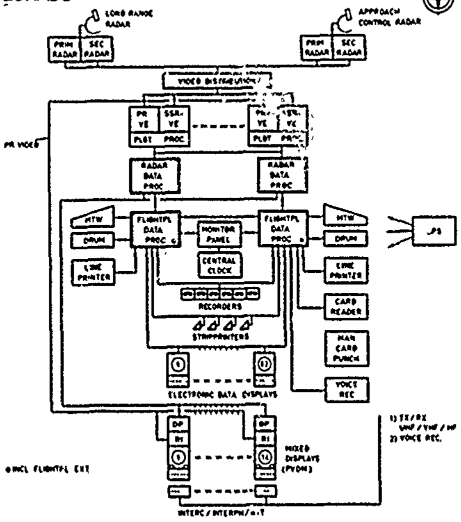
DISPLAY SUBSYSTEM

STRIPPRINTER SUBSYSTEM

COMMUNICATION SUBSYSTEM

㉕

LORADS



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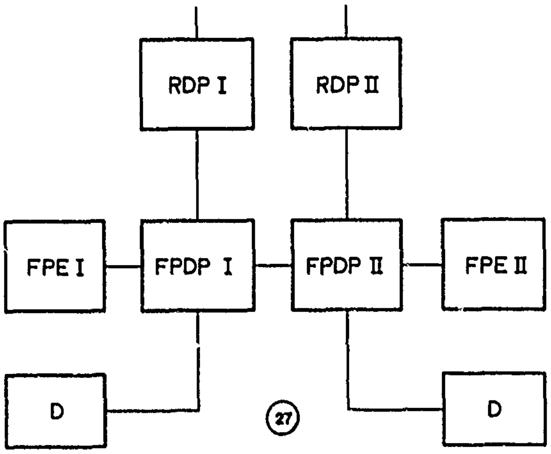
LORADS



RDP I

RDP II

FPE I

FPDP I

FPDP II

FPE II

D

D

㉗

LORADS
modes of operation

mode 0 : duplicated main comp. system

- controlled change-over
- non-controlled change-over

⇩

mode 1 : single main computer system

⇩

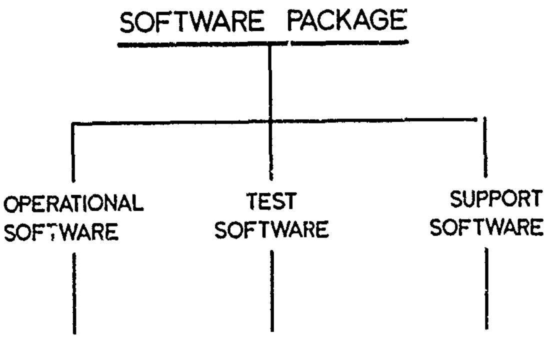
mode 2 : back-up system

⇩

mode 3 : minimum system

㉘

LORADS



SOFTWARE PACKAGE

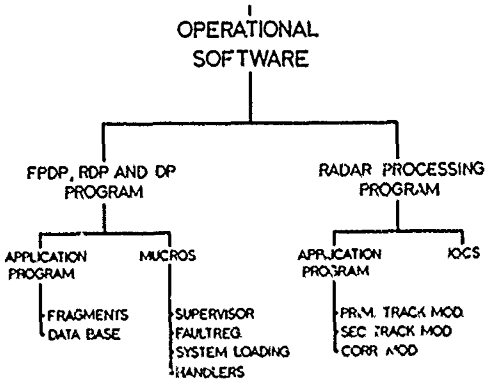
OPERATIONAL SOFTWARE

TEST SOFTWARE

SUPPORT SOFTWARE

㉙^{a}

LORADS



OPERATIONAL SOFTWARE

FPDP, RDP AND DP PROGRAM

APPLICATION PROGRAM

FRAGMENTS

DATA BASE

MICROS

SUPERVISOR

FAULTREG

SYSTEM LOADING

HANDLERS

RADAR PROCESSING PROGRAM

APPLICATION PROGRAM

PRIM. TRACK MOD

SEC TRACK MOD

CORR MOD

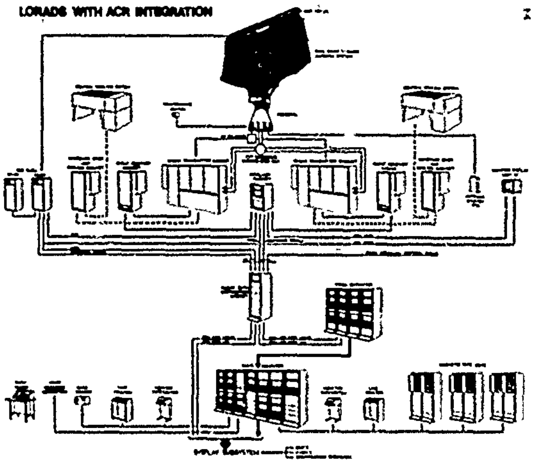
IOCS

㉙^{b}

LORADS

- TEST SOFTWARE
  - SPP
  - HPP
- SUPPORT SOFTWARE
  - PROGRAM SUPPORT
    - RTL2, FORTRAN, BASIC, BASTEL } COMPILERS
    - ASSEMBLER
    - LINK EDIT
    - LINK VERIFIER
    - FILE MAINT.
    - POINT, MAP, ROUTE COMPILERS
    - LIBRARY
  - OPERATING SUPPORT
    - JOB CONTROL
    - INPUT/OUTPUT CONTROL
    - DEBUGGING

(29)



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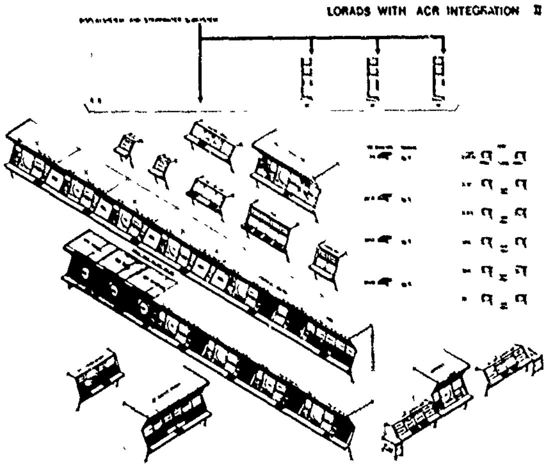
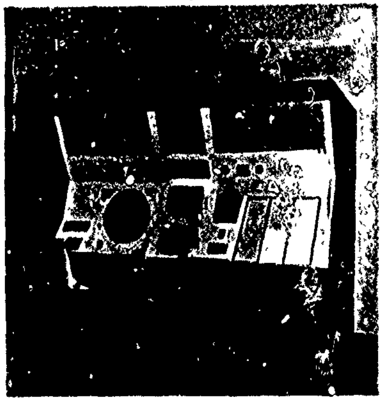


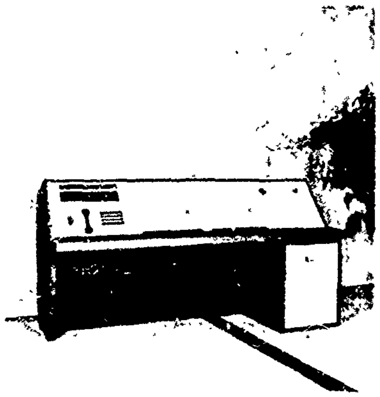
(31)

LORADS
operator console



(32)

LORADS



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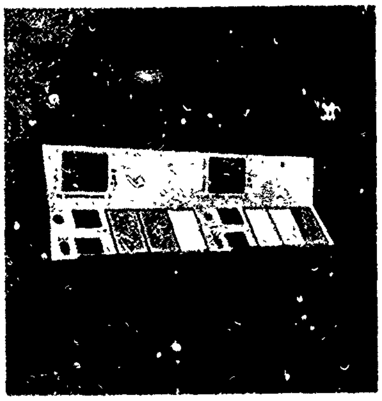
LORADS

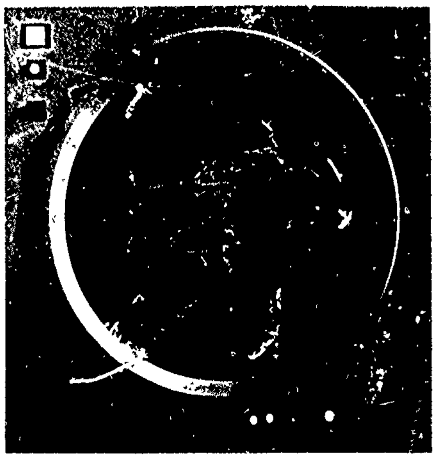


(34)

ASDE
airport surface detection equipment

ASDE
schiphol

ASDE
operator display



ASDE

MAIN FUNCTIONS :

- TO PROVIDE ACCURATE INFORMATION ON MOVING AIRCRAFT , VEHICLES AND STATIONARY OBJECTS AT AN AIRPORT
- TO PRESENT THIS INFORMATION UNDER HIGH AMBIENT LIGHTING CONDITIONS TO THE USERS

ASDE

WHAT HAS ASDE TO DO ?

- PRESENTATION OF RADAR VIDEO UNDER HIGH AMBIENT LIGHTING CONDITIONS
- HIGH RADAR AND DISPLAY RESOLUTION
- SATISFACTORY PERFORMANCE OF THE RADAR UNDER ADVERSE WEATHER CONDITIONS

ASDE

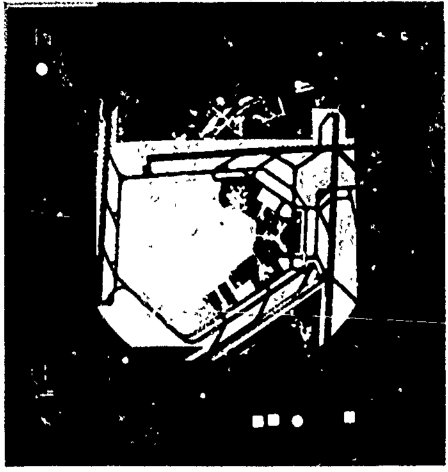
PARAMETERS DEFINING THE PERFORMANCE OF THE ASDE SYSTEM:

- TRANSMITTER FREQUENCY BAND
- ROTATIONAL SPEED OF THE ANTENNA
- PULSE REPETITION FREQUENCY
- ANTENNA
- OPERATOR DISPLAY

ASDE
antenna

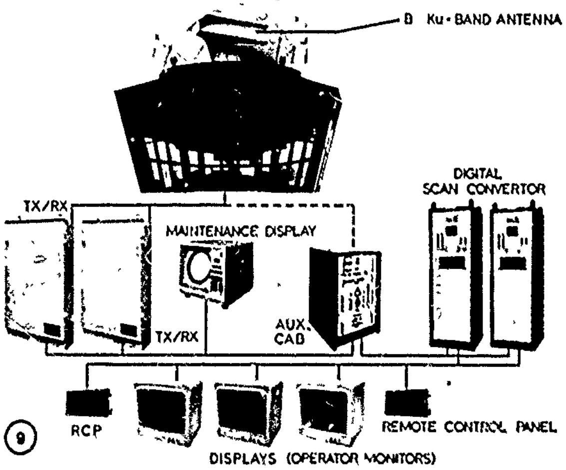
⑦

ASDE
operator display schiphol airport



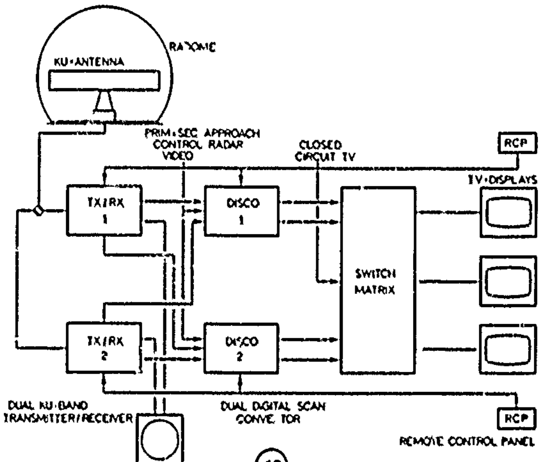
⑧

ASDE
simplified blockdiagram



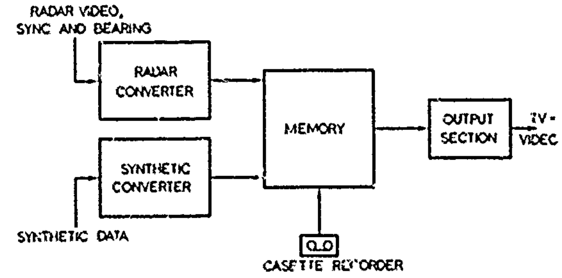
⑨

ASDE
basic blockdiagram



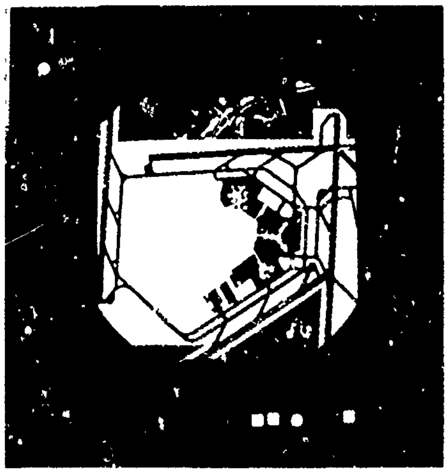
⑩

ASDE
basic blockdiagram of disco



⑪

ASDE
operator display



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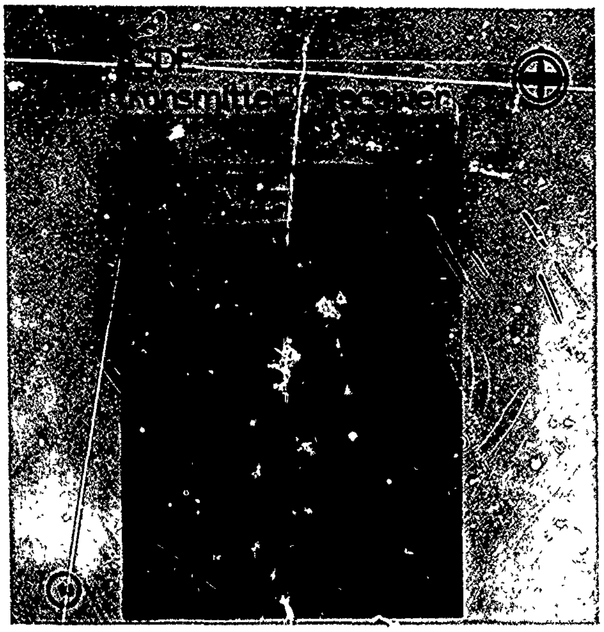
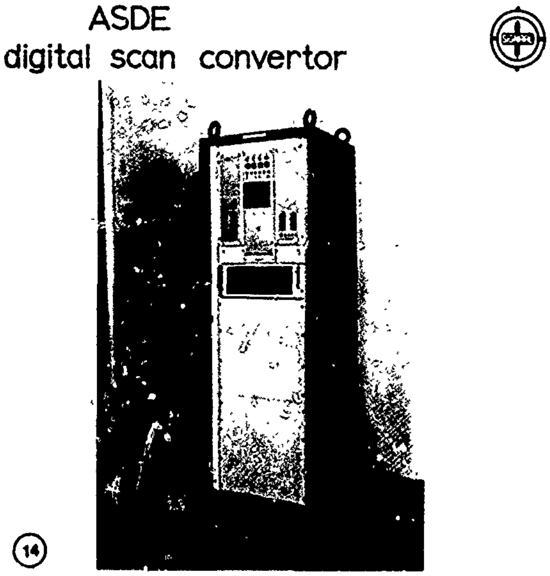
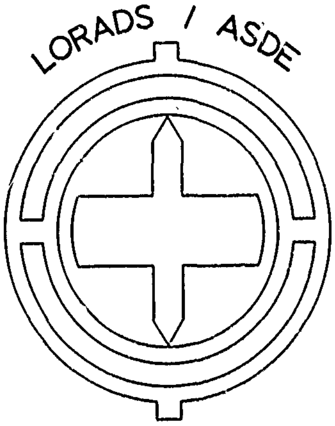

ASDE
transmitter / receiver


ASDE
digital scan convertor

⑭


LORADS / ASDE

⑮

Applications of Microprocessors in Air Traffic Control Systems

by

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RG12 1RA

1. SUMMARY

The availability of microprocessors and other LSI devices has enabled System Designers to use processing power in system elements which were previously denied them because of the cost and size of digital computers.

The characteristics of the microprocessor are compared with those of mini and main frame computers to identify the most suitable role of the microprocessor in ATC Systems.

The application of microprocessors for system functions such as Data Link Management, Display Console Management and Format Converters is discussed.

To emphasise the impact of microprocessors on system design a conventional display system is compared with one using microprocessors where this device is built into the overall design of the display system with consequent saving in display generation hardware. The design is extended so that the display microprocessor becomes the central element in display console management.

The F100L microprocessor has been used as a model in the paper to define the capability of a microprocessor. To allow the reader to evaluate this model the F100L is described in some detail.

2. CHARACTERISTICS OF MICROPROCESSORS

Since 1972 when microprocessors were first commercially available they have been used in many applications varying from pocket calculators to large ATC Systems. The reason for this is that computing power is now available to the system designer very cheaply and packaged so small that it can be used in applications where previously the physical size of digital computers made it impossible to use them. The size of these computers, made from a chip of silicon, is limited by the physical problem of external connections. Most are packaged on a 40 pin DIL, 5 cms long by 1.5 cms wide, but the size of the chip is only about 5mm square. The price of these devices vary from about $10 to $250.

Register to Register add times vary from 60 nanoseconds to 10 microseconds and the number of instructions vary from 32 to 158. Devices are available with word lengths from 1 to 16 bits, but most have a word length of 8 bits. Other important parameters are the access time to external store, the store addressing capabilities and the type of instructions offered.

It is useful to obtain a comparison between the computing power of a microprocessor and the established mini-computers. Comparisons are fraught with difficulties since the measurement depends on the type of program being used for the bench mark test. Measurements have been made of the Ferranti F100L microprocessor, which has above average processing capability and is a 16 bit device with a Register to Memory add time of 4.1 microseconds and a store addressing range of 32k words. Measurements show that the F100L has about 43% the computing power of a PDP11-34 and about 7% the power of the FM1600E, the largest machine in the Ferranti range of computers. From this it is seen that the processing power available from microprocessors is very limited and their role is best suited to be components of sub-systems or as elements in distributed processing systems.

3. DISTRIBUTED PROCESSING

In general ATC processing systems are not the conventional distributed processing system where a bank of processing power is available and the overall task can be broken down into self contained transactions such as for example in message switching where complex operating system software is used to allocate available resources for the numerous transactions. A simplified distributed processing system of this type is shown in Figure 1. This system has to support the considerable overhead of the Operating System Software.

Most ATC systems require access to a large central data base and a considerable amount of processing power. They therefore usually consist of a large Central Computer surrounded by satellite processors performing relatively simple tasks such as data link management and display processing. Microprocessors are used in these satellite machines as system elements. The whole complex can be considered as employing distributed processing but with the advantage that there is no need to support large Operating Systems to control resources.

An example of such a system is shown in Fig.2. The system is required to track primary radar and SSR targets and combine them wherever possible. Aircraft are represented on a number of displays as position symbols and associated data blocks. Visual Display Units (VDU's) are used to enter and display flight plan information. Radar data is digitised at the radar heads and transmitted to the control centre via voice band data links operating at 7,200 bits per second. If the lines are fully occupied they will carry 129 primary radar plots and 66 secondary radar plots per second. The processing tasks associated with tracking these targets require computing power equivalent to 50% the power of a computer such as the FM1600E, or the power of seven F100L microprocessors. The tracking task is therefore beyond the capability of the microprocessor. However Data Link Reception requires only 2% the power of the FM1600E for each Link and display processing about 5% the power of the computer. As the F100L has 7% the computing power of the FM1600E then Data Link Reception and Display Processing can be performed by this microprocessor, and the system looks like a powerful central tracking computer with front end and output processors.

Another example of an ATC System is the Flight Data Processing System shown in Figure 3. This system is based on a recent design study. The System consisted of a central computer complex, 11 Electronic Data Displays (EDDs); 8 VDUs and 11 EDDs with interactive input devices; 4 line printers and a number of Disc Units for backing store. It is basically a message handling system with the only real time requirement being that an operator should obtain a response from the system within 200 milliseconds of entering a request from a keyboard or interactive device. An analysis of the messages revealed that after allowing for a 100% increase in air traffic, the system had to be designed to accommodate 3828 messages per hour from all sources. This required efficient data management software and organisation. The analysis indicated that at least 372k bytes of main store was required directly addressable by the computer and 910k bytes of backing store. The processor utilisation under the worst case conditions required 2.5% the power of a FM1600E computer. The processing task was therefore within the capability of the F100L microprocessor but not within the addressing range of such a machine.

4. APPLICATIONS

General purpose microprocessors are suitable for applications where a limited amount of processing power is required and where the storage directly addressable by the device is restricted to under 32k words. This means that they are not suitable for fast time operations, such as signal processing in real time when there is only a limited time available before the next signal arrives demanding processing. Under these circumstances it is sometimes possible to digitise and store the incoming signal so that the signal can be processed at a later more convenient time. Such an application could be an Auto-Extractor where the number of radar returns received from the radar during one pulse repetition interval of the radar is limited to perhaps 200, but the resolution of the radar is such that under the worse case conditions there would be insufficient time to perform the necessary statistical processing of the returns within the azimuth window. To overcome this difficulty the radar returns would be digitised and stored during one p.r.i. and processed during the following p.r.i. The microprocessor would be chosen to have sufficient computing power to perform the statistical processing of 200 returns during one p.r.i.

A more obvious application for microprocessors is in Data Link Terminals. The main functions of a data link terminal are illustrated in Fig. 4. The input functions are:-

1. Demodulation of the Voice Frequency Signal.

2. Extraction of Data by eliminating framing bits, start code etc.

3. Error Detection and Correction.

4. Data Transfer to the Main Computer.

The complementary functions are required for output. The message usually occupies several fields, typically each containing 13 bits, with the first field specifying the message type. The Data Transfer operation would include message identity and message checking.

At a data rate of 9,600 bits per second, with a modulation rate of 2,400 baud, one data bit occupies 104 microseconds, a signal element 416 microseconds and one field 1352 microseconds. Functions 2, 3, 4 and their complements are essentially field processes and they can readily be performed by a general purpose microprocessor.

Modulation and demodulation are essentially processes at modulation rate on an analogue signal. These could be performed by a general purpose microprocessor with appropriate signal converters. However the speed and complexity of these operations make it more likely that a dedicated unit with fast multiply facilities, preceded by a sample and hold circuit and A/D converter would be used for demodulation. The modulation process is simpler, and more easily handled.

An extension of Data Link Reception is Format Conversion. In some systems the format of the data sent over the data link is different from that required by the software of the Centralised Computer Complex. Under these circumstances it could be cheaper and more convenient to perform format conversion external to the main computer by a microprocessor rather than modify the Central Computer Software.

The use of microprocessors in intelligent terminals, or VDUs, is now well established for display format control and screen editing. The introduction of these terminals has relieved the Central Computer of these time consuming functions. This is especially important where many terminals are required such as Flight Data Processing Systems.

5. DISPLAY PROCESSING

Conventional display systems (see Figure 5) used a central Display Drive Unit (DDU) to drive a number of displays each being capable of presenting raw radar and synthetic data, such as characters, symbols and lines. Usually the Display Unit (Figure 6) had separate circuits for analogue and synthetic signals. The major positioning voltage of the synthetic data was applied to the common offset and expansion amplifiers, but the character voltages were applied to auxiliary amplifiers and the output mixed with that of the major expansion amplifier so that the character sizes were not affected by the range expansion selected by the operator. The Display also incorporated deflection switching circuits to switch the major deflection amplifier between the time base and the major positioning circuits. This switch was controlled by a waveform generated in the DDU or within the Display Unit which defined the writing period for the synthetics, usually the radar "dead time". The waveform was initiated at the time of the radar transmitter pulse and terminated at maximum range. The inverse of this waveform defined the "dead time". The Character Generator was time shared between the displays therefore each character, or string of characters, was accompanied by a Display Address, or alternatively a separate switching signal would be sent to the appropriate Display. The DDU was driven either from a dedicated Processor or the Central Tracking Computer. The Display Store containing the synthetic data could either be part of the DDU, or the Display Proceesor store, if this computer had a Direct Memory Access capability.

The quantity of displayed data was limited by the speed of the Display Units and the Central Character Generator. The Display Processor arranged the data files for each display and converted positional data from system coordinates to display coordinates.

A serious disadvantage of this system was that the DDU organised data for the Displays assuming that they were all operating on maximum range. Those operating on shorter ranges would still receive all the data irrespective of the fact that some of it would be off screen. The other disadvantage was that noise on the major positioning waveforms would be amplified by the expansion amplifiers and drift in the positioning circuits and the time base amplifiers would affect the registration between the primary radar video and the synthetics.

If the system had to accommodate more than one radar it was usual to provide a DDU for each radar.

The availability of the microprocessor had enabled the display designers to integrate the device into the display to overcome many of the problems associated with conventional analogue units. The modern display is essentially digital with the conversion to analogue signals left as late as possible.

The microprocessor not only simplifies the display design but it can also be used for console management. (Figure 7). Each Display Console will not only contain a Display head but also a keyboard and a pointing device, typically a rolling ball, joystick or light pen. These input devices can interface with the microprocessor and can be used to define the range expansion and off-set required by the operator and select the display information he requires.

The Central Tracking Computer converts target information from polar to cartesian coordinates relative to the centre of the operational area. This information is sent to all Display Consoles over a high speed communications circuit and is processed by the console's microprocessor. The functions performed by this unit are as follows:

1. Convert target positions from system coordinates to display coordinates.
2. Select only those targets which are within the display range.
3. Store targets in the Display Refresh Store.
4. Filter information for display in accordance with the selections required by the operator.
5. Accept and check messages from the console keyboard.
6. Accept and check messages received from the Central Computer.
7. Process positional data from the pointing device.
8. Assemble messages for transmission to the Central Computer.

The output of the Display Store is applied to a Digital Graphics Generator which converts the digital information into analogue signals suitable to drive the deflection amplifiers of the display head. The Graphics Generator contains a character generator, line generator and possibly a Circle Generator. Information is drawn at a position on the screen defined by the major positioning voltage simply by modifying the digital position data with incremental data derived from the appropriate character, line or circle generator.

The above system used for presenting graphical information can also be used to display raw radar. This is achieved by using the line generator to produce the same effect as a rotating time base. One or more radial lines per p.r.i. are drawn centred on the radar head position in sympathy with the rotation of the radar beam The video is adjusted so that the lines do not appear on the display. The normal PPI presentation is produced by brightening up the trace with signal video in the normal way.

This system can be adapted very easily to produce a very fast radar display (see Figure 8) by drawing the radial lines at a constant rate irrespective of range expansion, typically at two or three times the radar time. This requires the radar video to be correspondingly re-timed. The video received from the radar is sampled in time and the amplitude digitised and stored. Only the video which occupies the area corresponding to the display range is stored. In this way the store is always matched to the resolution of the display and the presentation is the same irrespective of range expansion. At a convenient time after the store has been filled the line drawing operation is initiated and the store accessed at a rate consistent with the line drawing. The time saved in displaying raw radar information is used to draw synthetic data. A display system manufactured by Ferranti using the techniques described above with a F100L microprocessor has the following capability assuming a p.r.f. of 1K Hz and a refresh rate of 16 Hz.

(a) Raw Radar

and (b) 1100 data labels of 8 characters

or (c) 500 data labels of 8 characters with a position symbol and five history points

or (d) 600 full diameter lines

or (e) 5000 short lines

or any combination of the above.

6. THE MICROPROCESSOR

In examining the applications of microprocessors this paper has used the F100L as a model. To allow the reader to evaluate this model the microprocessor will now be described.

6.1 Construction

The F100L was designed for military applications, in particular it had to meet the following conditions:-

1. Operating temperature range -55°C to +125°C.
2. For Approval to BS9000.
3. Resistance to the effects of radiation.

This has been achieved by using an LSI technology known as Collector Diffusion Isolation. It is a Bipolar technology having the attributes of high speed and wide temperature range and because it is an in depth construction it is relatively immune to radiation hazards.

A number of investigations have been made by A.W.R.E. at Aldermaston by R. W. Williamson (Ref.1) into CDI in general and F100L in particular. The CDI process has also been investigated by Richards, Slater and Calaco (Ref.2). This latter work shows that the nature of the CDI process renders it inherently latch-up resistant. A high degree of tolerance to cumulative ionisation dose and to neutron displacement damage is achieved, in excess of 10^6 rad(Si) and 10^{13} n/cm^2. No catastrophic damage was obtained for dose-rate exposure up to approximately 10^{10} rad/Si)/S.

Work specific to the F100L by Williamson shows that the transient malfunction level, when exposed to an ionising radiation pulse of 1 microsecond duration, to be 5×10^6 rad/Si)/sec. F100L continued to operate normally after exposure to a total dose of at least 5×10^5 rad(Si). No tendency to latch-up was observed. A neutron fluence of 10^{13}n/cm^2 1MEV equiv (Si) produced insignificant effects.

The most important fact to come out of this work is that the device is not susceptible to latch-up as a result of radiation. Due to the inherent structure of an LSI circuit there are a number of P.N.P.N structures i.e. potential SCR's. Photo currents caused by radiation can set these SCR's into conduction, or latch-up. Often they are between the power supplies and thus large currents flow and the device is destroyed. CDI does not exhibit any form of latch-up due to the organisation and gain of its transistors consequently the F100L continues to function after a burst of radiation of the magnitude described above.

The F100L chip contains 7,000 components in a 5mm square and is mounted in an industry standard 40 pin package.

6.2 Characteristics

The F100L is a 16 bit computer with an address range of 32k words. Instruction times are on average 3 to 4 microseconds. There are 153 instructions available divided into a range of add and subtract functions and exclusive OR and AND. There is a range of conditional and unconditional jumps and also jumps according to the state of a particular bit. In the latter case the state of the bit is inverted on inspection after jumping. There are standard instructions for linking out to and returning back from subroutines. In addition to the basic range of instructions there are a number of double length functions which can be applied to various instructions allowing double or multi length working when high accuracy is required. Finally there are "external function" instructions allowing the programmer to access special logic external to the processor by a normal assembly language instruction. Such external functions could be a fast Fourier transform or a fast multiply or divide.

6.3 System Architecture (Figure 9)

The F100L architecture uses a single asynchronous bus on which can be connected memories and Input/Output devices. This reduces system interconnection problems and enables Input/Output devices to have Direct Access to Memory (DMA) without interfering with the microprocessor. With this architecture special arrangements are made to control access to the common bus. This is achieved by connecting the bus to an external device through an LSI chip Interface Set, which as well as controlling access to the bus also organises the priority control and provides a standard interface for any device which can be supported by the microprocessor system. The Interface Set is capable of operating in one of five modes, namely:-

1. Memory Mode - Memory and memory - mapped input/output.
2. Peripheral Mode - DMA and vectored priority interrupt.
3. Special Processing Unit Mode - Control of logic to perform External Functions.
4. Buffer Mode - High current drive for a terminated Input/Output Bus.
5. Bus Extension Mode - Multiple bus structures, Multiple processor systems.

DMA and interrupt priority are achieved by connecting the respective channels on the Interface Sets in series. This ensures that the Interface Set nearest the processor has top priority.

An example of a multi-processor system is given in Figure 10.

6.4 Software

The F100L is supported by the following software:-

1. Coral 66 Compiler.
2. Assembler.
3. Link Editor.
4. Simulator (Cross product only).
5. Debug Package.
6. Single Access Operating System.

The Assembler, Link Editor and Simulator are all written in ANSI standard Fortran IV and can, in general, be run on 16-bit computers.

7. CONCLUSIONS

Microprocessors and other LSI devices such as ROMs and RAMs have replaced dedicated hardware in many sub-systems with the result that these are more compact and flexible than the previous generation designs. The limited computing power and addressing range of present day microprocessors restrict their use to these sub-systems, but current developments in microprocessor design is aimed at producing higher computing power and when this is available there will be very little justification for using large mini and main frame computers in ATC Systems.

8. REFERENCES

1. P. W. Williamson, 1978 Radiation Effects on the Ferranti F100L Microprocessors A.W.R.E. Report.
2. R. F. Richards, S. R. Slater, S. E. Colaco, 1978 an Assessment of the Radiation Tolerance of Collector Diffusion Isolation Bipolar Technology.
   IEEE Conference on Nuclear and Space Radiation Effects. July 1978.

9. ACKNOWLEDGEMENTS

The author is indebted to his many friends and colleagues in Ferranti Computer Systems Limited for their help in preparing this paper.

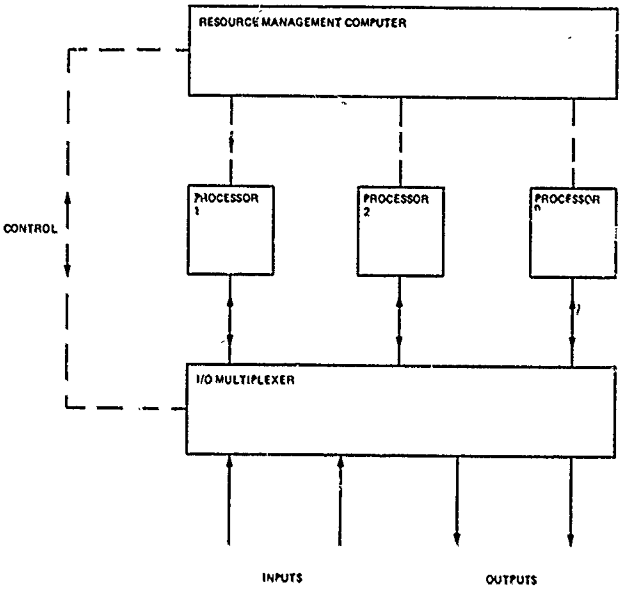

Fig.1 Distributed processing system

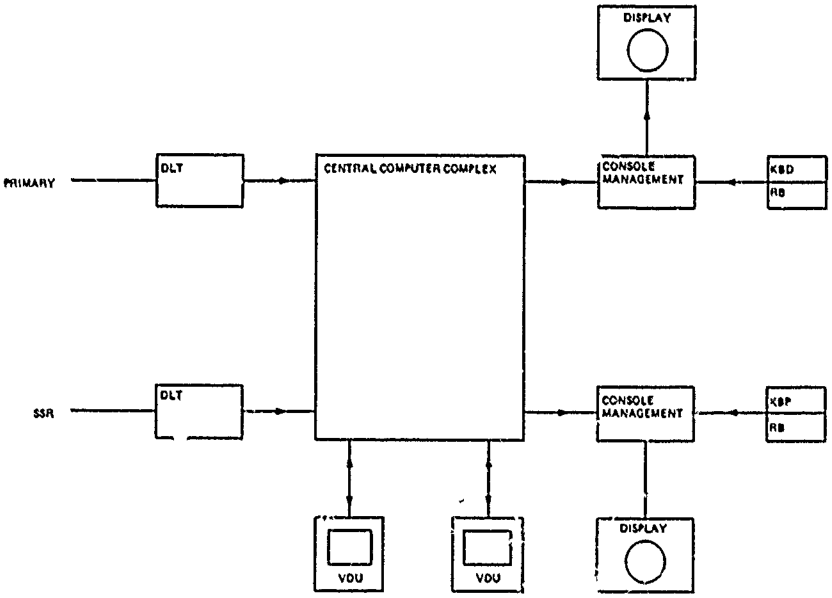

Fig.2 Block diagram of RDP system

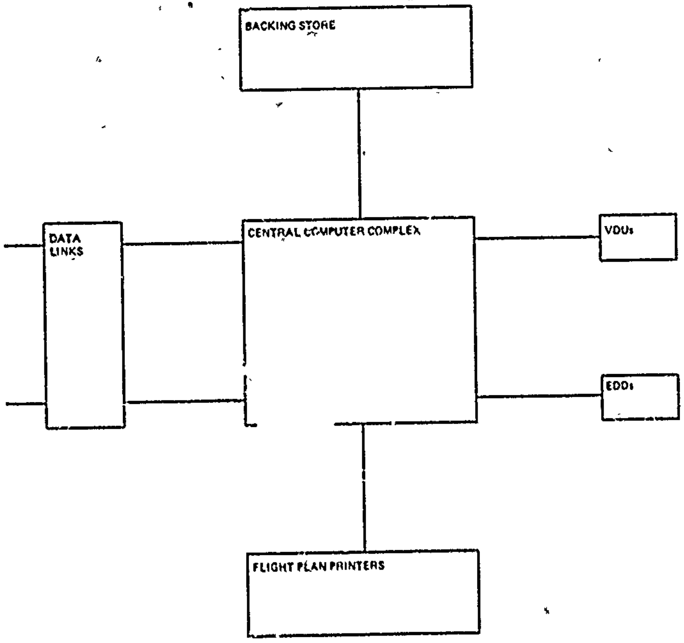

Fig.3 Flight data processing system

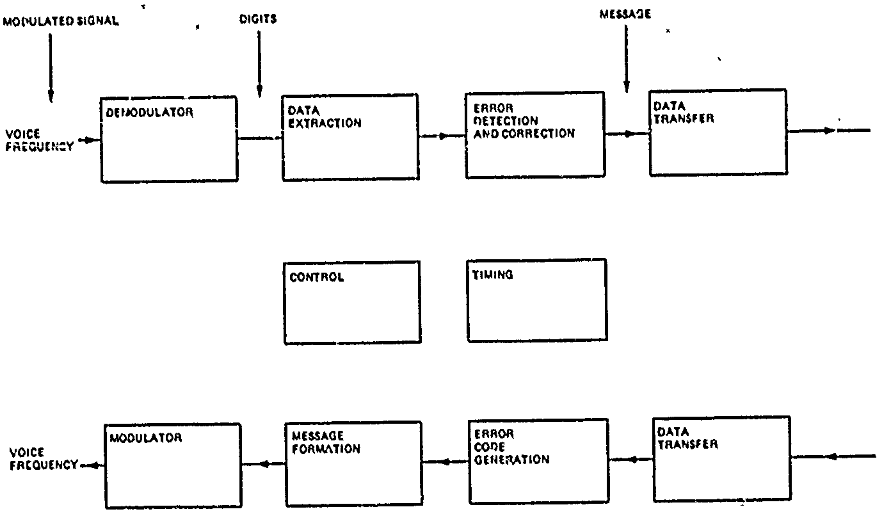

Fig.4 Data link block diagram

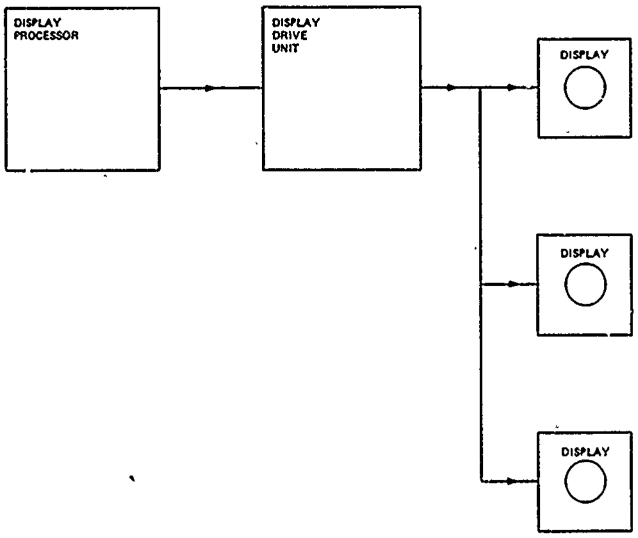

Fig.5 Conventional display system

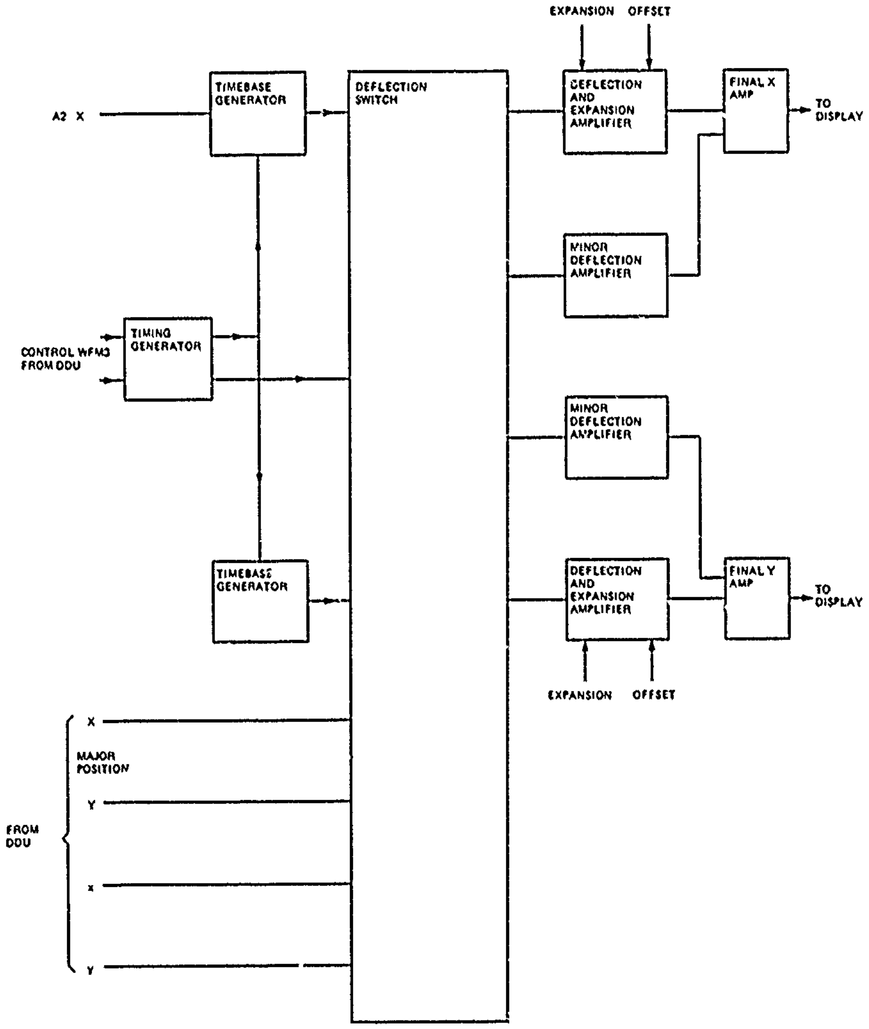

Fig.6 Display unit

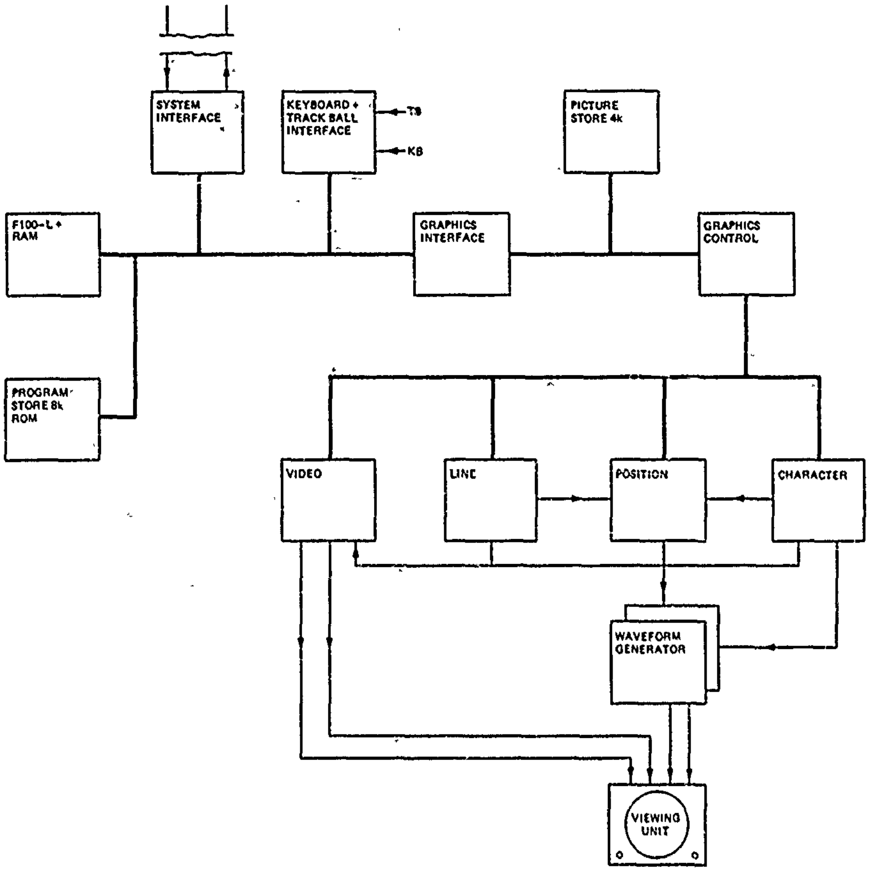

Fig.7 Synthetic display block diagram

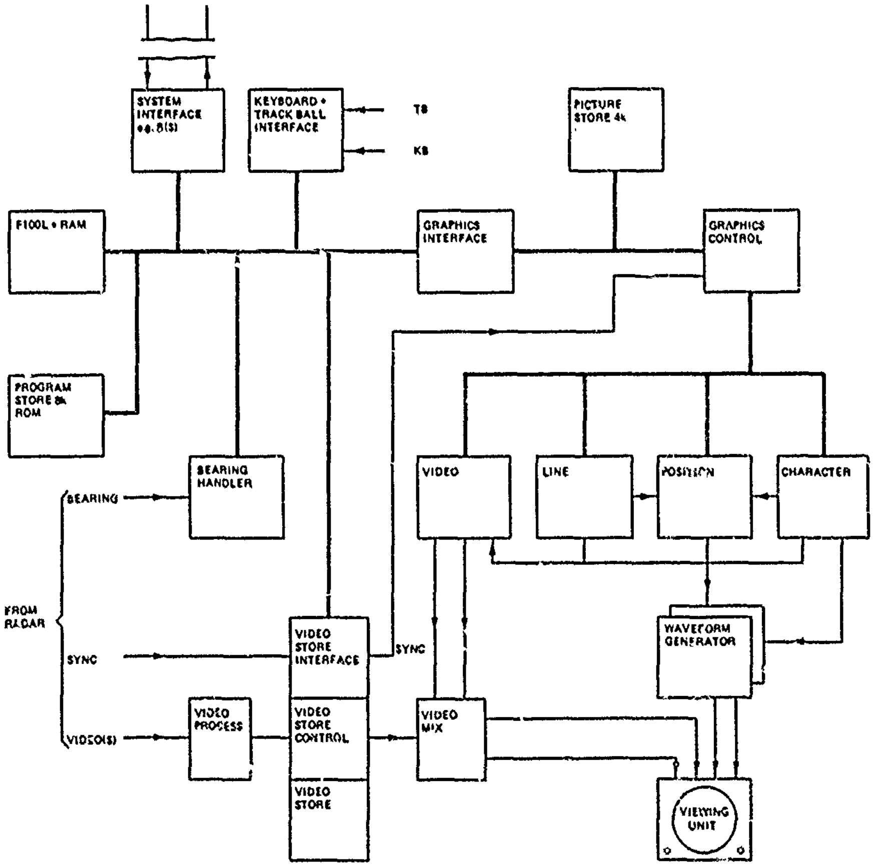

Fig.8 Radar display block diagram

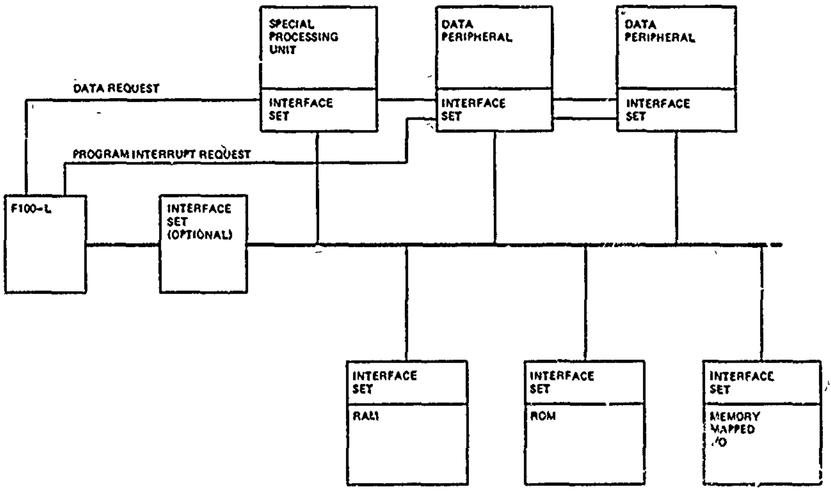

Fig.9 F100-L system architecture

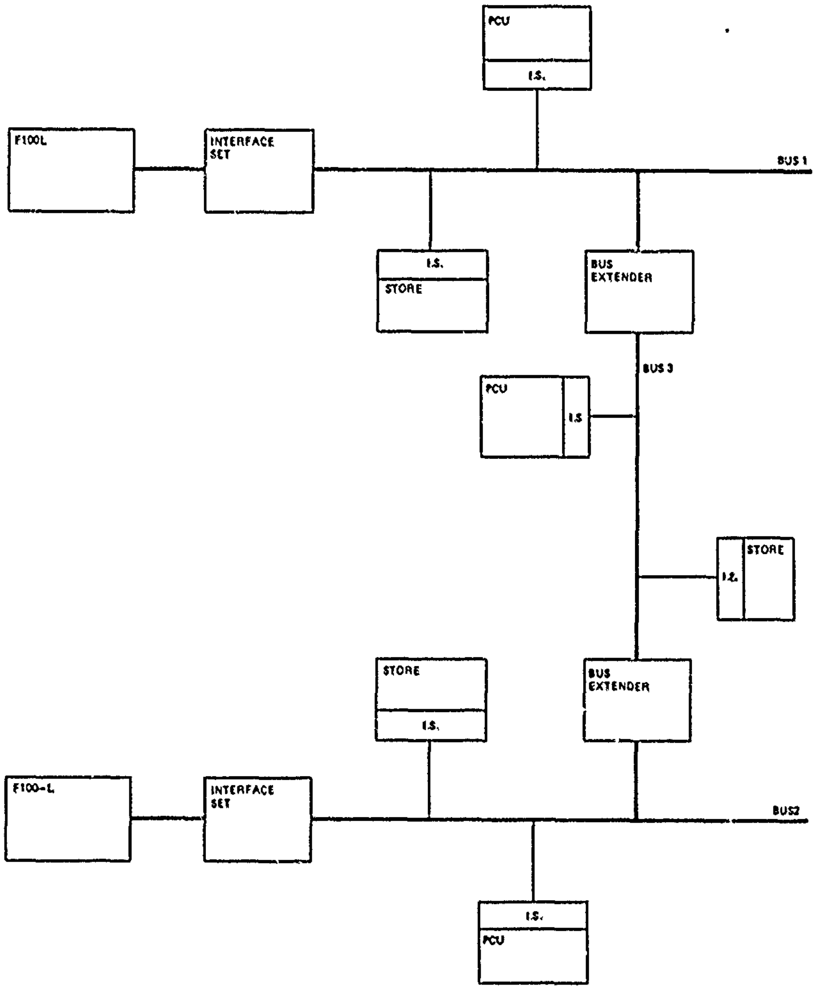

Fig.10 Dual F100-L shared resources system

PRECISION NAVIGATION FOR AIR TRAFFIC MANAGEMENT

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SUMMARY

Discusses the problems that would arise if airspace users had the use of NAVSTAR or some other much better position-fixing aid than at present, and the uses that ATC could, or could not, make of this capability. There would be formidable transitional problems in the vertical plane, because NAVSTAR measures height from the Earth's centre whereas current altimeters measure atmosphere pressure. In either vertical or horizontal planes much work will be necessary to prove that the separation standards can be reduced at all. The paper discusses changes that might be possible in the ATC system should appreciable reductions in separation standards prove possible.

NAVSTAR might form the basis of a collision avoidance system based on either the broadcast co-ordinates of each aircraft or on a time-frequency basis using NAVSTAR as the time reference. The latter scheme would offer protection of a fully-equipped aircraft against a threat that could not afford the expense of a NAVSTAR fit.

INTRODUCTION

The next two papers will discuss advanced navigational systems. The first of these, NAVSTAR, may enable even civil aircraft to fix their absolute position to much greater accuracy than can presently be achieved, eg by VOR-DME or inertia methods.

JTIDS, or at any rate some device based on the same technology, also offers interesting prospects, but the present paper will be confined to the possible application of a precision navaid, typified by NAVSTAR to the management of predominately civil air traffic. Our primary concern will be with traffic in controlled airspace, where the potential benefits, eg from reduced separation standards, are probably greatest.

The adoption of NAVSTAR in civil air transport may come about simply because it is cheaper to fit NAVSTAR instead of many of the existing navaids. Its introduction need not be accompanied by any major change in the existing ATC system, which must, in any case, be tailored to the continuing use by at least some of the traffic, of present-day navaids until these can be phased-out, a process that may take 20 years or more. No doubt airlines and other users of NAVSTAR, as well as avionics salesmen, would protest that ATC was failing to make full use of the magnificent capability which NAVSTAR offers.

More probably, perhaps, it may transpire that NAVSTAR will represent an added expense to the aircraft operators, but it will then be argued that the expenditure is justified by the improvements in safety and in efficiency of operation. In either of the above situations, we need to discuss the benefits or otherwise of NAVSTAR in a modified traffic management system.

Let us suppose then, that NAVSTAR is available for general use. The accuracy obtainable will depend on the operating modes which are available to the given class of user, and on other factors. For the purposes of the present discussion, however, we will assume that position fixes (in NAVSTAR co-ordinates) are available, at an adequate data rate, to an accuracy of a few tens of metres. We can now ask how such a system could be used in air traffic management. It will be found, throughout much of the present paper, that this approach gives rise to more questions than answers.

An incidental property of NAVSTAR is that it is an area navigation system, but the rather well-worn arguments about RNAV will not be again discussed in the present paper, since RNAV ability can be provided even with any VOR or DME and an airborne computer less elaborate than that needed for NAVSTAR.

NAVSTAR AND SEPARATION STANDARDS

The obvious way of exploiting great navigational accuracy is to reduce separation standards. We will discuss separately the exploitation of improved position-fixing accuracy in plan and in the vertical plane. Given a system based on measuring range from a number of satellites, it is probably impossible to determine position with any accuracy without finding it in all three dimensions, together with time. NAVSTAR also supplies the three components of velocity. To exploit this information in the vertical and horizontal planes involves different problems.

It should be remarked that a reduction in separation standards can only be achieved in areas where the device has been widely adopted. If only a fraction "k" of all aircraft carry the new system, the probability that at least one aircraft in any random pair is not carrying the new system will be $(1-k^2)$. For example, if 90% of the aircraft are fitted, 20% of all encounters will involve at least one aircraft that is not. There is a need for altruism on the part of any airspace user who fits a new type of navaid solely on the grounds that its general adoption will eventually make possible a reduction in separation standards.

Once the new navigation system is in service and important features such as reporting points and airfields have been mapped in NAVSTAR co-ordinates, there is no obvious traffic management problem if aircraft wish to use the navaid to determine their position in plan.

Consider the separation standards in the horizontal plane in a region where there is no independent radar surveillance system. Considerable theoretical study has been carried out for the parallel-track structure over the Atlantic, notably by Reich (1,2,3) and his colleagues at the Royal Aircraft Establishment in the UK. Later work is continuing under the aegis of the ICAO North Atlantic Systems Planning Group. Such practical data as is available on cross-track navigational error is derived from measurements made when aircraft come into radar cover on leaving the Atlantic track system. The technique requires a radar accuracy somewhat better than the navigational errors to be measured and there is little possibility of achieving NAVSTAR accuracy with any medium- or long-range ground radar system. Probably the only checks possible will require the aircraft to fly over some specially instrumented range which only works well at fairly high elevation angles.

Early results on NAVSTAR accuracy should be available from military trials, but such trials are likely to concentrate on operation in the P-mode, the results may not readily be released to civilian agencies, and for military purposes the emphasis is likely to be on the errors that occur with moderate probability, rather than on the blunders on the tails of the probability distribution which are our major concern. The total navigational and flight control system with which we are eventually concerned, is, in any event, likely to differ in many respects from that used by the military. The work of building confidence in NAVSTAR will therefore be slow and difficult.

If the navigation performance is normally much better than is needed for the separation standard in use, either because of the difficulty in building up confidence in the system or because there is no case for a reduction in separation, the unnecessary accuracy may have an adverse effect on safety. Consider for example an aircraft that for some reason or other departs from the cleared flight level. The risk of collision with an aircraft at the next level increases with the precision with which both aircraft are flying a common track. A possible solution would be to cause some deliberate dispersion about the nominal values.

A special case of particular interest arises on the N Atlantic where there is a ruling that the latitude of all waypoints for E and W traffic must be an integer multiple of 1°. Ref (4) indicates that a major source of blunders in aircraft with computer-aided navigation is errors by the crew inputting waypoint data on a keyboard. The effect of the "multiples of 1°" rule is to produce a high risk that the erroneous waypoint will lie on the track of another aircraft. It will be difficult totally to avoid the in-flight insertion of waypoint parameters. If these same values must also be inserted manually into an ATC computer the risks are even greater.

Designers of automated banking systems are careful to arrange that account reference numbers contain self-checking features so that the clerks and the computer can easily check for errors such as the transposition of two digits. Perhaps there is a need for corresponding measures to make waypoint co-ordinates self-checking. The relevance of this point to the immediate argument is that measures to increase the number of tracks or to introduce some measure of dispersion about existing tracks will almost certainly involve some increase in the complexity of the co-ordinates that must be exchanged between ATC and the aircraft, and in the length of the messages that must be input to the various computers. Consider now the situation when the aircraft are within radar coverage. It was earlier pointed out that the assumed accuracy of NAVSTAR is far higher than that of existing surveillance systems, or indeed of any likely area surveillance system that is based on the earth's surface and therefore surrounded by close-in reflectors. If all aircraft could be relied on to have a serviceable NAVSTAR system, then it would be possible to base control on air-ground telemetered position data. The difficulties are those of making the transition from the present system and of proving to an adequate confidence level that the system is reliably accurate. Clearly the first of these problems has to be overcome before we could accumulate enough data to cast light on the second.

It may seem intuitively obvious that two aircraft on nominally different tracks are more safely separated if there is radar surveillance. Lloyd (4) considering opposing direction parallel traffic streams has challenged this supposition. In the Lloyd model, a sufficiently safe separation between two tracks on which aircraft are flying with cross-track errors having a double-exponential distribution with an s.d of 0.5 NM is 5.1 NM. If radar monitoring were introduced, Lloyd assumes a total radar error in assessing the lateral separation of a pair of aircraft is 1 NM, and, rather charitably, that the radar is incapable of large errors. Under these assumptions, the radar intervention rate would be 0.035, ie the controller would have to intervene, unnecessarily, to "correct" the track of 3.5% of all aircraft movements. If this intervention rate is not tolerable the track spacing would have to be increased. A more general and rigorous treatment of the problem is still awaited. In Lloyd's study, the navaid was not much more accurate than the radar. NAVSTAR poses the problem in a more acute form. Perhaps the only effective form of ground surveillance now possible is to telemeter to the ground the NAVSTAR co-ordinates. This makes it possible on the ground to detect discrepancies due to data input blunders, or failures in the flight control system, between the planned path and that being flown, but there is no longer any independent cross-check on the navaid. Further, if the ground monitoring system is to consist of a human controller who detects failures in the flight control system and dictates corrective action, by voice, to the pilot, it is unlikely that the separations can be reduced much below their present values, if the controller is to have time to take effective action.

In the present ATC system there is a rough match between the accuracy of the navaids and of the surveillance system, and the separation standards are also consistent with the time needed by the controller, in an orderly traffic situation, to recognise when something goes wrong and to take effective remedial action. Any attempt to exploit the greater accuracy of NAVSTAR will throw open very wide questions about the functions of, and justification for, a ground ATC system.

Coming now to the vertical plane, we have some additional problems. Historically, because aircraft height and plan position could only be determined by different means and to very different orders of accuracy, a traffic system has grown up which assumes that a safe separation in plan is very many times greater than a safe separation in the vertical, 5 NM rather than 1000 ft say. Because NAVSTAR achieves approximately the same accuracy in all three dimensions, this approach may need to be reconsidered. For example, the earlier discussion about the horizontal plane would probably still hold if the GPS plan positions had random errors of the order of 100 m, or so. NAVSTAR-derived heights would, however, then be no better than those from a pressure altimeter.

The other new factor, of course, is that NAVSTAR defines position in NAVSTAR co-ordinates. In the horizontal plane we have only to establish once and for all the position of existing reference points in global co-ordinates. In the vertical plane the present flight levels are based on a quantity that NAVSTAR cannot measure. By whatever means we establish an equivalence between NAVSTAR height and flight level, a mixed system is likely to require an increase rather than a decrease in separation standards.

It should be remarked however, that in NAVSTAR co-ordinates it is possible to define, once and for all, the minimum safe altitude which can be used in a given area. This information may be made available in the aircraft either by looking-up a table carried on-board, or remoted from a ground station. This technique will work even if ATC and the pilots continue to work with pressure levels, as at present, and perhaps this is one area where NAVSTAR could make an immediate contribution to flight safety.

The safe separation between aircraft is determined by the accuracy with which they can fly a given track, and not merely their ability to detect departures from it. In the limit one factor that determines track-keeping accuracy is the ability of the aircraft to compensate for the effects of an atmospheric gust, and there is a need for study of the worst-case meteorological conditions and their effect on safe separation standards.

EXPLOITATION BY ATC OF REDUCED SEPARATION STANDARDS

It will be assumed that the adoption of NAVSTAR would have little effect on vertical separation standards, but that it should make possible a substantial reduction in lateral spacing. Unless the improved track-keeping accuracy is accompanied by a major improvement in time-keeping along track, a possibility that will be discussed later, traffic on intersecting routes are unlikely to be able to share a common flight level, since if it is necessary to monitor the relative position of aircraft on crossing routes, it will be necessary to leave time for remedial action in the event of conflict, and the end result would probably differ little from present-day procedures. The same argument applies to along track spacing, but this latter problem can be evaded by providing a multiplicity of parallel tracks

It is in the complex TMA's of today that the ATC problems are most difficult, because of the large number of potential interactions between routes flown by climbing and descending traffic. We have not undertaken the formidable task of redesigning even one major TMA to determine the payoff from the widespread adoption by the air carriers of a navaid having a significantly higher accuracy. What becomes clear from even a brief examination of the problem is that, given existing methods of ATC, attempts at closing up the spacing will soon hit the limitation mentioned earlier, the need to keep aircraft far enough apart to allow ATC time to detect conflicts or blunders and to take remedial action.

The alternative to the "tactical" approach to ATC, based largely on a pairwise comparison of aircraft positions, is a "strategic" approach which attempts to reserve a safe path for each aircraft for a significant part of the total flight. Such a system was proposed by Weiss (6) and by Stratton (7). Each aircraft is given a route which is separated from all others, like the inside of a strand of spaghetti in a bowl. The function of the ATC organisation is to assign routes to aircraft, to monitor adherence to the plan, en route, and to deal with any errors or emergencies.

The traffic capacity of the airspace, under the Weiss scheme, depends on the cross-sectional area of each "flight-tube" and on the length of time for which a given tube is allowed to reserve the airspace. Weiss apparently proposed to exercise tight control over the timing of the flight, but more recent studies of the problem (8) suggest that operation to a tight time-table would involve considerable penalties to the airlines, in guaranteeing that an aircraft would be ready for push-back at a given time. Even if we were content with only 80% successes in meeting the time-table the airline would have to add an additional 10 minute buffer to the turn-round time, which amounts to a 5% DOC penalty for a typical European operation. There are further time uncertainties after the aircraft has requested pushback. For example, an aircraft leaving Gatwick via Midhurst would have to face an extra 5 mins taxi and an extra 2 mins flight if the runway direction changed from 08 to 26 after the strategy was planned. Further operating penalties are entailed if the planned cruising speed and flight level are to be such that the aircraft has capability safely to increase or decrease airspeed by an amount great enough to compensate for wind, even, let alone any initial delay. The more realistic version of the Weiss scheme might allow reasonable latitude, say 30 mins, on the time at which an aircraft passed a given point on his flight tube, Weiss spoke in terms of each large metropolitan airport having 30-200 flight tubes leading to <u>each</u> of about 100 different cities, ie about 10,000 flight tubes per airport. It was assumed that the accuracy with which an aircraft can stay on track is such that 500 ft is a safe separation between his flight tubes. If the system is to be provided with ground monitoring and provision for tactical intervention to deal with emergencies such as engine or pressurisation failures or the need to avoid Cu-Nimb, it may well be that the safe separation between tubes is such that we wind up with a system having less capacity than at present.

OTHER POSSIBLE APPLICATIONS OF NAVSTAR-GPS

Earlier in the paper we discussed a possible ground monitoring system based on NAVSTAR data telemetered from the aircraft to the ground. It was argued that aircraft spacings had to leave time for the ground-based controller to recognise that a problem had arisen and to provide a solution. With a system having a strong procedural basis, the emphasis is on checking, that an aircrafts' position is consistent with a plan that has been laid down earlier. It is an advantage of such a system that the checking process can be readily automated, but in this situation it is less clear why the ground organisation should be involved so intimately in the process. No matter whether the departure of the aircraft from the planned trajectory is due to an aircrew blunder or to a failure in the navaid or in the flight control system, it is the pilot who should be informed and who must take the remedial action. Ford (9) has argued that the pilot should also be responsible for monitoring his position relative to his neighbours, and correcting his path as necessary. Since each aircraft could telemeter not only its position and velocity but also immediate intention (eg "turning right") the monitoring process would have much better input data than that available to present-day radar controllers. All these processes would have to take place within the framework of a central strategy derived on the ground but with relevant portions of the overall plan made available in the aircraft and displayed in some convenient format on the Air Traffic Situation Display.

Without proposing such a dramatic change, it would be possible for NAVSTAR aircraft to provide themselves with a collision-warning facility to be used as an adjunct to ATC, by eavesdropping on the air-ground telemetered NAVSTAR data. Such a system would serve only to prevent collision between pairs of aircraft both of which carried NAVSTAR.

An alternative approach to collision avoidance is the ATA time-frequency system (10), certain simplifications being possible if NAVSTAR is in service. Each aircraft broadcasts, at intervals of a few seconds, a time signal (derived from NAVSTAR time) from which another aircraft (also having access to NAVSTAR time) can measure range, a message giving height and immediate intention, and a burst of CW (on a frequency accurately controlled by reference to the NAVSTAR signals) from which another aircraft can determine range-rate by doppler measurement.

Both this system and that described earlier, in which an aircraft broadcasts its NAVSTAR position, can rely on NAVSTAR time to define a series of perhaps several thousand time-slots each of which is available for one aircraft to broadcast its data at intervals of a few seconds. There is a technique which enables aircraft automatically to search for and occupy a previously empty slot.

The elimination of the need for accurate airborne clocks represents an appreciable improvement over the original ATA scheme, the only snag being that the airborne collision avoidance device offers no protection in the event of a failure in NAVSTAR.

The merit of the ATA scheme is that the fully-equipped aircraft can be protected against a general-aviation threat which carries only a simple time-frequency transponder. The GA aircraft need not carry part of NAVSTAR, ref.(10) explains how an adequate time reference can be derived from the signals from a fully-equipped aircraft. The GA aircraft receives no collision warning, the escape manoeuvre is left to the fully-equipped aircraft.

The general aviation user must nevertheless pay for an additional transponder. This protects against collision with air carriers, the biggest collision risk which the latter have to face. The main collision risk to a GA aircraft is collision with another aircraft in the same category, and the simple time-frequency transponder offers no protection even if both aircraft are fitted.

In this respect the time-frequency device is at a disadvantage with respect to BCAS, since all the GA aircraft need carry to protect the air carrier is the SSR equipment that ATC is beginning to demand anyway. This may not protect two GA aircraft from collision, but at least there is no additional expense.

The general difficulty with airborne collision-avoidance devices is that they do not know what any ground organisation is trying to do with the traffic. There are some difficult compromises to be made in an attempt at providing adequate escape time without provoking clashes between the airborne system and ATC. These compromises will not be easier if they must apply world-wide.

CONCLUSION

It is possible that NAVSTAR-GPS will be adopted in civil aviation. The advantages of a navaid which gives good cover down to ground-level more or less world-wide are considerable. The advent of a common time-reference is a by-product that may find numerous applications.

The present paper has been concerned with the possibility that there may become available to air transport generally a navaid which makes possible significantly better track-keeping than is generally available at present. The navaid need not be NAVSTAR although the paper uses this example. Although ADSEL-DABS (11,12) offers the possibility of an improvement in the accuracy and reliability of the surveillance system on which ATC is based, the day may come when the general track-keeping ability of the aircraft population is better than the tracking capability of the surveillance system, and some re-thinking of the whole ATC concept may be necessary.

Disclaimer

The views expressed are those of the author and do not necessarily represent those of the Royal Signals and Radar Establishment or of the UK Ministry of Defence.

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JTIDS - AN INTEGRATED COMMUNICATIONS, NAVIGATION AND IDENTIFICATION SYSTEM - AND ITS POTENTIAL FOR AIR TRAFFIC MANAGEMENT

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1.0 SUMMARY

The Joint Tactical Information Distribution System, JTIDS, has been developed by the United States Department of Defense to provide secure, jamming resistant communications, navigation and identification functions capable of increasing the survivability and improving the effectiveness of mission execution elements, such as combat aircraft. Some of the intended uses for JTIDS, particularly United States Air Force applications associated with providing data to aircraft and control of aircraft, encompass many of the functions required for civil air traffic management. This paper provides a description of JTIDS and then explores its potential for air traffic management. Topics addressed include services provided to aircraft and ground centers, operation of JTIDS equipped military aircraft in the civilian airspace, potential benefits to civil aircraft, evolution and transition, network control techniques for air traffic management and cost of equipment for the austere general aviation user.

2.0 JTIDS DESCRIPTION

2.1 Connectivity

As shown in Figure 1, JTIDS is a Time Division Multiple Access system. Within each JTIDS network, time is divided into intervals called time slots, which are allocated to subscribers for transmission of digital data. When not transmitting data, subscriber terminals are continuously in a receive mode. Figure 1 shows the fighter aircraft broadcasting a message and all other terminals in receive mode. Message transmission always occurs at a known time within the time slot, as best estimated by each transmitter, and always terminates early enough within the time slot to allow for at least 550 kilometer propagation prior to the start of the next time slot. Transmissions are omnidirectional and occur in the UHF band where propagation is line-of-sight limited. The combination of omnidirectional transmission plus adequate guard time for propagation allows a network structure where each transmission can be received by every subscriber within line-of-sight without any prior knowledge about the location of the transmitter or its identity.

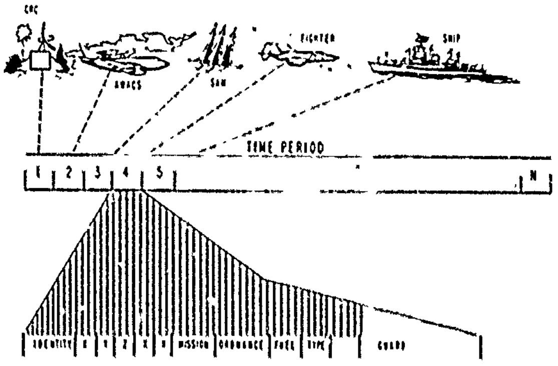
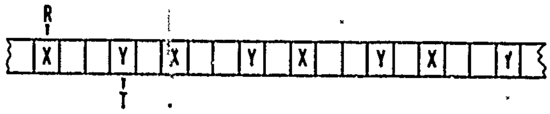


FIGURE 1. JTIDS TIME ORDERED COMMUNICATIONS

2.2 Beyond Line-of-Sight Coverage

Beyond line-of-sight coverage is obtained through use of a simple time delay radio relay technique shown in Figure 2. Terminals performing the relay function are conditioned so that all message transmissions received in a designated group of time slots (labeled "X" in Figure 2) are repeated in a subsequent group of time slots (labeled "Y" in Figure 2). The input and output slots are interleaved with each other to eliminate the need to store more than a single message at any time. The function is sufficiently simple that all terminals have been given the capability to relay messages thereby eliminating dependency upon special purposes, dedicated relay platforms.



ANYTHING RECEIVED BY THE RELAY IN AN X SLOT IS REPORTED IN THE NEXT Y SLOT

FIGURE 2. JTIDS RELAY DESIGN

2.3 Synchronization and Position Location

2.3.1 Clock Accuracy

As described in Section 2.5.2, JTIDS receivers are designed to determine the time-of-arrival of incoming messages without any a priori knowledge about the source of the data or its location. The ability to transmit and receive data has been made tolerant of timing error by providing enough guard time within each time slot to allow synchronization to be maintained for communication purposes for long periods of time using crystal oscillators within each terminal as a time reference. Each terminal dynamically models the frequency offset and drift rate of its oscillator with respect to system time and uses the corrected oscillator value to estimate current system time. Consequently, the absolute accuracy and stability of the oscillator are not the principal determinant of synchronization accuracy. The accuracy with which the offset and drift rate of the oscillator can be modeled or the key parameters. The system is designed to maintain communications synchronization for several hours with uncorrected drift rates of several parts in 10^8.

2.3.2 System Time

System time is arbitrary. It is the time maintained by a terminal designated Net Time Reference. Any terminal can be given this designation. Upon designation, that terminal ceases to correct its time estimates and broadcasts the highest time quality in messages containing this data field. Terminals that synchronize with the Net Time Reference assign themselves a quality one lower than that used by the Net Time Reference. Terminals synchronizing with these secondary terminals assign themselves a quality two lower than the Net Time Reference, and so on. Every terminal assigns itself a quality of one less than the quality of the terminal it synchronizes with. This technique prevents the feedback of timing errors within the system. Each terminal synchronizes with the best sources available and will use any source that improves its own quality. In the event of failure of a terminal designated Net Time Reference, any other terminal can assume the function. The system will continue to operate for hours until another terminal is activated as Net Time Reference.

2.3.3 Active Synchronization

System time and oscillator correction factors are automatically determined by each terminal in one of three ways. The first involves transmission of an interrogation message from a terminal seeking time correction to sources having a good estimate of system time. (Statements of each source's time and position quality estimates are included in transmitted messages.) The receiving terminal measures the time-of-arrival of the interrogation and transmits this information back to the interrogating terminal at a fixed predetermined time. The interrogating terminal, upon measuring the time-of-arrival of the return message, can ascertain the propagation between the two terminals. Since the interrogator knows the transmission of time of the reply message and has computed the propagation time, the terminal can determine the error in its estimate of system time compared to the estimate of system time at the responding terminal.

2.3.4 Passive Synchronization

The interrogate-reply method previously described requires an active exchange of messages dedicated to performing time synchronization. If a terminal has position data available from another source, such as Global Positioning System or Loran or Omega, then a passive synchronization procedure can be employed. In this case, receipt of any message containing the position of the source is examined to determine its time and position quality. If the quality values are higher than those of the receiver, then the propagation time from source to receiver is computed by the receiving terminal from the source position stated in the message and the terminal's knowledge of its own position. Since the time of transmission is known a priori, the terminal can determine the error in its estimate of system time compared to the estimate of time at the terminal generating the message.

2.3.5 Position Location and Synchronization

If the terminal does not have its position available from another source, both system time and own position relative to other subscribers can be determined passively by receipt of position data broadcast by others. Except as noted in the following sections, this technique is used only to determine horizontal position. Altitude is obtained from the on-board altimeter. The basic procedure employs a multilateration computation. Each terminal measures the times-of-arrival of a series of messages containing the position of the message source. Each message is transmitted at an a priori known time. Given the time of transmission and the measured time of arrival, range can be computed. As shown in Figure 3, arcs drawn from the positions of the sources as stated in the received messages, with radii corresponding to the computed ranges to the sources, should intersect at a point. The multilateration computation applies a correction factor to all computed ranges to cause the arcs to intersect with minimum error. The amount of correction corresponds to the receiver's system time error and the location of the intersection of the arcs corresponds to the receiver's location. This technique requires receipt of three or more messages containing source position and typically uses available on-board heading and speed data to extrapolate between measurements. There are no special requirements for the sources. They can be any terminals within line-of-sight broadcasting their positions. Again, quality checks are employed to prevent feedback of errors within the system and to allow the selection of sources that will provide the greatest improvement to the terminal's estimate of time and position. It should be noted that if two sources within the system have knowledge of their geodetic position, then the position location function is not only relative, but provides geodetic position as well.

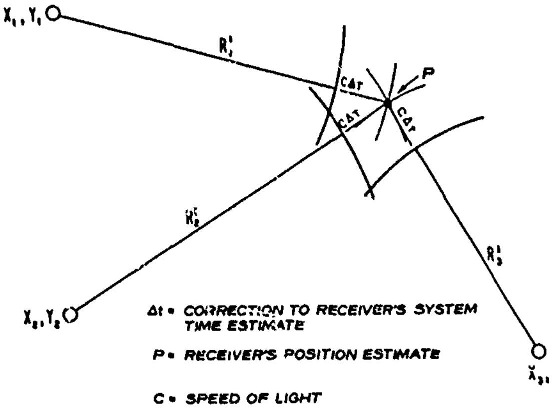


FIGURE 3. POSITION & SYNCHRONIZATION

2.3.6 Altitude Determination

Because of typically poor geometry in the vertical plane, altitude is not computed in the position determination process. However, if transmitting or receiving elements were properly placed to provide a favorable geometric situation, then altitude could be computed from the time-of-arrival of messages. This condition might be applicable in the civil environment for instrument landing as shown in Figure 4. As shown in the figure, the aircraft could determine relative position and altitude from the runway by measurement of messages from the specially placed transmitting antennas. Alternatively, the time-of-arrival of a message broadcast by the aircraft could be measured at each of the surface locations and the position and altitude computed on the ground and broadcast to the aircraft. Because of the short ranges involved and therefore high signal-to-noise ratios at the receivers, the accuracy of the computation should be limited only by terminal clock quantization accuracy. At present this is 6.25 nanoseconds.

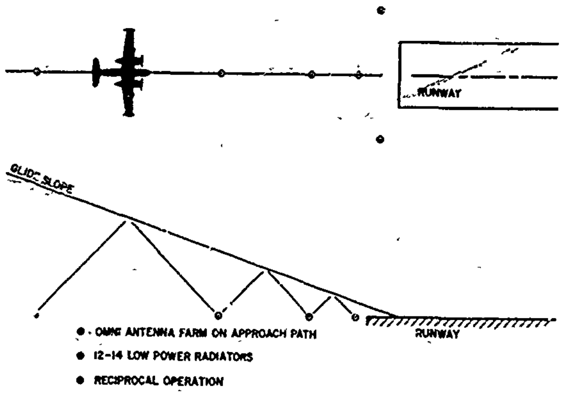


FIGURE 4. INSTRUMENT LANDING

2.3.7 Surface Traffic Location

One other possible application of interest to civil air traffic management is location and identification of traffic on the airport surfaces (runways, taxiways, etc.). In this case, receivers would be placed in geometrically favorable locations on the airport surface. Terminals in aircraft and other vehicles would periodically broadcast a message containing their identity. The time-of-arrival of these messages would be measured by the receivers and a multilateration computation performed to determine the transmitter's location. This technique has already been successfully demonstrated at several airports by the U.S. Department of Transportation's Transportation Systems Center using the Air Traffic Control Radar Beacon System (ATCRBS) waveform (a conventional waveform of 0.45 microsecond pulse duration).

2.4 Interference Protection

Within each time slot, messages are transmitted in the form of 6.4 microsecond pulses. Each pulse consists of a 32-bit continuous phase shift modulated sequence (5 megabit modulation rate). The coding process includes powerful error coding techniques to provide receivers the ability to correct incoming messages having up to 50% errors and to detect residual errors after message correction with an error rate no greater than one per million messages. The 32-bit sequence within each 6.4 microsecond pulse is varied from pulse-to-pulse and the carrier frequency used for transmission of each pulse is selected prior to transmission from a set of frequencies distributed across the band 960 MHz to 1215 MHz. The transmitted waveform is shown in Figure 5. Terminals have additional modes of operation where the frequency hopping and 32-bit code randomization is inhibited. However, these spread spectrum features, in addition to providing protection from intentional jamming, also provide increased protection against multipath, self-interference and unintentional interference.

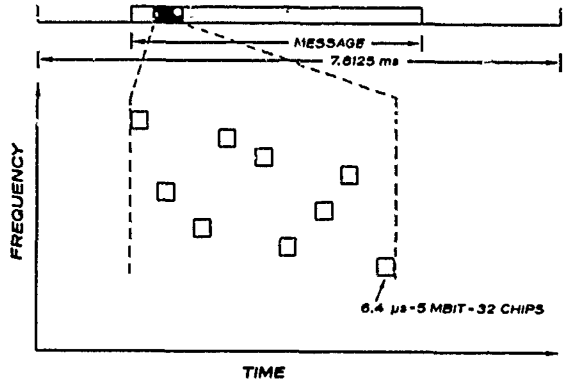


FIGURE 5. JTIDS SIGNAL STRUCTURE

2.5 Multiple Simultaneous Transmissions

The added interference protection provided by the spread spectrum signal structure, in combination with the forward error correction coding, allows system operation with multiple transmitters broadcasting in a time slot. Terminals have been designed to process the first signal arriving at the receiver having the proper frequency and phase code sequence. Signals with incorrect coding or signals that are delayed with respect to the first signal are rejected without preventing reception of the earliest properly coded signal (within the limits discussed in the following sections). Consequently, in addition to assigning time slots to transmitters for their exclusive use, other time slot assignment techniques have been developed. These techniques, which have potential application for civil air traffic management, are described in the following sections.

2.5.1 Code Division Time Slot Assignment

JTIDS terminals are capable of generating or receiving any one of 128 different frequency-phase code sequences in each time slot (see Figure 6). The particular sequence used in each time slot is selected dynamically according to pre-stored instructions that are changeable at any time either by radio message or operator input. This property allows a group of time slots to be partitioned among sets of users where each user set employs a different frequency-phase code sequence within the common time slot group. Signals generated by transmitters in other groups have sufficiently poor correlation with the desired signal, due to the different code sequences employed by each group, to cause them to be rejected. The error coding allows the desired transmission to be determined even though the interfering code sequences destroy occasional pulses of the desired transmission.

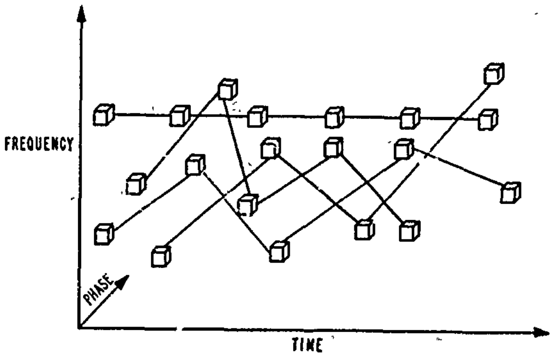


FIGURE 6. JTIDS CODE SEQUENCES

2.5.2 Time Slot Reuse

Given the current time slot number and the pre-stored instruction as to which of the 128 sequences is of interest within the time slot, the terminal has sufficient information to generate the frequency-phase code sequence of interest. Time-of-arrival of the sequence, however, is unknown due to the random separation distance between subscribers. Detection of messages occurs by generating within the receiver the sequence of interest for the current time slot and employing a matched filter detector to determine the earliest time-of-arrival of the transmission. The detector is matched to all or a portion of the first set of pulses of each transmission. These pulses constitute a synchronization preamble which enables receivers to establish timing for demodulation of the data portion of the transmission. Data demodulation occurs in synchronization with the earliest output from the matched filter detector.

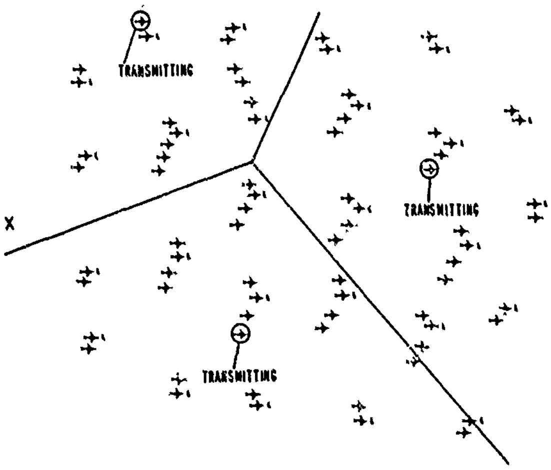


FIGURE 7. MULTIPLE USE OF TIME SLOTS - AREAS OF COVERAGE

Due to the 5 megabit pseudorandom phase modulation within each 6.4 microsecond pulse, multipath signals arriving more than approximately 400 nanoseconds after the direct signal are uncorrelated with the direct signal and do not influence the data demodulation process. (Signals arriving more than 6.4 microseconds after the direct signal are uncorrelated in frequency as well as phase.) Consequently, JTIDS receivers are insensitive to delayed signals having differential times-of-arrival greater than approximately 400 nanoseconds. This condition applies not only to multipath signals, but also to transmissions from several subscribers all using the same frequency-phase code sequence. The earliest transmission will be processed by the receiver and all others will be rejected provided their differential time of arrival is outside the 400 nanosecond ambiguity region. This allows subscribers sufficiently far apart geographically to be assigned the same slots. Receivers will process the transmission from the closest source using the frequency-phase code sequence of interest and reject the other later arriving transmissions. This is illustrated in Figure 7 which shows three transmitters broadcasting simultaneously and the areas within which their respective transmissions will be received. The boundaries between the areas are the perpendicular bisectors of the lines between the transmitting aircraft and change for each combination of simultaneous transmitters. The ambiguity region for receivers is 400 nanoseconds wide centered about each boundary line.

2.5.3 Contention Time Slot Assignment

Another technique that capitalizes upon the ability to process the first signal and reject all others is called contention access. In this mode, a group of time slots is designated for use in the contention mode. Subscribers broadcasting messages within this time slot group are assigned an average reporting rate and randomly select transmit time slots from the group at their average rate. The same frequency-phase code sequence is used by all transmitters in a time slot. Since time slots selection is random, the probability of more than one subscriber selecting the same time slot is determined by the number of time slots in the group, the number of subscribers and their average reporting rate. When multiple transmissions do occur, each receiver will process the transmission arriving earliest and reject the others. If the first two arriving transmissions happen to have a time-of-arrival difference within the ambiguity region, the random time slot selection process makes it highly unlikely that the two sources will select the same time-slot for their next transmission. Aircraft motion also causes the ambiguity situation to be a short term transient condition.

Static time slot assignment has the characteristic that messages broadcast in this mode are received at a constant rate equal to the assigned rate. In contrast, when contention access is employed, the received message rate is higher for sources close to the receiver than for sources further away. This occurs because the message from the closest source is the one processed whenever a contention situation occurs. If contention access were used for subscribers to transmit their position and identity, the result would be a situation where each receiver experiences higher update rates for closer sources than for sources further away. Figure 8 illustrates the update rate experienced by the aircraft circled in the upper right hand corner of the figure. A similar situation exists for all the other aircraft. For the parameter values of 120 time slots per second assigned to the contention pool and each aircraft reporting at an average rate of once per two seconds, circles drawn on the figure illustrate the average update rate from the n^{th} aircraft in range. For example, position reports from the 160th aircraft are received at an average rate of once per four seconds. Closer aircraft are updated more frequently and further aircraft less frequently as indicated on the figure.

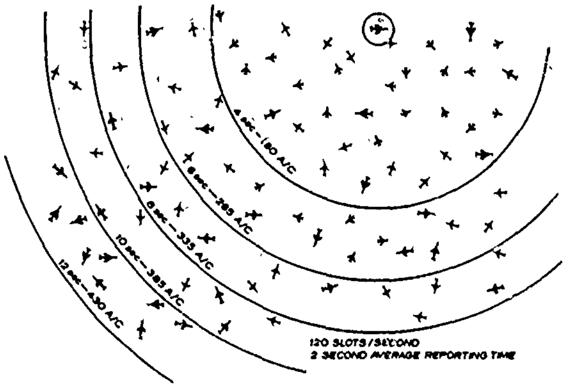


FIGURE 8. SAMPLE UPDATE RATES - CONTENTION ACCESS

3.0 SYSTEM FUNCTIONS

The JTIDS functions most related to civil air traffic management are listed in TABLE I. These functions include coordination among aircraft; providing aircraft with timely threat information; providing identification of friendly forces to each aircraft and identifying each aircraft to other friendly air and ground forces; providing for interaction between the command and control system and aircraft; and providing for coordination among surveillance and command centers. One principal feature required for each of these functions is the distribution of position and identity information. To satisfy this requirement JTIDS includes a position location function wherein each subscriber terminal derives its relative position with respect to all other subscribers as a by-product of the communication function (see Section 2.3).

TABLE I

JTIDS FUNCTIONS RELATED TO AIR TRAFFIC MANAGEMENT

- INTRAFLIGHT COORDINATION
- INTERFLIGHT COORDINATION
- AIR THREAT DISTRIBUTION
- SURFACE THREAT DISTRIBUTION
- AIR TO AIR IDENTIFICATION
- AIR TO SURFACE IDENTIFICATION
- TARGET ASSIGNMENT
- TARGET UPDATES
- COMMANDS
- SURVEILLANCE COORDINATION
- POSITION LOCATION

The system functions are achieved by exchange of fixed format digital messages and digitized voice communications. Each JTIDS equipped aircraft and ground center periodically broadcasts an automatically composed digital message containing its position, velocity, identity, and other related information. Other JTIDS equipped subscribers receive these messages and use them not only for the mission functions discussed above, but also for automatic position determination and navigation by the JTIDS terminal. The derived position information plus velocity and identification is in turn broadcast by the JTIDS terminal for use by all other system participants. It should be noted that identity information is distributed throughout the system by periodic omnidirectional broadcast by each subscriber rather than by the question and answer approach employed by the current Air Traffic Control Radar Beacon System (ATCRBS). Each transmission is available to all subscribers simultaneously without interrogation by any subscriber.

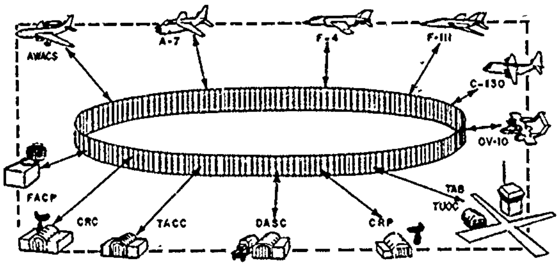


FIGURE 9. INFORMATION DISTRIBUTION CONCEPT

To the extent available, similar position velocity and identity information is broadcast by surveillance centers concerning hostile and unequipped friendly forces not being reported by others. In this fashion, the entire air situation is continuously broadcast on the JTIDS network for use by all subscribers. As shown in Figure 9, each subscriber contributes a portion of the total in such a manner that the composite total, or any selected subset, is available to each participant. Participants access the data by conditioning their JTIDS terminal to automatically filter each incoming message and only pass messages containing data fields whose values are of interest to the user. For example, a fighter aircraft might have its terminal conditioned to select, in addition to other items, hostile aircraft in close proximity on an approaching flight path. In this case the identity field of each incoming track message is examined, the position data field is compared to the terminal's estimate of its current position, and the velocity is compared to a computed closing velocity. Messages passing the selection criteria are displayed to the pilot, others are rejected.

In addition to broadcast of situation data, instructions and advisories are broadcast by control centers in the form of fixed format digital messages addressed by data field within the message to the affected subscriber. Terminals always accept messages containing their address independent of any other conditioned message selection criteria. These messages are also available to all other subscribers for informational purposes to provide for coordination of activity among aircraft.

JTIDS time slots can be used individually in a "stand alone" fashion as has been described for broadcast of position data concerning a hostile or friendly force element, or can be grouped into channels for transmission of digitized voice and teletype data. Time slots can be grouped to support digitized voice and teletype channels operating at rates of 75 bits per second (b/s) up to 19.2 kb/s including 8.0 kb/s and 16.0 kb/s. Each JTIDS terminal is initialized as to the time slot groups assigned for voice and teletype channels. When one of these channels is activated by the user, data received in these time slots are routed to the voice or teletype end instrument. Similarly, data generated by the end instrument are broadcast in these time slots.

4.0 AIR TRAFFIC MANAGEMENT APPLICATIONS

TABLE II lists the air traffic management functions that could be accomplished in aircraft using the features described in the preceding sections. Reception of position, velocity and identity messages repetitively broadcast by others allows susbscribers to, (1) locate themselves, (2) have a continuous air situation display, and (3) determine potential collision situations and perform collision avoidance. Continuous position determination coupled with heading and speed inputs from air data instruments allow for area navigation. As discussed in Section 2.3, use of appropriately placed ground terminals also allows for instrument landing and airport surface traffic location. Periodic reporting of position, velocity and identification by each subscriber allows for surveillance monitoring at centers, provides air situation and collision avoidance data to other aircraft and supports the position location function by other aircraft. Receipt of instructions and advisories both by fixed format digital messages and by voice provides for airspace management and control.

TABLE II

JTIDS FUNCTIONS IN AIRCRAFT

- FIXED FORMAT DIGITAL DATA
  - RECEIVE POSITION, VELOCITY AND ID FROM OTHERS
    - POSITION LOCATION
    - COLLISION AVOIDANCE
    - AIR SITUATION DISPLAY
  - DETERMINE POSITION AND NAVIGATE
    - AREA NAVIGATION
    - INSTRUMENT LANDING
  - REPORT POSITION, VELOCITY AND ID TO OTHERS
    - SUPPORTS SURVEILLANCE MONITORING
    - SUPPORTS POSITION LOCATION BY OTHERS
    - SUPPORTS COLLISION AVOIDANCE
  - RECEIVE INSTRUCTIONS AND ADVISORIES
- DIGITIZED VOICE

TABLE III lists the air traffic management function that could be accomplished in ground centers using the JTIDS functions. Ground centers, being stationary, do not require a position location function. Position information would be stored in the JTIDS terminal as a constant. Its periodic broadcast at known times (the start of a time slot) supports the position location and system synchronization functions in aircraft. Reception of position, velocity and identity data from others allows for surveillance monitoring, airspace management, airport surface traffic location and identification, and instrument landing. Ground center broadcast of track data concerning unequipped aircraft within surveillance coverage supports collision avoidance and air situation display in aircraft. Broadcast of instructions and advisories both by fixed format digital messages and by voice supports airspace management and control.

TABLE III

JTIDS GROUND BASED FUNCTIONS

- FIXED FORMAT DIGITAL DATA
  - REPORT POSITION, VELOCITY AND ID TO OTHERS
    - SUPPORTS POSITION LOCATION AND SYNCHRONIZATION
  - RECEIVE POSITION, VELOCITY AND ID FROM OTHERS
    - SURVEILLANCE MONITORING
    - AIRSPACE MANAGEMENT
    - INSTRUMENT LANDING
    - AIRPORT SURFACE TRAFFIC LOCATION AND IDENTIFICATION
  - BROADCAST POSITION, VELOCITY AND ID OF UNEQUIPPED AIRCRAFT
    - SUPPORTS COLLISION AVOIDANCE
    - SUPPORTS AIR SITUATION DISPLAY IN COCKPIT
  - BROADCAST INSTRUCTIONS AND ADVISORIES
    - AIRSPACE MANAGEMENT AND CONTROL
- DIGITIZED VOICE

5.0 CIVIL-MILITARY INTERFACE

The civil air traffic management system is continually evolving. In addition to the Air Traffic Control Radar Beacon System (ATCRBS) transponders required aboard aircraft flying in controlled airspace, the Discrete Addressable Beacon System (DABS) is currently under development within the United States to provide an improved surveillance/identification capability plus a digital data link for warnings, advisories and control. Both these systems have little future military value due to their lack of security and jamming protection and their exploitability. Furthermore, it is unlikely that any system developed for civil air traffic management would incorporate the unique military requirements. Consequently, the only future benefit from carrying these systems aboard military aircraft appears to be interface with the civil system.

Alternatively, placing the civil/military interface on the ground at civil air traffic management centers can be considered. In this case JTIDS terminals would be located at DABS facilities and other major air traffic centers. Position and identity data concerning JTIDS equipped military aircraft would be provided to the civil system surveillance tracking computers via JTIDS and not by ATCRBS/DABS. JTIDS data would be entered into the tracking computers using a digital data interface similar to the DABS interface or the radar data extractor interface in use today. Similarly, situation data from the tracking computers about non-JTIDS equipped aircraft, and instructions and advisories would be provided to JTIDS equipped military aircraft via the collocated JTIDS terminals. This approach has no impact on civil users and does not require any additional investment on their part. They continue to provide data to the air traffic management system via ATCRBS/DABS. However, the ground environment is now in place to support any civil user interested in the potential benefits available from JTIDS. The investment is entirely optional. It may, for example, be of interest to scheduled air carriers who can equip themselves without affecting other users of the airspace.

6.0 POTENTIAL BENEFITS

The multiple functions performed by JTIDS are integrated into a single waveform. These functions, as described in Section 4.0, are directly applicable to civil air traffic management as shown on the left-hand side of TABLE IV. The potential exists to use JTIDS, or a simplified variant, for civil air traffic management in such a manner as to achieve a substantial reduction in the number of avionics equipment aboard aircraft and also to achieve a simplification of the navigation and surveillance system ground based components. Whether such integration is cost effective remains subject to further study. However, the potential does exist to replace some or all of the civil systems currently in existence or under development shown on the right-hand side of TABLE IV with a single integrated JTIDS like design.

TABLE IV

POTENTIAL FOR REDUCTION OF AIRCRAFT AVIONICS EQUIPMENT

- SURVEILLANCE MONITORING
- AIRSPACE MANAGEMENT AND CONTROL
- COLLISION AVOIDANCE
- AREA NAVIGATION
- AIR-TO-AIR COORDINATION
- INSTRUMENT LANDING
- AIRPORT SURFACE TRAFFIC LOCATION & ID
- VOICE

- ATCRBS
- VOR
- DME
- ILS/MLS
- DABS
- IPC
- CAS
- AREA NAV

7.0 NETWORK ARCHITECTURE TAILORED TO AIR TRAFFIC MANAGEMENT

7.1 Capacity

If a JTIDS like approach to air traffic management were to be taken, the question arises as to the organization and utilization of the system such that it is responsive to air traffic management needs. Sample network architectures have been developed to answer this question using the time slot utilization techniques described in Section 2.5; namely, code division time slot assignment, time slot reuse and contention time slot assignment. These techniques will be applied to one variant of the JTIDS time slot structure which consists of 1536 pairs of time intervals per 12 seconds. Each pair of intervals can be used as a single entity or the two intervals in a pair can be used independently. When the two intervals of a pair are used as an entity, the entity is termed a full time slot. When the two intervals of a pair are used independently, they are termed half slots. Each full time slot consists of two half slots. Any time slot can be used as two independently assigned half slots. The system is designed to function with any arbitrary mix of half slots and full slots.

Half slots are of sufficient length to allow 550 kilometer transmission of 225 bits of error code data plus 35 bits of network control information. Half slot messages would be used for aircraft and ground centers to report their position, velocity, and identity data. Full slots are of sufficient length to allow 550 kilometer transmission of 900 bits of error coded data plus 35 network control bits. This message length is disproportionately larger than two half slot messages because propagation time, control bits and synchronization preamble need only be provided for a single message rather than two messages. This message length is sufficient for ground centers to report position, velocity, and identity of up to 8 aircraft, or broadcast 8 messages containing control, instruction or advisory information. Full slot messages would be used by centers to report into the network data about unequipped aircraft being tracked by ATCRBS or primary radar, and also be used to transmit control and advisory data to aircraft. Full slots would also be used for transmission of digitized voice. At 900 error coded bits per slot, 32 slots per 12 seconds provide for a 2.4 kb/s digitized voice channel. If 16 kb/s digitized voice were of interest, because of its greater robustness compared to 2.4 kb/s voice, error coding would not be required. In this case, more data can be transmitted in a time slot resulting in the ability to support a 16 kb/s digitized voice channel with 128 time slots per 12 seconds. (Even without error coding, 16 kb/s voice consumes four times more system capacity than 2.4 kb/s voice.) In summary, a time slot structure has been described consisting of full slots for track reports, control messages, advisory messages, and voice channels; and half slots for position and status reporting from equipped system participants.

As discussed in Section 2.5, for each time slot or half slot, terminals can generate or receive any one of 128 different frequency-phase code sequences. As a result, messages can be transmitted in 1536 time slots per 12 seconds on each of 128 frequency-phase code sequences as illustrated in Figure 10. Since terminals can only access one sequence number in each time slot or half slot, terminal capacity is 1/128 of the capacity illustrated in Figure 10.

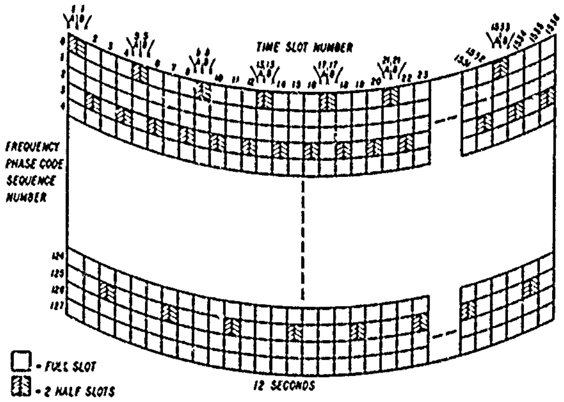


FIGURE 10. SYSTEM CAPACITY

7.2 Network Organization

System functions must be organized so that terminals do not require data from more than one sequence number per time slot or half slot. The system also should be organized to allow for a low cost terminal implementation for general aviation aircraft (see Section 8.0). This low cost implementation is easier if such terminals are not required to frequency hop or randomize the phase code contained within each transmitted pulse. However, such a design will limit the ability to have more than one transmitter active in time slots or half slots associated with austere terminal users since the dynamic frequency-phase code randomization provides interference protection against all but the first signal to arrive at each receiver with the proper code.

The following network architecture allows for an austere user terminal design while still providing the full range of services to the remainder of the population. System capacity will be organized into groups of time slots and half slots. Each group will be allocated for satisfaction of a particular system function. Functional groups may be time disjoint or may share the same time slots with other functional groups. When functional groups share the same time slots, they will be separated by frequency-phase code sequence. Terminals will be able to access any combination of time slots and half slots that are time disjoint. When functional groups are allocated common time slots and are separated by sequence number, the terminal will select the functional group of current interest for that set of time slots by subscriber switch action or through use of pre-stored information.

The functional groups and their relationship each to the others are shown in Figure 11. The length of each block represents the amount of capacity allocated to the function. The position of the block along the vertical axis represents the frequency-phase code sequence number used for the function. Blocks appearing in the same vertical column are allocated the same set of time slots or half slots but have different sequence numbers.

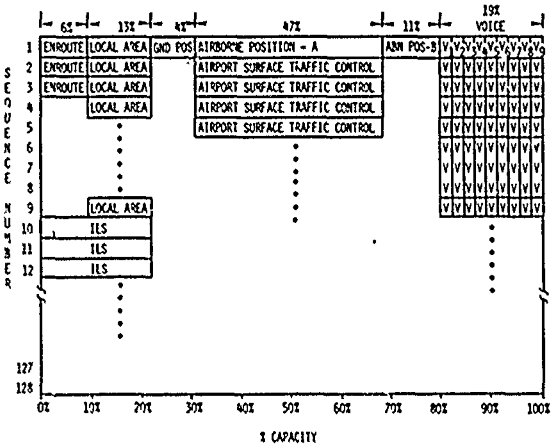


FIGURE 11. NETWORK ORGANIZATION

7.2.1 Enroute and Local Area Control

As indicated in Figure 11, the time slots allocated to the enroute and local area functional groups are time disjoint. By selecting the proper sequence numbers for time slots allocated to these groups, terminals will receive track reports, advisories and control instructions from an enroute control center and a local area control center. For the example under consideration, it is assumed that only a fraction of the total aircraft population are equipped with the JTIDS like system. Consequently, enroute and local area control centers have been allocated capacity to broadcast position, velocity and identity data about unequipped aircraft being tracked by the center. This capacity allocation decreases, and the capacity allocation to functional groups for airborne position reporting increases, as more aircraft become equipped with the new system and generate their own position reports. To avoid transmissions from adjacent centers interfering with each other at receiving terminals, adjacent centers can be allocated different sequence numbers for their transmissions. Sequence numbers are reused by centers far enough apart geographically to assure that messages have a large enough differential time-of-arrival at all possible receiver locations to preclude the possibility of mutual interference. Subscribers select the enroute sequence number and the local area sequence number applicable to their current situation. Because of the size of each enroute center's area of responsibility, it is likely that three sequence numbers properly assigned will suffice for the entire system. As indicated in Figure 11, local areas, being of smaller size, will probably require more sequence numbers in busy regions containing several airports. The capacity allocation for enroute centers allows for 16 control or advisory messages per second per enroute center and 576 track reports every 12 seconds per enroute center. The capacity allocation for local area centers allows for 16 control or advisory messages per second per center and 480 track reports per 4 seconds per center.

7.2.2 Instrument Landing

Capacity allocated to support instrument landing is time shared with the enroute and local area functional groups. Aircraft entering a landing pattern typically do not require the information broadcast in the enroute and local area functional groups. As with the enroute and local area functional groups, a separate sequence number is assigned to transmissions associated with each landing pattern in a given area. Subscribers select the sequence number for this functional group associated with the airport of interest and the runway of interest on that airport. The capacity allocation for this group provides for 50 transmissions per second per landing pattern.

7.2.3 Position Reporting-Ground Stations

Fixed location ground stations are allocated capacity to periodically broadcast their position and identity. These transmissions serve as the references for system synchronization and airborne position location. All of these transmissions occur on a single sequence number and the time slots allocated to this functional group are not allocated for any other purpose. Therefore all receivers can continuously monitor these transmissions. Ground stations within a given area are assigned different time slots for their transmissions to allow all transmissions in the area to be received by all airborne subscribers. The time slots are reused between locations sufficiently far apart to avoid mutual interference. The capacity allocation for this group is 10 time slots per second per local area.

7.2.4 Position Reporting-Airborne Subscribers

There are two alternatives for accommodating position reporting from airborne subscribers. The first alternative assumes that the general aviation user employs an austere terminal that operates on a single frequency with non-randomized phase codes. In this case, seqeunce number 1 would correspond to this mode of operation. All other sequence numbers would employ the full frequency hopping randomized phase code mode of operation. The austere terminal user could transmit and receive on sequence 1 only. Other terminals would dynamically select the sequence number of interest for each time slot group. Ground station and airborne position reports would always be transmitted on sequence number 1 so they would be available to the austere terminal user. In addition, the enroute and local area functional groups would reserve sequence number 1 for transmission of control and advisory data to this class of user. Using this approach, the time slots used by aircraft for position reporting would be assigned by control centers in such a manner that reuse of slots would only occur between users sufficiently far apart. The capacity allocation using this approach allows for 592 aircraft reports per 4 seconds per geographic area.

The second approach to airborne position reporting assumes that the austere terminal includes the ability for dynamic frequency hopping and phase code randomization. In this case, the contention mode of time slot assignment is employed. Two separate groups of time slots are allocated to this function. The Group A contention pool, which has been sized for an environment where only a fraction of the fleet is equipped, has been allocated 120 half slots and a 2 second reporting interval per aircraft. The Group B contention pool has been allocated 28 half slots and a half second reporting interval per aircraft. Every airborne aircraft broadcasts in both pools at the stipulated rates. The time slots for each pool and the sequence number are the same for all airborne subscribers independent of location. Therefore, no real time slot assignment or reassignment is required using this technique. The Group A pool provides for surveillance monitoring and situation display. Using this pool, the expected time between position updates is 4 seconds for the 160th aircraft, and 12 seconds for the 430th aircraft from each receiver independent of its location. (As explained in Section 2.5, the update rate is a function of the number of other transmitters closer in range to the receiver than the transmitter of interest. Closer aircraft are updated more frequently.) The Group B pool provides for collision avoidance. Using this pool the expected time between updates is one second for the 10th aircraft and 2 seconds for the 25th aircraft from each receiver. Therefore, each aircraft receives position reports from the 10 closest aircraft at an expected rate no less frequently than once per second. The next 15 aircraft have an expected update rate no less frequently than once per 2 seconds. The composite effect of all aircraft transmitting in both time slot pools is shown in Figure 12.

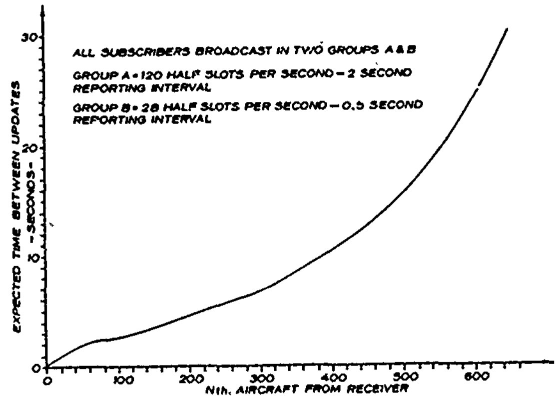


FIGURE 12. AIRBORNE SUBSCRIBER POSITION REPORTS - CONTENTION MODE UPDATE RATE

7.2.5 Airport Surface Traffic Control

Capacity allocated to airport surface traffic control is time shared with the airborne position reporting functional group since these two functions are not required simultaneously. Each airport in a local area is assigned a different sequence number to preclude mutual interference. Subscribers select the sequence number corresponding to the airport of interest for this functional group. The capacity allocation for this group provides for 120 transmissions per second per airport

7.2.6 Voice

Sufficient capacity has been allocated to the voice functional group to allow for nine time disjoint groups of time slots, each capable of sustaining a half-duplex 2.4 k/bs voice channel. Within each of the nine groups, multiple voice channels can be accommodated by assigning different sequence numbers to each channel within the group. Therefore, each terminal capable of the voice function can simultaneously access up to nine voice channels, the particular channels being determined by the sequence number selected for each of the nine groups. Ground centers would probably utilize a terminal configuration capable of operating on nine channels simultaneously. Aircraft might be configured for only one or two simultaneous channels. Considering the large number of possible channels available for use (128 sequence numbers for each of nine groups), it may be feasible to allocate some channels for company private use exclusively.

7.2.7 Composite Allocation and Utilization

An example has been presented where network capacity has been organized for air traffic management applications. A summary of capacity allocation and utilization is presented in TABLE V.

8.0 AUSTERE TERMINAL DESIGN

Application of a JTIDS like system to civil air traffic management not only depends upon the full range of capabilities available to subscribers but also upon the ability to provide a terminal of affordable cost to those general aviation users primarily concerned with flight safety at minimum cost. Therefore austere terminal designs for this class of user have been considered. As described in Section 7, the approach is one where the system architecture and signal structure will support the full capability, but user terminals need only implement a subset of the functions. A cost study has been performed where the functions allocated to the austere terminal are the ability to perform system time synchronization and position location, the ability to extract and process messages specifically addressed to the terminal, and the ability to broadcast horizontal position, altitude, velocity and identity data in assigned time slots for use by ground centers for surveillance monitoring and by other aircraft for collision avoidance and air situation display.

TABLE V

NETWORK ORGANIZATION FOR AIR TRAFFIC MANAGEMENT

FUNCTION	TIME SLOT ALLOCATION # PER SECOND	CAPABILITY	OTHER FUNCTIONS USING THE SAME TIME SLOTS	TIME SLOT SHARING TECHNIQUE
ENROUTE CONTROL	8 FULL SLOTS	16 CONTROL/ADVISORY MESSAGES/ SECOND PER CENTER AND 576 TRACK REPORTS/12 SECONDS PER CENTER	(a) ADJACENT ENROUTE CENTERS (b) INSTRUMENT LANDING	CODE DIVISION
LOCAL AREA CONTROL	17 FULL SLOTS	16 CONTROL/ADVISORY MESSAGES/ SECOND PER CENTER AND 480 TRACK REPORTS/4 SECONDS PER CENTER	(a) ADJACENT LOCAL AREA CENTERS (b) INSTRUMENT LANDING	CODE DIVISION
POSITION REPORTS FROM GROUND STATIONS	10 HALF SLOTS	10 REPORTS/SECOND/LOCAL AREA	GROUND CENTERS IN OTHER AREAS	GEOGRAPHIC SEPARATION
POSITION REPORTS FROM AIRBORNE SUBSCRIBERS	148 HALF SLOTS	592 REPORTS/4 SECONDS STATIC ACCESS OR CONTENTION ACCESS UPDATE RATE AS PER FIGURE 13	(a) OTHER AIRBORNE SUBSCRIBERS (b) AIRPORT SURFACE TRAFFIC CONTROL	(a) CODE DIVISION FOR AIRPORT SURFACE CONTROL (b) STATIC ASSIGNMENT OR CONTENTION ACCESS FOR AIRBORNE SUBSCRIBERS
INSTRUMENT LANDING	50 HALF SLOTS	50 TRANSMISSIONS PER SECOND PER RUNWAY	(a) ENROUTE CONTROL (b) LOCAL AREA CONTROL (c) OTHER INSTRUMENT LANDING CHANNELS	CODE DIVISION
AIRPORT SURFACE TRAFFIC CONTROL	120 HALF SLOTS	120 REPORTS PER SECOND PER AIRPORT	(a) AIRBORNE POSITION REPORTS (b) OTHER AIRPORT SURFACE CONTROL CHANNELS	CODE DIVISION
VOICE	24 HALF SLOTS	9 SIMULTANEOUS VOICE CHANNELS SELECTABLE FROM 1152 POSSIBLE CHANNELS AT 2.4 kb/s PER CHANNEL	OTHER VOICE CHANNELS	CODE DIVISION

The study used as its cost base a JTIDS mode of operation wherein frequency hopping of the transmitted 6.4 microsecond pulses is inhibited and radomization of the 32-bit phase code sequence within each pulse is inhibited (see Section 2.4). In this case, all pulses from all sources are transmitted on a single carrier frequency using fixed phase codes. This signal structure will support the design described in Section 7. Other cost reduction features also were incorporated into the cost baseline. Current JTIDS terminals radiate up to one kilowatt peak power in order to maximize performance in a jamming environment. The austere terminal radiated power was reduced to 30 watts peak, the minimum necessary to support reliable link performance for path lengths as great as 275 kilometers. Processing of the synchronization preamble of incoming messages by the austere terminal receiver was simplified and the position location computation was simplified. These modifications decrease the robustness of these functions but still maintaining their adequacy for the intended application. The forward error correction encoding function was retained as it is not a cost driver, but decoding was simplified considerably. Again, performance was reduced but would still be adequate for a non-jamming environment. After these and other similar simplifications were made to the design, its cost was projected exclusive of aircraft interface costs, which in this case would probably be an interface to an encoding altimeter and to a cockpit display indicator. The study projects that an austere terminal version of JTIDS is possible for a cost between $1500 and $3000 in 1985 depending upon market size. This cost projection does not take into account developing Very Large Scale Integrated (VLSI) circuit technology.

Although VLSI is still in its infancy, some projections(1,2) have been made for the technology. For example, it is projected that 50,000 logic gates or 3,000,000 memory bits can be placed on a single VLSI chip at a cost of about $100 dollars per chip in quantity production. Digital circuitry constitutes two-thirds of the cost of the austere JTIDS terminal discussed above. This circuitry has been sized and consists of 21,000 logic gates and 71,000 memory bits. Consequently, if the hopes for VLSI circuits are fulfilled, the digital portion of the austere terminal can be constructed in its entirety with one VLSI chip. In this case, the austere terminal cost is reduced to between $500 and $1,000.

The cost study is currently being extended to a more sophisticated performance baseline wherein the frequency hopping and phase code randomization features of JTIDS are retained. This would allow employment of the network control techniques discussed in Sections 2 and 7 that capitalize upon multiple transmitter broadcasting in a time slot. Since these techniques offer the promise of greatly reduced real time network management and greater access to information for the austere terminal, their retention is desirable provided the incremental cost burden is modest.

9.0 CONCLUSION

The integrated data communications, voice communications, navigation and identification features of JTIDS have been described with emphasis on those features applicable to air traffic management. The principal conclusions are summarized below:

1. The JTIDS system architecture simultaneously provides data at the ground centers and in the cockpit. The ground centers are provided the data to support their responsibilities for airspace management and control simultaneously with provision of the data in the cockpit for collision avoidance, navigation and air situation display. Airspace control and advisory data are made available to all aircraft to permit subscribers to be aware of, and comment upon, directions provided to others.

2. Network control techniques have been developed which support civil air traffic management applications. These techniques provide for the apportionment of capacity amongst subscribers in such a manner as to allow all subscribers access to all data in their area of interest without real time network management.

3. The potential exists for a substantial reduction in the avionics boxes aboard aircraft. A JTIDS-like system can simultaneously provide the data for airspace management and control, collision avoidance, area navigation, air-to-air coordination, cooperative surveillance, cockpit situation display, airport surface traffic control and possibly instrument landing.

4. An evolutionary transition from the existing air traffic management system to a JTIDS like system can be accomplished starting with interface of JTIDS equipped military aircraft with the civil air trafic management system via JTIDS terminals located at major civil system ground centers.

5. Austere terminal designs appear to be possible at a cost that is affordable for general aviation.

REFERENCES

1. R. W. Keyes, "Evolution of Digital Electronics Towards VLSI", IEEE Journal of Solid-State Circuits Volume SC-14, No. 2, April 1979.
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DISCRETE ADDRESS BEACON SYSTEM

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SUMMARY

The Discrete Address Beacon System represents a major systems development to provide upgraded Air Traffic Control Radar Beacon System (ATCRBS) surveillance with sufficient aircraft capacity to meet air traffic growth well into the next century. It will also provide improved air traffic control (ATC) automation services and ground based Automatic Traffic Advisory and Resolution Service (ATARS) through its integral high capacity digital air ground data link. After several years of extensive analysis and feasibility studies, including assembly and flight testing of a laboratory sensor, it was concluded that the DABS concept was completely valid and totally compatible with existing ATCRBS. As a result of this effort, three engineering models have been manufactured employing a unique distributed computer architecture. These sensors are now undergoing extensive test and evaluation at the National Aviation Facility and Experimental Center (NAFEC) with the NAS En Route and ARTS III ATC facilities under actual flight conditions. To date, the reliability data collected since June 1978 indicates the DABS dual-channel design will meet the predicted reliability design goal of 20,000 hours mean time between failure (MTBF). The performance results also indicate the use of distributed processing is highly advantageous. The Technical Data Package resulting from this effort, in April of 1980, will be used to procure DABS for implementation in the National Airspace System possibly commencing as early as 1983.

INTRODUCTION

The need for improvement in ATCRBS was recognized early in 1969 by the Air Traffic Control Advisory Committee (ATCAC). This committee was formed by the Department of Transportation (DOT) to examine the needs of the air traffic control system in year 1995 and beyond, and make recommendations for systems development. This report [1] recommended improvements in several areas which later became elements of the Upgraded Third Generation Air Traffic Control system. Among the several recommendations were two related to aircraft surveillance that were later combined to become the Discrete Address Beacon System. These were the recommendations to upgrade the ATCRBS by adding discrete addressing cability, and to develop a ground based automatic separation assurance capability known as Intermittent Positive Control (IPC), later renamed Automatic Traffic Advisory and Resolution Service (ATARS).

The specific surveillance needs identified were with regard to (1) increasing the capacity of the beacon system to meet future air traffic growth particularly in general aviation; (2) increasing automation through data link communications to improve productivity; and (3) improving performance of the beacon system in general. Improving ATCRBS was oriented toward eliminating problems such as synchronous garbling of beacon replies in a high aircraft density environment such as found in Los Angeles, California, false targets due to reflections and non-synchronous garbling due to overlapping replies or "fruit." Synchronous garble occurs when two or more aircraft are within 1 1/2 nautical miles (slant range) of each other and are simultaneously within the same interrogation beam width, but at different altitudes. The replies arriving at the ground station overlap one another causing cancellation or code garbling. Tabulations of the most severe ATCRBS problems reported in 1977 for terminal and en route ATC facilities are shown in Figures 1 and 2. It is expected that introduction of DABS in combination with a new beacon antenna system will overcome all known difficulties with ATCRBS while providing the increased surveillance capacity needed for the year 1995 and beyond.

TECHNICAL APPROACH

The Federal Aviation Administration, with support from the Massachusetts Institute of Technology's Lincoln Laboratory in Cambridge Massachusetts, initially undertook a conceptual design study for DABS. The objective of this first phase (Phase I) was to find frequencies and waveforms that were compatible with the nationally and internationally standardized Secondary Surveillance Radar (SSR) and ATCRBS. To provide a high degree of hardware commonality between ATCRBS and DABS both in aircraft and on the ground, it was decided to investigate the possibility of sharing the frequency channels with ATCRBS (interrogating on 1030 MHz and replying on 1090 MHz). Using the common frequencies required finding a way to reduce the Pulse Repetition Frequency (PRF) of ATCRBS sufficiently to allow time for DABS interrogations. The upper limit for the ATCRBS PRF today, established to limit interference, is 450 per second and many interrogator sites currently operate very close to this limit [2]. The use of monopulse direction finding was the method chosen for reducing the PRF; i.e., using sum and difference antenna patterns and the ratio of signal amplitude in each pattern to precisely locate the aircraft in azimuth on as few as four replies from the aircraft's transponder. Typically, the current ATCRBS, using conventional beam splitting techniques, requires up to 16 replies from each aircraft and is much less accurate than monopulse [3].

Although using monopulse for DABS was a radical departure from the traditional ATCRBS technique, the benefits were overwhelming in terms of improved accuracy combined with the much lower interrogation rate. The lower rates improve or reduce the ATCRBS self-generated interference, or "fruit," environment by as much as four times the present levels. The interrogation rates are dependent upon the amount of DABS data link being used, i.e., the lower the data link usage, the lower the interrogations and, consequently, interference level.

As for a compatible DABS/ATCRBS signal-in-space waveform, this was achieved simply by adding a fourth pulse P4 2.0 microsecond (usec) after the standard P1 - P3 combination presently used in ATCRBS as shown in Figure 3. This particular waveform with the P4 pulse is defined as the DABS/ATCRBS All-Call Interrogation and is used to interrogate all ATCRBS-equipped aircraft, and for initial acquisition of the addresses of all DABS-equipped aircraft for storage in a roll-call file. The ATCRBS transponders recognize the first three conventional pulses: P1, P2, and P3, but ignore the P4 pulse, whereas DABS transponders recognize the presence of P4 as a request for its discrete address. If there is no P4 pulse present, as there wouldn't be from an ATCRBS ground station interrogation, the DABS transponder will reply in the conventional ATCRBS mode. Once the DABS ground sensor has acquired a DABS aircraft on roll-call, the transponder is locked out from future all-calls, except under well defined operational rules, and replies only when specifically addressed with its unique 24-bit discrete address code.

The DABS Discrete Interrogation, as dfferentiated from the all-call interrogation, is accomplished by again taking advantage of the ATCRBS wave form. If an ATCRBS transponder receives a P2 pulse 2 usec after receiving the first pulse at the same relative amplitude or within 9 db, it automatically suppresses and will not reply. With ATCRBS, the P2 pulse is intentionally radiated everywhere, except in the main antenna beam, 2 usec after P1 to suppress ATCRBS transponders from replying to ground antenna side lobe emissions. The DABS uses this suppression scheme to cause ATCRBS transponders to suppress while interrogating DABS. This is accomplished for DABS by radiating P1 and P2 in the main beam at the same amplitude as shown in Figure 4. DABS transponders recognize the $P_1 - P_2$ combination as a DABS discrete interrogation and waits 2 usecs for the data block that follows. The data block contains either a 56-bit surveillance-only interrogation asking for the aircraft's altitude or a combination of surveillance and a 56-bit general data link message; a total of 112 bits. There is also a third format that replaces both the 56-bit surveillance and the 56-bit data combination with an 80-bit data only message. This latter format is used when long transmissions of data are required and is defined as the Extended Length Message (ELM). Up to 16 ELM segments can be transmitted sequentially to any suitably equipped aircraft while it is in the main beam, requiring only a single reply to acknowledge receipt. This allows large quantities of data to be transferred without causing excessive DABS replies.

Each of the shorter 56-bit or the combined 112-bit formats cause the transponder to reply at the end of each message. The modulation used for the uplink data block is Differential Phase Shift Keying (DPSK); i.e., a phase shift of 180 degrees during a .25 usec bit space represents a binary one; no phase shift in the bit space is zero[4]. DPSK was chosen for the uplink over Pulse Amplitude Modulation (PAM) because it showed a clear advantage in Signal to Noise Ratio (SNR) and Signal to Interference Ratio (SIR) [5].

The DABS reply format shown in Figure 5 uses a pair of double pulses as a preamble to the data block containing either the 56-bit surveillance-only reply, or the combination 112-bit surveillance and data message or ELM reply. The modulation used on the downlink is Pulse Position Modulation (PPM) where the position of the pulse determines whether it is a binary one or zero. PPM was selected for the downlink because it provided the best garble sensing; i.e., provides a number of pulses required for monopulse data editing[5]. When interrogated by an ATCRBS ground sensor, the DABS transponder will reply in the standard ATCRBS format. The bit rate for all uplink formats is four megabits per second and one megabit per second for the downlink.

The high uplink bit rate was required to transmit the longest DABS message (112 bits) to the aircraft during the ATCRBS suppression interval. The ATCRBS suppression interval is 35 ± 10 used[2].

For the downlink, the bit rate was established at one MHz to basically accommodate present ATCRBS type transmitter capabilities. There are a number of other important factors considered in the selection of both up and down link bit rates which are described in detail in Reference 5. The aircraft's address is contained in the last 24 bits of each frame in both the uplink and downlink message overlaid with parity. The parity error protection is generated in accordance with a polynomial of the form

$$G(x) = \sum_{i+0}^{24} g_i x_i \text{ where } g_i = \begin{array}{l} 1 \text{ for } i = 0, 3, 10 \text{ and } 12 \\ \text{through } 24 \\ 0 \text{ otherwise} \end{array}$$

The parity is summed module-2 with the 24-bit address to save overhead.

The combination of individual aircraft address codes, roll-call scheduling, and multiplicity of message formats allows considerable flexibility in manipulating the interrogations such that self-generated interference, can be virtually eliminated. Of even more importance perhaps, since DABS will co-exist with ATCRBS for many years, is the fact that extraneous ATCRBS replies or ATCRBS "fruit" will also be reduced, thus improving the overall performance of ATCRBS as well.

All of the other ATCRBS difficulties noted in Figures 1 and 2 are overcome by the use of monopulse and a new high performance antenna system currently in production.

The compatibility of the DABS/ATCRBS interrogations and reply formats just described was fully demonstrated during the initial feasibility phase. This was accomplished by constructing a laboratory model sensor at Lincoln Laboratory and conducting flight tests with industry-built feasibility model DABS transponders. Over 400 flights were flown in the Boston, Massachusetts, area without any difficulties noted with local Air Traffic Control operations. This was subsequently verified in comprehensive testing during Phase II, as described later in this paper.

Engineering Development

The results of the feasibility tests proved that the DABS conceptual design was suitable for proceeding into an engineering development and evaluation phase (Phase II), wherein the DABS sensors would be interfaced with both en route and terminal air traffic control facilities. Engineering specifications were then prepared and proposals solicited from industry for three engineering model sensors. Following extensive factory testing, these were installed for evaluation: the first, at the National Aviation Facilities Experimental Center, Atlantic City, New Jersey; the second, at the long range radar site in Elwood, New Jersey; and the third, just outside the Philadelphia, Pensylvania International Airport terminal in Clementon, New Jersey.

Coincident with DABS development is the Automatic Traffic Advisory and Resolution Service (ATARS)--a ground-based collision avoidance system whose objective is to improve the safety of civil aviation by reducing the potential for midair collisions and near miss encounters. It is an outgrowth of the Intermittent Positive Control concept which was described and recommended for development along with DABS by the Air Traffic Control Advisory Committee in 1969. ATARS utilizes surveillance data from DABS, computes traffic and resolution advisories using a totally automated ground computer system located at the DABS sensor site and delivers these advisories to ATARS-equipped aircraft via the DABS data link.

ATARS services can be provided to all aircraft, controlled and uncontrolled, in both the en route and terminal environments. To receive ATARS service, an aircraft must carry a DABS transponder, and encoding altimeter and an ATARS display. However, once equipped, protection is provided against all aircraft that are equipped with altitude reporting transponders. Equipped aircraft will receive traffic advisories regarding aircraft that are determined to be proximate or to constitute a potential threat. In the case of a proximate aircraft, information will be displayed to alert the pilot concerning the presence of the nearby aircraft and to aid him in visual acquisition. When an aircraft poses a potential collision threat, additional information will be displayed to aid the pilot in threat assessment. The threat data will enable the pilot to evaluate the potential threat and to avoid maneuvers which would aggravate the situation. If the aircraft separation continues to narrow such that the projected miss distance is less than the established threshold for that region of airspace, then both of the aircraft will receive a resolution advisory at a predetermined time (currently 20 - 30 seconds) before the estimated time of closest approach. The resolution advisory will be compatible with the threat data provided in the traffic advisory.

Whenever a threat advisory is issued to a controlled aircraft, an ATARS controller alert message is sent to the air traffic control facility responsible for the controlled aircraft in order to alert the controller(s) to the potential conflict. This message will also include a preview of the ATARS resolution advisory for consideration by the air traffic controller. An ATARS resolution notice will be sent to the responsible air traffic control facility at the same time that the resolution advisory is sent to a controlled aircraft in conflict. The resolution notice will identify the aircraft involved and the resolution advisories issued to each. Upon receipt, the air traffic control computer system will display these data to the responsible controller(s).

The ATARS capability was included in DABS as a resident function because of processing efficiency, although it could, of course, be processed in separate computers and still utilize the improved DABS accuracy and data link communications. The DABS design accommodates the addition of ATARS, which was flight tested in the feasibility model at Lincoln Laboratory. The specifications for the three DABS sensors included the original version of ATARS which is now being revised as a result of the flight tests[6].

Because of its very nature of providing backup collision avoidance protection to controlled aircraft and primary protection to VFR aircraft, ATARS requires very high data integrity and system reliability. These requirements were given primary emphasis in the contractor selection for DABS.

Texas Instruments, Incorporated, was selected because of their technical approach in solving this problem. They developed a redundant distributed processing minicomputer architecture to meet the DABS reliability and data integrity requirements via a unique combination of hardware redundancy and error detection/correction features. Such features are complemented by a distributed computer processing architecture that is modular in nature and yet simple in control design. The computer subsystem responds to all single component hardware failures in such a manner that logical operation and data integrity of the system are maintained.

In addition to the voting computers, the sensor has as an integral part of its operation a performance monitoring capability. The performance monitor checks the operating tolerances of each parameter vital to proper system operation. It does this by comparing the results of interrogation performed with a fixed ground transponder located at a precise distance and azimuth from the sensor with the proper location of that device stored in memory. If the results disagree by more than an acceptable amount, the performance monitor alerts the ATC and switches to the appropriate backup or standby subsystem. The ATC facility is alerted by the system status lights changing from green to yellow, indicating that the sensor is now operating without redundancy. If the standby fails, the performance monitor will shut the sensor down completely, indicating a condition "red" at the ATC facility. If the sensors are netted with other DABS in the geographical area, the failure condition is transmitted to the adjacent sensors, which immediately expand their primary coverage areas to include that of the failed sensor. Coverage is thereby maintained for the ATC facility even though one of the sensors feeding that facility has failed.

The DABS sensor consists of three main subsystems: an interrogator processor subsystem, which performs the interrogations and reply processing functions; a communication subsystem that transfers surveillance data to, and performs data link communications with the ATC facility; and, a computer processing subsystem which is described in the following paragraphs. Both the interrogator/reply processor and communications subsystems employ conventional electronics found in any transmitter, receiver and communication system and will not be described further in this paper.

Computer Processing Subsystem

DABS computers are grouped into ensembles with four computers in each ensemble (see Figure 6, Block A). The computers are connected to a data bus through which they communicate to the remainder of the system. The data buses are connected to other data buses via coupler pairs. Each DABS computer consists of two central processors (CP), voting logic for the CPs and 8K of local error correcting code (ECC) memory (see Figure 6, Block C).

The code of a DABS computer is executed simultaneously by each CP; i.e., each clock cycle and each CP executes identical code. CP execution results are compared, and if the results agree, they are passed on to local or global memory space; otherwise, the DABS computer is immediately switched off-line to prevent any erroneous data from being passed on to memory. This error causes a "bad computer" interrupt to be propagated throughout the system. The hardware failure recovery computer responds to reassigning the tasks of the failed computer to the primary standby computer. The primary standby computer downloads its assigned tasks from global memory program store. Other computer failures; e.g., an uncorrectable local memory error will cause the same interrupt to be generated with a standby computer, again assuming the responsibilities of the failed computer. The hardware failure recovery computer is "monitored" by the primary standby computer in the event that the recovery computer should fail.

DABS computers communicate with other DABS computers and external interface devices via the global memory address space. Each global memory module is provided with error correcting code such that all single bit errors are corrected and all double bit errors are detected. Global memory modules are configured in pairs (see Figure 6, Block D). In each pair, one module is designated the primary memory module, the other, the secondary.

Both memory modules occupy the same address range. When a DABS computer writes to the module pair, the data is written into both the primary and secondary module assuring that a backup copy of the data is always available. Data is "fetched" only from the primary memory module. If a primary memory module fails, an interrupt is generated and the hardware failure recovery computer responds by adjusting the status parameters of the memory module such that the primary is taken off line, and the secondary memory module will be declared "primary." Subsequent read and write commands will result in data being transferred only to/from the new primary module.

The global memory modules are partitioned between two major global data buses. This partitioning permits a more even distribution of data bus communications traffic and thus reduces the "wait time" overhead associated with bus availability.

Another distinguishing feature of DABS is its capability to operate in a sensor network. Where sensors are located relatively close together such that their surveillance and/or ATARS coverage volumes overlap one another, the sensors can be interconnected via phone lines for high speed data communications. This is done to insure adequate surveillance and communications for areas of common coverage and for transmission of ATARS coordination messages to resolve conflicts occuring in the ATARS overlap region of two adjacent sensors. Each sensor maintains a dynamic map of coverage responsibility based on the "status" of all sensors having coverage overlap. This coverage map specifies areas where the DABS is required to provide coverage and a "permitted" area where DABS may extend coverage only under special circumstances. One of these circumstances exists if a sensor in the network fails. In this event, the remaining sensors will expand their respective coverage volumes such that the area of responsibility of the work is maintained. When the failed sensor is returned to service, the other sensors in the network return to their normal coverage responsibilities.

As part of the continuing DABS development program, several alternative methods for intersite communications are being investigated. This is to reduce the present requirement for very high quality and capacity telephone lines. It is planned that netting will be used in high density aircraft environments such as found in the Los Angeles, California area.

Test and Evaluation

The objectives of the DABS test and evaluation program are to (1) determine the performance characteristics of the DABS sensor and its interaction with the ATC; (2) to determine the adequacy of the computer architecture selected to meet reliability, availability, and systems integrity goals; and (3) to serve as a test bed for further development of the ATARS and related data link functions provided by DABS.

With regard to sensor performance, full-scale systems testing began with delivery of the final sensor in May 1979, and will continue through 1980. Initial flight tests were conducted to determine system accuracy using the new open array SSR antenna system previously developed for improving ATCRBS. The minimum azimuth and range error (1-sigmas) using this antenna were 0.05 degrees and 10 meters, respectively, for aircraft elevation angles between 0 and 30 degrees. This is well within system specifications.

In addition, results of surveillance and communications capacity tests indicate that DABS will be able to accommodate anticipated traffic densities through 1995.

Considerable testing has been accomplished in Phase II to determine the capabilities of DABS with all the ATCRBS reply processors in the FAA and military inventories. To date, no degradation has been found with any of the ATCRBS processors tested.

With respect to possible oversuppression of ATCRBS transponders when using the DABS data link, the average suppression levels are less than had been predicted[7]. As can be seen from Figure 7, the only time the suppression level reached the level currently experienced with ATCRBS in the NAFEC environment was when the target aircraft was in the side lobe region of the DABS interrogator. The data in Figure 7 was obtained by first recording the transponder suppression level of the existing environment at the test facility which was known to have three ATCRBS interrogators operating, as well as other interrogators in the general area. The DABS comparison was obtained by shutting off one of the three ATCRBS interrogators and turning on DABS operating at an interrogation rate simulating the amount of average data link traffic that would be anticipated in the Los Angeles area in the year 1982. The one ATCRBS interrogator was turned off to simulate the actual implementation of DABS, i.e., replacing an existing interrogator with DABS.

The results of the compatibility testing[8] to date indicate the original interference analysis to be overly conservative with regard to the impact that DABS data link operation would have upon ATCRBS. No significant impact has been observed upon ATCRBS performance. Indeed, it is expected that the performance of ATCRBS will actually improve with the introduction of DABS, due to the overall reduction in self generated interference resulting from the lower DABS interrogation rates.

In parallel with sensor performance testing, testing is being conducted to evaluate air traffic control operational software that has been modified for DABS. The first phase of this testing, which focused on processing of simulated DABS surveillance data in a terminal ATC environment, was completed. The results indicate that tracking performance was improved over that of conventional ATCRBS data processing. The next phase of testing will involve processing of surveillance-related communications data in both terminal and en route environments using DABS sensor inputs in addition to simulated inputs. The final phase of ATC system testing will examine operational issues with air traffic controllers from field ATC facilities participating.

Soon to be taken are measurements to precisely determine computer capacity and throughput requirements which will be used to specify computer performance for a production DABS. Based on failure/maintenance data obtained to date, the mean-time-between-failure design goal for a dual-channel sensor of 20,000 hours can be achieved using the distributed computer concept.

The ATARS and data link program have not reached the flight testing stage as of this writing. However, tests are scheduled to commence in late 1979, and results may be available at the oral presentation of this paper.

The DABS sensor related performance testing is scheduled to be complete by April 1980 for preparation of production specifications. The ATARS and data link related algorithms to be coded into the DABS computer will be specified as part of the system to be procured. Some of the data link related functions may be coded in separate computers to facilitate interface with the ATC facility computers. Final testing of the ATARS and data link applications will not be complete until 1981.

Mr. Joseph DeMeo, of the DABS Program Staff, is gratefully acknowledged as having contributed significantly to the content of this paper, particularly as it relates to the design of the DABS computer architecture.

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SITES	SYMPTOM	CAUSE
54%	REFLECTION FALSE TARGETS	POOR RADIATION PATTERN; INEFFECTIVE SLS
49%	ERRONEOUS/MISSING MODE C REPORTS	INEFFICIENT REPLY PROCESSING/ SYNCHRONOUS GARBLE
41%	SIDE LOBE FALSE TARGETS	INEFFECTIVE SLS; POOR RADIATION PATTERN
36%	LOST TARGETS DUE TO HOLES IN COVERAGE PATTERN	POOR RADIATION PATTERN + IMPERFECT SITING
26%	AZIMUTH SPLITS	OVER-INTERROGATION + IMPROPER REPLY PROCESSING
16%	DOUBLE TARGETS (DOWN-LINK MULTIPATH)	HOSTILE TERRAIN + POOR ANTENNA

Fig.1 Most severe ATCRBS problems, ARTS III facilities reporting, 1977

SITES	SYMPTOM	CAUSE
55%	SIDELOBE/SPILLOVER FALSE TARGETS	LOW NADIF DIRECTIVITY + POOR SLS
54%	REFLECTION FALSE TARGETS	INEFFECTIVE SLS + HOSTILE TERRAIN
40%	LOW TARGETS DUE TO REDUCED LOW-ANGLE COVERAGE	IMPROPER NADIF TILT ADJUSTMENT
39%	AZIMUTH SPLITS	OVER-INTERROGATION + POOR REPLY PROCESSING
35%	RANGE SPLITS	IMPROPER REPLY PROCESSING
35%	PHANTOM TARGETS & GARBLED CODE DATA	IMPROPER REPLY PROCESSING
23%	ERRONEOUS/MISSING MODE C REPORTS	INEFFICIENT REPLY PROCESSING
17%	SYNCHRONOUS FRUIT/SECOND-TIME-AROUND FALSE TARGETS	NON-STAGGERED INTERROGATION PRF

Fig.2 Most severe ATCRBS problems, en route facilities reporting, 1977

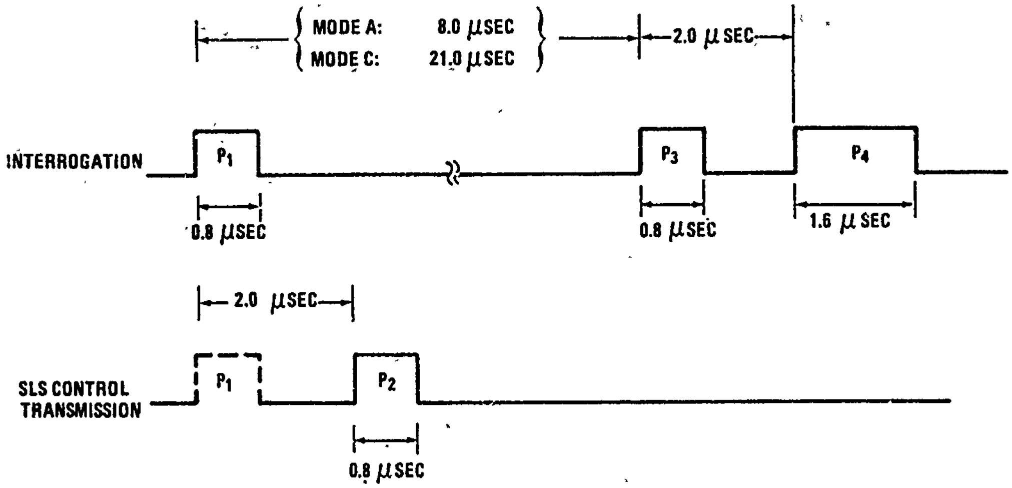

Fig.3 ATCRBS/DABS all-call interrogation signal format

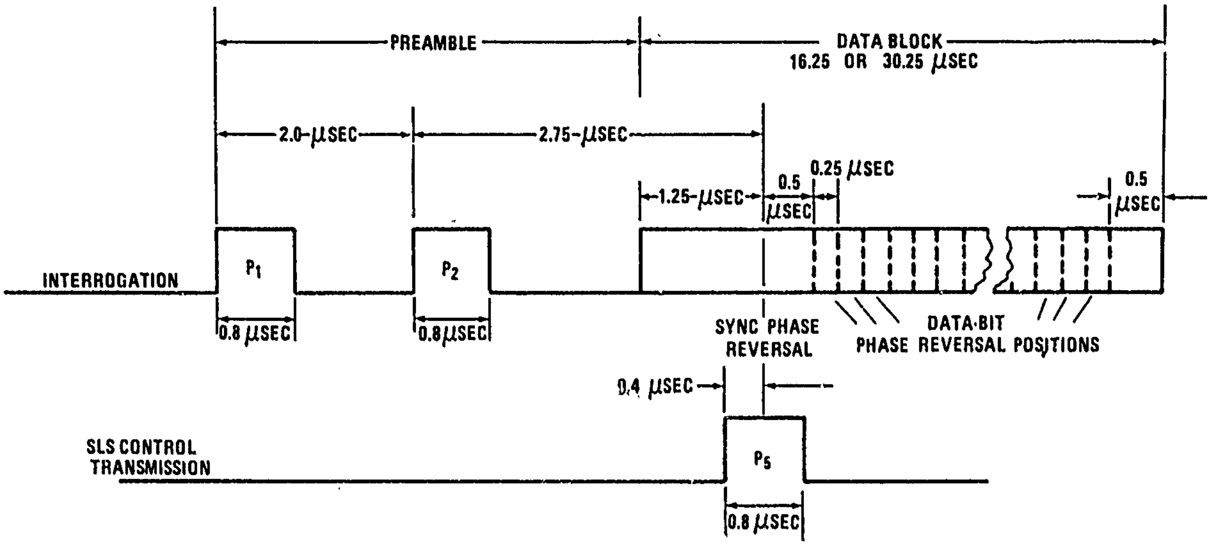

Fig.4 DABS interrogation signal format

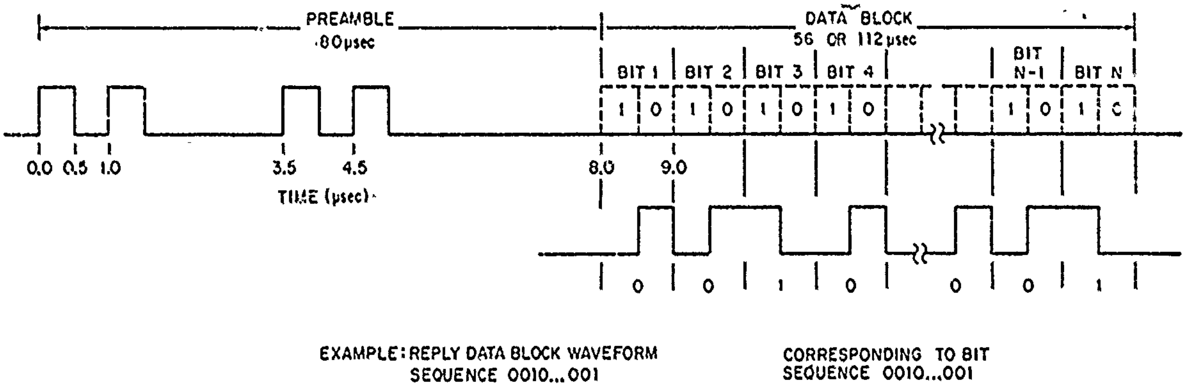

Fig.5 DABS reply signal format

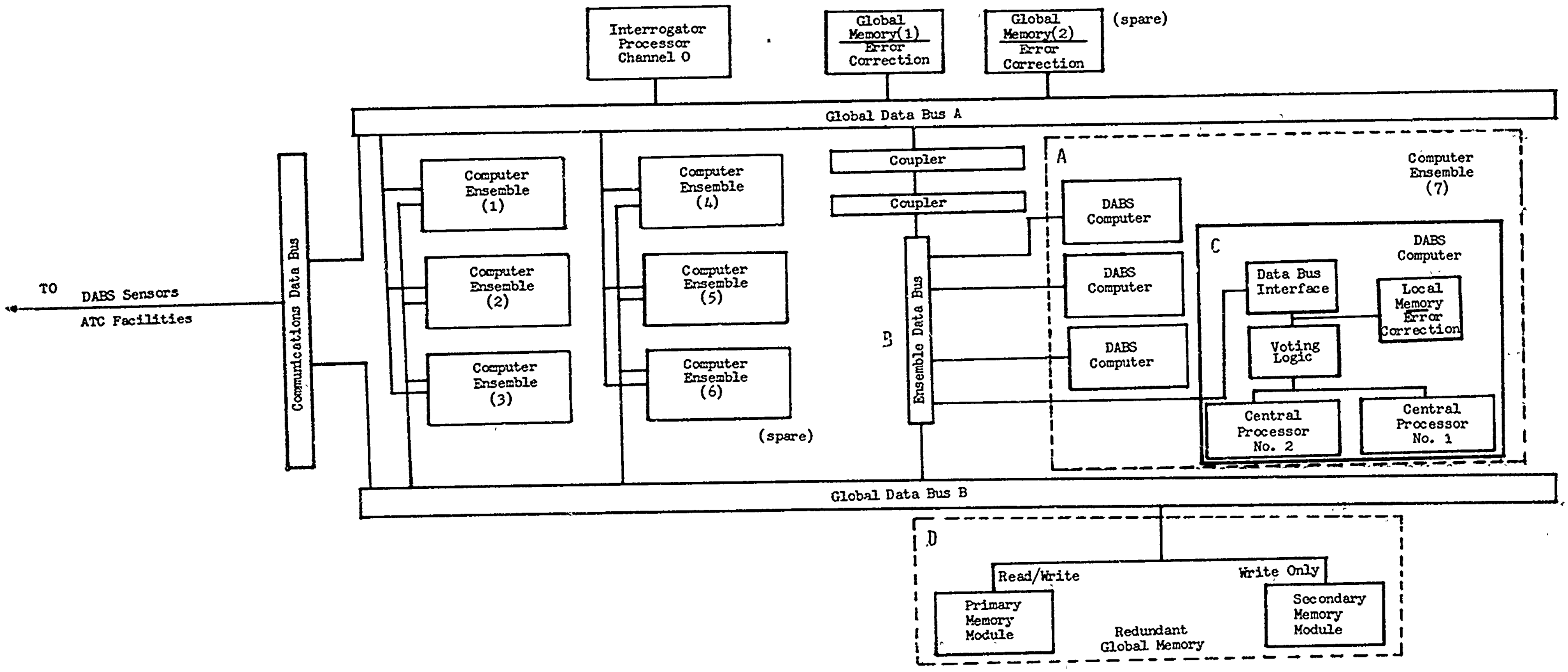

Fig.6 DABS computer subsystem architecture

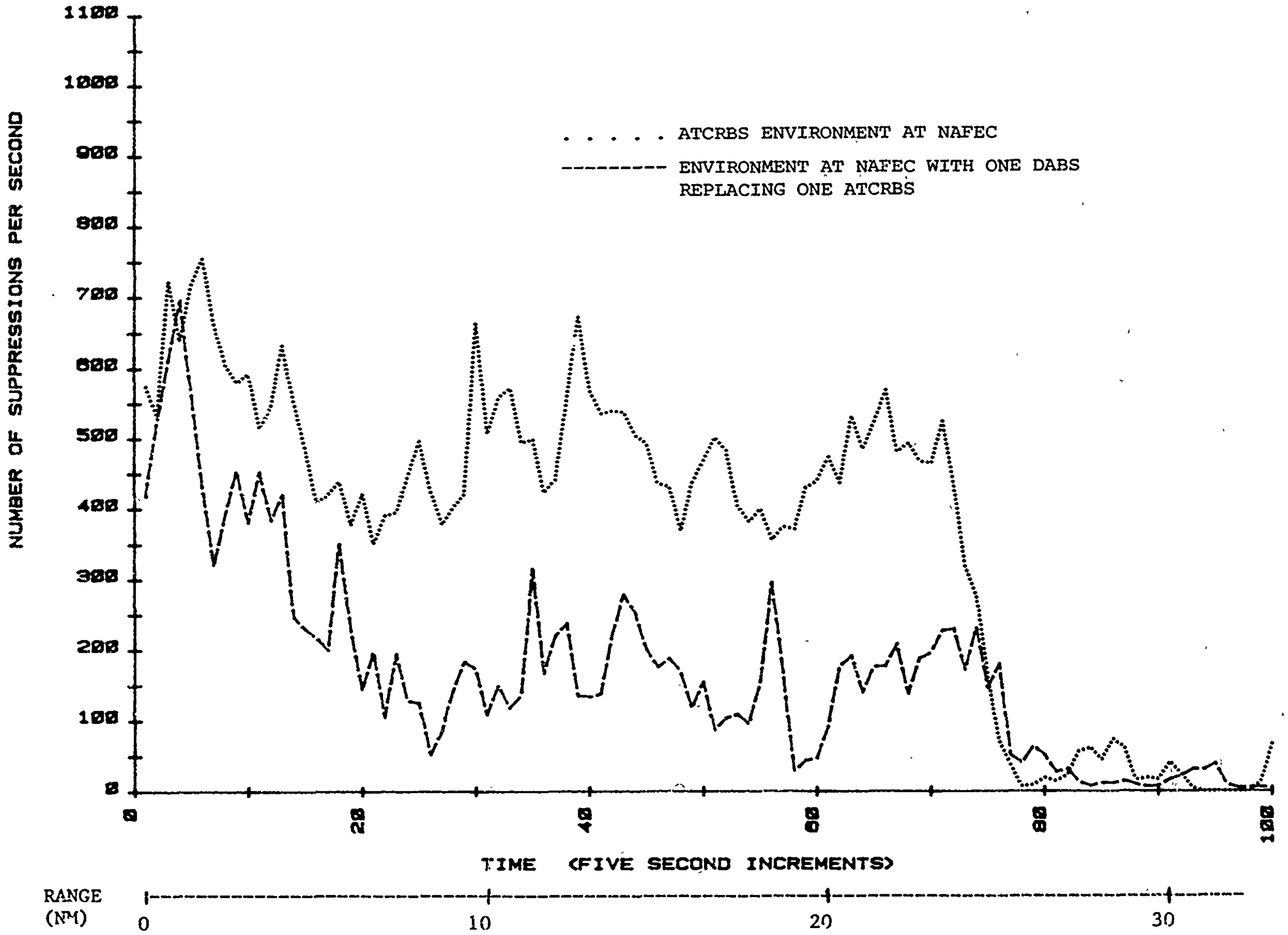

Fig.7 Suppression levels

ADSEL - SELECTIVE ADDRESS SSR - PERFORMANCE OF THE EVALUATION STATION

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SUMMARY

The ADSEL system is a selectively addressed radar system designed to overcome the 'garble' problem of the current SSR system and provide a data link facility. The system is entirely compatible with SSR and can be introduced over an extended period.

The system requires aircraft to carry a transponder which includes the selective address mode of operation and a ground station with monopulse direction finding system plus data processing facilities. In order to prove the system and develop the equipment a self-contained ground station and 20 ADSEL transponders have been designed and built.

This paper describes evaluation trials that have been carried out and gives the results of a large number of aircraft flights. The main aim of the trials is to assess the accuracy with which the position of an aircraft can be measured, the performance of the communication links, and to optimise the operating rules. A detailed analysis is given of the performance of the SSR and ADSEL system when monitoring two aircraft flying close together such that their transponder replies were 'garbling'.

1 INTRODUCTION

During the last 10 years the Civil Aviation Authority in the United Kingdom has supported work at the Royal Signals and Radar Establishment on a selective address secondary radar system which is designed to overcome the present SSR problem of 'garbled' replies when two aircraft are close together. The system provides the usual surveillance data, Identity, Height and position and in addition a data link communication facility is available on both the ground to air and air to ground channels.

In the USA the Federal Aviation Administration are developing a similar system called DABS (Discrete Address Beacon System). There is close co-operation between the CAA and the FAA which, in 1975, resulted in agreement on the formats for the up and down link messages and the transponder functions. This means that compatible systems are being developed in the two countries but there is still considerable freedom on how the system is implemented. In particular the design and mode of operation of the ground station, as well as the way a number of stations are interlinked, depends upon the requirements of the ATC system. The basic system has already been covered in a number of papers which are given in the references (Ref 1, 2, 3 and 4).

In 1975 Cossor Electronics were given a contract to manufacture an evaluation station and 20 ADSEL transponders and this phase of the system development was completed towards the end of 1977. Since then the CAA, Cossor and RSRE have jointly been conducting trials on the system performance and optimising the method of operation.

The system concept has changed very little over the years but the trials have highlighted a few problems which have led to worthwhile improvements. In particular the All-Call format has been changed slightly to reduce the effect of multipath signals. A stochastic mode of All-Call interrogation has been introduced to avoid 'garble' problems when acquiring aircraft. And, lastly, the system has been modified to enable two overlapping ground networks to work automonously.

These important changes are not described in detail in the paper but are mentioned to show that a new system requires a development period, during which realistic trials are undertaken, in order to produce an optimum design. This paper concentrates on the evaluation trials and gives the results obtained from a large number of aircraft flights.

2 ADSEL TRIALS FACILITIES

It is not intended to give a description of the design and engineering of the ADSEL station and transponders in this paper as this aspect is adequately covered in previous papers (Ref 1, 2 & 4) but an outline of the main facilities is appropriate.

The ground station is situated 20 miles north of London and is completely self-contained. The main units are the monopulse aerial, transmitter/receiver, plot extraction units for SSR and ADSEL working, two computers, displays and historic recorder. These are all installed in a transportable cabin thus enabling it to be moved, reasonably easily, to other sites.

The main modes of operation on SSR are as follows:-

a Normal SSR operation using a sliding window type of plot extractor to determine 'centre of gravity' of the group of replies from an aircraft.

b SSR operation using the monopulse direction finding system to measure accurately the azimuth of each reply. In this mode of operation the interrogation rate can be considerably reduced such that only two Mode A and two Mode C replies are obtained from each aircraft, i.e an interrogation rate between 50 and 100 per second is quite adequate.

Clearly there is no fundamental reason why the monopulse system should not measure the azimuth of every reply but in order to simplify the implementation only the following options are available:-

(i) Leading Edge Reply:- The azimuth is measured on the reply which causes the sliding window plot extractor to declare a leading edge.

(ii) Closest to Boresight:- The off boresight angle (OBA) is monitored throughout the group of replies and the azimuth is measured when the OBA is at its smallest value.

(iii) Average of Two Replies close to Boresight:- Here the azimuth is the average of the replies either side of boresight with the smallest OBA.

Each of the above monopulse measurements can be carried out on only the F_1 pulse in the SSR reply, or by taking the average of the first 2, 4 or 8 pulses in the reply.

The ADSEL mode of operation can be summarised as follows:-

a Acquisition:-

The address of an aircraft is obtained by using an All-Call interrogation which is transmitted at a low rate (about 50 per second). The address and position of the aircraft is then stored on the station 'roll' and all further interrogations are selectively addressed. Alternatively in an ADSEL system consisting of a network of ground stations the information can be received from another station via a ground data link. Only new aircraft reply to All-Call interrogations because of a lock-out feature described below.

b Selectively Addressed Interrogations:-

Every aircraft on the station roll is interrogated individually with a selectively addressed interrogation when scanned by the aerial. The normal surveillance interrogation elicits a single reply containing the height and address of the aircraft and its position is obtained in the usual way from range and bearing. As only one reply is received from each aircraft a monopulse receiver system is essential to the ADSEL system to obtain accurate azimuth information. In general, only one interrogation is required per aircraft but if this is unsuccessful repeat interrogations are made. The surveillance interrogation also includes a 'lock-out' instruction which prevents an ADSEL transponder replying to All-Call interrogations whilst it is being selectively addressed in a regular manner.

c Data Link Operation:-

The selective address feature offers a unique communication link to and from each aircraft. The surveillance messages have a limited data capacity but longer messages containing 56 or 80 data bits are also available.

ADSEL Transponders

ADSEL transponders have all the facilities of a normal SSR transponder plus the selective address feature. The extra circuits for ADSEL have been fitted within the same size of case as a normal SSR transponder meeting the ARINC characteristic 572. Thus the ADSEL transponders are electronically and mechanically interchangeable with existing SSR transponders. They are approved for commercial airline use and a number of them are carried by the British Midland Airways fleet. As these are flying routes mainly within the United Kingdom trials can be carried out on an opportunity basis. In order to exercise the data link feature the data sent on the up link is repeated, parrot fashion, on the down link, thereby enabling the performance of this feature to be evaluated without requiring any input or display devices in the aircraft or co-operation from the pilot.

A Civil Aviation aircraft is fitted with a special interface unit which enables on-board navigation data to be included in the down message.

Eurocontrol have also fitted an ADSEL transponder to a French Caravelle aircraft which is equipped with the SAVVAN precision navigation system. This aircraft is used to assess the absolute positional accuracy of the ADSEL system.

3 TRIALS AND RESULTS

The aim of the trials is to assess the performance of the ADSEL system and determine the optimum operating rules. The most important aspects of the system performance are the accuracy with which the position of an aircraft can be measured, (range and bearing) and the performance of the communication links.

Position Accuracy

The position of an aircraft is determined by measurement of range and bearing. Range is obtained from the time interval between an interrogation and a reply and the accuracy is mainly determined by the transponder 'reply delay time' and the time quantisation employed in the signal processing unit at the ground station. Range accuracy is not a problem and it has been measured experimentally and found to be entirely satisfactory for Air Traffic Control purposes.

Azimuth is the critical measurement in SSR and the trials period, up to the present, has concentrated on assessing the performance of the monopulse system. The station has a conventional sliding window plot extractor as well as a monopulse processor for measuring the azimuth of an aircraft; thus enabling comparative measurements to be made between the two systems.

The techniques used for assessing the azimuth accuracy are as follows:-

a by using a transponder at a fixed site on the ground.

b by calculation from a smoothed track of an aircraft - this gives the track 'jitter'.

c by comparison with a special trials aircraft fitted with a precision navigation equipment - the SAVVAN system.

d by comparison with the aircraft position measured by a precision tracking radar

These trials will now be described in greater detail.

3.1 Fixed Site Measurements

A transponder has been located at a number of fixed sites, on the ground, at ranges between 5 and 10 Km from the station. Range and azimuth measurements have been made, at various signal strengths, to simulate longer range performance. The range measurements are very stable and vary less than 30 m with 40 dB change in signal strength. As expected the long term stability is excellent.

The azimuth measurements gave a rms error of under 2 minutes, increasing to 4 minutes at minimum signal level. Variation in the mean of the measurements, both with signal strength, and from day to day, is under 2 minutes. These results give the intrinsic accuracy of the station aerial and electronics to measure range and bearing - they give the performance without any propagation errors due to multipath signals or misalignment errors.

3.2 Aircraft Trials

Many trials have been carried out using SSR equipped aircraft on a opportunity basis and comparative measurements have been made using monopulse and sliding window techniques. A large number of radial and tangential flights at various ranges have been analysed in detail by calculating the rms error relative to a smoothed track. Using this method an overall figure for the range error is 15 m rms. (This is mainly due to range quantisation error). The azimuth performance, for the same flights, is 3 to 4 minutes rms for the monopulse system and about twice this 'jitter' for the sliding window technique. The labelled plan display can be switched between the two azimuth measuring methods and the improvement when using the monopulse system is immediately apparent. A reproduction of a typical section of an aircraft track showing both methods is shown in Figure 1.

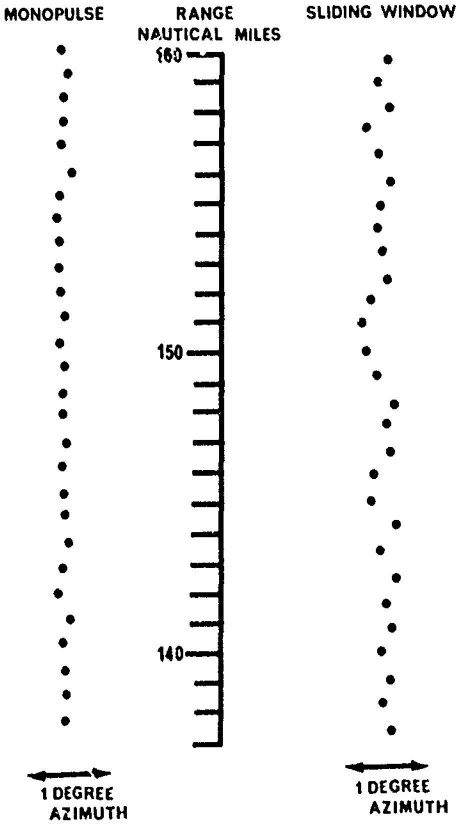

Figure 1
Track comparison on a typical aircraft using a monopulse and sliding window plot extractor

3.3 Absolute Accuracy Measurements

The absolute position accuracy of the station is one of the more important performance parameters. It is not an easy parameter to obtain from actual aircraft because of the difficulty of knowing their exact position. Two techniques have been employed at the ADSEL station.

1) Aircraft fitted with precision navigation equipment

A French Caravelle aircraft has been used for trials which is fitted with a SAVVAN navigation system which operates by measuring the range to three (or more) DME stations. A radio clock is also carried. All this air derived navigation data is recorded on magnetic tape for subsequent processing on the ground. The data tapes received from the French give the aircraft position in latitude and longitude and these are converted into range and bearing from the site at Matching Green for comparison with the measurements made by the ADSEL Station. The air derived data is recorded every second and hence by interpolation it is possible to calculate the position of the aircraft very accurately. With accurately surveyed DME stations the claimed accuracy is an error of under 100 m for one standard deviation.

2) Use of a tracking radar

A precision tracking radar, which is at Aberporth on the west coast of Wales has also been used. This system will operate as a primary radar but to enable it to work satisfactorily at long range a special aircraft transponder is fitted. Again the radar data is recorded together with standard time and is transposed off line to give the position of the aircraft in range and bearing from the site at Matching Green for comparison with the ADSEL station measurements.

This technique can only be used within radar range of the Aberporth and Matching Green sites but nevertheless the area of common cover enables some very useful flights to be carried out.

Results of Flight Trials

A number of flights have been made using both the techniques described in the previous section for determing the position of the aircraft. During these trials the aircraft was carrying a normal SSR transponder and at the ground station the monopulse direction finding system was used to measure the azimuth of the transponder replies. Interrogations were made at a fixed repetition rate and the various ways of operating the monopulse system, described in section 2 were evaluated.

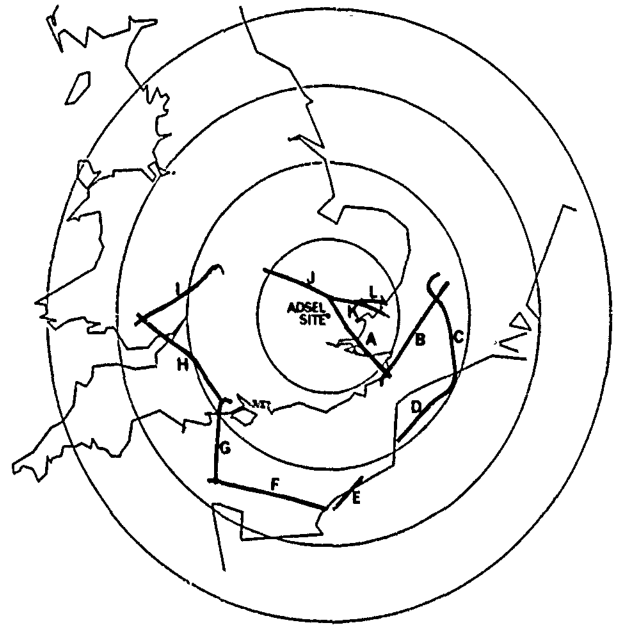

Figure 2
Flight path of SAVVAN equipped aircraft

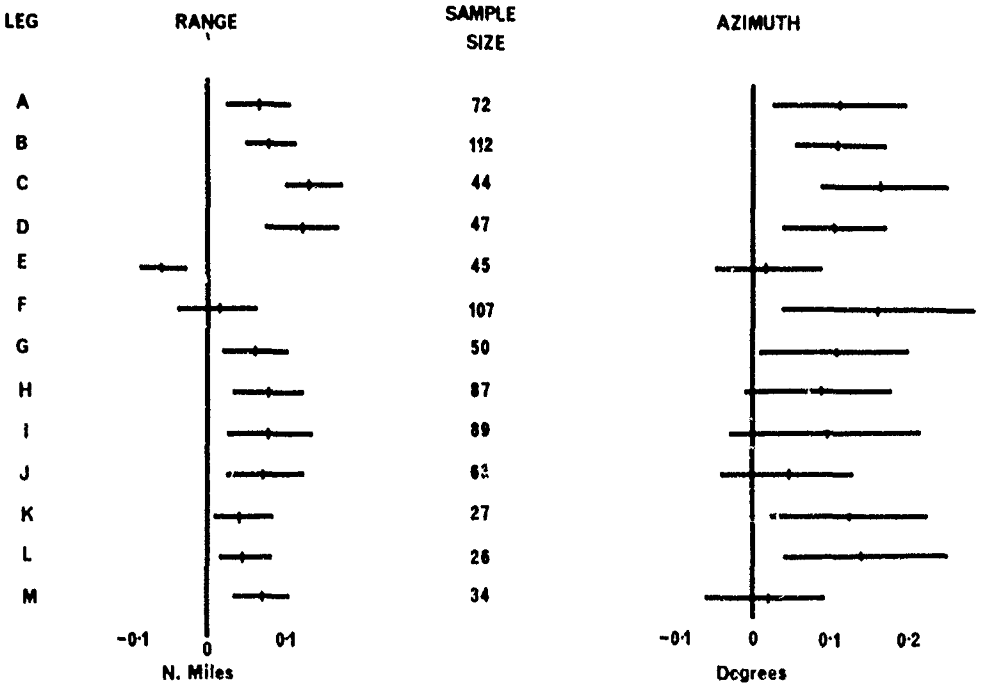

Figure 4
Range and azimuth errors for SAVVAN flight
(Length of bar represents ± 1 standard deviation)

A typical trial using an aircraft fitted with the SAVVAN navigation system is shown in Figure 2 where the flight consisted of a series of 'legs' forming an approximately semi circular course from 70 miles east to 120 miles west of the station followed by a return leg passing within 20 miles north of the ADSEL site. The straighter sections of the flight were broken into legs of about 50 to 100 plots and histograms of the range and bearing errors were calculated. Figure 3 shows histograms of the bearing measurements for two legs together with one for the whole flight. The top one is for a leg where the jitter is on the low side and the middle one shows a poor leg. The performance of the 'legs', range and azimuth, are shown diagrammatically in Figure 4. The centre of the bar shows the bias and its length represents ± 1 standard deviation. It should be noted that there was a power failure for a short time between legs D and E and the effect of the equipment warming up again can be seen in the negative range bias for leg E.

The overall figures for whole flight (800 plots) are:-

	Bias	Standard Deviation
Range	0.06 n ml	0.06 n ml
Bearing	0.1 degrees	0.1 degrees

The composite results from a number of flights are shown in Figure 5. These are from nearly 2500 plots, at varying ranges and bearings around the station and give results very similar to those quoted above.

It should be noted that the range jitter is mainly due to the range quantisation which was 1/8th of a nautical mile at the time. Since then the range quantisation has been reduced to 1/64th of a nautical mile and the measured jitter is now under 0.02 n ml for one standard deviation.

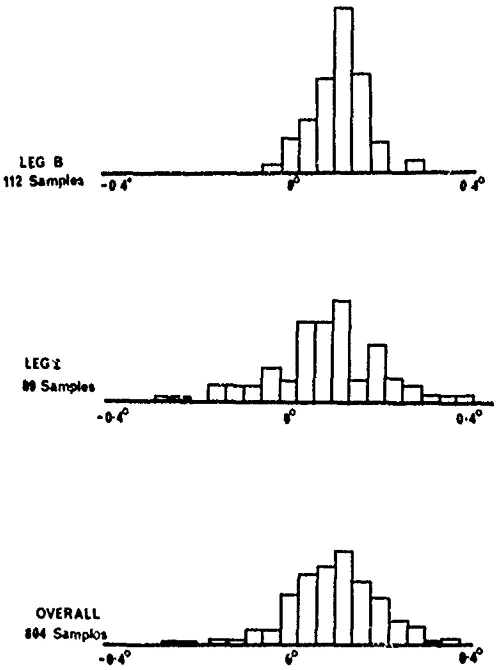

Figure 3
Distribution of azimuth errors
for SAVVAN flight

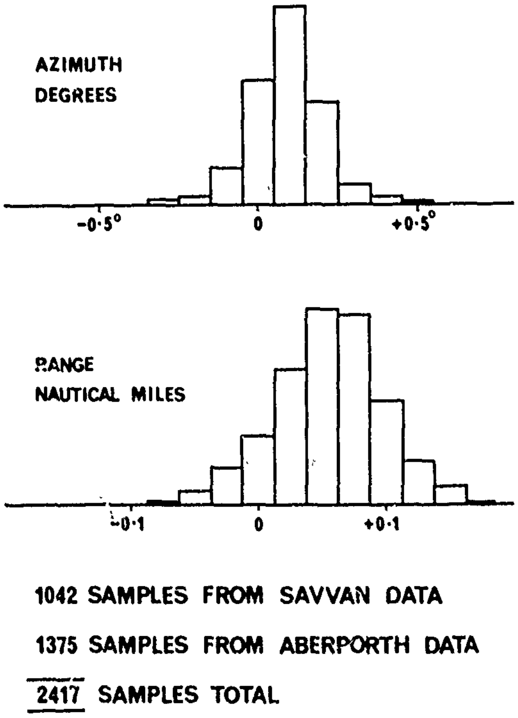

Figure 5
Distribution of range and azimuth
errors for a number of flights

During these trials the various ways of operating the monopulse system (described in section 2) were tried out but, up to the present, there is no clear pattern in the results. When conditions are good, that is, strong signals and no multipath problems, any of the alternatives give very good aircraft tracks. There is, however, an indication that under less than ideal conditions that measurements made close to the centre of the beam give less track 'jitter'. This can be explained by the fact that boresight measurements give the maximum gain to the wanted transponder reply signals and any multipath signals arriving other than on boresight will be attenuated by the aerial pattern. The technique of making monopulse measurements on a number of pulses in the reply and taking the average does not appear to have any value except perhaps at the limit of radar cover when the received signals are very weak.

3.4 ADSEL Surveillance Performance

When the station is operating in a selective address mode, aircraft are acquired by All-Call interrogations, its future position predicted, and an ADSEL surveillance interrogation made when it is next within the beam of the aerial. Therefore, in principle, only a single surveillance interrogation is required for each aircraft, but if this is unsuccessful the interrogation is repeated. Many flights of British Midland aircraft have been followed by the ADSEL station and the results analysed.

During the early trials once it was known an interrogation had failed to produce a correct reply from an aircraft it was immediately re-interrogated and this process was repeated (if required) up to 4 times. This means that aircraft close to the station receive up to 4 interrogations in quick succession (see Figure 6) and even for aircraft at maximum range four interrogations are completed whilst the aerial has only moved about 0.5 degrees. The results obtained from a large variety of flights using this 'quick burst' technique were:-

90% of all aircraft are successfully interrogated by the first interrogation - leaving 10% failures to be re-interrogated.

7% of all aircraft are re-interrogated successfully by a second interrogation. Because only 10% of all aircraft need a second interrogation it has a success rate of 70%.

The third and fourth interrogations are rarely successful.

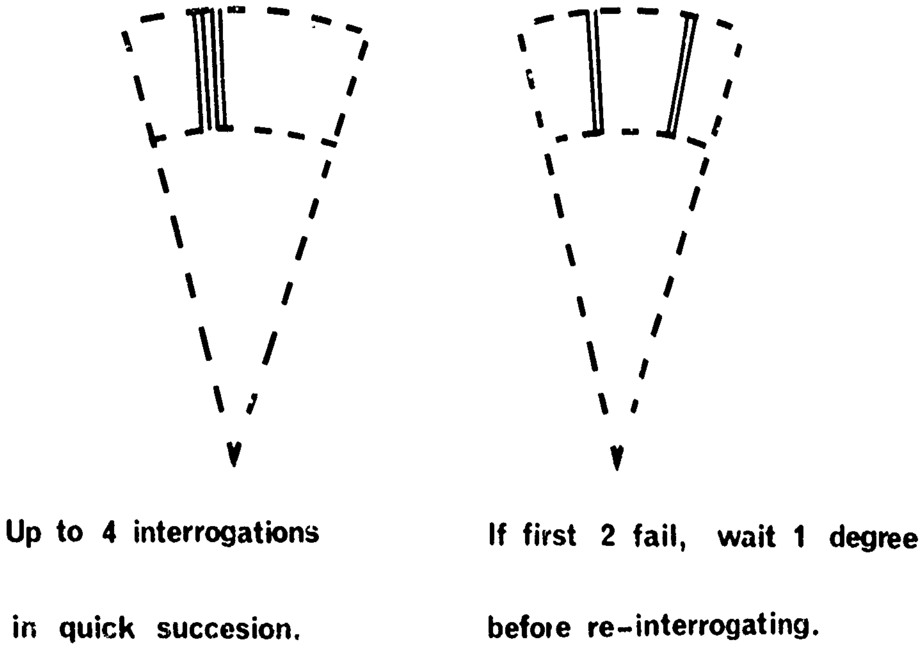

Figure 6
ADSEL surveillance - re-interrogation options

The poor success rate for the third and fourth interrogation suggests that the cause of failure tends to persist and a better performance would be obtained by waiting a short time. The interrogation rules were therefore changed so that two interrogations are made half a degree before the predicted position and (if required) two more interrogations about half a degree afterwards. (See Figure 6). The results from a large number of flights from acquisition until the aircraft was out of range were:-

90% of all aircraft are successfully interrogated by the first interrogation - leaving 10% failures to be re-interrogated

7% of all aircraft are re-interrogated successfully by a second interrogation. i.e The second interrogation has a 70% success rate and leaves 3% of all aircraft for further interrogation.

1.5 to 2% of all aircraft are successfully interrogated by the third interrogation. i.e The third interrogation has a success rate of better than 50%,

The fourth interrogation is rarely required.

Therefore the overall performance using these interrogation rules is approaching 99% with on average 1.13 interrogations per aircraft. It is interesting that if all four interrogations are made, even if the first ones are successful, that the success rate for the third and fourth interrogations are the same as for the first and second, i.e 90% and 7%. This indicates that although the reason for failure tends to persist when the interrogations are made in rapid succession, by making two bursts of two interrogations about one degree apart the failure mechanism appears to be uncorrelated.

The unsuccessful interrogations have been carefully examined for the cause of failure but up-to-date no very definite pattern has been found in the results.

However there is a tendency for aircraft replies at long range and hence low signal strength, to fail on parity. Also when aircraft are at short range, tracking is more difficult and sometimes a valid reply is received which is outside the limited angle over which the monopulse system can operate. Both these observations are consistent with how the system is expected to behave.

3.5 ADSEL resolving SSR synchronous garble

One of the principal aims of the ADSEL system is to overcome the synchronous garble problem of present day SSR. This occurs usually when aircraft are required to stack or when aircraft are flying in airways and a faster aircraft overtakes a slower aircraft (preferably at a different flight level!) The opportunity to prove the effectiveness of the ADSEL mode of operation occurred recently when a British Midland Airways aircraft, fitted with an ADSEL transponder, overtook a slower aircraft. This occurred near Manchester about 60 nautical miles from the ADSEL site. Surveillance of this situation was monitored, and recorded, in three ways; SSR operation using a conventional sliding window plot extractor, SSR with monopulse direction finding and by the ADSEL system. Figures 7, 8 and 9 show the performance of the three techniques.

Conventional SSR operation is shown in Figure 7. The Identity code of the aircraft carrying an ADSEL transponder is 4035 at an indicated flight level 169 and the Identity code of the overtaken aircraft is 4431 at flight level 121. For clarity the track of the overtaken aircraft is shown as a straight line, although the plots obtained from this aircraft were just as corrupt. (For SSR working but not in the ADSEL mode - see later). For the 26 aerial scans shown only 10 plots are completely correct, 2 have no valid Height, 4 have no valid Identity code, 4 have no Height or Identity, 3 have the wrong Identity, and 3 plots are completely missing. In addition there is plot jitter of about 1° in azimuth.

Figure 8 is also SSR operation but with the bearing of the replies measured using the monopulse direction finding system. Here the plot jitter is reduced but information content of the replies is as poor as before. It should be noted that the monopulse facility at the ADSEL station is only used to measure the azimuth of the aircraft replies. There are plot extractors under development in the USA and in Britain which make monopulse measurements on every pulse in the SSR reply and hence use this information to assist in the decoding of overlapping replies. This use of monopulse to help in the plot extraction process is not available at the ADSEL station.

Figure 9 shows the performance of the ADSEL mode of operation for the same 26 scans of the aerial. Complete and correct data is obtained on every scan and the track jitter is considerably reduced. It should be noted that when operating in this way the SSR data obtained from the overtaken aircraft, fitted with a normal SSR transponder, is also of good quality. This is not shown on the recording. In other words the garble problem between two aircraft can be avoided providing <u>one</u> of the aircraft is carrying an ADSEL transponder, and, of course, the ground station is capable of interrogating in the ADSEL mode. This record of a genuine garble situation shows convincingly the ability of the ADSEL system to obtain accurate surveillance information.

4 DATA LINK

As part of the ADSEL trials the CAA are carrying out data link experiments with special interface units fitted to their HS748 flight calibration aircraft. These special units sample on-board aircraft sensors and provide inputs to the data link message fields of the ADSEL transponder. The parameters include heading, along and across heading Doppler speeds, pitch, roll, VOR, DME, indicated airspeed and outside air temperature. These are encoded in 8 or 16 bit blocks into the data link reply message field giving a maximum of seven parameters which can be sent down the link in any one message. The system at present transfers information from air to ground only, although work is in progress on providing a two way communications capability. This latter development will allow data to be passed to and displayed in the aircraft.

The present equipment has been in operation since February 1978 and has provided a useful data base for a preliminary analysis of link performance. The station was operated using the interrogation rule described in para 3.4, i.e two bursts of two interrogations spaced about one degree apart. Not surprising the success rate obtained of 98.6% is very similar to the surveillance performance.

There are however minor differences between the operation of a surveillance interrogation/reply and communication messages. Firstly the communication messages are longer and secondly they do not require a valid monopulse measurement. In other words surveillance interrogations can only be made within the angle over which the monopulse system can operate (which is ± 1.25°) whereas communication messages can be sent over the full aerial beamwidth of about 4 degrees.

5 CONCLUSIONS

The trials are confirming the effectiveness of the ADSEL system for providing the essential surveillance and communication facilities of a future Air Traffic System. It completely overcomes the 'garble' problem of the present day SSR and provides a data link to and from the aircraft. Up-to-date the trials have concentrated on the performance of the data link rather than its application but future work will include the use of air derived data (i.e rate of turn) to assist in the tracking program at the ground station. Also the trials will be extended to investigate the operation of a number of ground stations and the requirements of the network for the exchange of data.

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7 ACKNOWLEDGEMENTS

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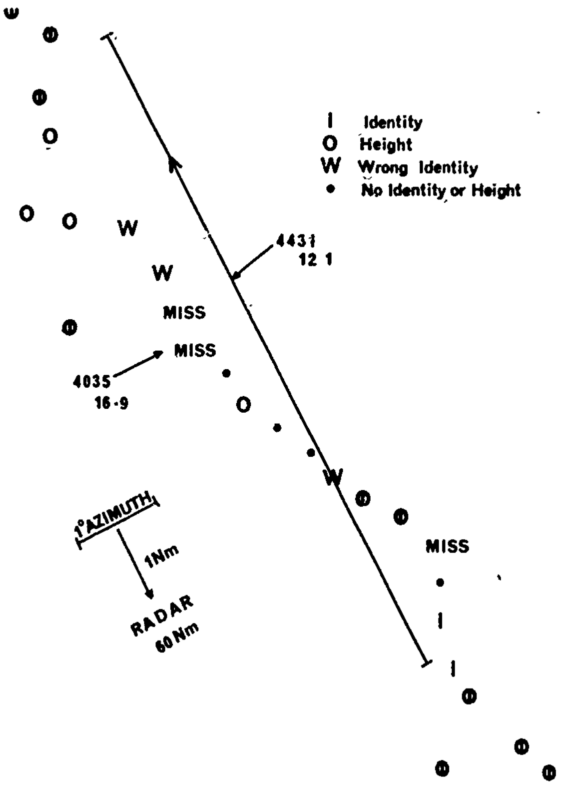

Figure 7
Track of overtaking aircraft using SSR sliding window plot extractor

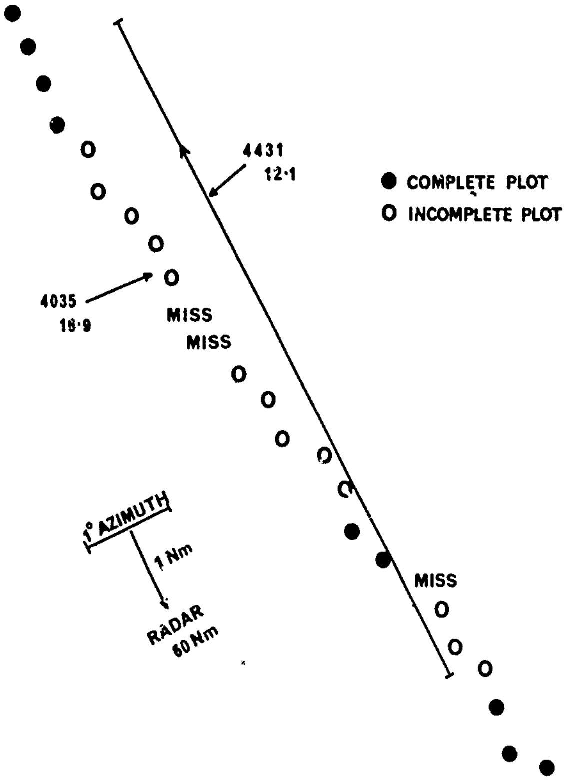

Figure 8
Track of overtaking aircraft using SSR monopulse plot extractor

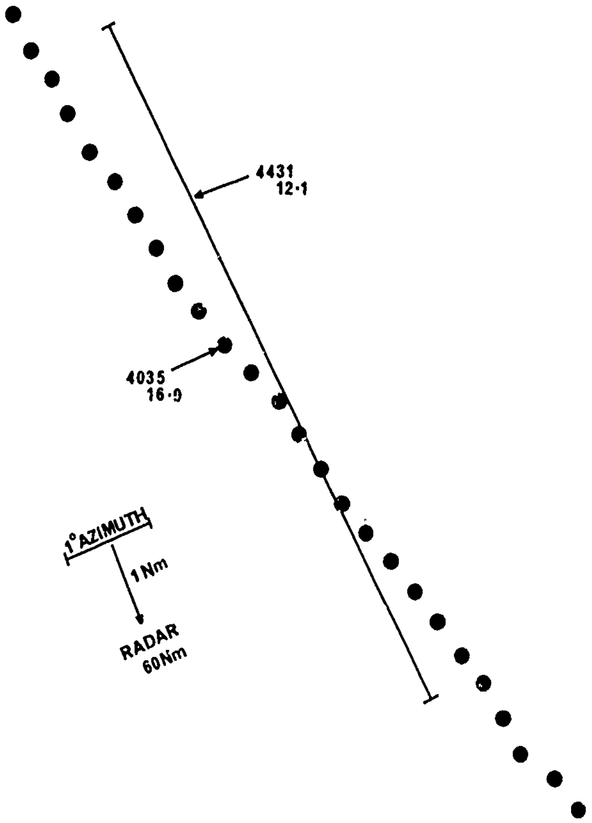

Figure 9
Track of overtaking aircraft using the ADSEL mode

SURVEILLANCE PERFORMANCE MEASUREMENTS* **
OF THE SSR MODE OF THE
DISCRETE ADDRESS BEACON SYSTEM

by

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Summary

A field measurements program was conducted by the Massachusetts Institute of Technology's Lincoln Laboratory to evaluate the surveillance performance of the Discrete Address Beacon System being developed by the United States Federal Aviation Administration as an evolutionary upgrading of the present secondary surveillance radar (SSR). This included the development of a Transportable Measurements Facility (TMF) and its deployment to FAA operational sites across the United States. Simultaneous measurements made by the TMF and the existing FAA ground stations provided the opportunity for a side-by-side comparison of DABS off-boresite monopulse and conventional surveillance measurement performance. Results indicate a substantial improvement in performance over conventional SSR processing techniques.

Introduction

The Discrete Address Beacon System (DABS[1]), under development by the United States Federal Aviation Administration, is an evolutionary upgrading of the current Secondary Surveillance Radar System (SSR) defined in Figure 1. DABS provides for selective addressing of individual aircraft in order to provide improved surveillance through the elimination of the inherent SSR problems of garble and over-interrogation. The discrete address feature also permits the incorporation of a high capacity data link system within the basic structure of DABS interrogations and replies.

The DABS ground station uses an off-boresite monopulse technique to determine aircraft azimuth on a pulse-by-pulse basis to permit highly accurate azimuth estimates to be made on a single DABS reply per scan. The same monopulse technique is employed in the SSR mode of the DABS ground station where monopulse azimuth measurement provides the means for improved reply degarbling and azimuth accuracy. Monopulse also permits SSR operation at a greatly reduced pulse repetition frequency compared to that required by current azimuth measurement techniques.

In order to validate the design of the off-boresite monopulse technique, the Massachusetts Institute of Technology's Lincoln Laboratory conducted extensive field measurements of monopulse performance at a number of FAA sites throughout the United States. Sites were chosen to include the spectrum of operational siting conditions. This ranged from "worst-case" sites that exhibited significant multipath, interference and obstructions to sites that were generally free of these problems.

Field measurements were made using a Transportable Measurements Facility (TMF) that is essentially a non-real-time DABS sensor. The TMF is composed of the DABS sensor "front end" (including antenna, transmitter, and reply detectors), and digital recording equipment. Recorded field data were returned to the Laboratory where the remainder of the surveillance processing was performed.

At a number of field sites, the TMF was colocated with an existing FAA terminal radar facility (the Automated Radar Terminal System). In these cases, simultaneous recordings of existing SSR data were made in order to serve as a baseline of comparison for assessing the performance of the SSR mode of DABS.

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*This work was performed under the sponsorship of the Federal Aviation Administration (FAA).

**The views and conclusions contained in this document are those of the contractor and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the United States Government.

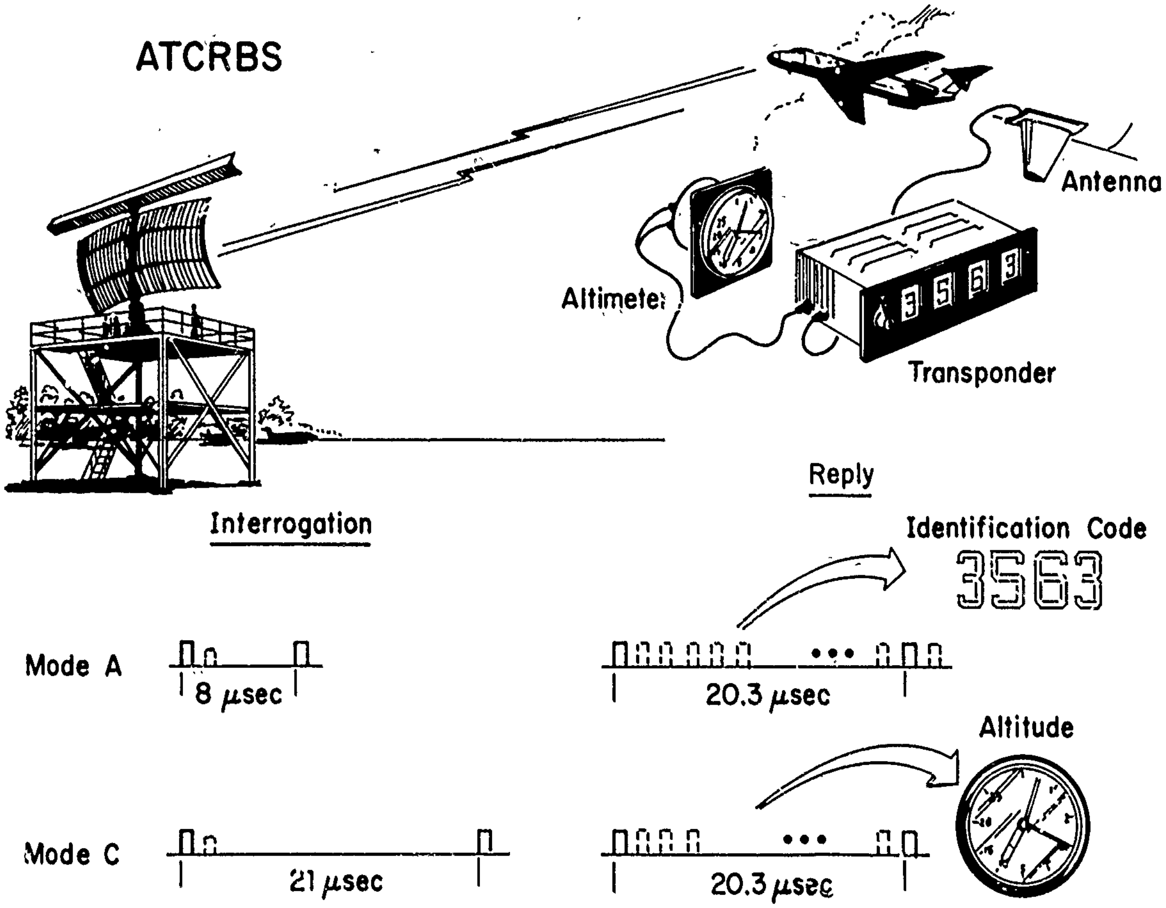
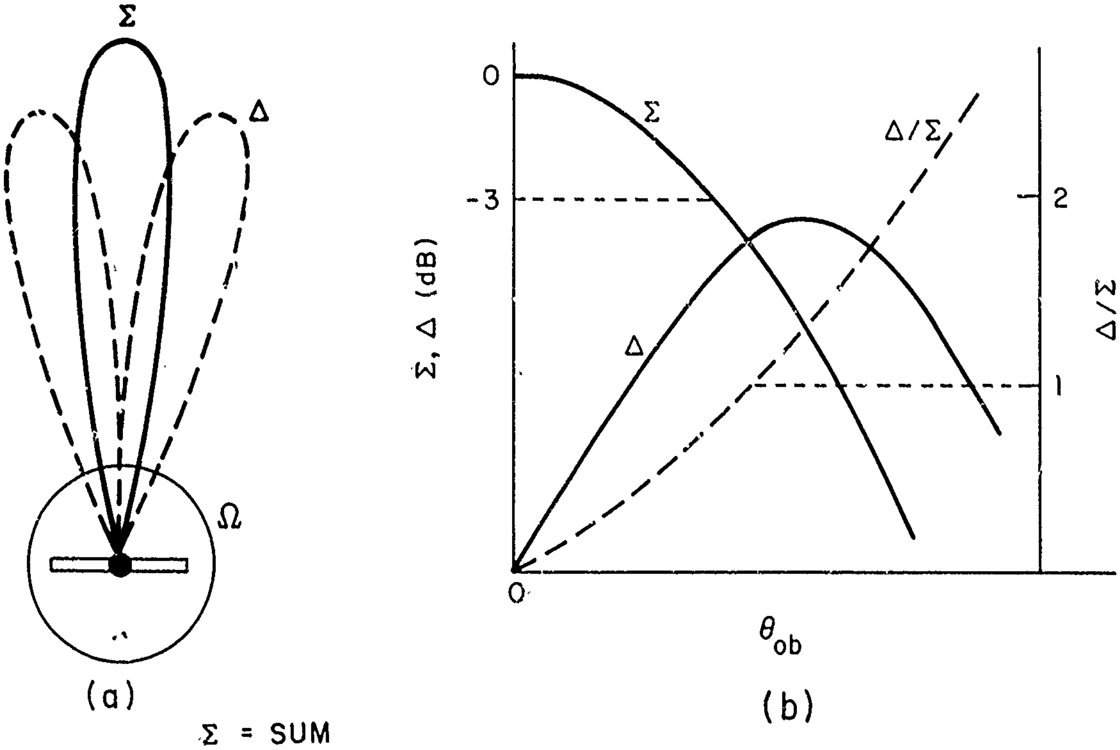


Fig. 1. Secondary Surveillance Radar (SSR).



Σ = SUM

Δ = DIFFERENCE

Ω = OMNI

θ_{ob} = OFF-BORESIGHT ANGLE

Fig. 2. Monopulse Antenna.

This paper describes the off-boresite monopulse technique developed for the DABS ground station and indicates the way in which it is used to obtain increased azimuth accuracy as well as improved SSR performance in garble situations. Next, the TMF is defined along with a description of the scope of the field test program including the sites visited and the extent of the data collection. Finally, results are presented for azimuth and range accuracy that apply to both DABS and SSR, as well as blip/scan ratio and decoding performance for the SSR-mode.

Off-Boresite Monopulse

Off-boresite monopulse measurement is achieved through the use of a multibeam antenna as shown in Figure 2(a). Target off-boresite azimuth is determined by the relative magnitude of the received signal strength in the difference and sum beams as shown in Figure 2(b).

Several techniques exist for generating monopulse values for the received signal. The one chosen for use in the DABS design[2] is a phase comparison technique shown in Figure 3. This processor generates a $f(\Delta/\Sigma)$ which is single-valued over the full range range of values of Δ/Σ, according to the relationship

$$f(\Delta/\Sigma) \quad 2\tan^{-1}(\Delta/\Sigma)$$

It also provides a highly accurate and stable calibration characteristic over a wide range of input signal amplitudes.

Conventional SSR Azimuth Determination

Conventional SSR processors determine azimuth through a technique known as a "sliding window detector" as shown in Figure 4. The presence of replies at a consistent range on m-out-of-n successive sweeps signals the leading edge of a target run length. The azimuth at which this occurs is stored as θ start. The trailing edge (θ end) is defined as the azimuth at which the reply count on successive sweeps drops below a second (usually lower) m-out-of-n threshold. Target azimuth is then determined by averaging θ start and θ end and removing the bias caused by the delay in detecting the leading and trailing edges of the reply run length. This azimuth measurement technique uses a high pulse repetition frequency (PRF) in order to provide the required sixteen to twenty-five (or more) replies needed for azimuth determination. A second disadvantage of this technique is that a failure to receive replies in the middle of the reply run can lead to an erroneous declaration of a θ end and a second θ start. This phenomenon is known as an "azimuth split" and leads to the declaration of the presence of two targets, neither of which is at the azimuth of the true target.

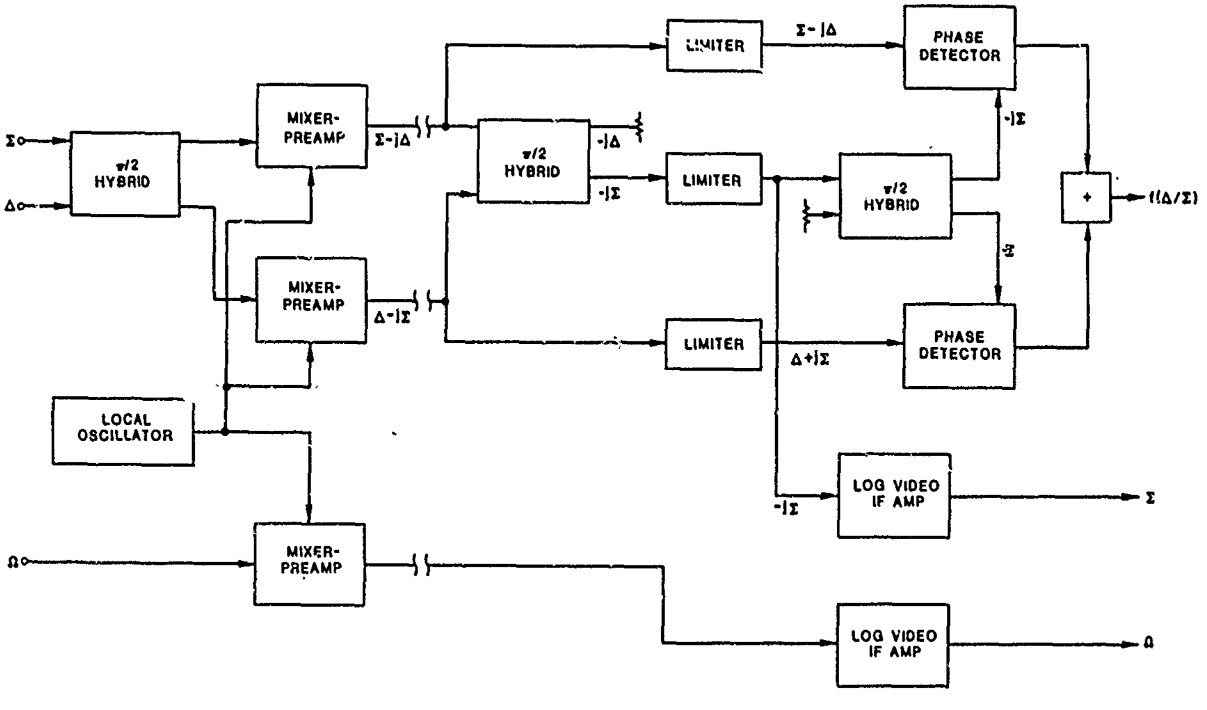


Fig. 3. DABS Monopulse Processor.

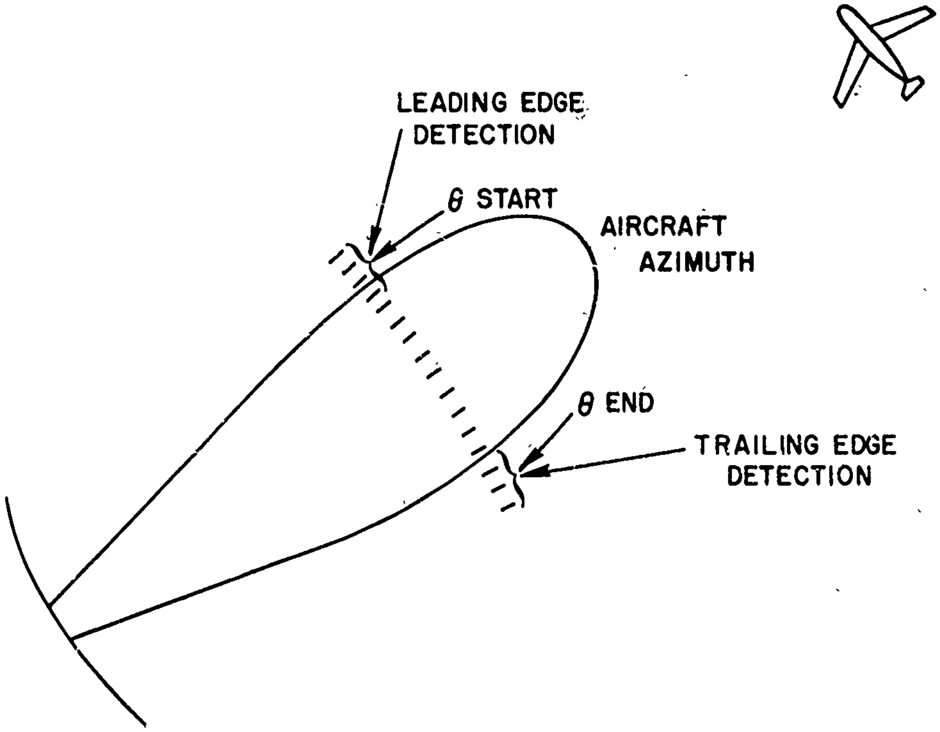


Fig. 4. Conventional Sliding Window Detector.

The SSR Mode of DABS[3]

The use of monopulse in the SSR mode of DABS eliminates the disadvantages of the sliding window detector. Nominally the sensor could operate with only one reply per SSR mode for each target during one scan of the antenna. However, this would lead to frequent target report declarations due to the chance reception of the replies (usually referred to as "fruit") elicited by adjacent sensors. To reduce this effect the DABS sensor is set to a PRF that produces 2 replies per SSR mode within the antenna 3 dB points. Typically, this is one-quarter to one half the PRF of a conventional sensor.

A second consequence of the use of monopulse is its ability to aid in the decoding of overlapped replies from aircraft near the same range and azimuth. This condition is usually referred to as "synchronous garble" since it may persist for many scans of the antenna. An example of a synchronous garble situation is shown in Figure 5. The monopulse estimates for each reply pulse readily identify the reply to which each of the received pulses belong. In the example shown the pulses themselves are not overlapped so that pulse timing alone could have lead to the correct sorting of pulses into replies. Monopulse degarbling however continues to operate into regions of pulse overlap that could not be resolved by pulse timing alone. It therefore reduces the susceptibility of the SSR mode to synchronous garble.

Mode A and mode C code declaration is enhanced through the use of receive sidelobe suppression. Signals received on the omni antenna are compared to the sum beam signals. If the omni signal is greater, the received pulse is flagged to indicate low confidence. When replies are correlated to form one report per scan, low confidence pulses are discarded in favor of high confidence pulses.

The scan-to-scan surveillance processing provides unambiguous track number labels for each SSR report, thereby relieving the air traffic control (ATC) facility of the burden of scan-to-scan correlation of SSR targets. Surveillance processing also flags target reports that result from reflections of the main beam. The mechanism for producing these "false targets" is illustrated in Figure 6. When tracks are initiated a check is made to determine if the target azimuth corresponds to the azimuth of a known reflector. If so, a check is made to see if an image track exists with the same mode A (and if available) mode C code at the point indicated by the location and orientation of the reflector. If so, the track is labelled as a false track and all reports correlating with it are flagged as false when disseminated to the ATC facility.

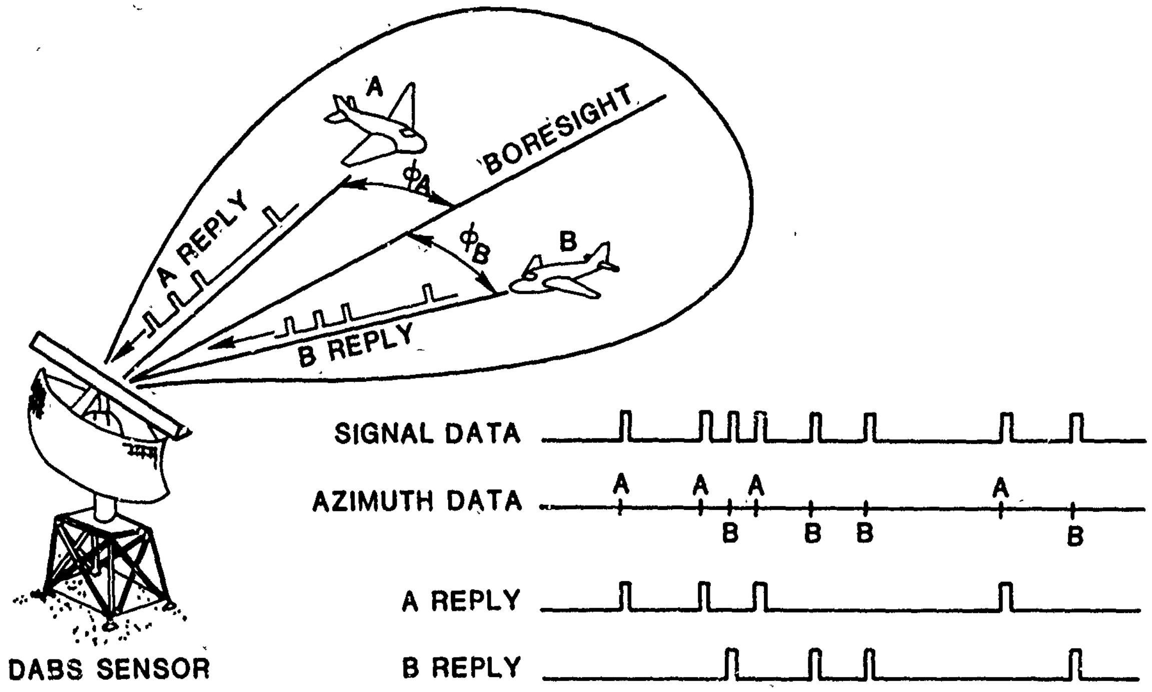


Fig. 5. Monopulse Reply Degarbling.

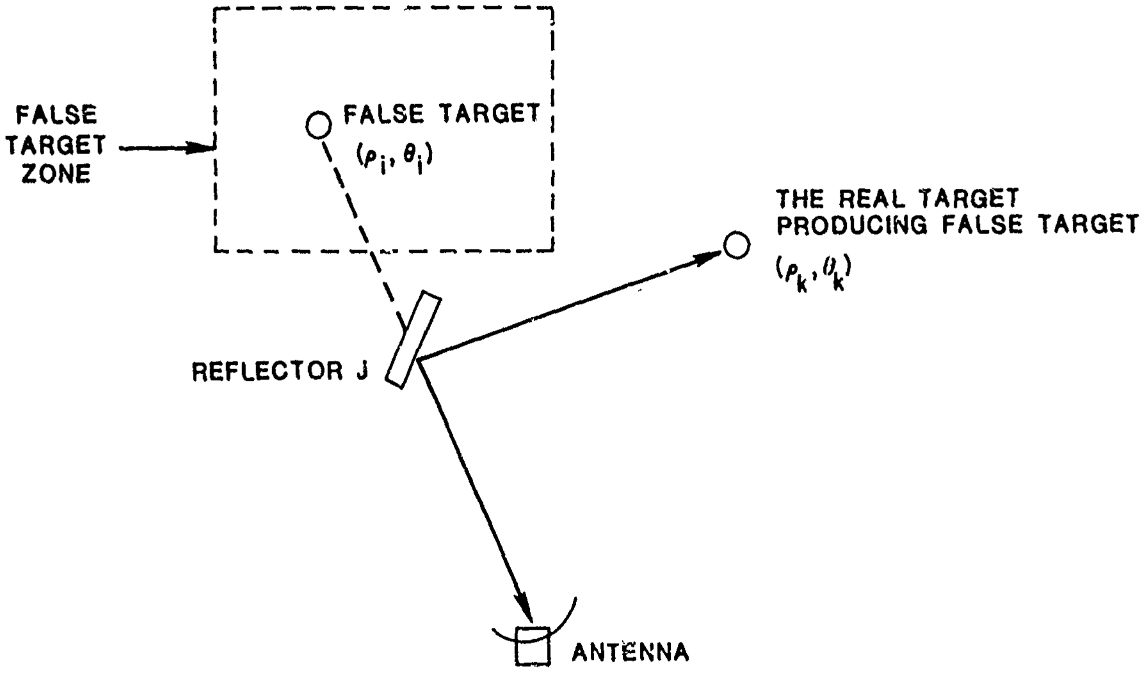


Fig. 6. SSR False Target Flagging.

DABS Design Validation

Initial validation of the DABS design was performed at the DABS Experimental Facility (DABSEF) located on a hill adjacent to Lincoln Laboratory. The DABSEF is a flexible beacon test facility that is capable of performing DABS and SSR mode processing functions.

While validation at DABSEF was a necessary first step, it was not sufficient to validate the DABS design since DABSEF is a very benign site in terms of problems frequently encountered at operational FAA sites such as high traffic density, fruit, multipath and false target reflectors. For this reason, a Transportable Measurements Facility was built and operated at a number of FAA sites across the United States.

The TMF, described in Figures 7 and 8, is basically the "front end" of a DABS sensor including a choice of two antennas, a transmitter and a receiver. The output of the receiver is digitized video, which in an actual sensor would be interfaced with the ATCRBS and DABS reply processors. In the TMF, this digitized video is recorded, along with timing and other information. The TMF data thus recorded at the operational site locations was returned to Lincoln Laboratory for data reduction and evaluation. This included playback of the recorded digitized video through simulated ATCRBS and DABS reply processors. The resulting target reports were then operated upon by the surveillance processing routines. Analysis of the output of these programs served to validate and characterize DABS design performance.

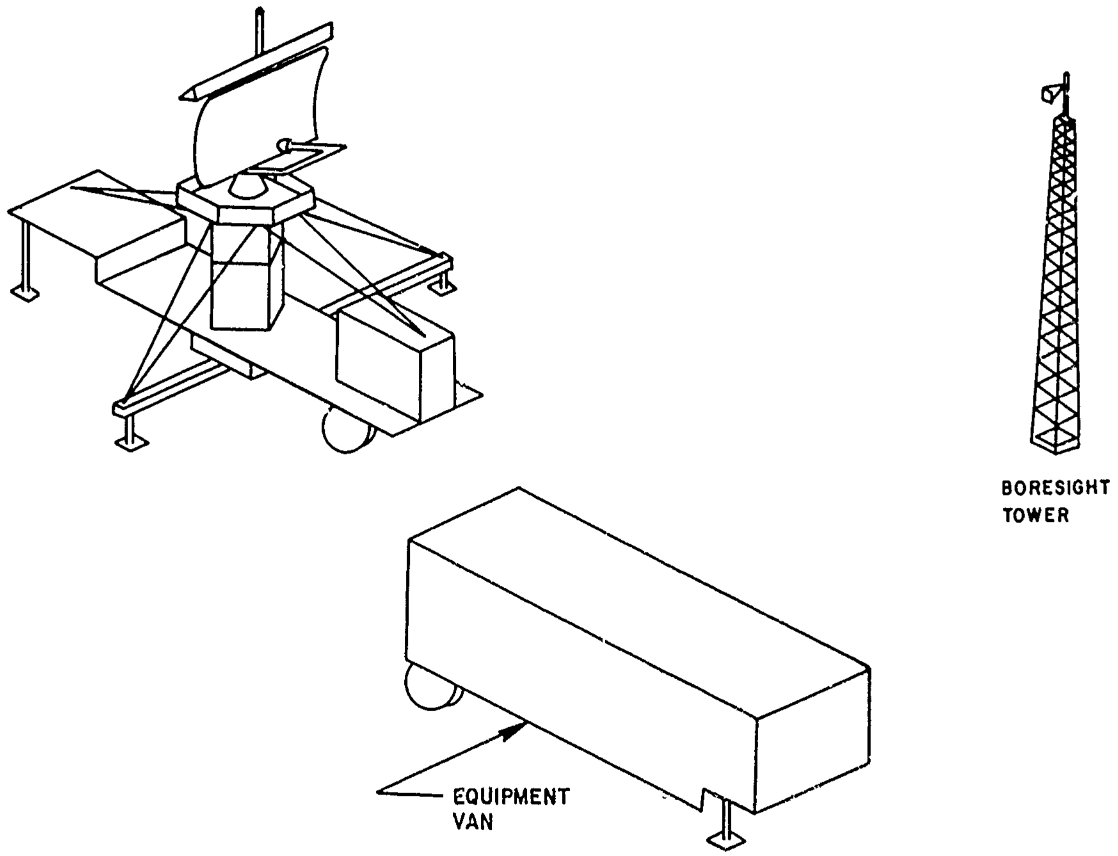


Fig. 7. The Transportable Measurements Facility (TMF).

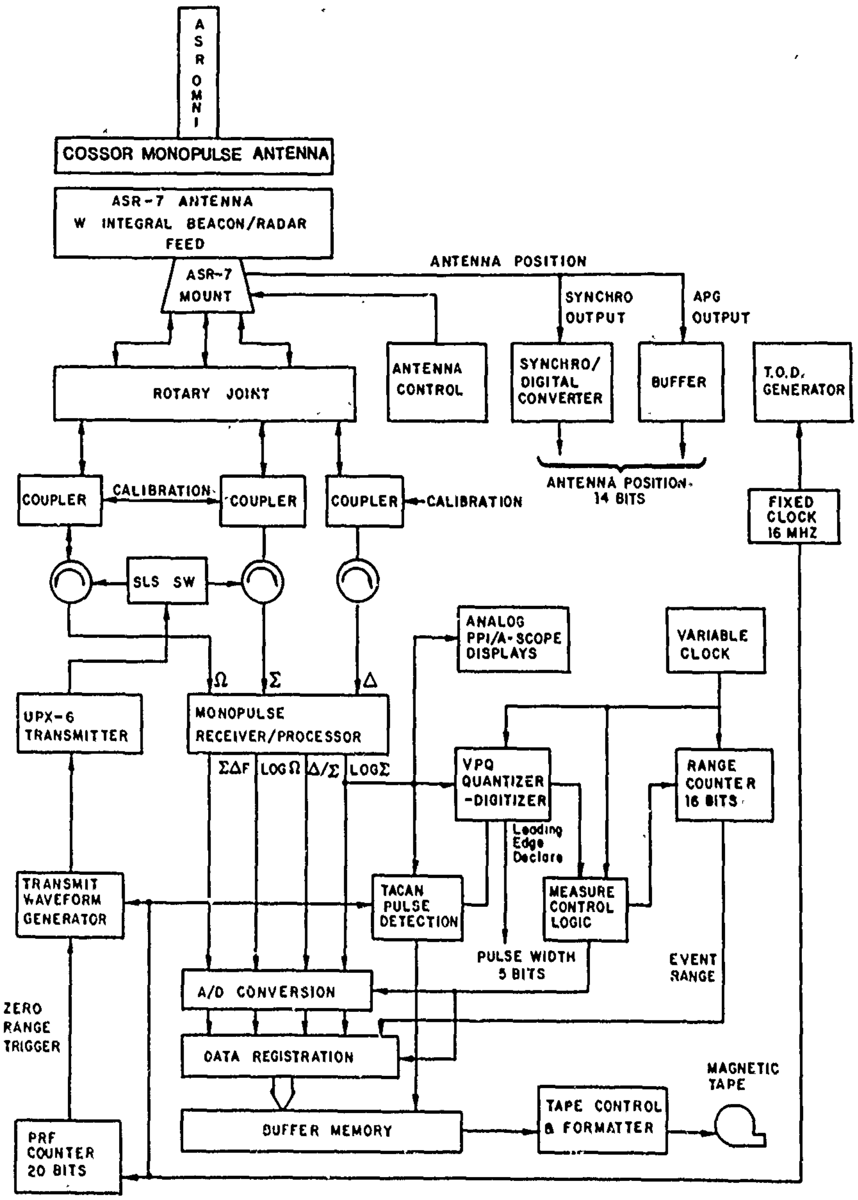


Fig. 8. TMF Block Diagram.

As indicated above, the TMF was operated in problem areas that offer high traffic densities and unusual siting difficulties[4]. A list of selected sites along with the rationale for site selection is presented in Figure 9. In addition, measurements were also made at Salt Lake City, Utah to aid the FAA in the selection of a new SSR sensor site and at Warwick Rhode Island as part of a multisensor experiment with the DABSEF. The complete set of TMF locations is shown graphically in Figure 10.

Experiments conducted at each site generally included data collection for a period of 20 minutes to one hour. In all, a total of over 350 experiments were run at the collection of TMF sites.

At each of the FAA site locations, the TMF was positioned near the existing SSR sensor in order to experience similar environmental conditions. At each of these sites, several experiments were run with simultaneous data recording performed at the existing Automated Radar Terminal System (ARTS). The resulting set of data provided the opportunity to obtain a side-by-side comparison of the SSR mode of DABS with the conventional ARTS processor.

ENVIRONMENTAL CHARACTERISTICS

TRAFFIC	FALSE TARGETS	GARBLE MULTIPATH	VERTICAL LOBING	OBSTRUCTION	INTERFERENCE	RADAR BEACON INTERROGATOR SITE
	×		×	×		BOSTON, LOGAN AIRPORT*
×					×	PHILA. INTL. AIRPORT*
	×	×		×		LAS VEGAS, AIRPORT
×	×		×	×	×	LOS ANGELES INTL. AIRPORT*
	×			×		WASH. INTL. AIRPORT

*MEASUREMENTS ALSO MADE AT A SECOND SITE REMOTE FROM THE EXISTING SSR SENSOR

Fig. 9. TMF Site Selection Criteria.

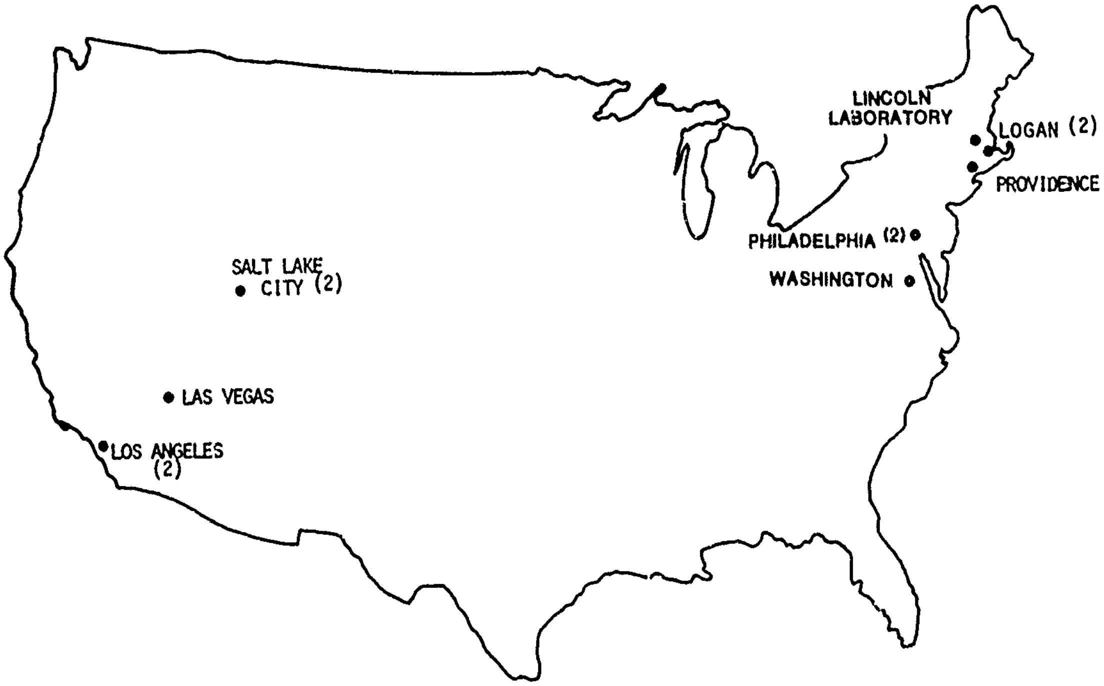


Fig. 10. Transportable Measurements Facility (TMF) Sites.

Experimental Results

Results typical of ARTS/DABS SSR mode comparison are shown in Figure 11 and 12. Each figure shows a dot corresponding to the unsmoothed, measured position of a single target report, hence the sequence of dots represent the flight paths of aircraft. A comparison of the figures readily shows the improved positional accuracy and track continuity of DABS SSR mode versus conventional processing. The improvement is most obvious in the case of crossing tracks.

Figure 13 shows a quantitative comparison of surveillance performance representing an average of typical data for each of the following sites: Boston, Washington D.C., Philadelphia, Los Angeles, Salt Lake City and Las Vegas. The quantities compared are defined as follows:

Blip/Scan Ratio - the probability of generating a target report during one scan.

No Altitude - the percentage of reports that did not contain a valid altitude.

No Code - the percentage of reports that did not contain a valid code.

Range Error - the standard deviation from a second order polynominal fit to a sliding sequence of range measurement points, centered on the report being evaluated. The error is calculated only for established straight-line tracks at elevation angles between 0.5 and 40 degrees and at ranges between 2 and 45 nmi.

Azimuth Error - some as range error, but in the azimuth dimension.

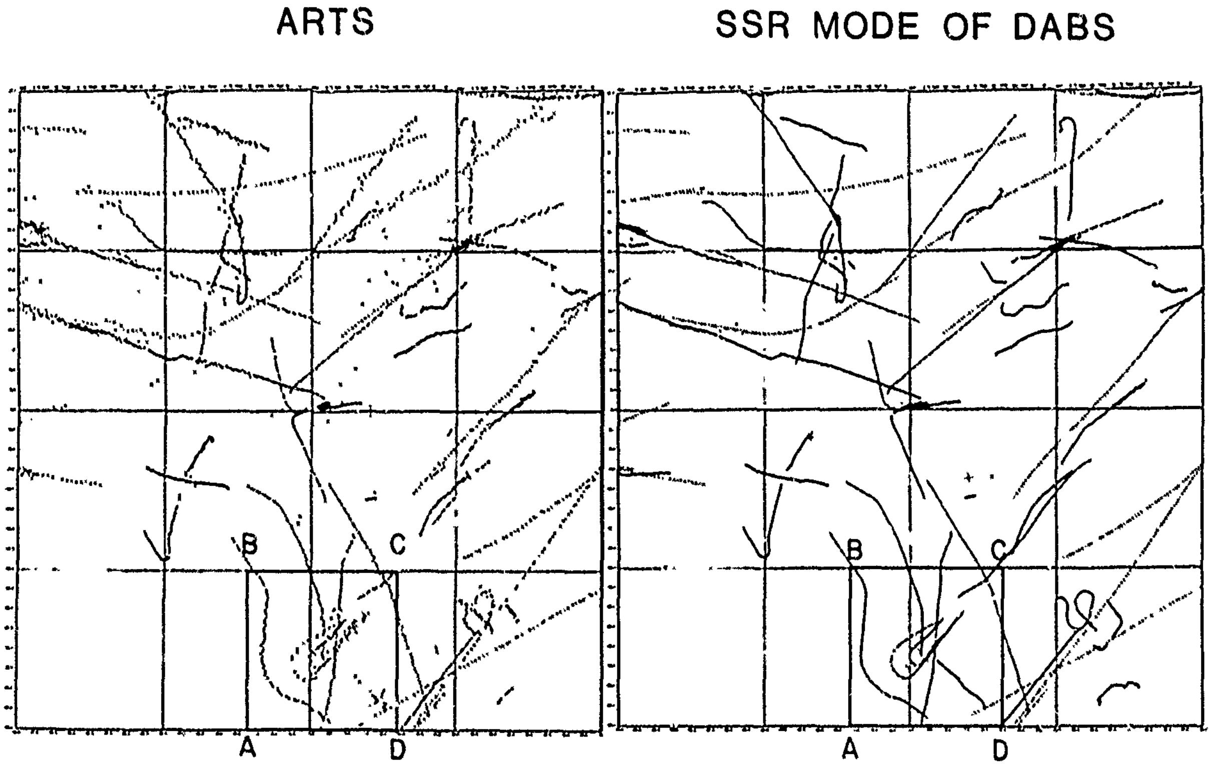


Fig. 11. ARTS/DABS SSR Mode Comparison, Philadelphia (150 x 150 Km).

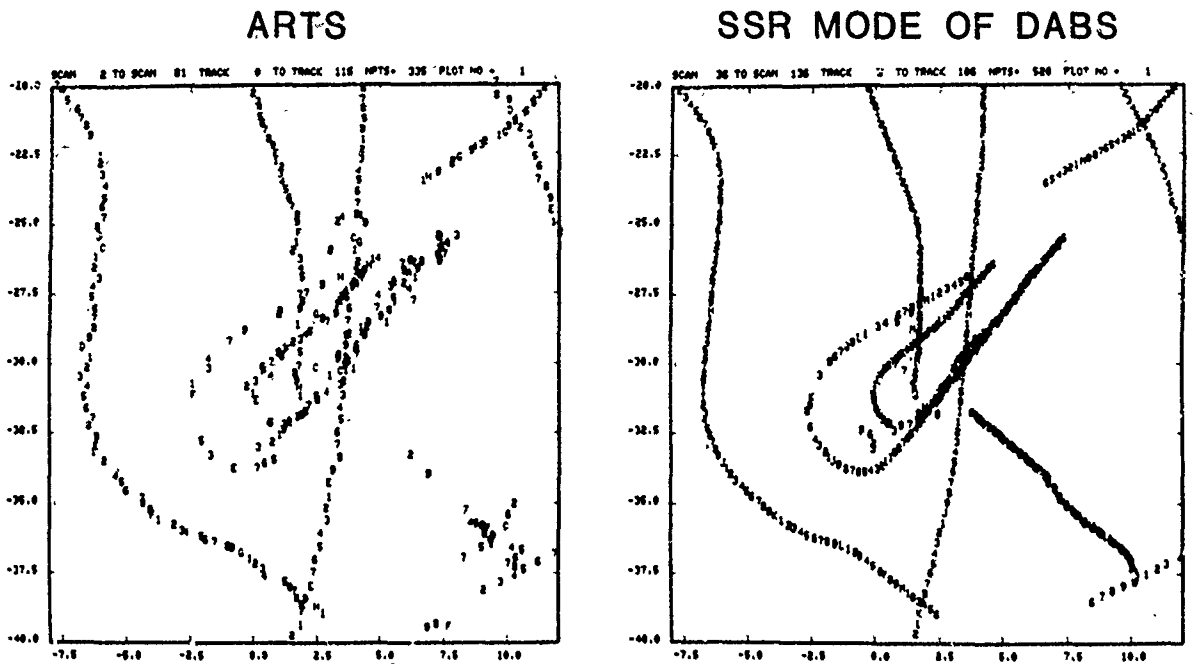


Fig. 12. Expansion of Figure 11 Square ABCD (37 x 37 Km).

	ARTS		SSR MODE OF DABS	
	ALL	CROSSING	ALL	CROSSING
BLIP/SCAN	94.6%	86.9%	98.0%	96.6%
NO ALTITUDE	2.7%	8.3%	1.4%	3.0%
NO CODE	1.5%	7.4%	.7%	3.0%
RANGE ERROR (1σ)	37.8M		7.3M	
AZIMUTH ERROR (1σ)	0.16DEG		0.04 DEG	

Fig. 13. Surveillance Performance Comparison, Average Site.

Summary

These results indicate that both range and azimuth accuracies of the DABS design are 4 times better than those provided by current terminal SSR equipment. Blip/scan ratio for monopulse SSR is 98% or better, and remains high in crossing track situations where the performance of existing equipment is observed to degrade. Significantly, this improvement in SSR performance was accomplished with 1/4 the PRF of the present equipments.

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EFFECTIVENESS OF ADVANCED FUEL-CONSERVATIVE PROCEDURES IN THE TRANSITIONAL ATC ENVIRONMENT

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SUMMARY

The Air Traffic Control (ATC) system is now in the midst of major changes in systems and procedures to cope with increasing air traffic congestion at hub airports and to achieve energy conservation and noise abatement. Difficult problems arise in the transition to new systems. Assessing the effectiveness of new operational procedures and navigation techniques for fuel conservation and capacity expansion has been the subject of several joint studies by FAA NAFEC and NASA Ames. This paper summarizes real-time simulation studies (involving both the pilot and the air traffic controller) concerning fuel conservative approaches, profile descents, and four-dimensional area navigation (4D RNAV). Generally, results indicate some difficulties with the procedures tested in a mixed traffic environment and point to the need for computer assistance for effective implementation of candidate procedures.

INTRODUCTION

The ATC system is now in the midst of major changes in systems and procedures to cope with increasing air traffic congestion at hub airports and to achieve energy conservation and noise abatement. Difficult problems arise in the transition to the new systems. The development of controller and pilot procedures in the transition period is a complex process, requiring the study of interactions between pilots and air traffic controllers. A key problem during the transition period is that a significant portion of aircraft will not execute new procedures or will be unable to because of a lack of appropriate onboard equipment. Assessing the effectiveness of new operational procedures and navigation techniques for fuel conservation and capacity expansion in such a mixed traffic environment has been the subject of several joint studies by FAA and NASA. The indispensible tool in these studies has been real-time pilot-and-controller-in-the-loop ATC simulations. This paper will focus on several advanced operational procedures that have been investigated in real-time simulations, as part of efforts to understand how to effect a smooth transition. In particular, the following three experiments will be discussed: (1) delayed flap and the International Air Transport Association (IATA) low-power noise abatement approach technique (hereafter referred to as the IATA approach), (2) profile descents, and (3) four-dimensional area navigation (4D RNAV). Prior to discussing the various experiment studies, some background on the simulation facilities will be presented.

SIMULATION FACILITIES

A block diagram of simulation facilities is given in Fig. 1. Two different ATC simulation facilities at FAA NAFEC and NASA Ames were used in the real-time simulation studies. For the profile descent experiment, the Air Traffic Control Simulation Facility (ATCSF) at NAFEC was used. The facility consists of a computer complex and a number of air traffic controller and keyboard pilot stations. The keyboard pilot positions are available to control the computer-simulated aircraft using the same clearances that are issued in today's ATC system.

Piloted aircraft simulators at Ames can "fly" in this ATC environment, which has been created by the ATCSF via transcontinental voice and data links. Aircraft identification, velocity, and heading were transmitted to NAFEC via the data link. Details of this communications link can be found in a separate NASA publication (Ref. 1).

Two flight simulators at Ames participated in the simulations. One simulator, the moving base transport cab, simulates a wide range of aircraft during takeoff, approach, cruise, landing, and taxiing. In the study, the cab was used as a fixed base, configured as a Convair (CV) 990. The CV-990, rather than a more commonly used turbofan aircraft, was simulated, because Ames had previously used the same type aircraft to conduct flight and simulation tests of the delayed-flap procedures. The second simulator, a general purpose simulator called the flight management research simulator, was also used. It can provide the controls, displays, and tasks of a large number of advanced avionics systems. This simulator was configured as a Boeing (B) 727. For the remainder of the paper, the piloted simulators are referred to as B-727 and CV-990.

For the other studies (delayed-flap and IATA approaches, 4D RNAV), a less elaborate ATC simulation facility at Ames was used. This facility was developed with the assistance of FAA to provide a versatile ATC research simulator for investigating the interaction between the ATC system and the advanced aircraft guidance systems. The facility consists of two alphanumeric displays (for up to four controller positions) and three keyboard pilot stations.

THE DELAYED-FLAP AND IATA APPROACHES EXPERIMENT

Flightpath Descriptions

The delayed-flap approach uses the conventional ILS glideslope, except, in contrast to a conventional approach, the delayed-flap approach begins with the aircraft in a clean configuration at a high initial

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airspeed (Ref. 2). An onboard digital computer determines the proper trimming for the deployment of the landing gear and flaps. Power is reduced to idle during the early part of the approach and at a predetermined altitude (about 500 ft) above the runway, approach power is added and a normal stabilized approach is flown from this point down.

Lufthansa Airlines developed a low-drag/low-power approach technique that is being considered for adaption by the International Air Transport Association (Ref. 3). This technique also comprises a decelerating approach technique. However, no onboard computer is used; rather, the pilot determines when to lower flaps and gears, and the aircraft is stabilized with full approach power at about a 1000-ft altitude. Figure 2 shows speed profiles vs distance to touchdown for typical delayed-flap, IATA, and conventional approaches. Note that the difference in speeds in these approaches occurs between 12 and 2 n. mi. from touchdown. The touchdown speeds are the same for a given aircraft type.

Description of Experiment

The delayed-flap and IATA experiment consisted of 32 runs, each of them 70 min in duration (4 runs per day). This simulation took place at Ames using the Ames ATC simulator, computer-generated aircraft, and two piloted simulators. The route structure was based on two routes at the John F. Kennedy International Airport (JFK). The route structure is shown in Fig. 3. The controller subjects were FAA research controllers from NAFEC; the pilot subjects were airline pilots affiliated with major airlines operating out of San Francisco and Oakland.

Experiment Variables

One variable was arrival rate in the terminal area. The delayed-flap flight experience shows that in light traffic, controllers had no difficulties accommodating the delayed-flap approaches. However, analysis and fast-time simulation studies indicated that difficulties might be encountered in handling a mix of approach types at, or near, ATC system capacity. Therefore, it was important to pinpoint the arrival rates that could be accommodated without excessive workload and without introducing additional aircraft delays. An arrival rate of 25 aircraft/hr was expected to be a moderate rate, while 35 aircraft/hr was expected to be near saturation. Additional data were taken at 30 aircraft/hr. It should be emphasized that the variable is arrival rate in the terminal area, not runway operations rate. For the 70-min duration of each experiment run, these can be considerably different.

The second variable was the mix of the approach types. The following approach mixes were examined: 50% conventional, 50% IATA; 50% conventional, 50% delayed flap; and 33% conventional, 33% IATA, 33% delayed flap. Random arrival sequences were generated for each of the mixes. (Randomness was introduced into order of arrival types as well as times of arrival at the feeder fixes.) Data were also taken for single approach types: 100% conventional, 100% IATA, and 100% delayed flap. These were used as baseline runs.

Controller Instructions

Two air traffic control positions were established. The approach controller handled all incoming traffic. Handoff to the final controller from Cassville (South approach route) occurred about halfway down the route; the Deerpark (North approach route) handoff was at the turn to the base leg.† The final controller used the base leg to provide the required spacing between aircraft.

Prior to taking data, the controllers were given the following instructions:

1. All aircraft must have an in-trail separation of at least 3 n. mi.

2. Aircraft on a missed approach were directed to proceed over the runway and then to the Deerpark route to merge with incoming traffic as soon as adequate spacing was available.

3. The delayed-flap and IATA approaches should generally be flown without altering the speed profile. Data next to the aircraft tag on the controller screen indicated the type of approach the aircraft wanted to fly.

On occasion, speeds could be reduced to establish spacing. Also, the approach controller was told to accept only as many aircraft as he could handle without requiring large path-stretching maneuvers. All other aircraft were to hold at the start points. Additional spacing could be obtained by this method, though at the expense of delays outside the terminal area.

RESULTS: DELAYED FLAP AND IATA

First, qualitative results, including observations and controller evaluations, are discussed followed by data on air space and fuel usage. Additional results are discussed in Ref. 4.

Observations and Controller Evaluations

Qualitative data were obtained from controller-written evaluations and by observing the controller activity during the course of the experiment.

Controllers had no trouble controlling air traffic when only one approach procedure was flown by all aircraft, even at the high arrival rate. If anything, the 100% delayed-flap case seemed easier, possibly because each aircraft was in the system for the least time (approximately 1 min less than a conventional approach). Next in ease of handling was the 50% conventional, 50% IATA mix; with only a 20-knot speed

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†Only 20% of the traffic was from Cassville. If there were a more even mix of traffic from Deerpark and Cassville, a second approach control position would have been required. Since the Ames ATC simulation facility was limited to one final and one approach control position, it was necessary to restrict traffic from Cassville.

difference between these two types, the controllers learned that they could essentially handle all aircraft as a single type. The most difficult mix was 50% conventional, 50% delayed flap.

Controllers felt that the arrival rate of 25 aircraft/hr caused little difficulty with any mix. In fact, aircraft arriving at a rate of 30 aircraft/hr could be handled without increased delay or excessive controller workload, even with the 50% conventional, 50% delayed-flap mix. Major difficulties were experienced with the heavy arrival rate of 35 aircraft/hr. Controllers felt that more concentration was required at 35 aircraft/hr and that it was more difficult to accommodate a diversion (i.e., the system was unforgiving of any error). At lower arrival rates, controllers might have to path stretch an aircraft or two, but the delays would eventually die out. However, no catchup time existed at the higher arrival rate. Thus, the number of delays increased, as a result of either holding at the feeder fix or increasing path stretching, and these delays persisted for the duration of the run.

Based on the above, it is no surprise that the combination of the most difficult mix (50% conventional, 50% delayed flap) and the high arrival rate (35 aircraft/hr) was the test condition that provided the highest workload for the controllers.

Airspace Used

Table 1 summarizes the envelope of airspace used, in (n. mi.)^2, for six different run conditions shown on the left of this table. The airspace envelope is the maximum excursion boundary obtained by plotting the x-y position of all aircraft in a given run. (The data presented are for the Deerpark approach only.) Columns of data are also presented showing the envelope of airspace usage normalized to the 25-aircraft/hr IATA approach case and the average hold time. The average hold time is the time spent holding prior to feeder fix departure.

Consider the data shown for conditions (e) and (f), both of which are for the 35-aircraft/hr arrival rate. Condition (f) shows an earlier run (in fact, the first run of 50% conventional, 50% delayed flap at 35 aircraft/hr). The average hold time was zero, but the airspace required was 445 n. mi.^{2}, almost double that required in condition (e). Note, however, that condition (e) has an average hold time of 4 min compared to no holding for condition (f). These differences reflect a difference in controller technique. In the earlier runs in the experiment, the controllers were reluctant to slow traffic; rather, they would take all traffic into the system and path stretch when delays were necessary.

Thus, operation at 35 aircraft/hr for the 50% conventional, 50% delayed-flap results either in additiona. holding time per aircraft at the start point or additional airspace to provide delays through path stretching. Conditions (a) through (d) represented arrival rates of 25 or 30 aircraft/hr. At these arrival rates, the airspace used was about half that used under condition (f) and little or no holding was required.

Comparison of Fuel Used

Table 2 examines the fuel used under different run conditions. The left side shows the additional delay per aircraft compared to the baseline average. The baseline runs used here were those in which all aircraft executed conventional approaches. These additional delays were translated into pounds of fuel based on the assumption that on the average, delays were accomplished at a 5000-ft altitude and a speed of 250 knots for each aircraft type. (The delay data presented include keyboard aircraft and both piloted simulators.) The fuel used to execute these delays was then subtracted from the fuel saved as a result of the fuel-conservative approaches,[5] giving the net fuel savings. The right side shows the net fuel savings per aircraft over the baseline. Negative numbers represent fuel loss.

Based on the table, the following conclusions are drawn:

1. Net fuel savings are feasible for any mix for arrival rates of 25 and 30 aircraft/hr.

2. At 35 aircraft/hr, fuel was lost for the following mixes: 50% conventional, 50% IATA; and 50% conventional, 50% delayed flap. The data also indicate a small fuel savings for the mix of 33% conventional, 33% delayed flap. As previously noted, controller comments and observations made during the course of the experiment indicate considerable difficulty with this mix at the high arrival rate. Thus, even though a modest fuel gain is indicated for this latter mix of traffic, operations for this condition would not be expeditious from a controller workload standpoint.

Given the limitations on the number of runs in a real-time simulation, other variables were not considered. For example, winds were not considered, nor were the separation regulations regarding light, large, and heavy aircraft. Also, as pointed out earlier, the traffic flow was primarily from Deerpark, rather than being evenly split from the two directions. One might speculate that the effect of including the above would be in the direction of increased delay and workload. However, additional studies are required before definitive conclusions can be drawn.

PROFILE DESCENT EXPERIMENT

Flightpath Description

Recent FAA studies have indicated the possibility of reducing fuel consumption by minimizing the amount of time high-performance aircraft operate at low altitudes in the terminal area. Besides saving fuel, other benefits of flying these so-called profile descents are: 1) increased safety by reducing exposure time between controlled and uncontrolled aircraft at lower altitudes in the vicinity of airports; 2) reduced aircraft noise in the vicinity of airports; and 3) standardized high-performance aircraft arrival procedures.

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[5] In this table, it was estimated that each IATA approach saved 250 lb of fuel compared with a conventional approach. The delayed-flap savings was 425 lb/flight. The estimate was based on simulated and actual flight tests.

As implemented in this study, arrival flights cruising at or above FL240 used a profile procedure. For a given cruise speed and altitude, descent began at a distance that allowed for a descent angle of 300 ft/mi. A typical descent profile, as flown by the B-727 simulator, is shown in Fig. 4. The profile descent procedure was patterned after those published by the FAA for Stapleton Airport, Denver, in 1976.

Description of Experiment

The NAFEC ATCSF laboratory provided the simulation environment, and two Ames Research Center piloted flight simulators participated together with the computer flights generated at NAFEC. The Denver Terminal ATC Facility was simulated and the Denver En Route Facility was simulated only in part as necessary to support the tests. The Denver Center positions handled the aircraft from entry to one of four corner posts: Keann, Bison, Drako or Kiowa (Fig. 5). Approach control handled aircraft from the corner posts to about 15 mi from the airport. The final controller picked up traffic from the approach controller and merged them into a single stream for landing on a single runway. Controllers issued clearances only as necessary for purposes of separation. All arrivals conformed with the Stapleton runway 26L ILS procedure, and it was assumed that weather conditions precluded the use of runway 26R.

Traffic Sample

The traffic sample was developed from an analysis of Denver traffic on a busy day. The traffic sample defined by this analysis resulted in an average landing rate of 35 aircraft/hr. About 25% of these flights were low-performance aircraft. Representative departure flights were programmed in accordance with the same parameters as the arrivals.

Main Variables

The main variable was the descent procedure. Either a profile descent or a conventional descent was flown. For the conventional descent, altitude change and speed control clearances were given by ATC in the usual manner. For the profile descent, altitude and speed profiles were specified on an approach plate as well as horizontal guidance information. Controllers monitored the progress of flights and gave alternate clearances only as necessary for ATC purposes.

In addition to the two descent procedures, two landing approach procedures were tested. In one case, all aircraft flew conventional approaches; in the other, delayed-flap and IATA approaches were flown. For the delayed-flap and IATA runs, half the aircraft flew delayed flap, and the other half flew IATA. Note that as a ground rule for this simulation, no aircraft cruising below FL 240 (approximately 25% of the sample) flew any fuel-conservative procedure. Thus, there was a mix of landing approach types as follows: 37.5% delayed flap, 37.5% IATA, 25% low performance. In this experiment the controllers were instructed to handle the delayed-flap and IATA approaches as they saw fit, that is, to alter the approach speed at their option.

These variables resulted in the four test conditions below:

1. Conventional descent, conventional approach (baseline)
2. Profile descent, conventional approach
3. Conventional descent, mix of landing approaches
4. Profile descent, mix of landing approaches

These conditions (hereafter referred to as conditions 1-4) were replicated eight times for a total of 32 runs.

RESULTS: PROFILE DESCENTS

Controller Workload

Controller workload is defined as the number of ATC control messages per run. These messages were of three types: radar vectors, speed changes, and altitude changes. As compared with the baseline (condition 1), controller workload reductions of 32.5, 17.8, and 37.4% were found for conditions 2, 3, and 4, respectively. As expected, the greatest reductions were found when the profile descent procedures were used, because the profile descent procedures provided the pilot with both horizontal and altitude guidance information.

However, the controllers expressed some difficulty with handling the profiles. Since it is ideally a hands-off procedure from cruise to about 1500 ft above ground level, the controller's last decision on spacing the aircraft had to be made at cruise. Since this is not the way the present ATC system operates and since no computer assistance was provided to controller or pilot, many profile descents had to be terminated to achieve better aircraft spacing. Thus, the final controller's workload in the profile procedure was not reduced as significantly as that of the center or arrival controllers.

Fuel Used

Table 3 summarizes the average fuel saved for an aircraft flying from approximately 150 n. mi. out to touchdown for each of the four test conditions previously noted. Each number presented is the fuel averaged over approximately 250 flights. The percent savings in fuel for test conditions 2, 3, and 4 compared to the baseline conditions are also shown. It can be seen that there was an 11.6% reduction in the amount of fuel consumed for the aircraft that flew the profile descent (condition 2). For aircraft flying conventional descents and a mix of landing approaches (condition 3), no fuel savings were evident.

For aircraft flying profile descents and a mix of landing approaches (condition 4), the percentage of fuel reduction was about 13%. However, statistical tests showed no significant difference in the fuel used between conditions 1 and 3, nor between 2 and 4. In essence, any fuel saved was entirely attributable to the profile descents, not to the delayed-flap or IATA procedures.

Several reasons account for the lack of significant systems fuel savings attributable to the delayed-flap and IATA approaches. First, a 70-knot difference in approach speed existed at 10 n. mi. from touchdown between an aircraft executing a delayed-flap approach and a low-performance aircraft. Thus, controllers found it necessary to path stretch the delayed-flap aircraft, and flight pattern distances were increased from 8 to 10 mi per aircraft. The additional fuel consumed because of the path stretching offset the fuel saved by the delayed-flap and IATA procedures. Second, fuel was not saved because landing rates were at or above 35 aircraft/hr. From the study reported in the first part of this paper, under conditions of high arrival rates and a mix of aircraft approaches with large speed differences, the controller workload would be excessive and the en route delays large if the controllers chose to accommodate the delayed-flap and IATA approaches. (Note, however, that controllers did permit the IATA approach aircraft, which were slower than the delayed-flap approach, to complete more approaches.) Only 67% of the aircraft requesting delayed-flap approaches were allowed to complete them, while 88% of the IATA approaches were completed. Thus, the test conditions in this experiment, that is, the difficult mix and high arrival rate, precluded effective use of the delayed-flap and IATA approaches.

4D RNAV EXPERIMENT

Use of four-dimensional area navigation (4D RNAV) concepts in high-density terminal areas are under consideration in an effort to increase the efficiency of terminal area operations of current and future short-haul systems. The purpose of this study was to examine airborne and ground interactions when operating short-haul aircraft in a 4D RNAV environment, obtain evaluations of system operation from both airline pilots and FAA controllers, and examine the effect of emergency and unusual stress situations on system operation.

System Operation

The advanced terminal area RNAV system used in this study operates as follows. In the 4D mode, based on knowledge of previously scheduled aircraft and on limited knowledge of those aircraft awaiting scheduling clearance, the controller issues a route and time clearance to a given aircraft. The pilot then enters these data into his onboard computer, which generates a time sequence of commands to descend and change heading or speed, thereby holding the aircraft on a specified route and to a specified delivery time. The 3D mode used was the 4D mode less any time specification. In 3D, a route assignment is required when the aircraft enters the controller sector and a speed clearance can be given. These clearances can be altered as the aircraft progresses along the route. Details of airborne and ground procedures developed for this study can be found in Ref. 5.

DESCRIPTION OF EXPERIMENT

Scenario

The New York Terminal area was selected as the geographical environment for these tests. An earlier STOL aircraft simulation study (Ref. 6), which had a similar need for conducting operations within a restricted airspace, used this airspace and a hypothetical STOL airport site (Morris Canal) on the west side of the Hudson River. This site and the geographical area, together with the attendant restriction on available airspace for maneuvering STOL aircraft, provided an ideal situation for testing 3D and 4D equipped aircraft within a multiairport, high-density terminal area. Procedures for traffic flows and for controlling the traffic at the three major airports, Newark, LaGuardia, and Kennedy, as well as Teterboro and White Plains, were almost identical to those used in this simulation. The procedures were modified only slightly to change the geographical dimension of the airspace available for STOL aircraft. The resulting procedures are not necessarily those that would be adopted in the New York area if the hypothetical STOLport and the RNAV-equipped, STOL traffic situation were to develop. However, the procedural design is workable and reasonable in all respects. Figure 6 depicts the STOLport route system and how it is confined by Newark and LaGuardia procedures. Note that, because of these other routes, the STOLport routes are confined strictly to the routes shown at the altitudes specified.

Route Structure

The STOLport route structure (shown in detail in Fig. 7) consists of four parallel routes from the north (denoted Carmel 1, 2, 3, and 4) and one route from the south (denoted Robbin). The north and south routes merge and proceed to a single runway. Note that two independent altitudes, 5000 and 6000 ft, are available on both Carmel 1 and 2 for about half the route length. Thus, a faster aircraft can overtake a slower one on the same route so long as proper altitude separation is maintained. The single southern route carried only 20% of the traffic and was included so that the problem of traffic merging from opposite directions could be investigated. Standard 1-min racetrack holding patterns could be executed at five waypoints (including two altitudes at one of the holding points on C1) within the control sector. A missed approach procedure was used in which traffic was directed out and to the left of the runway and then returned via the Robbin route.

Aircraft Types

This route structure was designed to handle three types of STOL aircraft (Twin Otter, Buffalo, Advanced Jet STOL) with arrival speeds of between 155 and 250 knots. At the merge points, the speed of the aircraft must be down to 96, 120, or 140 knots, depending on the type. The final approach speed at the outer marker varied between 70 to 90 knots, depending on the particular aircraft. As previously noted, the lengths of route used and the route structure permitted aircraft to pass.

Traffic Sample and Wind Model

Time control was limited to a single point, the merge point of the north and south routes. Aircraft arrived at one of the two feeder fixes every 2 min (uniformly distributed with a deviation of ±30 sec).

Aircraft were scheduled to pass through the merge no closer than 2 min apart, which corresponds to a separation of more than 3 mi for the slowest pair of aircraft. In addition, 10% of the aircraft executed missed approaches. Thus, although the system was initially empty, a heavy traffic situation soon prevailed. As in the present system, controllers were instructed to accept as many arrivals as they could reasonably handle. They could halt the arrival flow (which has the effect of having aircraft hold outside the control sector) whenever they felt they could not handle additional traffic and then resume flow when traffic subsided.

A wind profile was used in which wind magnitude and direction varied with altitude; it was based on a wind study for the STOLport site chosen.

Experiment Design

The experiment consisted of 24 runs, each of which was 75 min in duration. Data collected included voice tapes of all conversations during the runs as well as data tapes of key variables measured for each aircraft. Pilot and controller evaluations were collected after each run, and a summary evaluation was obtained at the completion of the study.

The experiment used the ATC simulation at Ames as well as one piloted simulator.

RESULTS: 4D RNAV

Results on capacity, communications, and orderliness are presented first, followed by a discussion of the evaluations of the controller and pilot. Additional results can be found in Ref. 5.

Capacity

Table 4 presents the following traffic flow data: 1) the time that the traffic was held at the feeder fix,[¶] 2) the maximum number of aircraft in the sector, and 3) the landing rate per hour. These data are compared for all 3D and 4D runs. Traffic was halted in the 4D mode an average of 721 sec (out of a 4500-sec run), compared with an average of 1500 sec in the 3D mode. Thus, it was necessary to halt flow in the 4D mode for only half as much time as in the 3D mode. In addition, in a given run in the 4D mode, controllers generally handled 25% more aircraft at one time and had a landing rate 25% higher than in the 3D mode.

Note that in some ways, these data are conservative since it is possible to further increase 4D capacity by making the time separation at the merge dependent on the speed capacity of consecutive aircraft. In this experiment, a 2-min separation was always used, which yielded a separation greater than 3 mi for even the slowest pair of aircraft. Clearly, for consecutive faster aircraft, a smaller time separation could be used, which would still result in a minimum distance separation of 3 mi. Hence, a significant increase in capacity should result from 4D operation.

Communications

In this experiment, controller and pilot communicated only by voice; the potential benefit of data-link developments was not considered. The simulator and keyboard pilots acknowledged clearances as in the present system and notified the controller via voice if compliance was not possible. Thus, the results discussed below can be regarded as an upper bound on the verbal communications requirements 4D would impose.

Table 5 shows communication data obtained from four representative runs (a 4D and 3D run from each of two controllers). The number of clearances issued in the 4D mode was about half the clearances issued in the 3D mode, even though there was considerably more traffic in the 4D operation. In fact, two to three times as many clearances per aircraft were issued in the 3D mode. The primary reason was that, although each aircraft in the 3D mode was given a route and speed assignment as it entered the control sector, only after the aircraft was halfway down the track could the controller visualize the exact slot the aircraft would occupy in the landing sequence. At this time, a second set of instructions involving a speed change, a route alteration, or both was given to the aircraft. In contrast, the aircraft in the 4D mode was issued a route and merge time assignment as it entered the sector and this instruction was usually sufficient to guide the aircraft through the terminal area. Note that clearances in the 4D mode tended to take longer but there were fewer of them. The average communication time per aircraft was considerably smaller than in the 3D mode. The last two items in Table 5 show that many aircraft in the 3D mode received additional clearances beyond those already discussed in the 3D mode. The number of times more than three clearances were issued to an aircraft was seven and eight, respectively, for the two controllers, while zero and two were the numbers for the 4D mode. The maximum number of clearances issued to a single aircraft during the 3D run was 10 and 12, respectively, and was much lower in the 4D case. Extra clearances were necessary for aircraft executing missed approaches.

Orderliness

The orderliness of traffic in the two modes was strikingly different. Figures 8 and 9 show composite trajectories of two 4D runs and two 3D runs, respectively. The numbers next to each standard route refer to the total number of times the route was flown during the two runs. The ground track composite for the 4D runs shown are actual routes flown, but deviations between flights along the same route and between actual and reference routes are too small to be shown. Note further that for the 4D runs shown (Fig. 8), there was no path stretching or path shortening of routes by any aircraft except for path stretching needed to meet revised merge times during missed approaches. As mentioned in the discussion of communications, in the 4D mode, the route assigned near the feeder fix was rarely altered. By contrast, it is evident from the 3D composite (Fig. 9) that frequent alterations to original clearances were required. Note also the large number of missed approaches in the 3D mode. In both modes, 10% of the aircraft were selected for missed approaches. In addition, in the 3D mode, the controllers found it difficult to establish proper

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[¶] Since the arrival rate equalled the maximum landing rate and since some of the aircraft executed missed approaches, it was necessary for the controller to halt the arrival flow at some time in every run.

separation at the merge when a slow aircraft was followed by a faster one. Since there is no room for path stretching in the merge area, additional missed approaches were commanded. Four additional missed approaches were required in the 3D mode, bringing the missed approaches to 15% for these runs.

The difference in orderliness between 3D and 4D modes is also evident in the distribution of time increments between consecutive aircraft at the merge. Figure 10 shows the distribution of these incremental times — called "interarrival" times. For the 4D case, 95% of the aircraft interarrival times at the merge were between 1:45 and 2:15 (an interval of only 30 sec), with a mean interarrival time of 2:07. In the 3D case, 95% of the interarrival times were in the 4-min interval 1:15 to 5:15, with a mean interarrival time of 2:51.

The 4D mode was also more orderly in handling merging traffic flows from the north and south. In fact, merging traffic from opposite directions was no problem for the 4D system, but caused considerable difficulty in the 3D mode.

Controller Evaluations

The aim of this experiment was to evaluate one set of procedures and displays for both the 4D and 3D RNAV system. Time limitations did not allow iteration of procedures and displays to determine an optimum set. In fact, because of display limitations at the controller station, it was necessary to use display formats known to be nonoptimum. However, the controller did not feel that the display limitations affected the results significantly.

The controller subjects agreed that 4D when compared with 3D was more expeditious and orderly. They believed that more traffic could be accommodated in the 4D mode, a conclusion verified by the objective data. Also, in agreement with the objective data were the controller opinions that handling traffic from opposite directions and from different speed classes was greatly simplified in the 4D mode. Hence, controllers felt that 4D increased safety at a given traffic level.

However, in the 4D case, there were generally more aircraft in the control sector at a given time. This increase gave some concern to the controllers, probably because they knew that in an emergency situation more aircraft would require immediate processing. Some computer algorithms to aid in resolving this problem would be required before the controller would feel comfortable with such a large number of aircraft in his sector.

The controller subjects disagreed with regard to stressfulness, frustration, and workload. One subject felt that the major tasks of ordering and creating slots for aircraft was considerably simplified in the 4D mode, and so the workload as well as the stress and frustration of the task was reduced. Another subject disagreed — he felt that he could place an aircraft where he wanted to and when he wanted to with radar vectors and that the waypoint structure used in both 3D RNAV and 4D RNAV was too cumbersome.

With regard to workload, one subject believed that in the 4D mode as simulated, too much time was spent observing the flight data table and making hand calculations on time assignments than in monitoring the situation display. He believed it would be extremely helpful if the ground computer could provide him with a suggested conflict-free merge time for each aircraft entering his sector. Both subjects did agree that such computer assists would be necessary in scenarios with more than one time control point per sector or where the minimum time separation between aircraft was a function of speed capability.

Pilot Evaluations

The pilot subjects believed that 4D and its associated horizontal map display improved their geographic orientation and decreased workload, but they had no clear reaction with regard to safety. From one viewpoint, safety was improved because there seemed to be less chance of human error in scheduling aircraft. However, because of the limited number of clearances issued in the 4D mode, there seemed to be less awareness of surrounding traffic. One pilot suggested that surrounding traffic be presented on the horizontal map display.

Pilots ultimately disagreed on whether 4D would decrease delays or whether it should be implemented. One subject, who objected to implementing 4D, had the opinion that workload in today's system is not unreasonable and that RNAV makes a human virtually unnecessary. Other pilots who participated in the experiment and others who had participated in simulation and flight tests of the onboard system felt that the workload should be decreased, and that this was desirable.

This completes the discussion of results for the 4D RNAV study. The experiment just described had two major limitations. First, no mix of 4D equipped and unequipped was considered. The experiment investigated a 4D mode of operation in which <u>all</u> aircraft are 4D equipped and compared it to a 3D mode in which all aircraft are 3D equipped. The reason for this was that no operational procedures for 4D RNAV had been tested, and it was decided to first check out the procedure in the simplest mode, that is, when all aircraft are 4D equipped. A second major limitation was that all aircraft were scheduled at least 2 min apart, regardless of relative speed class. The reason this was used was that the controllers were generating the assigned times manually, and a more complex time assignment scheme (such as one based on relative aircraft speed) would have resulted in considerable workload.

The next 4D RNAV simulations should address both of these limitations. One of the main variables should be the mix of 4D equipped and unequipped aircraft. Procedures are being developed to mix unequipped aircraft into a stream of 4D equipped aircraft. Clearly, one important constraint here is to limit the number of clearances to the unequipped aircraft so that the workload for this class is not excessive. In addition, the ground control system must provide some guidance to the controller in issuing clearances to the unequipped.

An efficient algorithm for time scheduling of aircraft is being incorporated into the simulation (Ref. 7). This algorithm utilizes a sequencing methodology termed constrained position shifting (CPS).

CPS improves system performance through local resequencing of the first-come, first-serve order with respect to arrival at the runway. The algorithm as implemented will be interactive; that is, it will present a candidate scheduling and ordering of aircraft to the controller who will either accept it, or ask for an alternate schedule, and/or provide additional constraints to be incorporated.

CONCLUSIONS

Two general conclusions concerning the development of advanced operational procedures are in order. First, a mix of equipped aircraft for the candidate operational procedure and unequipped aircraft is more difficult to implement than when all aircraft are equipped to handle the new procedure. In the case of the delayed-flap and IATA experiment, the difference in speeds between aircraft flying conventional and fuel-conservative approaches was the primary source of controller difficulty. The procedures caused no controller problems when all aircraft were executing the same type of approach. Similarly, in the profile descent experiment, controllers encountered difficulty with merging aircraft flying the profiles with those flying low-speed approaches. For the 4D RNAV case, difficulties arise, not because of speed differences, but because 4D equipped aircraft respond to time clearances while other aircraft need speed vectors. Mixing speed and time clearance while attaining some of the potential capacity improvements with a pure 4D system is an important problem.

Second, as the demand for airport capacity increases and the need grows for decreased fuel usage per aircraft, new operational procedures are considered that require more exacting decisions from both the pilot and the controller. To implement these procedures effectively airborne and ground computers seem to be required. For the delayed-flap aircraft an onboard computer effectively assisted the pilot in executing a precisely timed deceleration and flap extension schedule. Analogously, precise spacing of aircraft when there is a mix of approach types could be simplified with computer assists. This is especially important as the separation distance requirements change due to various factors such as wind, light, and large and heavy aircraft landing on the same runway. Ground computers could assist in controller handling of profile descents; they could be used to assist in establishing minimum spacing between aircraft. Finally, in the 4D RNAV study an onboard computer generated the 4D flightpath, directing the aircraft along the desired route and meeting the specified time. The controller could have benefited from computer assists to establish a feasible, nonconflicting time schedule; otherwise, 4D will merely switch controller thinking from distance separation to time separation without increasing capacity.

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TABLE 1. TERMINAL AREA AIRSPACE USAGE[a]

Arrival rate		Mix	Airspace used, (n. mi.)^2	Normalized airspace	Average hold time per aircraft, min
(a)	25	Baseline (100% IATA)	242	1.00	0.0
(b)	35	Baseline (100 % IATA)	252	1.04	0.3
(c)	25	50% Conventional 50% Delayed flap	189	0.78	0.0
(d)	30	50% Conventional 50% Delayed flap	240	0.99	0.0
(e)	35	50% Conventional 50% Delayed flap	240	0.99	4.0
(f)	35	50% Conventional[b] 50% Delayed flap	445	1.85	0.0

[a] Data shown are for last data run under this arrival rate and mix.

[b] Data shown in this row only are for first data run under this arrival rate and mix.

TABLE 2. COMPARISON OF FUEL USED

	Extra delay per A/C (min:sec) over 100% conventional			Net fuel savings per aircraft over 100% conventional (lb of fuel)		
Mix	25 aircraft/hr	30 aircraft/hr	35 aircraft/hr	25 aircraft/hr	30 aircraft/hr	35 aircraft/hr
50% Conventional 50% IATA	00:00	no data	01:30	125	—	-84
50% Conventional 50% Delayed flap	00:00	00:09	01:58	213	186	-142
33% Conventional 33% IATA 33% Delayed flap	00:34	00:00	00:58	134	224	70

TABLE 3. FUEL USED FROM APPROXIMATELY 150 n. mi. TO TOUCHDOWN

	Run conditions	Fuel (lb)	% savings (with respect to baseline)
(1)	Conventional descent, conventional approach (baseline)	3325	—
(2)	Profile descent, conventional approach	2936	11.6
(3)	Conventional descent, mix of landing approaches	3388	-2.0
(4)	Profile descent, mix of landing approaches	2891	13.1

TABLE 4. TRAFFIC FLOW DATA

	4D	3D	Ratio 4D/3D
Total time traffic flow halted (sec)	721	1500	0.481
Maximum number of aircraft in the sector at one time	9.1	7.4	1.27
Landing rate (aircraft/hr)	24.2	19.1	1.27

TABLE 5. REPRESENTATIVE COMMUNICATIONS DATA

	Controller A		Controller B	
	4D	3D	4D	3D
Number of clearances issued	40	81	53	81
Average communications time/clearance	5.4	3.6	7.6	4.8
Average communications time/aircraft	6.4	12.6	11.9	15.5
Clearances/aircraft	1.2	3.4	1.6	3.2
More than three clearances	0	7	2	8
Maximum number of clearances	3	10	4	12

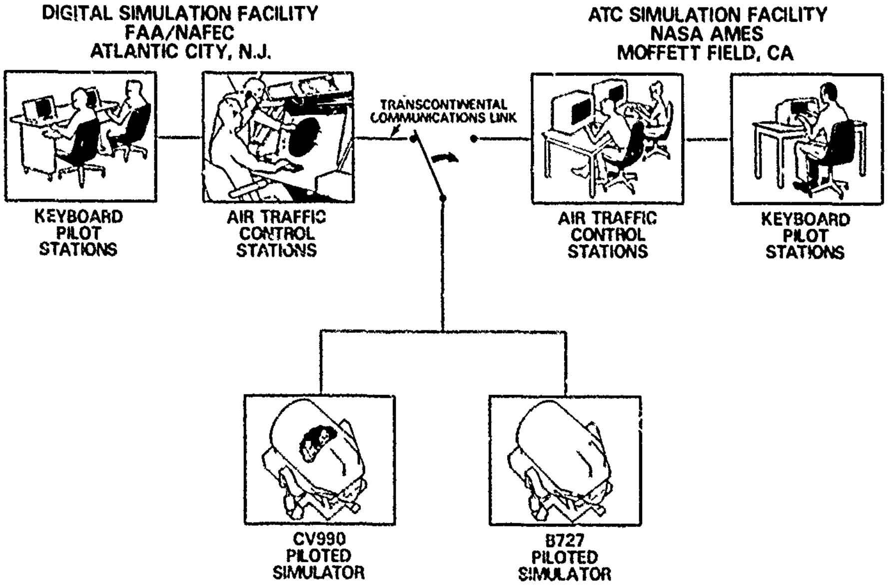

Fig. 1. Joint FAA-NAFEC/NASA Ames Simulation Facility.

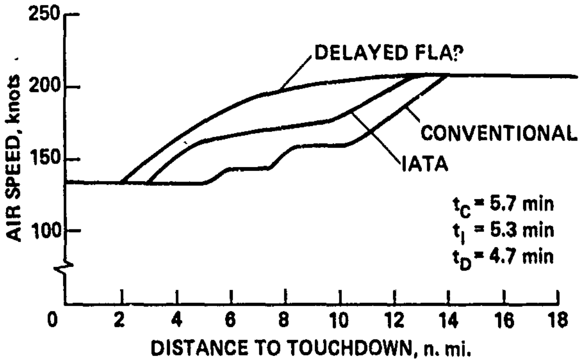

Fig. 2. Speed profile for conventional, IATA, and delayed-flap approaches.

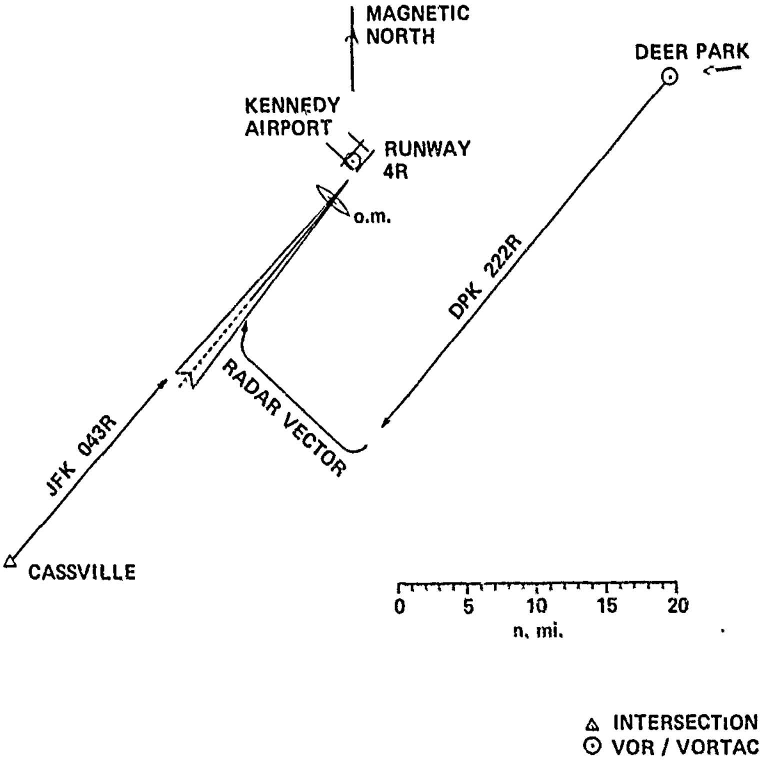

Fig. 3. Route structure for delayed-flap and IATA approaches experiment.

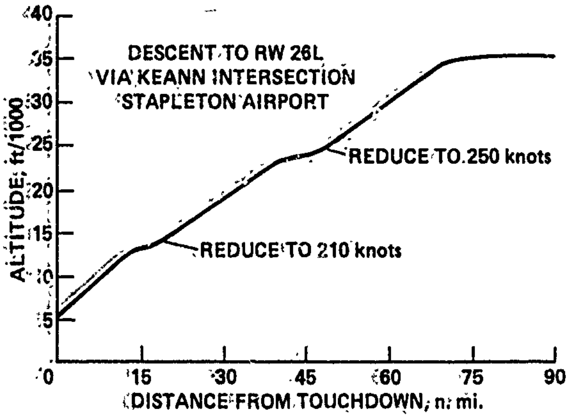

Fig. 4. Profile descent flown by B-727 simulator.

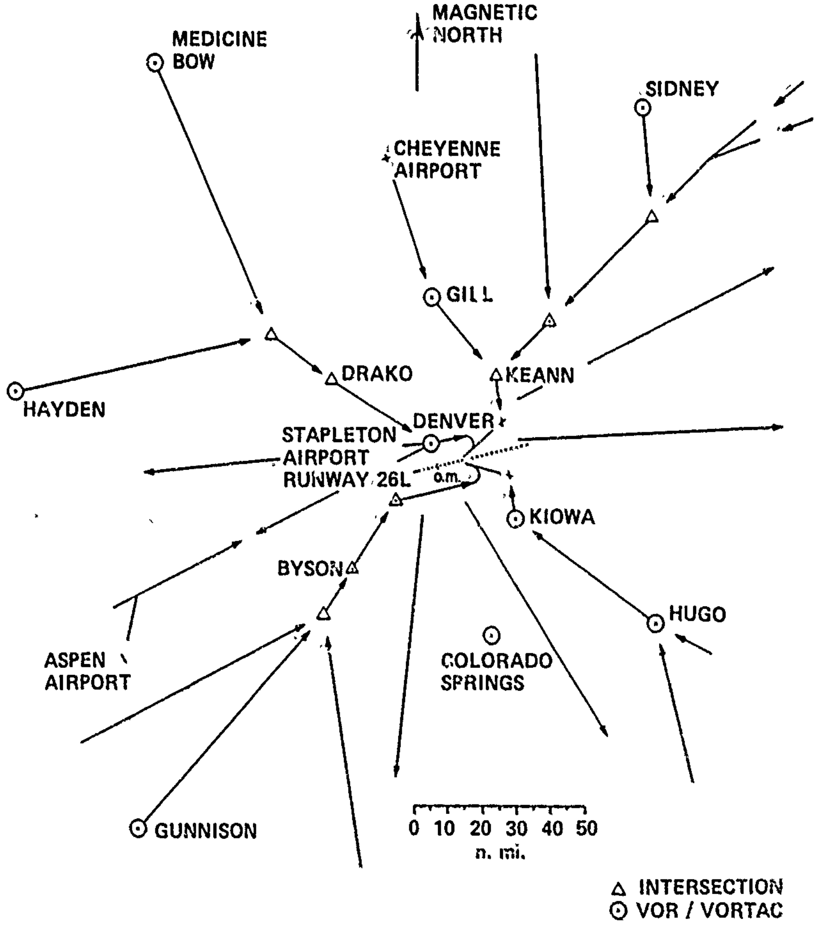

Fig. 5. Route structure for the profile descent experiment.

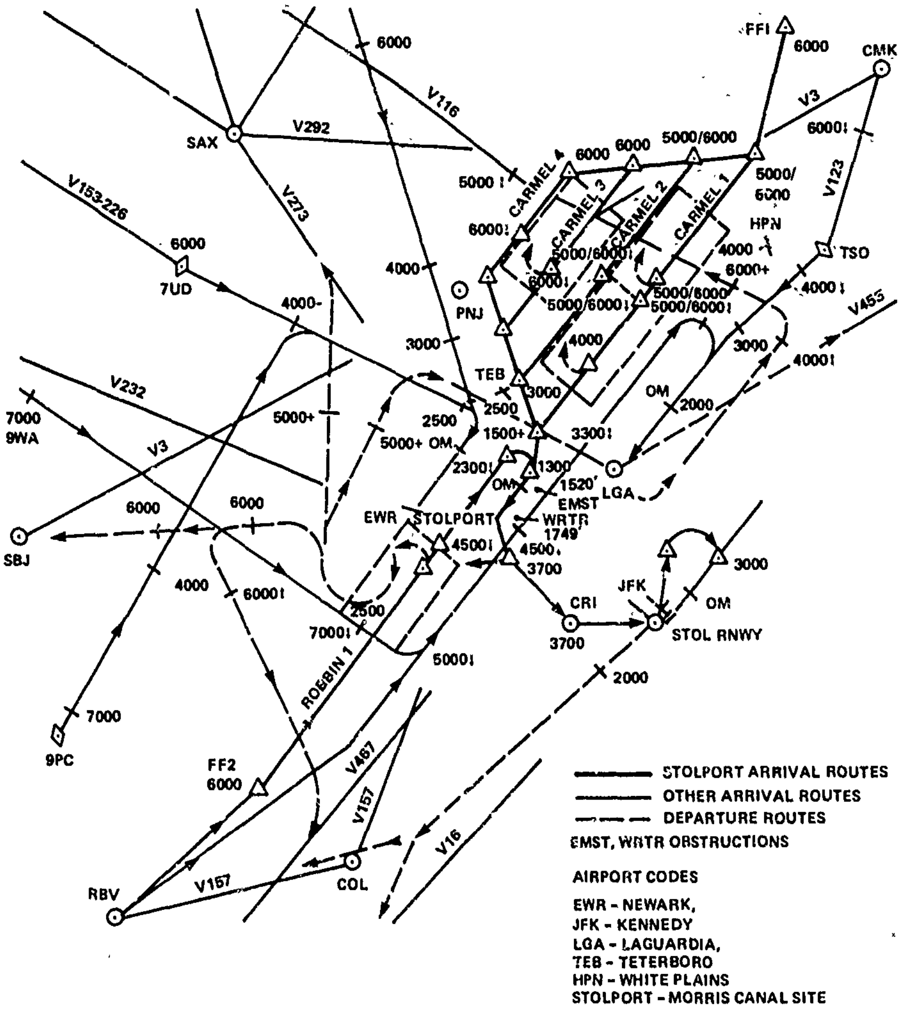

Fig. 6. STOLport routes with selected Newark, LaGuardia, and Kennedy routes.

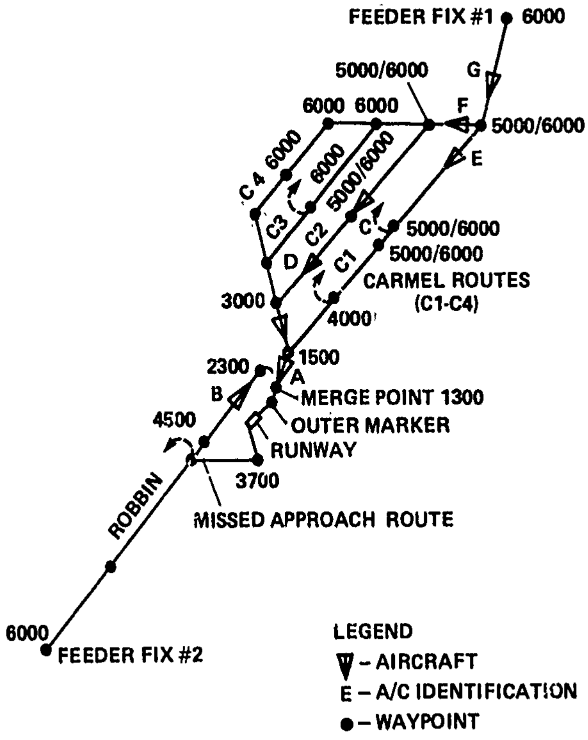

Fig. 7. Route structure for the 4D RNAV experiment.

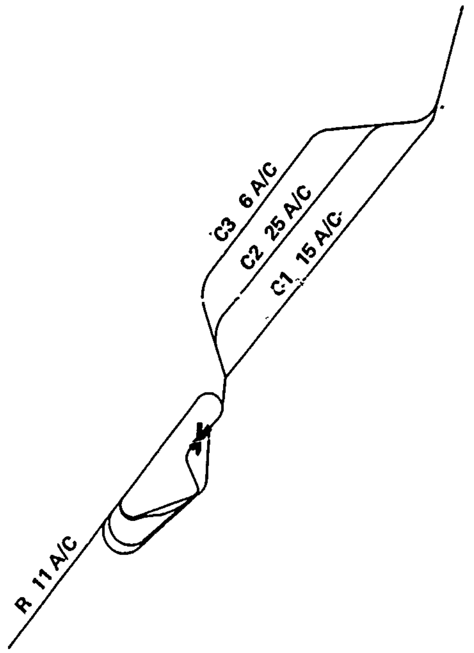

Fig. 8. Ground track composite, two 4D runs.

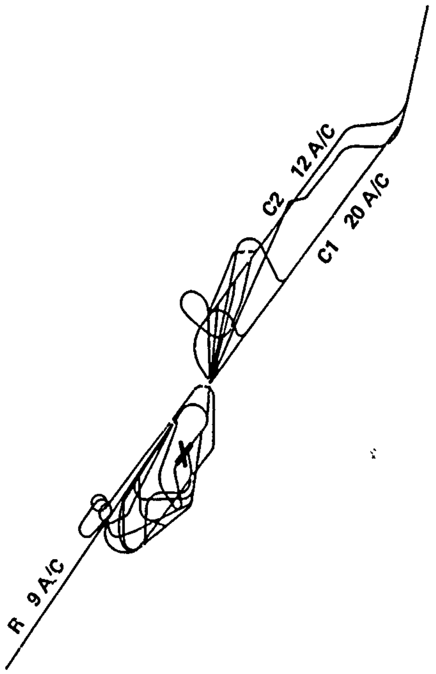

Fig. 9. Ground track composite, two 3D runs.

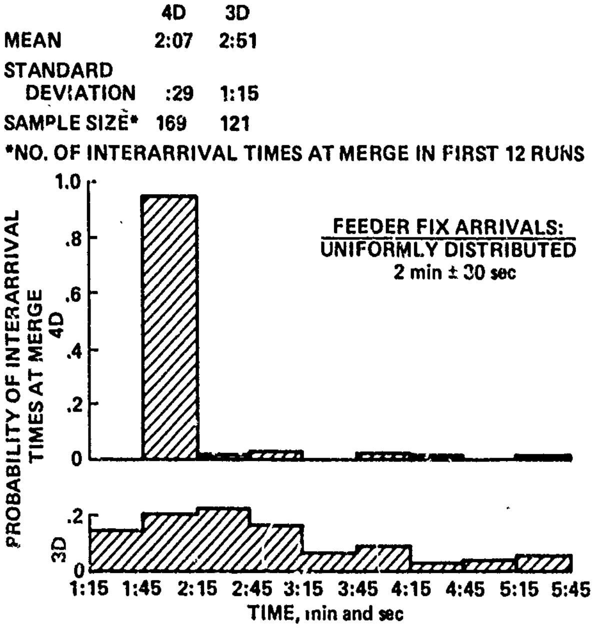

Fig. 10. Distribution of interarrival times.

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- Aspects of air-traffic management philosophy
  - Criteria and human factors
  - Communications and separation
- Air traffic management in hostile environment
- Flight management in terminal area
- Subsystem technology
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