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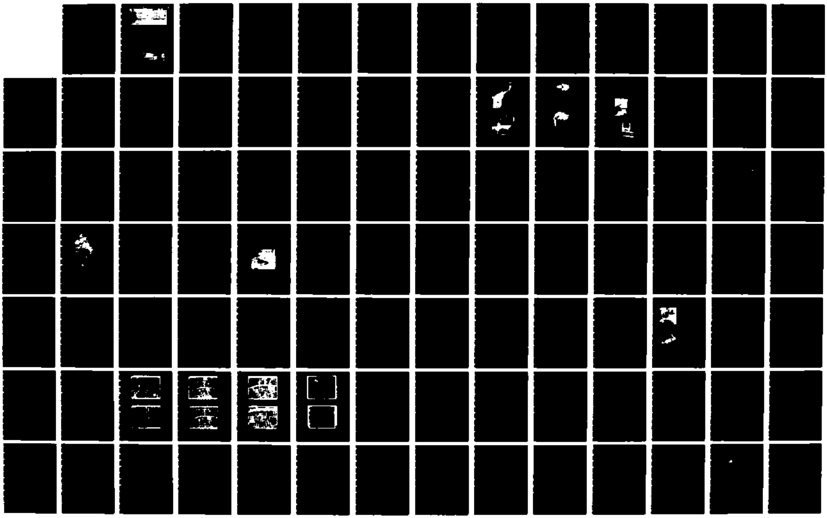

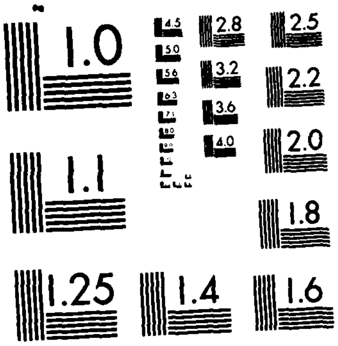

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Guidance — Control — Navigation Automation for Night All-Weather Tactical Operations

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PREFACE

The need to achieve night all-weather operation of tactical air forces in the face of increasing lethal threats is becoming critical and suggests a requirement for increased automation in order to reduce pilot workload and improve performance under such adverse operational conditions. Recent studies and recent experience in the tactical fleet suggest an approach to this problem in which an integrated and automated guidance — control navigation — display system would become a core structure around which further automation could be developed as required.

For night all-weather operations, such a core structure might include aided flight path control through generation and display of optional trajectories, generation of imagery for synthetic visibility, and display of both expected and unexpected threats in addition to automation of the functions of accurate positioning, precision tracking and automatic terrain following and avoidance. The techniques described in recent symposia on technical integration and on microprocessor applications to guidance and control, together with continuing rapid developments of technology in integration of multifunctional sensors, computer architecture, microprocessor and data distribution systems, will permit many different approaches to automated core structure. The purpose of the symposium was to explore the design characteristics and trade-offs involved in the components, the functions and systems integration required to support the evolution and development of alternative core structures which are capable of enabling effective and routine night all-weather operations.

PREFACE

Il devient actuellement essentiel pour les forces aériennes tactiques, face aux menaces mortelles croissantes, de pouvoir effectuer des operations de nuit et tout temps; il semble donc nécessaire d'accroître l'automatisation afin de reduire la charge de travail du pilote et d'améliorer les performances dans ces conditions opérationnelles défavorables. De récentes études ainsi que l'experience accumulées ces temps derniers par la flotte tactique semblent indiquer que, pour resoudre ce probleme, on doit faire appel à un système de guidage, de pilotage, de navigation et d'affichage intégré et automatisé qui deviendrait une structure centrale autour de laquelle on pourrait développer une automatisation additionelle selon les besoins.

Pour les operations tout temps et de nuit, cette structure centrale pourrait inclure un contrôle assisté de la trajectoire de vol grâce a l'elaboration et à l'affichage de diverses trajectoires possibles, un système générateur d'images pour visibilité synthetique, et l'affichage des menaces prévues ou non, qui s'ajouteraient à l'automatisation des fonctions de positionnement exact, de poursuite precise et de suivi de terrain et d'évitement d'obstacles. Les techniques exposées au cours des symposia recents sur l'intégration technique et sur les applications du microprocesseur au guidage et au pilotage, ainsi que les developpements technologiques rapides et continus qui caractérisent l'integration des capteurs multifonctions, l'architecture des ordinateurs, les systemes de microprocesseurs et de diffusion de données, permettront d'aborder le principe de la structure centrale automatisee de bien des façons differentes. Le symposium a eu pour but d'explorer les caractéristiques et les compromis relatifs aux composants, ainsi que l'intégration des systèmes et des fonctions requise par l'évolution et le developpement d'un choix de structures centrales qui permettraient d'effectuer des opérations de routine tout temps et de nuit

GUIDANCE AND CONTROL PANEL

Chairman: Prof. Dr Ing.R.C.Onken
Universität der Bundeswehr München
Inst. für Systemdynamik und Flugmechanik
Werner-Heisenberg-Weg 39
D-8014 Neubiberg
Federal Republic of Germany

Deputy Chairman: Mr Kenneth A.Peebles
Director, Research and Development
Communications and Space R & D Branch
National Defence Headquarters
101 Colonel By Drive
Ottawa, Ontario K1A 0K2, Canada

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	Mr J.C.Mabberley (FMP)	UK
	Mr J.K.Ramage	US

PANEL EXECUTIVE

Lt Colonel P.Carré, FAF
AGARD-NATO
7 rue Ancelle
92200 Neuilly-sur-Seine
France

HOST NATION COORDINATOR

Lt Commander E.J.H.Bleeker (Rtd)
National Aerospace Laboratory (NLR)
Delft, The Netherlands

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Chairman: Mr J.K.Fellows, UK

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ASPECTS TECHNIQUES ET OPERATIONNELS

DES SYSTEMES AVIONIQUES MODERNES

S. CROCE-SPINELLI
Avions Marcel Dassault - Bréguet Aviation
92214 SAINT CLOUD BP 300

RESUME

Les missions par mauvaise visibilité nécessitent d'utiliser des senseurs adéquats, mais aussi de résoudre le problème aigu de charge de travail de l'équipage. On doit décharger l'équipage dans les tâches d'exploitation des senseurs et dans les tâches d'exécution, mais on doit aussi l'assister dans son rôle essentiel de décision et d'adaptation rapides aux conditions opérationnelles qui évoluent. Ces considérations doivent orienter l'architecture et l'intégration de nos systèmes à partir des possibilités technologiques modernes.

1 - INTRODUCTION

Un petit nombre seulement des missions confiées aux avions d'armes peut être effectué dans l'état actuel des techniques, de nuit ou par tout temps. Il est certain que l'extension des possibilités aux conditions où la visibilité fait défaut permettrait une augmentation considérable des capacités opérationnelles des forces aériennes.

Il est évident que le problème est de remplacer la vue de l'équipage partout où elle est l'instrument pour trouver l'objectif : acquisition directe ou indirecte (via des recalages de position), navigation vers la cible, etc. Un problème complémentaire, y compris dans certaines missions où la capacité tout temps existe déjà, comme l'interception air-air ou le tir missile air-mer, est de permettre le vol à proximité du sol ou de la mer ; ceci nécessite des moyens de même nature que pour l'acquisition d'objectif, mais correspond à des durées d'utilisation beaucoup plus longues encore.

Il va donc s'agir d'abord de trouver des "senseurs" adéquats.

Mais il ne faut pas perdre de vue que la performance globale d'un système d'arme réside non seulement dans les performances techniques d'équipements, mais aussi dans l'aptitude à l'emploi par l'équipage. En effet, nous parlons ici de systèmes pilotés où l'opérateur humain est "dans la boucle".

Si l'automatisation semble être, comme l'indique le titre même de ce symposium, une clé aux problèmes, il est toutefois nécessaire de préciser son rôle. Il ne peut être question pour nous d'imaginer qu'elle permette de se substituer à l'homme, bien au contraire ; elle doit l'assister dans sa tâche de décideur où son cerveau reste de façon evidente la machine la plus puissante et la plus adaptative qui soit.

C'est de ce point de vue que nous souhaitons placer cet exposé, en tant qu'intégrateur de systèmes. On peut d'ailleurs dire que les architectures matérielles et logicielles de nos systèmes sont dictées autant sinon plus par les rôles de l'équipage que par les aspects techniques purs.

Les considérations qui suivent s'articulent donc avant tout autour de la charge de travail du pilote et de son impact sur l'efficacité opérationnelle globale. Les capacités de travail de nuit ou par mauvais temps rendent particulièrement aiguë cette charge.

2 - POSSIBILITES TECHNIQUES DES SYSTEMES MODERNES

De quoi disposons-nous pour construire nos systèmes ? Sans entrer dans les détails, que nous laisserons aux spécialistes, dressons la liste des principaux éléments qui nous intéressent.

2.1 - Les senseurs

- Les senseurs inertiels. Les techniques se diversifient (centrales à plateforme ou à composants liés, gyromètres laser ou à bille, etc.) et les performances s'améliorent. Ces senseurs fournissent un paramètre essentiel pour les conduites de tir, mais aussi pour le pilotage : le vecteur vitesse.

- Les radars voient également leurs performances et leur technologie évoluer. Les possibilites actuelles apportent en particulier une diversification des modes de fonctionnement dans un même radar (formes d'ondes, traitements associés, modes de balayage, balayage électronique,...) permettant une adaptation plus fine aux multiples conditions opérationnelles.

- Des senseurs nouveaux apparaissent ou se développent dans le domaine électro-optique : le LIDAR, actif comme le radar mais fonctionnant dans le domaine infrarouge, permettant une grande résolution ; les FLIR, passifs, avec de grands champs fixes par rapport à l'avion (présentables en tête haute) ou de petits champs gyrostabilisés et orientables ; les caméras télévision conventionnelles ou télevision bas niveau de lumière (LLTV) ; les détecteurs de points chauds ou de taches laser, etc.

- Les systèmes de radiolocalisation : NAVSTAR, ILS, MLS... ou fonctions de localisation des systèmes de transmission de données (JTIDS, SINTAC) ; ils nécessitent une "infrastructure" externe.

- Les détecteurs de menace fonctionnant le plus souvent dans les bandes radar, mais pouvant s'étendre au domaine laser. On peut mettre dans cette catégorie les détecteurs de missiles. Ces dispositifs sont intégres dans des ensembles d'autoprotection (brouillage, leurrage) aussi automatisés que possible.

- On pourra associer à ces senseurs directs des sources fournissant des données indirectement sur le monde extérieur : les sytèmes de transmission de données qui deviennent multilatérales, résistantes aux contre-mesures et discrètes (JTIDS, SINTAC) et qui peuvent avoir des fonctions de radiolocalisation, et les mémoires de masse qui peuvent stocker à bord des données préparées avant la mission.

2.2 - Les dispositifs de visualisation et de commande

- Les visualisations collimatées tête haute voient leur champ s'accroître (optique holographique). Elles sont maintenant capables de présenter des tracés en mode cavalier, mais aussi des images de type *télévision*, utilisables de nuit (faible luminosité).

- Les visualisations cathodiques de planche de bord, éventuellement collimatées (ce qui apporte une solution de protection aux forts éclairements du soleil et évite l'accomodation lors de transitions tête haute-tête basse). Ces visualisations sont capables de tracés cavaliers et de trames (type télévision). Elles peuvent utiliser la couleur, dimension supplémentaire aidant à résoudre les problèmes de charge de travail. Elles peuvent être complétées et éventuellement remplacées par des écrans plats.

- A ces visualisations sont associées des générateurs d'images numériques permettant une grande variété de présentations et de symboles.

- Le multiplexage des commandes se généralise et on explore le parti à tirer des commandes et synthèses vocales.

2.3 - Les commandes de vol

Elles sont entièrement électriques et utilisent les capteurs et boucles nécessaires pour assurer la trajectoire demandée de la façon la plus indépendante possible des conditions extérieures. Elles assurent automatiquement les limitations nécessaires à l'aérodynamique, à la résistance structurale, etc., et ceci dans les différentes configurations d'emport de charges. Elles sont sûres, assurant à la fois une détection automatique des pannes et une reconfiguration automatique après panne, avec une redondance élevée permettant de résister à de nombreuses pannes, et ceci avec des temps de réaction extrêmement réduits.

Le moteur est maintenant considéré comme une commande de vol comme une autre.

2.4 - Les moyens de calcul et de liaison

La capacité des calculateurs augmente rapidement. Les systèmes actuels comportent déjà plusieurs calculateurs dont les unités de traitement effectuent plus de 300 Kopérations par seconde ; sont disponibles maintenant des unités de traitement de 700 Kopérations par seconde et même 4.000 K (VHSIC).

Les capacités mémoire augmentent encore plus rapidement et régulièrement. On dispose de mémoires de masse de plusieurs Mégabits.

L'utilisation des bus numériques (GINA, 1553 B) se généralise. Leur débit de 1 Mbit/seconde aujourd'hui sera multiplié par 10 ou plus dans la prochaine décennie, rythme déjà atteint pour des liaisons spécialisées point à point.

3 - TACHES A LA CHARGE DU PILOTE

Pour le besoin de l'exposé, on peut distinguer les tâches suivantes :

- établissement de la situation,
- évaluation de la situation,
- prise de décision,
- réalisation de la trajectoire-pilotage,
- mise en oeuvre des armes ou autres dispositifs de mission (matériels de reconnaissance, de brouillage offensif,...).

3.1 - Etablissement de la situation

C'est essentiellement la mise en oeuvre des senseurs pour recueillir les informations nécessaires sur le monde extérieur : terrain, superstructures, menaces, objectifs...

Beaucoup de senseurs ont un fonctionnement très délicat et nécessitent une intervention importante de l'équipage. Par exemple pour les radars : adaptation permanente du mode d'émission et de traitement, choix des échelles, des balayages (site, amplitude, nombre de lignes...), participation à la détection-identification des cibles, initialisation des poursuites ou contrôle d'une initialisation automatique, surveillance de la poursuite, etc.

La sophistication des traitements devrait dans l'avenir améliorer la situation, on l'espère, malgré un accroissement constant des exigences sur les performances. Les possibilités de corrélation multisource devraient également apporter une amélioration importante.

3.2 - Evaluation de la situation et prises de décision

C'est là qu'il est important de conserver tout son rôle à l'équipage humain qui doit rester dans la boucle. C'est son rôle noble.

Mais il faut l'assister au maximum dans ses tâches, en lui présentant des synthèses claires, naturelles, des aides à la décision.

Un type d'aide essentiel consiste dans la prédiction d'évolution de la situation en fonction des actions envisageables.

3.3 - Réalisation de la trajectoire et mise en oeuvre des armes

Les prises de décision concernent en permanence un choix de trajectoire et ponctuellement la mise en oeuvre des armes ou matériels autour desquels la mission d'attaque est articulée, ou bien permettant l'autodéfense ou l'autoprotection.

Pour alléger la charge de travail, des automatismes doivent assister l'équipage dans les tâches non intelligentes en lui laissant le contrôle (évaluation de la situation). Il faut le décharger des problèmes de sécurité chaque fois qu'on peut le faire de façon automatique, d'autant plus que les réactions correspondantes nécessitent le plus souvent des temps de réponse très brefs, hors des possibilités du pilote ou qui mobiliseraient complètement le pilote pour les obtenir.

3.4 - Monoplace - Biplace

La question peut être posée de savoir si, pour résoudre les problèmes aigus de charge de travail rencontrés dans un grand nombre de missions, il ne faut pas préconiser l'utilisation d'un équipage double : pilote et officier système.

Ce n'est pas le rôle de l'ingénieur de prendre de telles positions. C'est par contre son rôle de proposer aux utilisateurs un maximum de solutions techniques et ergonomiques permettant de retarder le plus possible le moment où le biplace devient indispensable. Il nous apparaît clairement en effet que le "coût" humain correspondant (formation, entraînement, permanence,...) est très élevé.

4 - INTEGRATION DES SYSTEMES

4.1 - Etablissement de la situation

Nous pouvons développer un peu le concept d'utilisation de fichiers de renseignements qui peuvent être emportés dans des mémoires de masse et preparés avant la mission.

Ces fichiers comportent :

- des données altimétriques et planimétriques sur le terrain,
- des renseignements tactiques divers, par exemple la localisation de menaces connues, leur volume léthal, position d'objectifs, etc.

La position horizontale de l'avion est mesurée en permanence par la centrale à inertie. Elle peut être recalée ponctuellement à l'aide des autres senseurs disponibles. Par exemple, ce recalage peut être réalisé par corrélation d'une carte radar ou de la hauteur de la radiosonde avec des données prévisionnelles stockées dans la mémoire de masse.

La centrale inertielle mesure également les attitudes.

L'altitude, elle, est entretenue par un couplage adéquat entre les informations inertielles et anémobarométriques et peut être ponctuellement recalée par rapport au sol à l'aide du radar, de la radiosonde ou d'un système de radiolocalisation.

Après recalage, le système propose donc des données permanentes, pour représentation au pilote, du terrain en remplacement de la vue directe et des renseignements tactiques dont on dispose. Pour la sécurité à très basse altitude, cela n'exclut probablement pas de disposer d'un capteur externe de sécurité.

On peut dresser un tableau des possibilités d'utilisation des différentes ressources qui doivent être corrélées entre elles pour assurer les différentes fonctions :

Fonction Ressource	Localisation	Recalage	Détection Obstacles	 Menaces	 Objectifs
Centrale inertielle	0				
Radiosonde		0			
Radar		0	0	0	0
Lidar		0	0		0
FLIR, TV, LLTV		0	0		0
ILS, MLS	0	0			
NAVSTAR	0	0			
JTIDS/SINTAC		X		X	X
Détecteur de menaces				0	0
Fichiers terrain + renseignements	X	X	X	X	X

0 = senseur direct
X = renseignements

On ne détaille pas ici les nombreuses corrélations envisageables dans les différentes missions air-air ou air-surface. On ne détaille pas non plus les différentes fonctions correspondantes des radars et des senseurs optroniques.

On notera le rôle particulier joué par les systèmes nouveaux de transmission de données protégées à grand débit pour créer une coopération de plusieurs avions entre eux et avec la surface. Ces systèmes apportent une dimension supplémentaire à la mise en commun de plusieurs ressources (chaque avion pourra disposer des informations recueillies par les autres), et une dimension supplémentaire dans la coordination des attaques.

[illegible] - Présentation de la situation - Aides à la décision

Avec les données dont on dispose ainsi en permanence ou par détection directe, on peut présenter au pilote des synthèses dans le but :

- de remplacer la vision extérieure,
- d'enrichir cette vision par adjonction de volumes virtuels correspondant à des zones dangereuses, à des volumes de manoeuvre, axes préférentiels d'attaque,...,
- de fournir le cas échéant une anticipation en permettant au pilote de consulter des renseignements en avance de phase sur le déroulement de la mission.

La forme même des synthèses doit permettre une interprétation naturelle, facilitant la prise de décision.

Nous avons déjà dit que les équipements de visualisation modernes permettaient une grande richesse d'image ; ceci est très utile par exemple pour obtenir des représentations très figuratives pour remplacer la vision extérieure.

Mais cela ne doit pas nous conduire à des présentations complexes pour le pilote. On doit au contraire opérer en permanence pour chaque phase de mission et chaque situation une stricte sélection de toutes les informations nécessaires mais des seules informations nécessaires. Ainsi, il faut faire des choix et des synthèses.

Dans le processus de prise de décision, la présentation de la situation doit s'accompagner d'aides à la prédiction des conséquences des décisions. Ainsi, l'utilisation du vecteur vitesse pour ce qui concerne le pilotage de la trajectoire est-il un moyen évident de montrer la trajectoire future.

L'état de la machine (carburant, moteur,...) intervient dans l'analyse de la situation et il est nécessaire de mêler aux présentations les informations correspondantes sélectionnées et synthétisées de façon convenable.

4.3 - Réalisation de la trajectoire et mise en oeuvre des armes

Ces actions peuvent être manuelles ou automatiques.

4.3.1 - Réalisation manuelle

L'assistance au pilote peut consister en "guidages", le terme devant être pris au sens large, couvrant aussi bien la trajectoire que les actions de mise en oeuvre d'armes ou d'équipements particuliers à certaines missions (reconnaissance, brouillage offensif,...). Ces guidages peuvent être élaborés si l'on dispose de tactiques d'action fixes ou reprogrammables avant la mission.

On peut utiliser la notion de "directeur d'ordre" qui dicte au pilote ses actions, mais il est intéressant de noter que le pilote les exécutera d'autant mieux qu'il gardera une perception aisée de la situation, c'est-à-dire du résultat permanent de son action, plutôt que de suivre "en aveugle" un directeur d'ordre.

On préfèrera donc généralement la notion de "couloirs de guidage" présentés en superposition, dans le même espace, que la synthèse de situation. Et bien souvent la synthèse de situation pourra se suffire à elle-même, si elle est bien conçue.

C'est une façon de permettre au pilote de jouer tout son rôle d'adaptation aux changements opérationnels. Réfléchissons par exemple à ce qui se passe dans les premiers jours d'un conflit !

4.3.2 - Réalisation automatique

Nous avons déjà dans nos avions d'armes des systèmes qui réalisent automatiquement les séquences de tir, initialisées ou autorisées par le pilote. De même, les contre-mesures d'autoprotection comportent des automatismes. Nous avons également dans nos avions des modes de pilotage automatique : tenue de route, de pente, de virage, d'altitude, approche ILS, etc.

Ce sont ces notions qui se généralisent dans les concepts d'intégration pilotage/conduite de tir (IFFC).

Ceci est rendu possible dans la mesure où on dispose dans les systèmes modernes :

- de commandes de vol sûres,
- des interfaces nécessaires avec le reste des systèmes d'armes.

Dans les phases de mission où des tactiques peuvent être programmées à l'avance, il y a intérêt à remplacer le pilotage manuel par un pilotage automatique, laissant au pilote une charge de surveillance (incluant - malheureusement - la surveillance du bon fonctionnement des capteurs) et une charge d'innovation pour s'adapter aux variations de l'environnement. Cela signifie que le pilote peut modifier à volonté les consignes d'entrée des automatismes.

4.4 - Problemes de sécurité

Nous avons déjà signalé l'importance de la sécurité des commandes de vol. Evoquons aussi celle des informations de pilotage dont dispose le pilote.

Dans les systèmes modernes en développement, une redondance d'ordre deux (sans compter les instruments "get you home") est respectée globalement pour l'ensemble de la chaîne d'élaboration et de présentation des informations de pilotage et de conduite machine, à savoir essentiellement :

- sources inertielles et anémobarométriques,
- interfaces avec les systèmes avion (carburant, moteur,...) et avec les commandes de vol,
- visualisations.

Le but est d'obtenir :

- une détection automatique des pannes de la chaîne des informations de pilotage et d'alarme,
- une reconfiguration pour poursuite après panne - si possible avec les mêmes informations de pilotage (vecteur vitesse par exemple).

4.5 - Préparation/restitution de mission

Nous avons présenté des concepts d'utilisation en vol de données de mission emportées dans des mémoires de masse :

- fichiers de terrains,
- fichiers de renseignements sur les menaces (localisation, signatures,...),
- programmes d'attaque, de brouillage, d'évasives,
- etc.

Le rôle de la restitution des missions est évident pour l'obtention des renseignements, qui seront d'autant plus frais qu'ils pourront être recueillis au cours de toutes les missions, sans oublier bien entendu les missions spécialisées de reconnaissance (y compris ELINT).

La préparation de mission recouvre de nombreux aspects, tels que :

- sélection des données à emporter pour la mission,

- recherche préalable de trajectoires ou manoeuvres optimum (par rapport au relief, aux menaces,...),
- familiarisation, entraînement.

Une compatibilité étroite entre les moyens de restitution, de préparation et les systèmes avion eux-mêmes est indispensable.

Nous pouvons insister sur le fait que la préparation des missions est, grâce à la richesse des moyens disponibles, en particulier grâce à la capacité sans cesse croissante des mémoires, une voie efficace pour la diminution de la charge de travail en vol et l'amélioration des performances opérationnelles globales.

Mais en laissant, la aussi, intervenir les équipages, on leur permet leur rôle d'adaptation rapide aux conditions opérationnelles.

5 - CONCLUSIONS

Nous avons essaye de presenter un certain nombre de concepts pour illustrer la façon dont les techniques disponibles doivent permettre d'assurer avec les avions d'armes des missions de plus en plus complexes, avec des performances croissantes, malgré une charge de travail élevée pour les équipages.

Nous avons cherché à faire ressortir quel équilibre nous pensons devoir réaliser entre l'automatisation et le rôle de l'équipage, ce dernier se voyant résolument maintenu dans la boucle pour assurer aux systèmes le comportement le plus adaptatif et intelligent possible.

A Cost-Effective Night Attack System for Ground Attack Aircraft

by

J F Fisher, Marketing Executive, and
G R Sleight, Airborne Display Divisional Manager

GEC Avionics, Rochester, Kent, ME1 2XX, UK

SUMMARY

Current ground attack fighters have a good day VFR capability. However, they are generally ineffective at night. GEC Avionics have developed a simple integrated night vision system which allows a pilot to operate effectively at high speed and low level. The system uses a fixed forward-looking FLIR sensor to display imagery to the pilot on a raster head-up display. This allows him to terrain-follow and acquire targets. He then uses a touch-sensitive head down display to designate targets to his weapon system for subsequent attack. The pilot is also equipped with night vision goggles to permit hard maneouvring, and with a digital map to enable him to navigate flexibly. By designing the entire system as an integrated whole, cockpit workload is minimised. A series of flight trials has clearly proved the concept. The US Marine Corps AV-8B and RAF Harrier GR5 will soon be equipped with just such a system.

1. Introduction

For many years, all ground attack and strike airplanes have had an impressive operational capability by day in favourable weather conditions. This had not however been matched by their bad weather and night capabilities, which have until recently, been very limited. Indeed most attack aircraft have been incapable of flying at low level, acquiring targets or attacking those targets unless the pilot is able to see a reasonable distance ahead of his airplane; this distance is a function of terrain, airspeed, weapon, system accuracy and pilot skill. In general, it can be assumed that most attack airplanes are only fully effective in day VFR conditions. Figure 1 shows the average conditions which are to be found in Central Europe in winter. It can be seen that in winter the attack airplane is fully effective on average for just 20% of the 24 hour period. This is highly undesirable both because of the reduction in overall capability of the attack force, and because it allows an enemy force to operate freely for a large proportion of the time.

If we can give the pilot a full night and all weather attack capability, he will be able to fly at low level at all times. However, such systems are expensive and he still has to be able to acquire, identify and attack tactical targets to be fully effective. A cost-effective compromise is to provide the pilot with a full night VFR low level operational capability; this will not on its own permit all-weather operations, but it will expand the operational period from 20% to 60% of the 24 hours. GEC Avionics has been instrumental in developing such a system, which has been demonstrated on a Hunter aircraft at the Royal Aircraft Establishment, Farnborough, and on a TA-7C Corsair aircraft at the US Naval Weapons Center, China Lake. These flight trials have clearly demonstrated that a relatively simple system can allow a single seat ground attack or strike pilot at night in VFR conditions to:

1) Operate from a totally darkened airfield.

2) Take off and land from a darkened airfield without any ground-based visual assistance.

3) Fly at high speed and low level over a wide variety of terrain without any active aircraft emissions.

4) Locate both static and tactically mobile targets, including tanks, in a designated area.

5) Attack those targets with standard unguided weapons using normal day time techniques.

6) Alternatively, to designate targets for attack by a guided weapons system, while flying at low level.

Traditionally, any one of these tasks would have been considered to be a very high workload at low level by night. We have conclusively demonstrated that they can all be achieved by relatively inexperienced pilots with a comparable workload to normal daytime low level operations. The key to this achievement has been the design of a fully integrated system, designed to operate synergistically in the fighter cockpit to minimise workload. Currently GEC Avionics can claim to be the only company in the world with this capability and experience.

2. The Operational Task

The first essential is the ability to safely and consistently fly at low level by night.

Without this capability, the aircraft will be too vulnerable to enemy defenses to survive. However, it is of little value on its own. The pilot must also be able to navigate, locate, identify and attack targets and, not least, operate covertly from his home base. We can define the pilot's operational tasks while flying at high speed and low level as comprising:

1) Terrain following.

2) Manoeuvring the aircraft with large (85 degrees plus) angles of bank.

3) Navigation.

4) Target acquisition.

5) Target designation.

6) Weapon aiming.

Plus:

7) Covert airfield operation.

3. The Integrated System

The first task, terrain following, can be achieved using an electro-optical sensor with its imagery overlaid on the real world and scaled one to one. The scaling and registration are both necessary to maintain pilot orientation and to allow him to use the same low flying techniques by night as he does by day. The sensor/display combination can be either a fixed forward looking FLIR with its imagery displayed on a raster HUD, or a pair of night vision goggles (NVGs). Extensive flight trials, both in the UK and the USA, have conclusively demonstrated that either system will allow a pilot to fly a straight course, following the terrain contours with a low workload.

However, the pilot also needs to be able to maneouvre the aircraft at low level. Initial trials using a fixed sensor/HUD combination showed that hard maneouvring was only possible when the HUD had a large instantaneous (particularly vertical) field of view. For example, Figure 2 shows the effect of attempting a high rate turn with a conventional HUD with a 20° by 15° field of view. The look angle into the turn is not adequate to clear the aircraft's flight path, and the orientation cues are limited. This factor dictated the USAF requirement for the raster HUD for the LANTIRN programme, with its field of view of 30° by 18°. As shown in Figure 3, this offers a greatly increased ability to look into a turn, and hence maneouvre hard at low level. The LANTIRN HUD uses holographic optical techniques to provide the large instantaneous field of view while remaining within the space constraints of the F-16 (Figure 4) and the A-10 cockpits. It has been sucessfully and extensively tested in both aircraft and is approaching the production phase. Indeed the F16 LANTIRN HUD has now flown over 750 missions and the contractor involvement provided by the combined test force has proved to be of significant assistance in the achievement of the impressive capability now demonstrated in the LANTIRN equipped F16 aircraft.

The alternative system using night vision goggles permits hard maneouvering, since the pilot can look around freely using the NVGs mounted on his helmet. Conventional goggles, such as GEC Avionics "Night Owl" system (Figure 5) provide electro-optical imagery directly in front of the pilot's eyes; however, he has to look around them to monitor the cockpit instrumentation.

NVGs have one major disadvantage; they cannot detect thermally-significant targets, unlike a FLIR which can acquire "hot" military targets. Trials at RAE Farnborough and US NWC China Lake with GEC Avionics' systems have shown that the combination of FLIR imagery on a HUD with NVGs can be very effective. The pilot uses the NVGs to scan freely, and the FLIR imagery to detect targets. However, he is then looking at his FLIR imagery through the image intensifier tubes of the goggles. Seeing an electro-optical image of an electro-optical image in this way severely degrades the FLIR resolution. In addition, there is a basic frequency incompatibility between NVGs and a holographic HUD (such as either the F-16 and A-10 LANTIRN HUDs or a conventional HUD with a holographic combiner). GEC Avionics therefore developed "Cats Eyes" NVGs (Figure 6). These have a unique optical arrangement. A clear "see-through" glass combiner is mounted in front of each eye, with the image intensifier line of sight 1 $^{1}/_{4}$ inches (3 cms) above the pilot's direct line of sight (Figure 7). This allows the pilot to view the electro-optical imagery from the image intensifier tubes, as on conventional NVGs. In addition, he retains his direct view of both the cockpit instrumentation and the HUD. This means that he does not lose any of the resolution of his FLIR image. Flight trials at both NWC China Lake and NATC Patuxent River have confirmed the validity of this technique, and the US Marine Corps are buying a number of sets to continue the evaluation.

The key element in the system is the FLIR. This must be of sufficient performance to provide the necessary resolution whilst also giving an adequate field of view to allow not merely carrying out manoeuvering and also cover wide swathes to give effective ground coverage for target detection. There are many complex and subtle trade offs in FLIR/HUD fields of view to achieve optimum performance. In addition, the FLIR benefits from a high degree of automation of gain/contrast control to minimise pilot work load in the demanding low altitude environment. The very high resolution UK Common module TICM FLIR, as developed for airborne applications by GEC Avionics, provides the performance to meet this requirement.

Excellent resolution on the FLIR is a prerequisite for target acquisition and the NWC trials demonstrated that the necessary FLIR performance levels were achieved. Target acquisition can be further enhanced by automated processing technology of the IR detected emissions to cue the pilot onto probable targets. This capability is being further developed and demonstrated in continuing flight trials at RAE Farnborough.
Next, the pilot has to be able to deliver his weapons onto the target. There are two distinct problems, one for conventional unguided weapons, the other for guided munitions. The simplest solution is to directly aim an unguided weapon at the target. The pilot achieves this by first acquiring the target on the FLIR image displayed on his HUD, and then aiming using the normal HUD weapon aiming symbols. This gives comparable accuracies to those achieved using the same display by day.

More complex delivery techniques such as CCRP (Continuously Computed Release Point) or guided weapon attacks require the target to be designated. For this purpose, GEC Avionics have developed the "Tactile" touch-sensitive head down display. This uses an infra-red beam system on a conventional CRT display to allow the pilot to designate a point on the CRT by touching it with his finger (Figure 8). If the FLIR imagery is displayed on the head down display, as well as on the HUD, the pilot will be able to acquire his target and then designate it to his weapon system by touch. He can then either complete a CCRP attack or release a guided munition. This technique does, however, require the head-down display to be positioned on the centre or left of the instrument panel, for obvious reasons.

This still leaves the task of navigation. It is clearly not practical to constantly refer to a paper map in a darkened cockpit. Navigation at night therefore involves a somewhat modified technique. The simplest system uses an inertial navigation system to steer the pilot to a waypoint where he updates the system. However, the combination of IN drift rate and limited HUD azimuth field of view means that the system must be updated every few minutes, or the pilot may miss a waypoint because it has drifted ouside his field of view before acquisition range. Once he misses a waypoint, it becomes very difficult for the pilot to recover the situation. In addition, this technique is relatively inflexible;it does not allow for major track deviations because of weather or hostile action. For this reason, a cockpit map display becomes highly desirable. It must show not only the aircraft's present position but also his desired flight path across the ground, to offer flexibility and independence from hand-held maps. In the past this has only been possible with complex projected map displays or remote map readers. However, their very complexity increases cost and greatly reduces reliability. Moreover, the fixed colour palette can cause problems of frequency incompatibility with night vision goggles. GEC Avionics has recently developed a novel digital map system. This is a solid-state system which produces a fully digitised image of a standard paper map; this digitisation is done at a base ground station, once for each map to provide overall map coverage. The resulting image quality is remarkable. The pilot can use a local planning station to overlay track and other mission planning data immediately before each flight. In flight, the digital map can offer a variety of facilities, including north or track-oriented displays, zoom, look-ahead and different map scales. It can also change the colour palette at night to make it compatible with night vision goggles. If a DMA data base is available, it can use this as an alternative to the paper map digitisation. The system also offers outstanding flexibility and reliability (because it is solid-state); the prototype (Figure 9) is flying very successfully on a Wessex helicopter at RAE Bedford and this approach is further discussed in paper 36 tomorrow.

4. System Applications

The equipments and techniques described have been evolved over a number of years. The first significant application was the two seat experimental Hunter at RAE Farnborough. This first investigated low level techniques using a fixed low light television sensor mounted in the nose, displaying its imagery on a head down display. Further developments included the use of a raster HUD, the replacement of the low light television with a UK common module FLIR, and the use of NVGs.

The exceptional results from this relatively simple system generated considerable interest in the United States. GEC Avionics therefore proposed to install a similar system in a demonstrator aircraft for the US Marine Corps. The proposal was accepted in December 1983; the system flew successfully in a TA-7C at China Lake in April 1984, as Project "Cheap Night". It consisted of:

- A UK Common module FLIR in a pod.
- An A-7 raster HUD, modified to UK line standard.
- A head down display in the front cockpit.
- A Tactile touch sensitive display in the rear cockpit.
- Cats Eyes night vision goggles.
- Modified cockpit lighting.

The results were so encouraging that the trial was extended from its planned two months to six months, covering some 80 flights. It was demonstrated to a wide variety of

Service and Government personnel, including the Secretary of the Navy. As a direct result of the trial, the US Marine Corps decided to procure such a night vision system for the AV-8B. The same system will be installed in the RAF Harrier GR5 in co-operation with the US Marine Corps.

A further similar flight trial is planned for an F-16 aircraft operated by General Dynamics at Fort Worth. The first flight is planned for next month. A similar system will then be flown in the Netherlands on an F-16 of the RNLAF. These systems will incorporate a number of refinements, including the use of a wider angle HUD, a new low drag 10 inch diameter pod and a revised Mk 3 version of Cats Eyes.

The overall synergism of these various system elements is of vital importance to achieve effective operational capability. The HUD/FLIR fields of view (and any optical corrections) need to be most carefully matched, the overall colour palette used in the cockpit and the operating light wavelengths of all displays and sensors need also to be subject of the most careful control. In addition various peripheral equipments such as the FLIR/Cockpit TV/Video recording system also need detailed interpretation in order to achieve a usable operation overall weapon system.

5. Future Systems

GEC Avionics has now developed the integrated night vision system described here to full production status. We have proved that this system can be safely and consistently operated as an effective weapon system by the average squadron ground attack pilot. It is neither fully automated nor all-weather. However, it is relatively low cost and is totally passive. The consequences of installing such a capability will be very significant. It means that Warsaw Pact ground forces will no longer be able to use cover of darkness to regroup, mobilise and gain the element of surprise.

We are now studying improvements in this concept. These include the development of similar systems for attack helicopters, the use of helmet mounted displays with a gimballed FLIR to provide biocular imagery, and the development of more advanced FLIR systems. There is no doubt that the introduction of these cost-effective night vision systems is going to be one of the most significant improvements in the ground attack pilot's capability in the future.

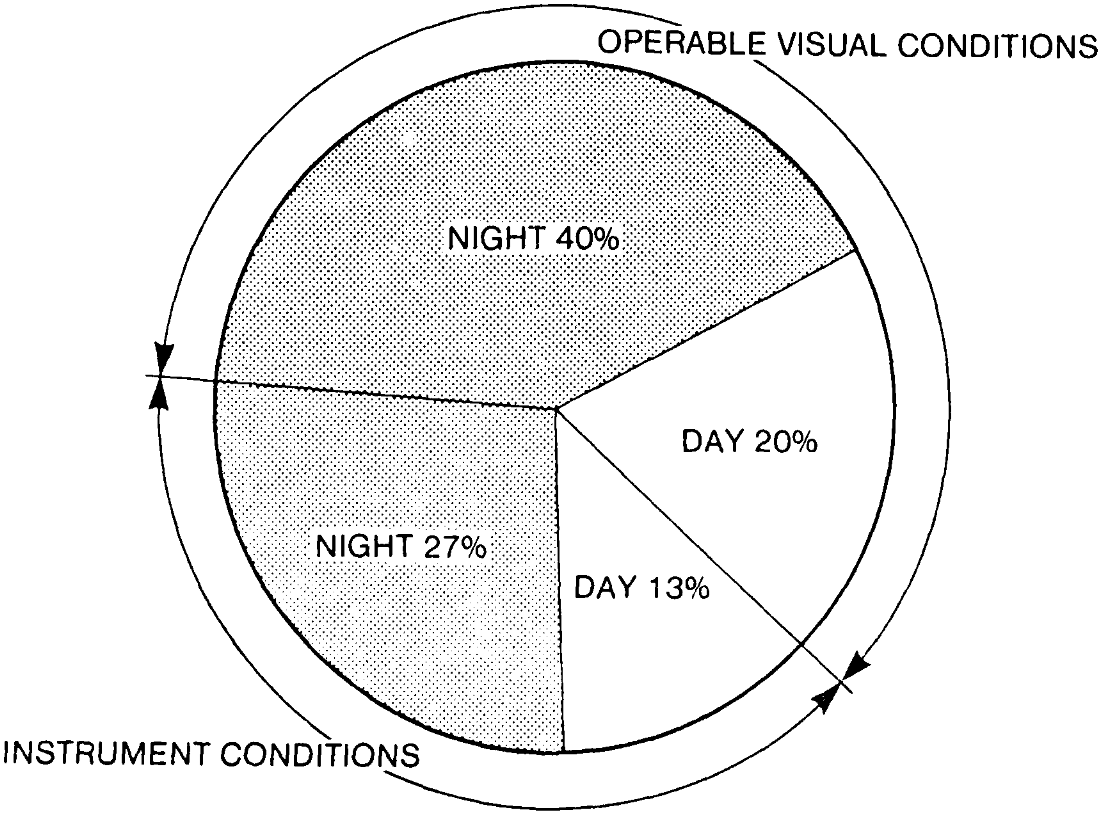

Fig.1 Central Europe in Winter

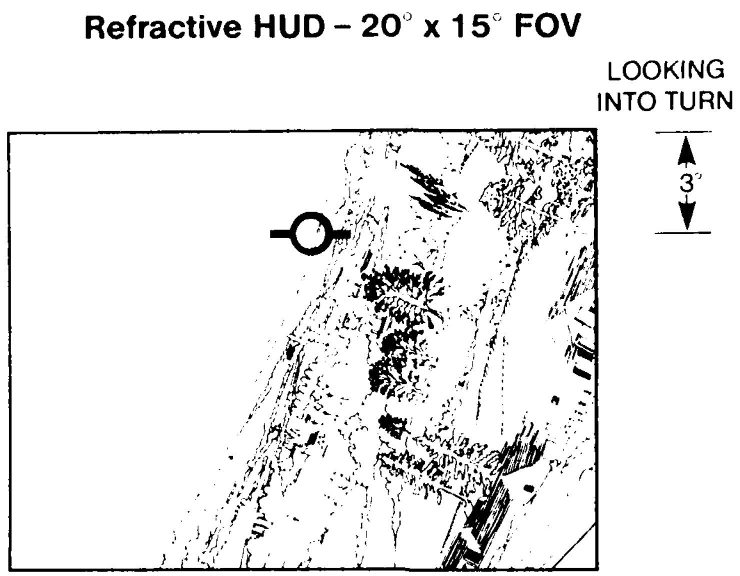

Fig.2 HUD field of view — turning flight

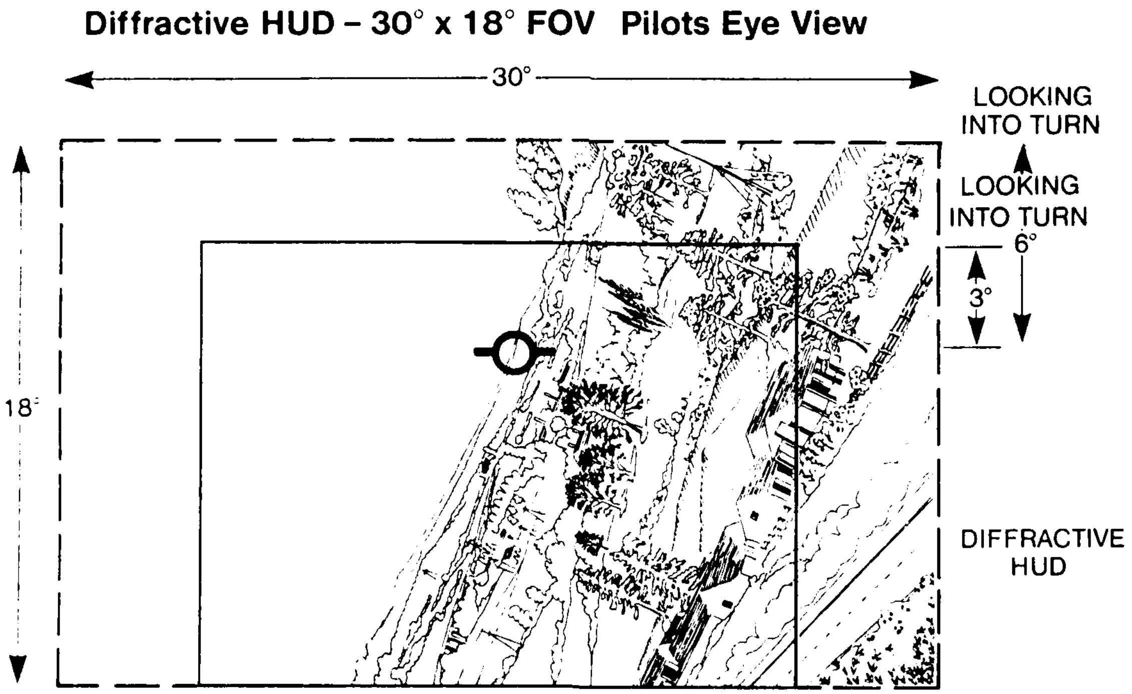

Fig.3 HUD field of view — turning flight

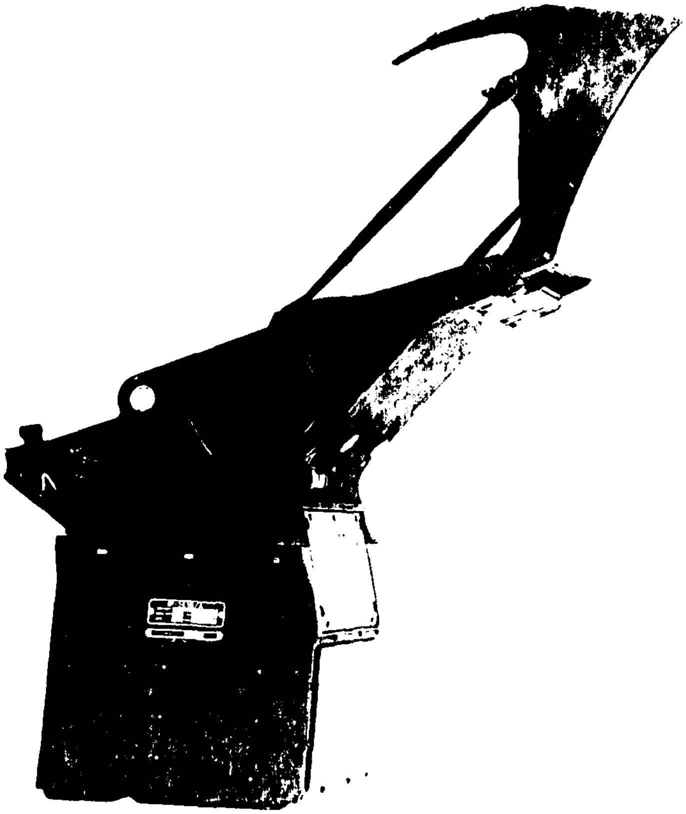

Fig.4a A-10 HUD

Fig.4b FCP (Lantirn) HUD

Fig.5 Night Owl

Fig.6 Cats Eyes

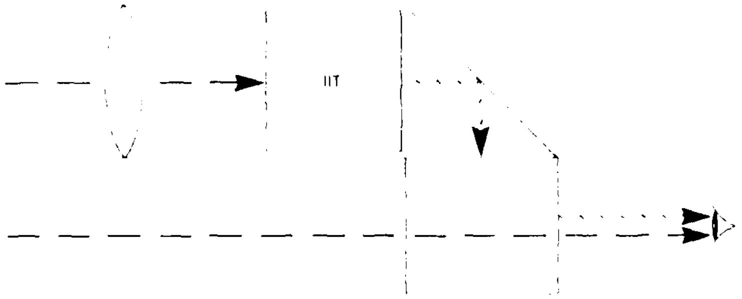

Fig.7

Fig.8 Tactile

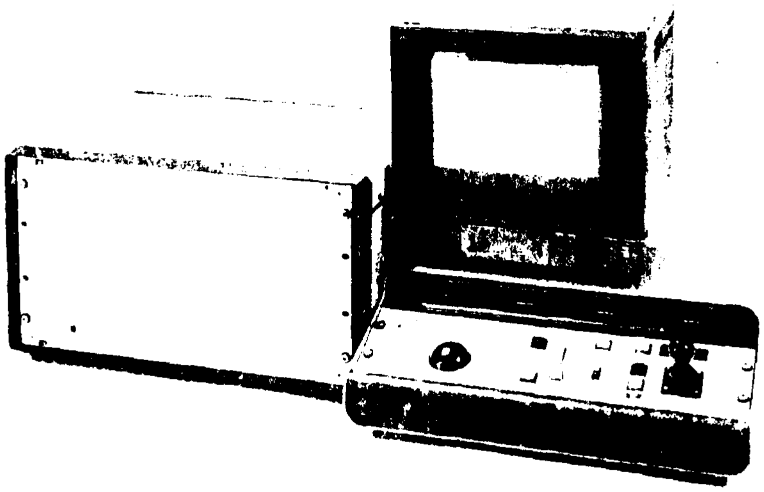

Fig.9 Map demo unit

COCKPIT AUTOMATION REQUIREMENTS DERIVED FROM MISSION FUNCTIONS DATA

by

Bernadette Faulkner, R.Seifert, K.D.Richter
Messerschmitt-Bölkow-Blohm GmbH, LHE 143
Postfach 80 11 60
D-8000 München 80
Federal Republic of Germany

1. Description of the problem

It is known that today the human operator forms the bottleneck for the operational utilisation of manned weapon system capabilities.
The reason is the immense increase in performance based on a great extension of the technological limits of the system /1/.
This is achieved by automating more and more functions of the aircraft's systems.

This development has brought about a gap in the engineering concept of the man-machine interface. There is a discrepancy between the real functional interface and our conceptual thinking or our mental picture of this interface, Hudson and Young said /2/:
"The man-machine interface is commonly thought of as the controls and displays in the cockpit or crew stations of an aircraft.
These controls and displays are, in fact, only the tip of an iceberg; the real man-machine interface will be deep in the computer systems of the next generation of aircraft."

Consequently, we have to develop a system engineering concept for the design of the man-machine interface, which accounts for this fact. Our problem is: we know that we have to automate a greater number of man-machine interface functions; however we do not know which functions, by how much, how and why to automate.
We lack a method of defining the concept for automation at the man-machine interface.
Bröcker /3/ has suggested a set of guidelines and criteria for the functional integration of man into avionic systems with high complexity and degree of automation.

In the study "Automation in Combat Aircraft" /4/, Summer 1981, sponsored by US National Research Council, it was revealed that there is a knowledge gap concerning the system engineering methodology of the functional integration of man into advanced combat aircraft.

In 1983 the Guidance and Control Panel of AGARD established an international Working Group, tasked:

- to look into the availability of knowledge in the participating countries
- to derive guidance information for this functional integration of man from expert knowledge
- to recommend R & D activities to fill the revealed knowledge gaps.

In 1984 the "Cockpit Automation Technology" programme (CAT) was launched by the USAF to develop the tools for automation engineering at the man-machine interface.

We in Germany also started a research programme in 1984. The funding of this programme is negligible compared with that of CAT. However, it does represent a first step in the total task of man-machine interface system engineering.

The first phase included the development of:

- A mission task list for selected mission and weapon systems.
- A method for rating the relative importance of each of the tasks related (a) to the frequency of occurrence (in the respective mission phase), (b) to mission effectiveness and (c) to flight safety.
- Criteria and/or categories for automation at the man-machine interface, against which the individual mission tasks could be rated.
- A method for rating the mission tasks in relation to the automation categories derived.

This programme is a trial meant to approach man-machine interface engineering from the operational and the human task aspect. Only if we know the set of tasks man has to fulfil with his system during the course of a mission and mission phase, can we engineer the technical system functions appropriately to meet the needs and not to exceed the limits of man and his capabilities.

2. Concept for automation at the man-machine interface

The concept for engineering the automation at the man-machine interface is to approach the selection of functions for automation, and to determine the why and how of their automation from both sides, operational and technical.
The general concept of man-machine interface automation engineering is shown in fig. 1.

Based on a mission analysis, basic data for the automation requirements at the man-machine interface are collected in a first step, using a special interview method. This is detailed in fig. 2.

3. The method

The method comprises:

o a mission task list

o a catalogue of defined automation categories

o an interview format with instructional guidelines

3.1 Mission task list

A mission analysis is performed based on the tactical requirements for the weapon system in question, and based on expert knowledge concerning procedures, regulations and technological system options applicable to the design driving mission.

The resulting mission function list will contain a great number of function or task items, dependent on the level of detail applied in the analysis. This is in turn a function of the knowledge of the expert performing the analysis.

In an air-to-air mission analysis we arrived at more than 400 mission functions. A good mission analysis should contain no fewer items if operational and technical functions are taken into account.

This very detailed mission functions list is then reduced to a list containing not more than about 110 to 130 mission tasks. This level of detail is required for the interviews.

Too great a level of detail would result in an unacceptable interview duration. An interview should not last longer than about 6 hours. An inadequate level of detail would render results which might give insufficient information for determining the automation requirements.

An example of a mission phase task list together with typical scenario is presented in the appendix.

3.2 Automation categories

The determination and definition of distinct automation categories is required for two reasons:

(1) A standardized interview technique, as is presented here, requires defined terms of reference for the operators and experts involved in the interview.

They should thereby be enabled to make their choice and decision concerning the suggested level of automation, based on a set of comparable cues.

(2) The automation categories allow the design engineer to decide upon the level of automation applicable to certain candidate functions.

The Air Force Study "Automation in Combat Aircraft" /4/ contains guidelines for automation, indicating when and how to automate.

However, the design engineer does not want to know the workload and human capability conditions which indicate automation. He wants to know for which system functions he should provide which form of automation and what degree of operator involvement concerning control, selection and display of information of that function is required.

3.2.1 Automation categories for the control of functions

These categories are:

- manual
- manual augmented
- manual augmented with limit-monitoring
- cooperative manual and automatic
- automatic with variable settings or control laws
- automatic with given control conditions
- autonomous automatic.

Flight control functions in modern aircraft cover the range:

- manual augmented, based on augmentation by the CSAS (control stability augmentation system)
- limit-monitoring, as e.g. manual augmented control with α- or g-limiting
- cooperative, e.g. overriding the autopilot "height hold" function by manually applied force control
- automatic, autopilot function with variable settings.

In the area of utility systems control most functions are:

- automatic functions, as e.g. landing gear retraction
- autonomous automatic functions, i.e. hydraulic and electric.

Autonomous functions do not allow manual interference - provided the power is on and the APU or engines are running - the automatic functions, as gear or flaps handling, require manual selection.

3.2.2 Automation categories for the selection of functions

These categories are:

- manual
- accept/reject
- automatic

Manual means: switch, set, select, enable following pilot decision.

Accept/reject means: the function could be triggered automatically, however it requires the provision for the pilot to decide upon accepting or rejecting the activation of the function.

Automatic means: an automatically controlled function is activated automatically if the relevant conditions for its activation exist or develop. No pilot action required.

3.2.3 Automation categories for the display of information of functions

These categories are:

- continuously displayed
- displayed only if a selection is made of:
    - mission or flight phase
    - main mode
    - system mode or function
- displayed owing to conditions:
    - flight condition (e.g. obstacle warning)
    - mission condition (C^3, threat etc.)

The interview format allows for the additional denotation of displaying the information head up, head down or on helmet-mounted sight/display. This addition is important, because an extremely critical challenge for the interface engineering is to predetermine the operational tasks and mission elements, which should be flown head-up and/or head-down respectively.

3.3 The interview technique

Fig. 3 shows the layout of the interview format. The interview technique allows assessment of each mission task according to:

- the frequency of its use on occurrence within the mission phase or within a duty cycle, e.g. attack
- its relative weighting in terms of mission effectiveness within the total mission
- its relative weighting in terms of flight safety within the total mission
- the automation categories recommended for control, selection, and display of the functions and functional conditions possible, related to the task
- the responsibility assignment for the task in a more than one man crew.

The number of decisions and statements required during the course of the interview show that there are limitations regarding the number of mission tasks to be included in the interview.

If we accept an interview to have a maximum duration of about 6 hours, we can only allow the inclusion of the number of mission tasks that can be assessed within this time. The mean time per assessment decision is about 30 s. The interview requires 7 assessment decisions per task. Consequently 6 hours allow for 720 decisions, or a little more than 100 mission tasks, to be included in the interview.

The mission task lists show that there is a great amount of redundancy in individual tasks within the mission.
The number of tasks can therefore be reduced by including only one of corresponding tasks.
Each assessment made is denoted by a number. This allows easy adaption to computerised evaluation of the results.

3.4 Evaluation of results

Evaluation is made concerning:

- importance rating
- recommendations for automation
- denotation of task responsibility

The mission tasks listed are grouped in different ways to allow the analysis of the results to differentiate between mission phases, task function groups, and task types. In other words: the analysis of the interviews should render results covering:

- mission,
- systems, and
- human tasks

(1) The mission phases and tasks therein are predetermined by the mission analysis.

(2) The task function groups reflect the systems related to the task. The function groups are:

- Flight Control
- Navigation
- Weapon/Combat Management
- Threat Management
- C^3
- Management of Aircraft Systems

(3) The task types reflect the nature of human acitivities related to the tasks. The task types used are:

- Observation
  observe, monitor, scan, look-out, listen
- Sensu-motor precision
  detect, acquire, track (manual), lock-on, guide
- Communication
  communicate, report, alert

- Memory linked functions
  check, follow procedure, inspect, review
- Decision linked functions
  decide, evaluate, assess, update, navigate
- Discrete manual activities
  switch, set, select, engage
- Flight Control activities
  manoeuvre

A further analysis is then made with the aim of determining the systems, and the functional loops and interactions related to each of the operational tasks in a given mission phase.

4. Further activities

The detailed description of results achieved so far lies beyond the scope of this paper. Besides that, we could at this time only present preliminary results.

During the first phase of our activities in Germany, two missions were analysed and transformed into the interview format. One is an anti-tank helicopter mission, the other an air-to-air mission. The method was then tested for applicability using helicopter and fighter pilots. Some improvements had to be made concerning the automation categories and the mission task redundancy applied.

In 1985 we are contracted to perform and evaluate 30 anti-tank mission and 15 air-to-air mission interviews.
We expect thereby to obtain a data base, which will help us in better defining the air-crew-helicopter and pilot-aircraft interface requirements for our future weapon systems.

The rationale is that we use the mission task requirements in combination with the aircrew's/pilot's operational activity or performance requirements to derive the concept for automation and functional integration at the man-machine interface.

As far as feasible and possible, the results of our study will be included in the report of the GCP WG of "Guidance and Control Automation" at the Man-Machine Interface, which is due for publication early next year.

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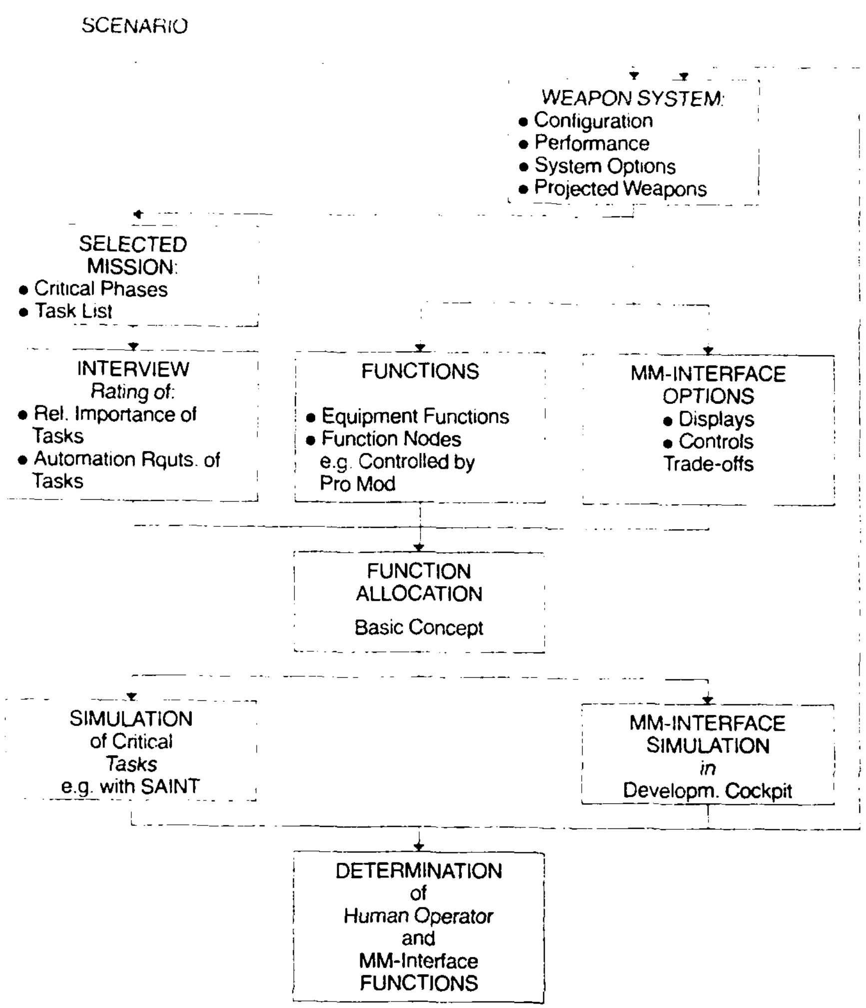


Fig. 1 Concept of human operator and man-machine interface functions engineering

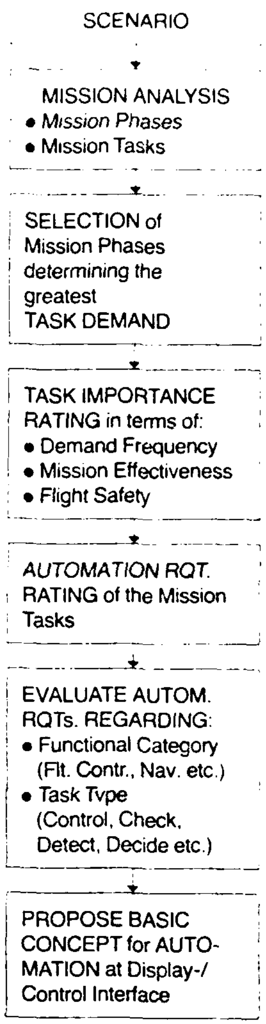


Fig. 2 Task oriented derivation of man-machine interface requirements

[illegible] System
Mission Type
Mission Phase

Unit
Nr

Nr	Mission Task	Importance Rating			Function			
		Frequency of Use	Mission Effective-ness	Flight safety	Control	Selection	Display	Responsibility
		1 to 5	1 to 5	1 to 5	1 manual 2 augmented 3 limited 4 co-operative 5 auto-preselect 6 automatic 7 autonomous	1 manual 2 accept/ reject 3 automatic	101 103 continuous 211 233 selection 311 333 on condition 001 visual 002 acoustic	1 pilot 2 copilot 3 both-more p 4 both/more co 5 co-operative

Fig. 3 Sample of Interview Format

Appendix

Mission task list for combat helicopter
Example of two mission phases

F APPROACH TO INGRESS POINT (BATTLE ZONE)

1. Proceed Low Level Under Cover (Terrain Following Flight)
2. Monitor Radios
3. Maintain Visual/Sensor Look-Out Procedures
4. Update Navigation Data
5. Receive and Evaluate Situation Data
6. Communicate with Ground Forces
7. Recheck Flight Data
8. Monitor Subsystems
9. Observe Obstacle Clearance (Visual/Sensor)
10. Perform Combat Systems Check
11. Conduct Pilot/Copilot-Gunner (P/CPG) Intercom.

G INGRESS - APPROACH FIRING POSITION

1. Proceed NOE to Firing Position (Flight Control + Navigation)
2. Conduct P/CPG Intercom.
3. Maintain Visual/Sensor Look-Out Procedures (Navigation Combat, Threat)
4. Alert Other Crews if Enemy Attack Encountered (Threat, Communication)
5. Provide Self-Defence Security
6. Observe Obstacle Clearance (Visual/Sensor)
7. Select Firing Position
8. Receive and Review Attack Data
9. Conduct P/CPG Intercom.
10. Perform Final Weapon Systems Check
11. Approach Firing Position
12. Establish Suitability of Firing Position

(13. Manoeuvre to new Firing Position)

14. Report Readiness for Attack

AUTOMATION AND PILOT INTERACTIONS IN NIGHT OR ALL-WEATHER TACTICAL OPERATIONS

by

Mr. W.H. McKinlay

Ferranti Defence Systems Limited
Ferry Road
Edinburgh EH5 2XS

SUMMARY

This paper examines some of the areas in which automation could be used to reduce pilot workload when operating at night or in low visibility. It is shown that in navigation the pilot's task extends from the planning stage before take off to the point at which tactical decisions are taken in the air. The role of the Mission Planning System and the features of a system developed for this purpose are covered. The paper looks at the nature of the man-machine interface including its required features and suggests the impact of the latter on the core avionic system including navigation and the MMI.

1. Introduction

Tactical night all-weather operations, particularly in single-seat aircraft, will produce a substantial escalation of the pilot's task. Although much is now known of the feasibility of operating at night with the assistance of electro-optical sensors the workload will still become extremely high when the tasks associated with navigation, weapon delivery, survivability etc are aggregated in a fluctuating operational situation. It is particularly important for any system to cope with the peaks in such operations. The purpose of this paper is to examine some of the more demanding aspects of the pilot's task and suggest how they can be mitigated by attention to system design and by the use of the technologies which are now becoming available. In particular the paper considers tactical routing and workload imposed by navigation together with the associated problems of information display and the man-machine interface. In system terms there are references to the development of a system core structure concerned with tactical control, navigation and the man-machine interface.

2. The Pilot's Task

The pilot's task can only be defined and optimised as part of a total system design responding to an operational requirement. Subjective conclusions based on pilot handling and workload in earlier systems may be invalid if the operational concept has moved into unknown territory. The first stage in defining the man-machine interface must inevitably be to consider a complete architecture in which functions are partitioned between pilot and machine.

Initially it is also helpful to consider the pilot's task as occuring at a number of possible levels in which the man-machine relationship will have different characteristics. Working bottom-up these levels include (see Figure 1):

House keeping: the control and monitoring of basic aircraft services capable of being handled by relatively simple rules.

Control tasks concerned with power plant or flight control and capable of being realised automatically or pilot in-the-loop.

More sophisticated tasks involving decisions about or control of sensors, weapons etc.

The acquisition of information about the external tactical environment through sensors, communications, pilot's eye etc.

Tactical decisions involving judgment and the control of the total system.

[illegible] decisions at all these levels may have varying degrees of priority in the presence of hazards or failures. The pilot must of course operate at a number of these levels simultaneously depending on the pilot/automatics split. The task of automation is most difficult in considering the higher levels at which decision making is involved.

The workload imposed on the pilot depends on a number of factors. When tasks in a number of areas coincide they can produce peaks as can any individual degree of difficulty. When delivering weapons at high speeds and low altitudes a compression of actions with time can arise. Other papers have suggested cases in which a series of actions and decisions required in a weapon aiming sequence have to be compressed into times of the order of 15 seconds. When accompanied by the need to control the flight profile close to the terrain, at night, this represents a formidable task. Similarly, in navigation, tactical decisions about route changes under pressure must involve judgment which can be translated into action with as little manipulation of the system controls as possible.

Automation and the MMI

Since there is only one pilot his function in the system is inevitably centralised although the system itself may be distributed. The interface between man and machine is governed by this fact and the resulting architecture before the detailed interfaces through controls and displays can be considered.

The way this interaction has been developed with increasing system integration can be visualised historically.

In systems which were not substantially integrated separate aircraft installations concerned with navigation, communications, flight control, weapon delivery etc were controlled through dedicated controllers giving complete flexibility in terms of the modes of operation of the different sub-systems at any time. The pilot carried a mental model of the operation and what he wished to achieve, setting the sub-systems up manually to achieve the desired response. The two methods available to reduce such workload are integration and automation.

It would be possible to automate the different sensors and sub-systems for at least two reasons: to permit them to do their own house keeping, being thus easier to handle, or to allow them some further autonomy in determining their mode of operation. The second is likely to prove an unpromising approach because the pilot must retain an accurate mental model of system behaviour and what he has to do to change it.

The arrival of the digital databus and the presence of computing within sub-systems both imply additional design flexibility. The crucial man-machine relationship becomes that between pilot and whatever controls the configuration and behaviour of the system.

In essence the pilot must have a higher order dialogue with the total system which the avionics translate into total system behaviour. One possible translation is from the man-machine relationship to a chosen mode of flight which implies an unambiguous definition of the modes of operation of all the constituent parts of the system. Each sub-system is given a blue print for its state of behaviour: e.g. a radar is told whether to switch on or off, how to scan and how to choose between any other options as to its method of radiation. Any sub-system may have its own means of controlling its internal behaviour provided that it responds with whatever parameters are part of the prevailing total system mode.

The MMI design task now becomes one of devising an effective and comprehensive interface between pilot and system with the behaviour of the latter being credible to the former whatever happens. This credibility has to be reflected in control inputs, in the system response to them and in the supporting monitoring information supplied to the pilot. Such a system can operate up to the level at which intangible decisions have to be taken, based on information from communications, sensors or pilot's eye.

Up to this level it seems more important that the system should operate reliably and unambiguously than that it should have any ability to take machine decisions involving anything like artificial intelligence. It would seem easy to construct systems driven by simple rules which would not be particularly transparent to the pilot, so that the emphasis should be to make them so.

Navigation

The essential navigation requirement is to guide the aircraft along a pre-planned track, permitting deviation from it, with an accuracy such that its chances of survival will be greatest and the probability of acquiring the target sufficient. However an emphasis on operations at night or in low visibility, in difficult battle-field conditions, may change the emphasis of these requirements.

Before the advent of automatic navigation systems navigation over short sorties was essentially pilot's eye, using experience and a topographical map. The advent of digital systems based on Inertial Navigation made it possible to fly a profile consisting of a number of way-points with an accuracy which, although variable, was generally dependable. Monitoring the progress of the flight relative to the terrain was still highly desirable, a fact which has made moving map displays popular. However at night, possibly using sensors, the area of terrain available for cross-checking may be greatly reduced. There is therefore a need for a more accurate navigation system.

A further consequence of night operations in the years ahead is likely to be a considerable increase in pilot workload, so that the workload due to navigation must be minimised. To some extent this should be possible given greater accuracy and a measure of integrity but there will still be a considerable workload, particularly if it is necessary to change a mission plan in flight or deal with eventualities such as a return to a different base. It is then profitable to look at the man-machine relationship concerned with navigation as a continuous process from the flight planning stage to the arrival of particular incidents in flight. It is for this reason that Ferranti have been working for some years on Mission Planning Systems as well as on Navigation Systems and airborne Displays. A planning system can enable a much higher degree of planning and anticipation without significant additional workload before take-off. The database thus created can help to reduce workload in the air, particularly when amending a flight plan on the basis of stored information as well as information obtained through communications.

Mission Planning

Experienced pilots have always set great store on adequate mission planning as a means of reducing workload. Planning a mission on the ground remotes some of the workload from the cockpit in both space and time. The act of planning navigation relative to time, fuel, the terrain, possible threats etc can validate a mission as being possible as well as revealing alternative options. Where missions are likely to take place in a given area a second removal to pre-planning is possible in which alternative missions are planned in very great detail before being recorded ready for use when required.

However, particularly where aircraft have to respond at short notice, the planning activity itself generates a workload on the ground. The information which can be taken out to the aircraft and then consulted in flight is limited if it is confined to paper, topographic maps etc. Therefore, with the advent of digital technology, it is natural to conceive a system solution using digital techniques to process, store and transfer the information. Some years ago Ferranti initiated a research programme in this area which has since led to several generations of production systems.

The first system, Autoplan, consisted of a small computer linked to a map board permitting any flight profile to be digitised direct from the map. A keyboard and a printer were also included. An important function was the ability to load a Portable Data Store which could then be plugged into the aircraft avionics and thus load the mission computer with a canned flight plan.

Inevitably later systems such as the Total Avionic Briefing System (TABS) have made it possible to use a more comprehensive database which can include both navigation and intelligence information. The PODS technique is still used to load the aircraft system although clearly later developments in datalinks will [illegible]. The more advanced stores can also record information in flight.

The ability to load the results of the briefing into the aircraft automatically of course reduces workload in the cockpit pre-flight and sets no limit on the amount of information stored in the Navigation System except that it must be useful and accessible in flight.

A Typical Mission Planning System

Although such systems vary depending on the application a typical system consists of the following units (see Figures 2 and 3):

A map table including a cursor.

An electronics unit including a digital processor.

A printer.

A VDU.

A loader unit which can also house a Portable Data Store.

A flight plan can be assembled from way-point coordinates entered in several different ways. Keyboard entry or entry through the map table and its cursor are possible. Alternatively pre-planned way points can be held in the system so that standard canned flight plans can be used.

The VDU is useful for prompting the operator through the different stages of planning, for compiling and editing mission data, for displaying error messages and generally to increase the integrity of the man-machine interface of the planning system itself. This is particularly important as it may be used under conditions of pressure.

The presence of a processor also means that the characteristics of different topographical maps, e.g. the grid system used, can be accommodated automatically. Maps produced to a range of scales and projections can be used in any area of the world. Different coordinate systems such as latitude/longitude, grid or bearing and distance can be accommodated.

The operational scope of such a system depends on several factors. The data assembled in the Portable Store can be transferred direct to the aircraft, and its scope depends in turn on the provisions included in the airborne mission computer and cockpit displays. Apart from the flight plan in terms of way points, intelligence information or information related to the weapon system as a whole can be included. There is also growth potential to interface a Mission Planning System with any suitable ground-based communication system: i.e. integration with [illegible]. A reverse mode of operation is possible in which in-flight information is loaded into the Portable Data Store for recovery after the mission.

Ferranti have now built several generations of these systems. It has been shown that, for success, several different requirements must be observed:

> The aircraft system, including the organisation of its computer, the way the displays are used and the pilots controls must all be configured to make use of stored information.
>
> The Mission Planning System must be specified for use with the aircraft and the capacity of the Portable Data Store must be specified as a result of examining the total system.
>
> The man-machine interface of the Mission Planning System itself must be designed to suit its operator's task, his experience and his total workload in Mission Planning.

Given these requirements it is possible to enhance the capability of existing or new avionic systems provided that they can accept an additional data store.

7. Pilot Factors In The Design Of Future Systems

This paper has referred to a number of areas in which the pilot's task is made more difficult when flying at night, or in low visibility, close to the ground. Figure 1 shows a Hierarchy of Pilot Tasks which, although highly simplified, can enable a more detailed consideration of the problem.

The tasks have been placed in order of the extent to which they require the pilot to exercise his highest faculties. Thus house keeping, or monitoring basic aircraft systems, is basically a routine task while controlling the aircraft is skilled but not complex in mental terms.

The central tasks, controlling sensors and acquiring or assessing information from them, occupy an area in which the workload can be expected to expand when flying at night. Information on threats or hazards can only come from sensors. Tactical Decisions and controlling the total avionic system are the essential part of controlling the mission and the essential reason for the pilot's presence.

In considering whether or how to apply automation several questions must be asked:

> To what extent is automation possible in a particular area?
>
> Can the task be automated so as to off-load the pilot completely or is intervention still required?
>
> [illegible] is an automatic solution possible at all?

[illegible] automatic flight control can remove the pilot from the loop provided that it has sufficient integrity. The problem is more to define the desired flight trajectory, a more complex problem than merely following a defined two-dimensional track or radio facility. Since navigation belongs in this area proper Mission Planning can improve this situation but a viable system of terrain avoidance is necessary. Many of these problems have also been dealt with in other papers about the Integration of Fire and Flight Control.

It is probable that, given a high integrity system, pilots will hand over to automatic control because the mental model required to monitor a flight control system is relatively simple. Much less is known about the mental model employed by pilots when operating through sensors and acquiring or assessing information. They must presumably have a picture of each sensor in terms of its mode of operation, ability to detect particular features, ability to produce misleading information under certain conditions. Thus the degree of sensor processing and automation required to produce a proper combination of pilot and system must be [illegible]. There will also be trade-offs between the cost of different system solutions and the extent to which they can reduce the pilot's workload.

[illegible] within a system concerned with tactical decisions, and the way a system is integrated to make it easy to control, both determine the possibility [illegible] the pilot's highest order functions. However the most promising [illegible] from the bottom upwards, re-assessing pilot [illegible] by automation of lower order functions.

[illegible] several ways of reducing pilot workload:

[illegible] the technology and the [illegible] relationships between pilot and [illegible].

[illegible] through high integrity systems.

[illegible] assessment of the information from [illegible].

[illegible] of high integrity unless it is [illegible] them and thus detect a fault. With [illegible] will become increasingly difficult [illegible].

[illegible]

[illegible] in low visibility pilot and [illegible] the hazards of operating near the ground [illegible]. The problem can be considered [illegible] of the flight path from the slightly [illegible] determine the best trajectory.

[illegible]

[illegible] him to steer the aircraft [illegible] detected by the navigation system [illegible] receives basic flight [illegible] altitude, speed etc. He can change his flight [illegible], the changes resulting in a flight profile [illegible] related to various hazards [illegible].

[illegible] from the terrain and also information about [illegible] which can either give him an enhanced [illegible] evidence of any dangerous proximity to the terrain.

[illegible] system can also be used in conjunction with stored data to prompt [illegible] the nature of the terrain ahead or any features which he should [illegible].

[illegible] short to medium term control of flight trajectory depends on [illegible] properties of the avionic system which are of greater importance [illegible].

[illegible] must be of sufficient accuracy and integrity [illegible] planned [illegible] dangerous extent [illegible].

> The basic display of attitude information must have a higher level of integrity because of increased dependence on the displays at *night* when there may be no visual horizon.
>
> If the sensors are to be used to pick up anticipated features or turning points the navigation accuracy *must* be such as to ensure that they appear within the sensor field of view.
>
> It is not possible to use a combination of navigation and stored data about the terrain as a means of hazard avoidance unless position and velocity are known with sufficient accuracy and integrity.

As the diagram shows the pilot will ultimately want to combine visual clues with information from sensors and stored data. This combination must deal with any errors in the different systems.

Figure 5 illustrates some longer term tactical considerations.

The pre-planned strategy in terms of a flight profile exists as the flight plan and supporting information received from the Mission Planning System before take-off. Without tactical intervention the pilot will fly this plan through the Navigation System and the information acquired at the planning stage is also essential when considering any tactical departure from the plan.

Some information about threats, hazards or possible changes of plan will reach the pilot visually but most will come through his communications or sensors. He may also have to take account of the status of the aircraft and its systems. All of this information must be handled and displayed in some way if he is to be able to take tactical decisions. The task of flying low at night compells the pilot to operate head-up as much as possible so that the information will have to be processed and displayed in the simplest possible form so that he can assimilate it rapidly and determine action. *He must* then be able to control the avionics in such a way as to change the demanded flight profile and then see immediately the implications of any change.

Therefore, at the tactical level, the main impact on the avionics concerns this need to bring information together and display it in a way in which it is readily apparent to the pilot and can facilitate his decisions. One possibility is that the stored flight plan may include some optional alternate routings which can be displayed together with the most critical items of information needed to assess them. These will include the latest information on any threats or hazards on an alternate route as well as the ability of the aircraft and its systems to carry out the change in terms of fuel, recovery to base etc.

It has been shown above that in the short term and in taking tactical decisions the pilot will depend on the core avionics to varying degrees. It is important that he should know whether any equipment or system failures have taken place which would change that dependence. This could be done by making failure warnings relate as much as possible to degradations in system capability as well as to the loss of particular functions or sensors.

The above have all related to an operation in which the pilot is in the short term control loop as well as taking longer term tactical decisions and being free to insert changed intentions into it. Various degrees of system automation would change this picture. Automation of flight path control near the ground would demand a failure survival system. The combination of visual clues and displays of flight information or information from sensors would then provide a monitor of the automatics. But the monitoring system would have to have an integrity at least as great as that of the automatics if failures in monitoring displays were not to run the risk of the automatics being disconnected unnecessarily. This balance may not be easy to achieve because the techniques for assessing the integrity of a fully automatic system and a pilot partially dependent on displays are different.

A different problem arises when considering a degree of automation of the merging and display of information from sensors and from the navigation system, either to give a synthetic picture of what lies ahead or for fault detection purposes.

Generally there are three levels of automation likely to change the pilot's role:

> Automatic flight control applied to the planned trajectory including avoidance of the terrain.
>
> Automatic mixing of sensor inputs and stored data to provide a synthetic display of what lies ahead.

Automatic presentation of alternative departures from the pre-planned strategy using stored information, information from communications or inserted pilot's intentions to allow tactical changes to be made.

Conclusions

The paper has dealt with some aspects of the automation of the pilot's task when flying at night or in low visibility, with particular emphasis on navigation and mission planning.

The following are the more important conclusions.

It is probable that automation will be applied progressively, starting with monitoring or control tasks which are relatively easy to define. Higher order tasks such as tactical decisions will be more difficult.

The navigation task starts at the planning stage, before take-off. Therefore minimising the total workload is likely to involve both tasks and the paper has described a typical Mission Planning System.

The mental model created by a pilot when control tasks such as flight path holding are automated is relatively simple. The model of a highly automated system processing sensor data or information from multiple sources and translating them into a form suitable for tactical decisions could be much more complex and there must be a match between the models used by pilot and system.

Any avionic system intended for continuous flight at night and at low altitudes will have requirements driven by certain features of this task. Basic flight information will have to be of high integrity and the accuracy of the navigation system, without pilot intervention will have to ensure that the pilot can readily correlate sensor or visual data with data generated within the aircraft.

The most important requirement will be to bring information together and display it in a way which can facilitate pilot decisions and permit choices between different tactical options without undue workload.

The author is grateful to his colleagues in Ferranti Defence Systems Limited for their help in the preparation of this paper and to the Company for permitting him to publish it.

FIGURE 1

TACTICAL DECISIONS AND CONTROL OF TOTAL SYSTEM

ACQUISITION/ASSESSMENT OF INFORMATION

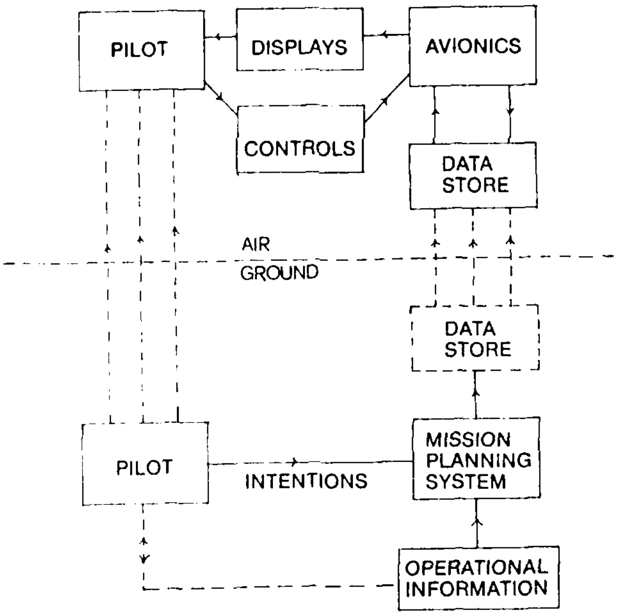
CONTROL OF SENSORS

PILOT IN LOOP CONTROL OF AIRCRAFT

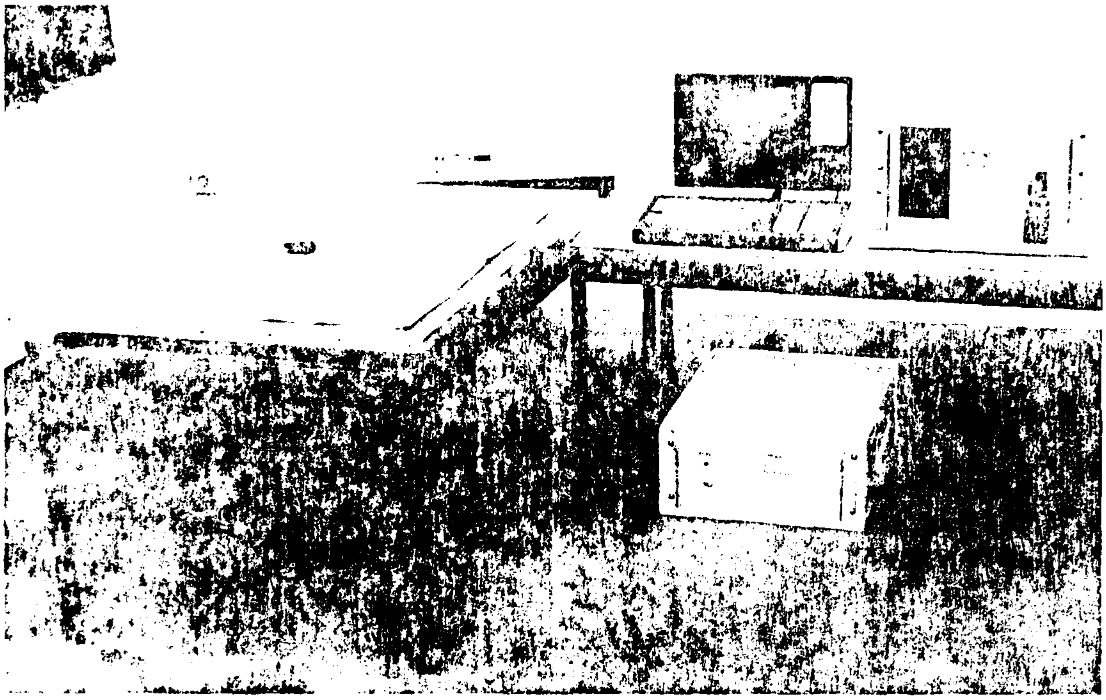
HOUSEKEEPING

HEIRARCHY OF PILOTS TASKS

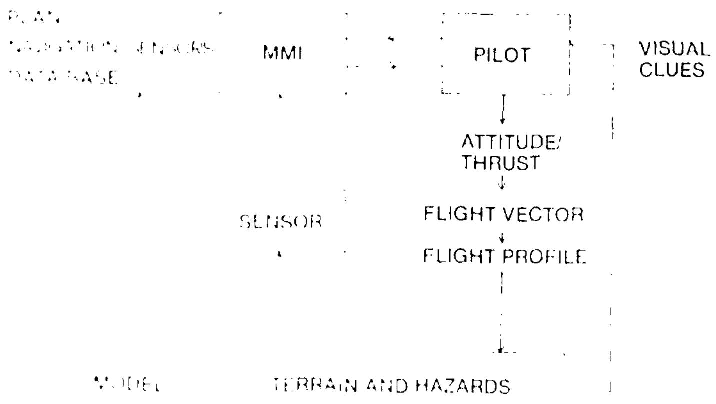
FIGURE 2



PILOTS RELATIONSHIP TO MISSION PLANNING

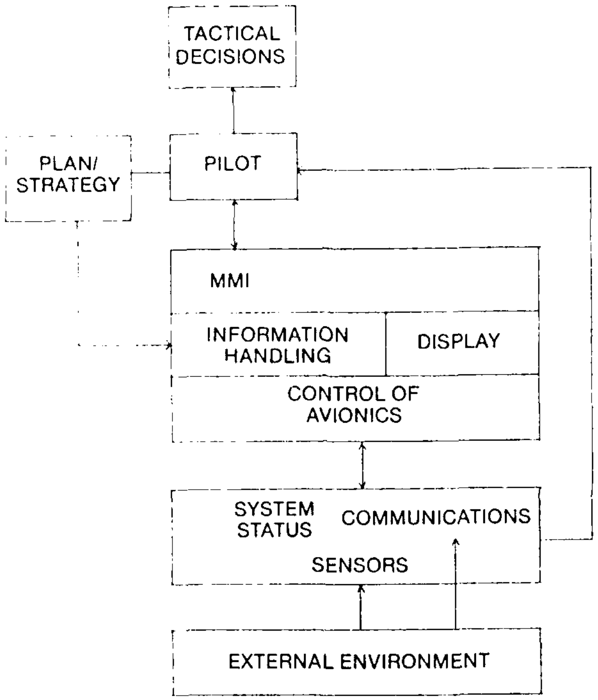


[illegible]



SHORT TO MEDIUM TERM FLIGHT PATH CONTROL

FIGURE 5



TACTICAL DECISIONS

SOME QUANTITATIVE METHODOLOGY FOR COCKPIT DESIGN

Charles Bates, Jr.
and
Maris M. Vikmanis
Human Engineering Division
Air Force Aerospace Medical Research Laboratory
Wright-Patterson Air Force Base, Ohio 45433

SUMMARY

The rapidly developing technology in sensor systems, microprocessors, artificial intelligence and communication systems has blurred the traditional lines between avionics subsystems and offers new design options for integrating the aircrew into the weapon system. These developments, together with the stressful flight regimes imposed by advanced threat systems and the night-in-weather environment required for survival in air-to-ground attack/interdiction, require new approaches to crew station design. These new design opportunities are limited only by the design tools and data bases available for their execution.

A simplified cockpit design process can be summarized as conceptual design, detailed design, and design verification. With the many tools needed to pursue this process the subset involving man/machine interface must provide a decision track quantifying and predicting the impact of design decisions on crew performance. To meet the objective of the full utilization of the weapon system crew, each technology option under consideration for incorporation in the cockpit must be judged with consideration of both mission and human performance. The cockpit design process must be embedded in an adequate human performance data base tailored for use by design personnel and must take full advantage of operational experience. The development of a family of cockpit design tools, together with the required data bases, has been one of the objectives of the Air Force Aerospace Medical Research Laboratory research program for the last five years. From this program a select set of methods will be described and examples provided.

INTRODUCTION

The cockpit by necessity has traditionally been the integrating focus of the aircraft. In the early days of aviation, it generally contained a single information port for subsystems and vehicle status and depended upon the pilot crew member to perform the integrating function. Indeed, in many instances the human sensory systems were the direct sensor system as in the case of the Wright Brothers when negative "G" was first experienced in the cockpit without a restraint system. This paradigm of a separate information port for each aircraft subsystem has persevered to this day albeit with increasing sophistication in displays and their information content; a very satisfactory solution in many instances when appropriately human engineered. The early work of Fitts and Simon (ref. 1) resulting in better alignment and altimeter design are excellent examples of parsimonious quantitative solutions to enhance crew member assimilation of large amounts of individually displayed data. Figure 1 is an example of this traditional approach to cockpit design and layout in a modern aircraft.

Two major developments are clearly demonstrating the deficiencies of this approach to cockpit design. We are forcing our aircraft into more hostile environments and flight regimes, e.g. night and in weather attack, and the tremendous strides in electronic technology present exciting new design options from the standpoint of information/display management and synthesis. Early applications of cockpit automation technology in the design of aircraft to operate in severe environments have resulted in reported workload problems apparently brought about by the subtle integration of information quantity, physiological stress and display media. In addition, piecemeal additions of avionics and weapon system capability have frequently been added to rather than integrated into the existing crew station.

Early, technology and weapon system requirements are forcing a whole new look at the cockpit design process. The emphasis must be on quantitative methods, structured traceability of design decisions and clear cost/performance trade-offs. It is the intent of this paper to present examples of the current technology of such methods, those that will be available in the near future, together with outyear objectives. The night in weather mission is generally accepted as one of the most difficult and is the framework around which the methodology discussed has been developed.

INTEGRATED PERCEPTUAL INFORMATION FOR DESIGNERS (IPID)

The development of data bases has traditionally not been a popular research and development endeavor. It is generally accepted in the scientific community that an extensive accessible data base is necessary for meaningful research and that such a requirement is the foundation for the engineering development of complex systems. Allen, in his excellent book on program management (ref. 2), demonstrated from his review of a number of research and development projects that engineers view and utilize data bases entirely differently from the scientific community; a perfectly understandable result of the rather well defined engineering discipline. However, the field of human

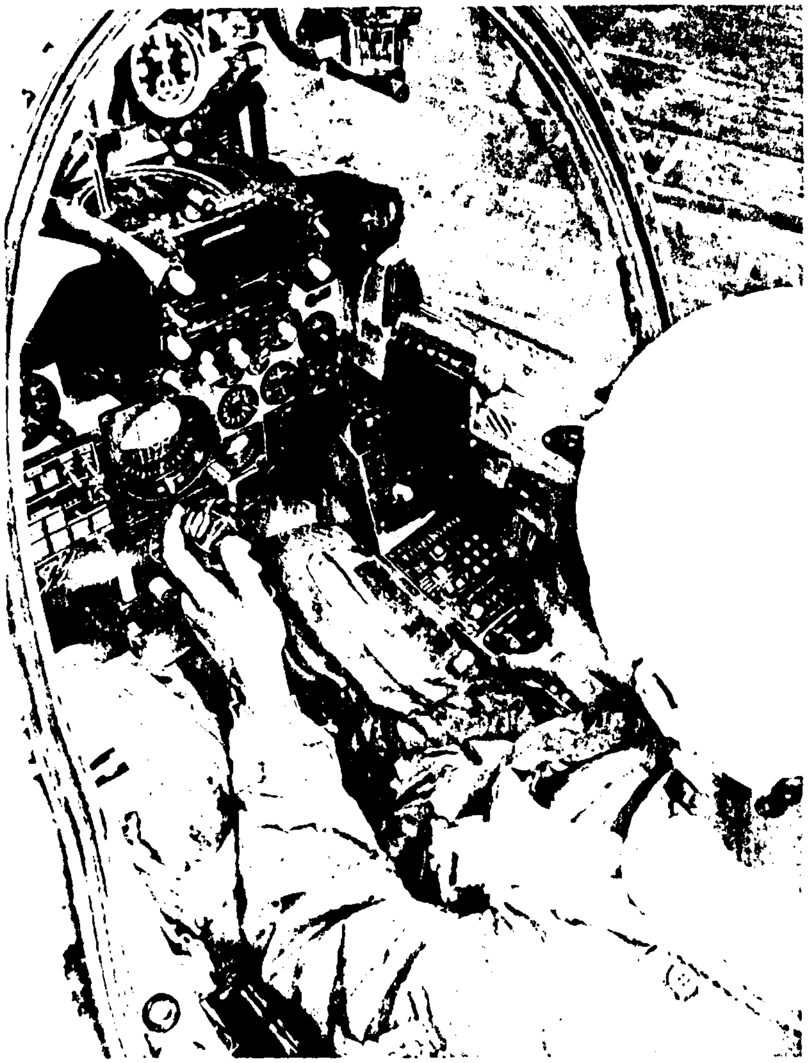


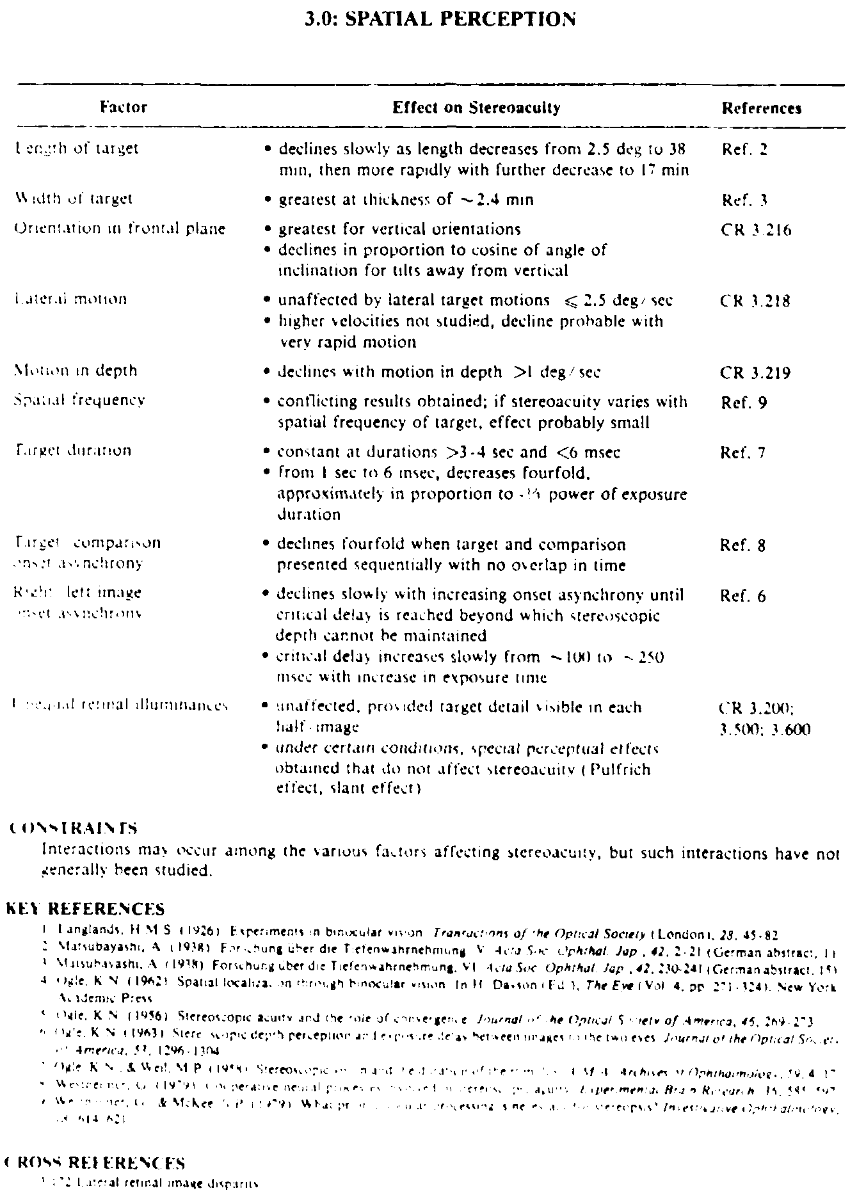
Figure 1.--A 1980's Cockpit

engineering must deal with fundamental data and design principles from experimental psychology, industrial engineering, physiology and aerospace medicine and, unfortunately, no practical multidisciplinary data base exists. Some excellent attempts have been made to provide human engineering data for designers, most notably, Tufts (1952 ref. 3), Heapy and Conway (1971 ref. 4) and Shurtleff (1980 ref. 5). Examination of the cockpit design process in the Air Force has revealed that most of these efforts have had little direct influence on cockpit design. The most probable reason for this fact is the degree of consideration given the human engineering of these data bases with respect to the needs of the intended user.

In order to provide a practical human engineering data base for use in conceptual and detailed crew station design, the Air Force Aerospace Medical Research Laboratory initiated the IPID project in 1979 (ref. 6). The objectives of this program were to first compile the appropriate human performance data germane to crew station and simulator design in a format that can be understood by the multidisciplinary design team required for crew station design. This fundamental data will take the form of a handbook of perception and human performance. This handbook will be composed of more than 40 subareas including visual, auditory, vestibular, workload measurement, performance modeling, etc., prepared by over 60 recognized experts in the various areas. Great attention has been paid to the format and organization of the data to enhance its accessibility. This two volume work of over 3,000 pages will be published by John Wiley and Sons in the summer of 1986.

The second phase of the IPID program is to take the data from the handbook, synthesize it into a problem oriented applied research format and index, cross-reference and organize it into an engineering compendium. Figures 2 and 3 illustrate typical data entries. This engineering compendium will take the form of a loose-leaf design guide with the ability for rapid updates. However, the feasibility of digitizing and further automation of the design compendium is being explored. Such a computer aided and accessed data base is certainly technically feasible and, in our opinion, has a high probability of achievement in the near future.

Throughout the IPID development process each step has been accompanied by a test and evaluation phase with engineers and typical crew station development problems. The data from these test and evaluation activities have been fed back into the development process in order to maximize the usability of both the handbook and compendium. The practicality of the data base is further tested by the formal participation of the U.S. Army, U.S. Navy and the National Aeronautics and Space Administration (NASA).



3.0: SPATIAL PERCEPTION

Factor	Effect on Stereoacuity	References
Length of target	• declines slowly as length decreases from 2.5 deg to 38 min, then more rapidly with further decrease to 17 min	Ref. 2
Width of target	• greatest at thickness of ~2.4 min	Ref. 3
Orientation in frontal plane	• greatest for vertical orientations • declines in proportion to cosine of angle of inclination for tilts away from vertical	CR 3.216
Lateral motion	• unaffected by lateral target motions ⩽ 2.5 deg/sec • higher velocities not studied, decline probable with very rapid motion	CR 3.218
Motion in depth	• declines with motion in depth >1 deg/sec	CR 3.219
Spatial frequency	• conflicting results obtained; if stereoacuity varies with spatial frequency of target, effect probably small	Ref. 9
Target duration	• constant at durations >3-4 sec and <6 msec • from 1 sec to 6 msec, decreases fourfold, approximately in proportion to -½ power of exposure duration	Ref. 7
Target/comparison onset asynchrony	• declines fourfold when target and comparison presented sequentially with no overlap in time	Ref. 8
Right/left image onset asynchrony	• declines slowly with increasing onset asynchrony until critical delay is reached beyond which stereoscopic depth cannot be maintained • critical delay increases slowly from ~100 to ~250 msec with increase in exposure time	Ref. 6
Unequal retinal illuminances	• unaffected, provided target detail visible in each half-image • under certain conditions, special perceptual effects obtained that do not affect stereoacuity (Pulfrich effect, slant effect)	CR 3.200; 3.500; 3.600

CONSTRAINTS

Interactions may occur among the various factors affecting stereoacuity, but such interactions have not generally been studied.

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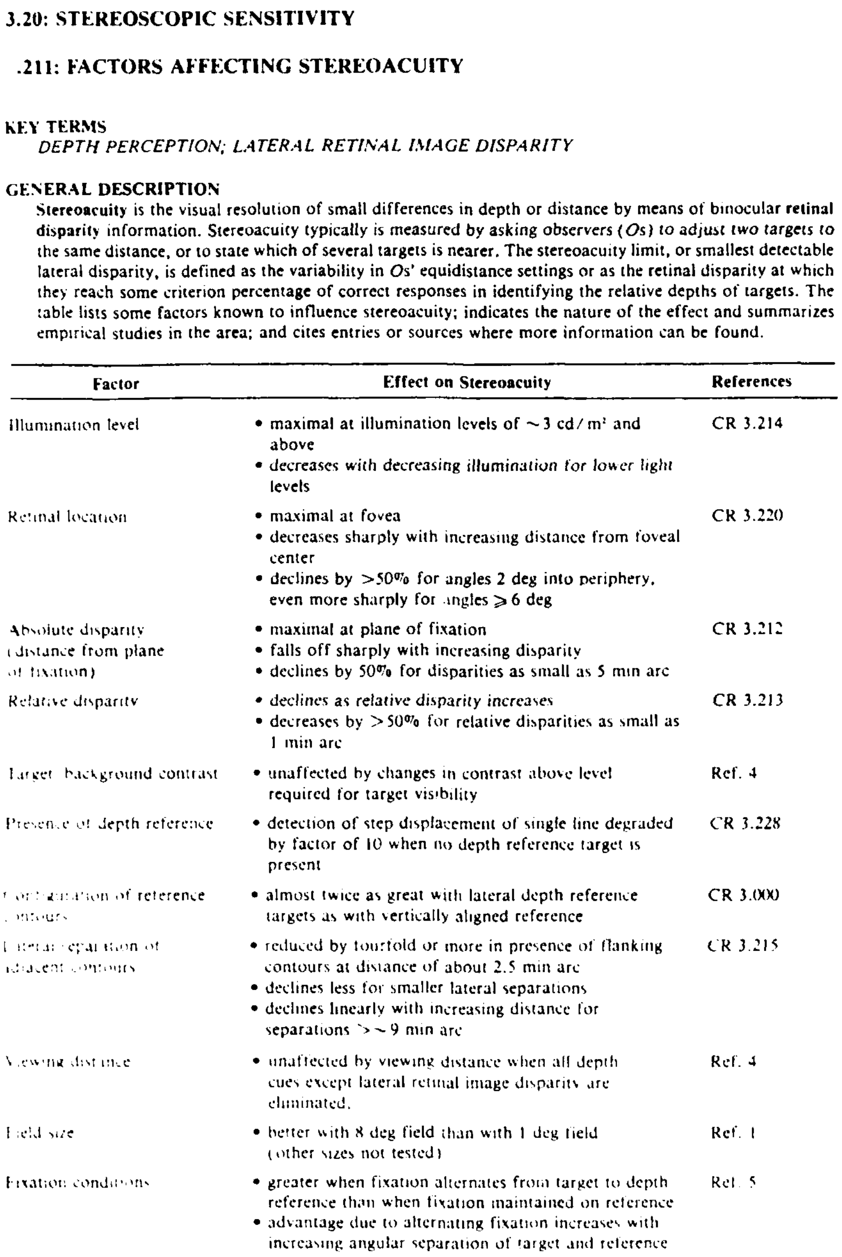
CROSS REFERENCES

3.172 Lateral retinal image disparity

Figure 2.--IPID Data Base Entry



3.20: STEREOSCOPIC SENSITIVITY

.211: FACTORS AFFECTING STEREOACUITY

KEY TERMS

DEPTH PERCEPTION; LATERAL RETINAL IMAGE DISPARITY

GENERAL DESCRIPTION

Stereoacuity is the visual resolution of small differences in depth or distance by means of binocular retinal disparity information. Stereoacuity typically is measured by asking observers (*Os*) to adjust two targets to the same distance, or to state which of several targets is nearer. The stereoacuity limit, or smallest detectable lateral disparity, is defined as the variability in *Os*' equidistance settings or as the retinal disparity at which they reach some criterion percentage of correct responses in identifying the relative depths of targets. The table lists some factors known to influence stereoacuity; indicates the nature of the effect and summarizes empirical studies in the area; and cites entries or sources where more information can be found.

Factor	Effect on Stereoacuity	References
Illumination level	• maximal at illumination levels of ~3 cd/m² and above • decreases with decreasing illumination for lower light levels	CR 3.214
Retinal location	• maximal at fovea • decreases sharply with increasing distance from foveal center • declines by >50% for angles 2 deg into periphery, even more sharply for angles ⩾6 deg	CR 3.220
Absolute disparity (distance from plane of fixation)	• maximal at plane of fixation • falls off sharply with increasing disparity • declines by 50% for disparities as small as 5 min arc	CR 3.212
Relative disparity	• declines as relative disparity increases • decreases by >50% for relative disparities as small as 1 min arc	CR 3.213
Target background contrast	• unaffected by changes in contrast above level required for target visibility	Ref. 4
Presence of depth reference	• detection of step displacement of single line degraded by factor of 10 when no depth reference target is present	CR 3.228
Configuration of reference contours	• almost twice as great with lateral depth reference targets as with vertically aligned reference	CR 3.000
Lateral separation of adjacent contours	• reduced by fourfold or more in presence of flanking contours at distance of about 2.5 min arc • declines less for smaller lateral separations • declines linearly with increasing distance for separations >~9 min arc	CR 3.215
Viewing distance	• unaffected by viewing distance when all depth cues except lateral retinal image disparity are eliminated.	Ref. 4
Field size	• better with 8 deg field than with 1 deg field (other sizes not tested)	Ref. 1
Fixation conditions	• greater when fixation alternates from target to depth reference than when fixation maintained on reference • advantage due to alternating fixation increases with increasing angular separation of target and reference	Ref. 5

Figure 3.--IPID Data Base Entry

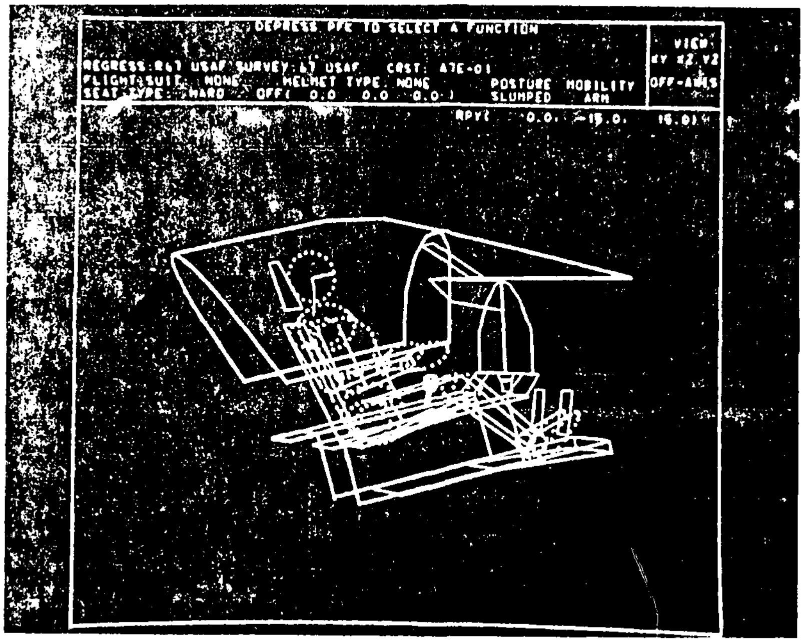
Computerized BioMechanical Man Model (COMBIMAN)

Traditionally conceptual crew station design has been performed using a three-dimensional physical mock-up. The basic dimensions for reachability of controls and line-of-sight to displays can be specified through actual testing with representative subjects. This method, however, was inherently limited because of the difficulty in obtaining subjects with the desired body-size characteristics to properly fit the required range of user population.

Computer modeling and graphics offer an effective alternative to the traditional physical mock-up. The Computerized BioMechanical Man Model (COMBIMAN) (ref.) developed at AFAMRL has gained wide acceptance by the aircraft design community. It allows the construction, manipulation and evaluation of three-dimensional models of crew stations. In addition, a geometric representation of the human operator based on anthropometric data is used to evaluate interactions with the crew station designs.

A number of crew station design features can be interactively assessed with COMBIMAN's graphics capability. They include physical size accommodation, visual accommodation, reach accommodation, and operator strength compatibility. The first area refers to operator fit and body clearance in the crew station. Visual field accommodation refers to analysis of line-of-sight with displays and outside the cockpit windscreen. Reach accommodation refers to the ability to operate the necessary controls. This is also combined with the operator strength compatibility analysis to ensure ease of usage.

COMBIMAN programs are coded in FORTRAN IV and are compiled with an IBM FORTRAN G compiler. The IBM System/360 Operating System Graphics for FORTRAN IV is used to generate the CRT graphics. Versatec VERSAPLOT-07 software is used for on-line plotting. The COMBIMAN program uses about 650K bytes of storage and at least 20K bytes of graphics buffer. Six external data sets on disk are used for Input/Output operations. A typical CRT display is shown in fig. 4. The above specifications are for version 6 of COMBIMAN which was released in 1984. Further improvements are planned in particular to the anthropometric data bases and graphics capabilities.



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DEPRESS PFK TO SELECT A FUNCTION
REGRESS:R67 USAF SURVEY:67 USAF   CRST: A7E-01
FLIGHT SUIT: NONE    HELMET TYPE: NONE        POSTURE  MOBILITY
SEAT TYPE: HARD   OFF( 0.0   0.0   0.0 )      SLUMPED    ARM
                                RPY(   0.0, -15.0,   15.0)
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Figure 4. COMBIMAN CRT Display with Man-Model and A7E-01 Crew Station Rotated -15 Degrees in Pitch and 15 Degrees in Yaw.

Workload Assessment

The final phase of the simplified cockpit design process is design verification. This phase has historically been neglected, partially because the proper quantitative methods have not been generally available. Also, the less complex aircraft systems of the past allowed design flaws to be more easily overcome by the adaptive nature of their human pilots. Now, however where difficult missions require complex capable aircraft, cockpit design and integration errors must be minimized before final design and production decisions are made. This verification must include both system measures of effectiveness and importantly pilot performance and workload.

In this paper we will concentrate on recent developments to measure operator workload. The concept of workload stems from the psychological construct that humans possess various mental resources which are depleted during the performance of tasks. The goal of measurement is then to tap the appropriate resources within a person to estimate how much of these resources are expended and their interaction with task demands and response variables.

The measurement of pilot workload is particularly important in the context of the theme of this symposium. It is recognized that night all-weather tactical missions pose high workload and stress conditions on pilots. Technological developments in the areas of guidance, control and navigation automation afford opportunities to reduce this workload and improve the effectiveness of the overall aircraft system. However, as discussed earlier, the pilot interface with these automated systems, indeed even the choice of what to automate, must be carefully human engineered.

Underscoring the importance of workload assessment in the design of cockpits are some of the potential pitfalls of interfacing pilots with automation. It is likely that as functions are automated in aircraft systems pilots will still be responsible for monitoring the health and status of this automation. The attention required for this will naturally result in a workload penalty which must be evaluated with respect to the benefits of the automation. Pilots must also maintain their situation awareness and system confidence to perform effectively. This requires the use of resources as well and may become more difficult when some functions are automated.

A comprehensive set of operator workload measures has been developed over the last five years at the Air Force Aerospace Medical Research Laboratory. They have fallen into the three general categories of subjective, behavioral and physiological measures. The development of these improved measures are individually significant to design and performance assessment problems, however, their utility is magnified when combined with a framework on how and when to use them. Research efforts at our Laboratory have focused on providing this measurement framework as well as the equipment, software, and procedures for use in simulation and field settings.

In assessment of operator workload levels related to guidance-control-navigation automation for night all-weather tactical operations, a multi-stage process will be used. First, broadly based measures such as performance timeline analysis and subjective opinion will be used to focus further study and identify specific problem areas. This initial screening will uncover workload "choke-points," potential operator overload with degraded performance, that will then be more intensively studied using specific subjective, behavioral and physiolgoical measures. Results of these studies will then be used diagnostically to refine crew station designs and perhaps re-examine the functional allocation of automation in the overall aircraft system. We will now describe the details of the specific subjective, behavioral and physiological measures that have been developed.

1. Subjective Workload Assessment

First is the use of subjective judgement as a measure of operator workload. Recent trends in the psychological literature support the inclusion of subjective techniques as an important element of an overall workload assessment methodology (ref. 8). This position stems basically from the conclusion that if an operator feels loaded and must use considerable effort while performing his tasks he really is loaded and effortful. This is true despite the actual measured performance level of his tasks because, prior to actual performance degradation, subjective feelings indicate the added effort that is being expended. Subjective measurement techniques also offer the potential of being relatively nonintrusive to the performance of the primary mission tasks and can be easily implemented in complex simulation or actual operational setting. In any case, however, it must be emphasized that subjective measurement is part of an overall system of workload assessment and is not necessarily used as the sole technique.

The Subjective Workload Assessment Technique (SWAT) (ref. 9) has been developed at the Air Force Aerospace Medical Research Laboratory and has gained wide acceptance and usage throughout the United States and allied nations by both researches and weapon system developers. SWAT uses a psychometric technique called conjoint measurement to construct interval workload scales from ordinal rankings of subjective load levels. This has solved some of the historic problems with subjective assessment that suffered from limitations because of nonstandardized scales. With conjoint measurement only the ordinal relationship of the data is required to produce an interval scale. Also the joint effects of several factors are represented algorithmically by rules that are directly identified from the subjective data. The power of this technique has significant advantages over the strictly ordinal results that were obtained from subjective opinion in the past.

The rating factors that have been included in SWAT are adopted from a theoretical framework developed by Sheridan and Simpson (1979 ref. 10) for workload assessment. These dimensions are time load, mental effort load and psychological stress. It is assumed that subjective workload can be represented by a combination of these three dimensions. The definitions of the three dimensions as well as the levels that are solicited subjectively are as follows:

Time Load

1. No or very few interruptions in the planning, execution, or monitoring of tasks. Spare time exists between many tasks.

2. Task planning, execution and monitoring are often interrupted. Little spare time. Tasks occasionally occur simultaneously.

3. Task planning, execution and monitoring are interrupted most of the time. No spare time. Tasks frequently occur simultaneously. Considerable difficulty in accomplishing all tasks.

Mental Effort Load

1. Little conscious mental effort or planning required. Low task complexity such that tasks are often performed automatically.

2. Considerable conscious mental effort or planning required. Moderately high task complexity due to uncertainty, unpredictability, or unfamiliarity.

3. Extensive mental effort and skilled planning required. Very complex tasks demanding total attention.

Psychological Stress Load

1. Little risk, confusion, frustration, or anxiety exists and can be easily accommodated.

2. The degree of risk, confusion, frustration, or anxiety noticeably adds to workload and requires significant compensation to maintain adequate performance.

3. The level of risk, confusion, frustration, or anxiety greatly increases workload and requires tasks to be performed only with the highest level of determination and self-control.

Procedures for the application of SWAT have also been developed and validated. As an example, consider the evaluation of a particular automation/cockpit configuration in a piloted aircraft simulator. Once the subject pool has been identified and briefed on the purpose of the study, they are asked to develop an overall ranking of the combined workload factors. That is, the 27 combinations of workload level and dimension are ranked to produce a scale that represents the joint effect of time load, mental effort load, and psychological stress load. These results are then used to develop the overall interval workload scale. SWAT applications to date have shown that subject ranking data can be grouped into three clusters representing individuals that weigh time, mental effort or psychological stress load more heavily. Conjoint scaling routines are then used to derive numerical values for each combination of levels that preserve the original ordering.

Next the actual event scoring phase of SWAT can be accomplished. Some preplanning is required to determine what mission phases and tasks should be scored. Ratings should be taken temporally as close to these as possible. During the actual simulator experimental run, the pilot would be asked to rate each of the three load dimensions for the event of interest. The actual administration should be planned so that it does not interfere with the mission tasks and events. The scale value solicited then becomes the actual subjective workload score for that event.

SWAT has also been used in two alternate modes that prove very useful. Reflective SWAT (ref. 11) is used after experimental runs and is usually combined with post-trial interviews where subjects are asked to reflect on particular events. This allows rating of events that could not be obtained in real-time. Secondly, SWAT has been used successfully in a projective mode as well (ref. 12). This is the case when a system does not exist and subjects are asked to rank workload for hypothetical systems and situations. Projective SWAT is a powerful tool for obtaining estimates of workload during concept definition and early design of avionics and cockpit configurations. Projective ratings have agreed well with eventual piloted simulator data.

Applications of SWAT have been numerous within the Air Force and aircraft industry. Notably it has recently been used to select from among control/display alternatives for implementation in a transport aircraft. Also initial German and French versions have been developed. Further improvements to SWAT procedures and software are being developed at the Air Force Aerospace Medical Research Laboratory. Two areas receiving attention are additional validation of projective SWAT because of its potential importance to the evaluation of Air Force weapon systems early in development, and automated support for SWAT application and analysis.

2. Behavioral Workload Assessment

The second major category of operator workload assessment technique being investigated at the Air Force Aerospace Medical Research Laboratory is behavioral. As the name implies this involves direct measurement of pilot performance, usually in terms of time and error to perform certain tasks. Workload investigators have historically used a technique known as secondary task as a measure of primary task workload. In this approach a pilot is given a task unrelated to his mission responsibilities, for example a tracking task. Then as the pilot performs his primary mission tasks, changes in workload are detected by changes in performance of the secondary task. This technique stems from the multiple resource theory of human cognitive processing (ref. 13). A variation of this approach called embedded secondary task uses one of the routine mission tasks as the actual secondary task. This has obvious advantages because it is nonintrusive.

The techniques mentioned above have historically lacked a cognitive process framework in selection of the secondary tasks and interpretation of performance results. Research at our laboratory has resulted in the development of the Criterion Task Set (CTS) Resource Framework to address this problem (fig. 5) (ref. 14). The CTS model defines three stages of processing for input, central and motor output resources (ref. 15). Each stage is also associated with appropriate modes for input (visual/auditory), output (manual/vocal) and the central processing code (spatial/symbolic). The central processing stage is furthermore subdivided into a working memory and three different levels of central decision activity.

The CTS framework has rapidly gained acceptance by both researchers and applied performance analysts as a useful tool for organization of human performance studies. It is being considered as a possible international standard and is currently a major part of a Tri-Service performance battery for the assessment of chemical defense pretreatment drugs.

In terms of automation for tactical aircraft operations the CTS is not just a measurement framework. When combined with the subjective techniques discussed earlier and the electrophysiological measures that will be described next, the CTS provides insight into which operator resource pools (that is, input, output, central) are being tapped by scenario demands and also the control/display and automation configuration. Thus further insight into the cause of potential workload choke points can be obtained for the purpose of evaluation of cockpit design and impact of automation on the pilot.

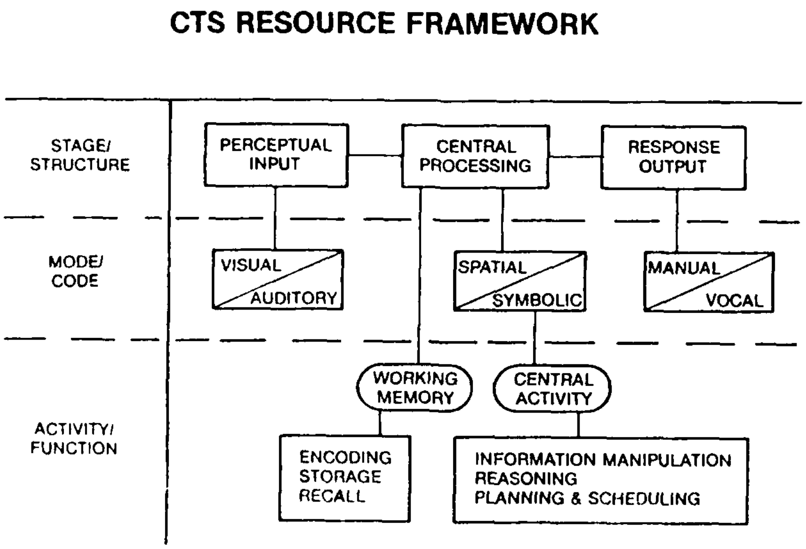

Figure 5. CTS Resource Framework

3. Electrophysiological Workload Measures

The third major category of workload measurement technique to be presented is electrophysiological. In the past physiological measures of performance, stress and workload have not been very successfully applied. The primary problem was that all measures were somewhat equated in terms of providing an overall level of "arousal" or "activation level." Experimental results were therefore inconsistent depending on task and environment. More recently, however, studies have indicated that specific psychological functions are reflected by certain physiological measures. The Air Force sponsored a large number of studies to further validate this construct. A final set of six electrophysiological measures was selected and built into a hardware measurement system called the Neurophysiological Workload Test Battery (NWTB). The NWTB provides an easy to use workload measurement system for general laboratory, simulator and limited field assessment of workload. Of particular importance is to provide sufficient automation and explanation so that the system can be widely used by other than psychophysiology experts. To achieve this goal the initial version of the NWTB is currently being validated on contract with a major aircraft manufacturer. Guidelines for application of the individual measures to specific design, evaluation and simulation problems will result as well as suggestions for improvement for a next generation measurement system. A brief description of the specific tests implemented on the NWTB follows.

First is the Transient Cortical Evoked Response. This represents the brain's response to a slow rate (below 1 hertz) discrete stimulus such as on auditory or visual input. In medical terminology this measured activity is called the electroencephalogram. The measured waveform has several peaks, the early peaks correlate with human sensory function, while the later components are associated with central and output processing. The P3 (or P300) peak is most highly correlated with mental workload and decreases in amplitude as cognitive processing load increases. To acquire the signal surface electrodes are pasted to several locations on the scalp.

The second category of tests is the Steady State Evoked Response. Here the brain is stimulated more rapidly (faster than 4 hertz) and eventually reaches a steady state so that electrical activity at the same frequency as the input signal can be measured. Phase lag measures and calculation of the latency of the visual system indicate that the Steady State Evoked Response is useful as a measure of sensory system workload. Surface scalp electrodes are again used to gather this data.

Next, the NWTB also measures eye movement and blink pattern data. The eye blink frequency has been shown to be indicative of operator attention and fatigue or long-term workload. Basically, a more demanding task requires increased operator attention and, thus, data indicate that blink frequency decreases. Preliminary evidence also shows a comparable decrease in blink duration based on the same rationale. This data is gathered again by electrodes placed above and to the side of the eyes (often called the electro-oculograph).

A measure of muscle activity is also included in the NWTB to monitor physical workload. Electrical signals measured by electrodes are used to assess overall muscle fatigue such as may be encountered in a difficult tracking or manual control task.

The final type of measure included in the test battery is the electrocardiogram (EKG) which is also acquired through the use of surface electrodes. To date, preliminary data indicate that cardiac variability holds promise as a measure of cognitive workload.

From the brief summary of the electrophysiological measures described above, the importance of the validation effort is underscored. That is, procedures for when and how to apply the measures are necessary to effectively evaluate workload levels imposed by crew station configurations. The neurophysiological measures in particular offer the potential to evaluate fine grain performance associated with particular control, display and automation alternatives. Plans for the next three years include the development of an advanced battery suitable for field test and airborne applications.

COCKPIT AUTOMATION TECHNOLOGY (CAT)

As you can see from our previous discussion, it is our opinion that the technology must provide a comprehensive data base and individual design methodology for the solution of specific problems, e.g., COMBIMAN, but this, of course, is not enough. An overall design methodology is required that provides structured quantitative traceability of design decisions usable throughout the development process from conceptual design through the inevitable modification programs. To provide this design process the United States Air Force instituted the Cockpit Automation Technology (CAT) advanced development program. If successful, this program by 1989 will provide a basis for the standardized crew station design process for use by government and contractor personnel which will reduce overall development risk and result in optimized cockpit design. Most importantly the process will integrate into a unified system including all air vehicle subsystems, e.g., avionics, armament, propulsion, flight control, life support and escape, etc., insofar as they impinge on the cockpit design. Once the methodology is developed in phases one and two of the program a specific cockpit crew system will be designed, mechanized and demonstrated utilizing ground based man-in-the-loop full mission simulation to test the practicality and goodness of the process. The night in weather air-to-ground mission will be the focus of this test crew system and will, hopefully, represent a point of departure for future designs in this difficult mission area. A similar point design will be developed for the air-to-air combat mission in a subsequent phase of the program.

The Cockpit Automation Technology program is contractually structured to ensure the appropriate multidisciplinary skills are brought to bear on the problem. In phase one of the program, three contract teams are employed utilizing a combination of airframe companies, avionics developers, analysis/modeling houses, and human engineering organizations. These three teams of primary/subcontracting groups are providing the skills and technology sets necessary for a unified design process and have already resulted in some promising synergistic integration of design approaches.

The Cockpit Automation Technology design process, including the design procedures, individual design tools, data bases, human performance metrics and models will be implemented to the extent practical using computer aided design and engineering (CAD/CAE) to improve both the efficiency and the technology transition of the process to the varied design community involved. The Cockpit Automation Technology Program will complete phase one in 1985 with the development of the three competing design processes. Phase two of the program beginning in 1985 will fund two independent development efforts to further develop the design methodology and provide the above discussed point design. Phase three of the program to be completed in 1989 will take the best process/point design and accomplish an evaluative man-in-the-loop simulation with simultaneous translation of the design process into a computer aided design system. Once such a system is in place, it is anticipated that both user experience and technology push will require its periodic refinement and approaches to accomplish this very necessary function are currently in planning.

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PRESENTATION DE RELIEF SYNTHETIQUE EN TEMPS REEL

POUR LES MISSIONS AEROPORTEES TOUS-TEMPS

J.N. BOTELLA
THOMSON-CSF
31, rue Camille Desmoulins
92132 ISSY LES MOULINEAUX
FRANCE

RESUME

Dans le cadre des missions aéroportées tous-temps, il s'avère nécessaire de donner au pilote des informations sur le monde extérieur, même et surtout en l'absence d'informations des capteurs radar ou optroniques. Le développement des banques de données numériques altimétriques amène THOMSON-CSF à étudier la présentation d'un relief synthétique dans un cockpit. L'étude des diverses mémoires de masse montre qu'un film couleur a des capacités de stockage remarquables. Les données altimétriques sont stockées sur un film qui est lu par le lecteur MERCATOR (dont la vocation initiale est la lecture d'images cartographiques). Les algorithmes de synthèse 3D utilisés profitent des possibilités exceptionnelles que permet l'analyse du MERCATOR. Cette étude montre comment un produit unique, le lecteur cartographique MERCATOR, destiné à présenter des images planes, est utilisé pour réaliser des visualisations tridimensionnelles de terrain.

1.0 INTRODUCTION

Le département Avionique générale (AVG) de THOMSON-CSF, division AVS, produit, en particulier, les tableaux de bord EFIS des AIRBUS A310 et A320, les systèmes de visualisation du Mirage 2000 et de l'Atlantique nouvelle génération. Ont été également développés les lecteurs cartographiques couleur ICARE puis MERCATOR. Ils visualisent sur un écran cathodique couleur la carte choisie, ainsi que diverses informations de navigation et de pilotage. L'étape suivante consiste à présenter une image synthétique perspective. Le système que nous allons décrire est directement issu de MERCATOR dont il reprend les éléments principaux, nous y reviendrons. Son but : construire un paysage synthétique. Précisons tout d'abord le rôle que nous voulons attribuer à cette image.

1.1 ROLE D'UNE IMAGE SYNTHETIQUE DE PAYSAGE

On peut être tenté d'utiliser une image synthétique générée en temps réel et projetée en tête haute pour compléter le paysage de détails importants qui ne sont pas visibles soit pour des raisons de météorologie ou de niveau lumineux (vol de nuit), soit pour des raisons de masquage par le relief. On conserve ainsi les réflexes de pilotage du vol à vue, tout en donnant confiance au pilote par la superposition des images. Ceci est raisonnable pour des symbologies telles que les pistes artificielles destinées à guider le pilote et que l'on peut superposer au paysage extérieur, via une visualisation tête haute. Mais les primitives graphiques de ces «objets» sont le plus souvent extrêmement simples (rectangles) ; et les appareils de localisation utilisés (radiolocalisation d'approche) sont très précis.

Il est beaucoup plus délicat de superposer un paysage synthétique construit à partir d'une banque de données altimétriques et du système de navigation embarqué. Et ce, pour des raisons de confiance dans l'information présentée. En effet, une erreur minime sur le positionnement de l'aéronef, ou sur une des altitudes stockées, peut se traduire par une image perspective éloignée angulairement de l'image réelle, surtout sur les plans de vision proche. La cause en est le principe même de la projection perspective : l'image d'une erreur (en altitude par exemple) se traduit à l'écran par une erreur inversement proportionnelle à la distance de l'observateur au point où se situe l'erreur.

Enfin, n'oublions pas l'incertitude due à la couverture végétale.

Donc, nous pensons pour l'instant, que ce type d'images ne doit pas être présenté en tête haute. Il peut néanmoins servir à l'aide au pilotage, en tête basse, en prenant en compte l'enveloppe des erreurs possibles, surtout avec les nouveaux systèmes de navigation dont la précision s'améliore énormément grâce aux recalages automatiques. Il est aussi très utile pour l'aide à la prise de décision. Dans ce but, on peut proposer plusieurs types d'images :

l'observateur est situé à la position avion, le champ de l'image est large, et la direction de vision au choix. Une vision faible champ (zoom) peut être présentée dans toute direction,

l'observateur est situé à la position de l'avion, mais à une altitude supérieure. On présente dans ce cas la scène que le pilote a ou devrait avoir sous les yeux vue d'une position plus élevée. La visualisation de la route à suivre ou des objectifs sol est facilitée,

on supprime sur le paysage de synthèse les premiers plans. Les zones qu'ils cachaient sont alors visibles.

D'autres fonctions d'aide à la décision pourront être ajoutées.

Toutes ces présentations peuvent être effectuées à partir du point actuel, ou, par exemple, à partir d'un point futur correspondant à une phase critique de la mission.

1.2 AUTRES SYMBOLOGIES

Notre propos n'est pas de les décrire. D'autres auteurs l'ont fait et l'originalité de notre travail est ailleurs. Cependant rappelons que l'on peut superposer aux images générées des figurations graphiques visualisant en 3D les zones dangereuses (présence de batteries ennemies), la route de sécurité maximale, etc... Précisons seulement que la méthode de stockage et d'accès aux données altimétriques que nous allons exposer facilitera grandement le positionnement de ces informations.

2.0 MERCATOR

Etudions brièvement l'indicateur cartographique MERCATOR (figure 1). MERCATOR est un analyseur de film couleur à spot mobile (flying spot).

Le contenu du film (une carte, et, plus généralement, toute image) est affiché sur un tube cathodique couleur. Chaque position du spot du tube d'analyse à large bande spectrale «éclaire» le point étudié du film. Le rayon correspondant traverse le film, puis est décomposé en ses trois composantes : rouge, vert, bleu, par le séparateur trichrome. Les trois photomultiplicateurs terminent la chaîne d'analyse. L'intérêt principal d'une analyse de film par spot mobile est que de simples modifications du balayage réalisent des rotations ou des zooms des images visualisées. Il suffit d'appliquer une rotation ou un facteur d'échelle au balayage de type télévision du tube d'analyse. Le seul sous-ensemble mécanique de MERCATOR asservit l'avance du film.

3.0 LA MEMOIRE FILM

3.1 INTERET DE LA MEMOIRE FILM

Dans MERCATOR, le film mémorise la carte sous la forme de son image. Le film est en effet un moyen de stockage d'informations remarquable tant sur le plan volume/poids que capacité. Le tableau I le montre. Il *compare les mémoires habituellement utilisées, à une* bobine de 17 m de film.

Deuxième point important : le film est une mémoire bidimensionnelle. Chaque point est accessible aléatoirement. Il est possible de lire les données séquentiellement le long de toute droite. Il suffit pour cela que le lecteur à spot mobile suive cette droite.

Synthétiser un paysage nous permet de tirer pleinement parti de cette mémoire surfacique en mémorisant sur le film, non plus une carte, mais des données altimétriques.

TABLEAU I : RECAPITULATIF DES MEMOIRES DE MASSE

TYPE	LIMITATIONS
Mémoires électroniques	1 boitier = 1 Mbits (épaisseur estimée avec support à 10 mm) 10 Gbits = 10000 boitiers et 1,25 kW en moyenne
Bulles magnétiques	1 boitier 5" x 5" = 4 Mbits (45 x 15 x 5 mm) 10 Gbits = 2500 boîtiers et 1,2 kW en moyenne
Disques magnétiques	1 disque de 200 mm = 100 Mbits (non formaté) sur deux faces 10 Gbits = 100 disques
Bandes magnétiques	Toute la bande défile en au moins 6 min. 300 kbits/pouce**2 10 Gbits = 3000 m de bande (une bobine de 15")
Video disque	Militarisation à faire 10 Gbits = 1 disque de 300 mm (1,25 disque de 200 mm)
Film photo	9,7 Mbits/pouce**2 10 Gbits = 17 m de film

3.2 STOCKAGE D'ALTITUDES SUR UN FILM

Nous disposons des fichiers *altimétriques* numériques réalisés par IGN (Institut Géographique National). Ce sont des fichiers maillés. C'est-à-dire que les altitudes du terrain sont données selon un maillage tracé sur le sol. IGN code les altitudes sur 16 bits.

Nous établissons une correspondance surfacique entre chaque point du fichier et le film. Chaque pixel du film est impressionné de telle sorte que ses pigments portent l'information altitude du point correspondant du fichier.

Pour cela, les altitudes sont transcodées en une table de transparence dans chaque couleur, rouge (R), vert (V), bleu (B). Donc à *chaque altitude correspond un triplet* de transparences R, V, B. Le film est réalisé afin que ce triplet soit retrouvé à l'analyse et, ainsi, fournisse par décodage une altitude.

Le codage choisi utilise quatre niveaux dans le rouge, huit niveaux dans le vert et huit dans le bleu, soient 256 altitudes possibles.

Le diamètre du spot d'analyse provoque un effet d'interpolation entre pixels ; *notre code doit en tenir compte pour préserver* la cohérence de l'analyse. Cette interpolation sera utile par ailleurs.

4.0 TRACE DU RELIEF

4.1 TYPE D'IMAGES

Le type d'images que nous avons choisi est adapté au système de lecture des données. Il s'agit d'images lissées et ombrées. Il est également possible de générer uniquement les lignes de crêtes «observées». C'est en fait les points du terrain à la frontière des parties vues et cachées. De même on peut choisir de tracer des coupes de terrain.

4.2 CONCEPT DE BASE

Dans ce qui va suivre, nous supposons une vision horizontale. L'image perspective est construite sur un écran de 512 lignes et 512 colonnes, couvrant un champ de D degrés.

Considérons une ligne radiale tracée sur le terrain (voir figure 2). Elle relie la position de l'observateur, projetée au sol, à un point situé à la distance de vision maximale. De plus, elle appartient au secteur S, projection au sol de la pyramide de vision. La transformation perspective (transformation qui projette tout point du sol sur l'écran) de tout point de cette radiale se trouve sur une colonne de l'écran. Ce fait, lié au système de balayage du lecteur à spot mobile, simplifie grandement le processus de calcul. Le spot décrit les 512 radiales nécessaires sur la banque de données, comprises dans un secteur de D degrés, chaque radiale servant à construire chaque colonne de l'écran.

Modifier
    le champ d'observation,
    la direction d'observation,
    la distance maximale de vision,
revient à modifier uniquement le balayage du tube d'analyse.

La transformation perspective elle-même, se termine par le calcul de la hauteur dans l'écran de chaque point échantillonné sur la radiale. C'est un simple calcul de tangente (voir figure 3).

4.3 TRACE DE L'IMAGE

4.3.1 OMBRAGE ET LISSAGE

L'aspect final de l'image et la compréhension de la perspective dépend de cette opération.

4.3.1.1 Ombrage (voir figure 4)

Nous disposons une source fictive de lumière (soleil) qui éclaire le paysage et, donc, le rend intelligible. On calcule alors la luminance à attribuer à chaque point du champ de vision.

Pour ce faire, on évalue le vecteur normal au point du terrain considéré.

Deux radiales successives sont nécessaires, sur lesquelles on utilise les trois points A, B et C (voir figure 2). A est le point courant. Le triangle ABC constitue une facette dont l'inclinaison est déterminée par le calcul de son inclinaison latérale (suivant AC) et de son inclinaison longitudinale (suivant AB).

Ces deux données et le vecteur soleil permettent le calcul de la luminance du point A (produit scalaire du vecteur normal à la facette par le vecteur soleil), en supposant que l'albédo est constant dans la pyramide de vision.

Pour simplifier le calcul, on place la source de lumière sur la verticale au point d'observation. Le vecteur soleil en chaque point observé est contenu par le plan vertical de la radiale associée.

Nous savons donc calculer la luminance de la transformée écran de chaque point du terrain.

4.3.1.2 Lissage (voir figure 5)

D'une radiale à l'autre, le lissage est naturellement réalisé par l'interpolation du spot entre facettes, et par le fait que l'on travaille parfaitement à la définition écran (512 radiales, 512 colonnes).

Le lissage le long d'une radiale se fait par interpolation sur les luminances calculées.

Le résultat obtenu est assez proche d'un lissage de GOURAUD (interpolation bilinéaire sur les luminances en chaque point d'une facette), mais la méthode est plus simple et parfaitement adaptée au système de lecture du MERCATOR.

4.3.2 ELIMINATION DES PARTIES CACHEES

Synthèse d'images va de pair avec parties cachées. La méthode d'élimination que nous avons choisie utilise, elle aussi, la particularité du système de lecture des données. Elle s'effectue le long d'une radiale (soit une colonne écran), donc en série avec les autres traitements.

Le principe de base est le suivant : Le balayage des données d'altitude se fait de l'observateur vers l'horizon. Soit h la hauteur d'un point du paysage dans l'écran et d la distance du point à l'observateur. Un point à la distance dl est visible si et seulement si la fonction h(d) est croissante au voisinage de dl et si h(dl) est supérieure au maximum de h(d) pour d compris entre 0 et dl :

$$h'(dl) > 0 \quad \text{et} \quad h(dl) > [\ \mathrm{MAX}(h(d))\ ;\ 0 \leq d < dl\ ]$$

Ces conditions sont faciles à cabler. L'utilisation de ce détecteur de parties cachées rend possible le tracé des lignes de crêtes seules.

4.4 SCHEMA GENERAL (figure 6)

On reconnait sur ce schema les blocs correspondant aux fonctions décrites précedemment. Précisons que la lecture des données est analogique, puis l'ensemble du traitement est numérique (câblé). On y ajoute un filtrage permettant de réduire le bruit de lecture. De plus un transcodage adéquat permet de colorer l'image finale en fonction, par exemple, de l'altitude.

La cadence de génération des images est réglée par la vitesse de balayage du tube d'analyse. Actuellement, on travaille à 25 images par seconde.

5.0 AUTRES DEVELOPPEMENTS

D'autres possibilités sont offertes grâce à la lecture à spot mobile du fichier altimétrique :

- simulation radar : les données sont explorées avec un balayage similaire à celui d'un radar,
- détermination de zones d'intervisibilité : par détermination des zones vues ou cachées à partir de tout point,
- calcul d'un profil de terrain : le profil peut être déterminé selon un trajet quelconque. Il suffit que le spot du tube d'analyse suive ce trajet.

6.0 CONCLUSION

Nous venons de décrire l'intérêt d'un tel système :

- le stockage chromatique des altitudes sur un film, utilisé comme une mémoire bidimensionnelle,
- acquisition des données par un lecteur de film à spot mobile, ce qui permet un calcul des images en temps réel de manière simple et un encombrement faible de l'ensemble,

Les tests d'un prototype viennent de commencer et vont nous conduire à évaluer l'ensemble du concept.

Notre objectif : un système opérationnel en 1990.

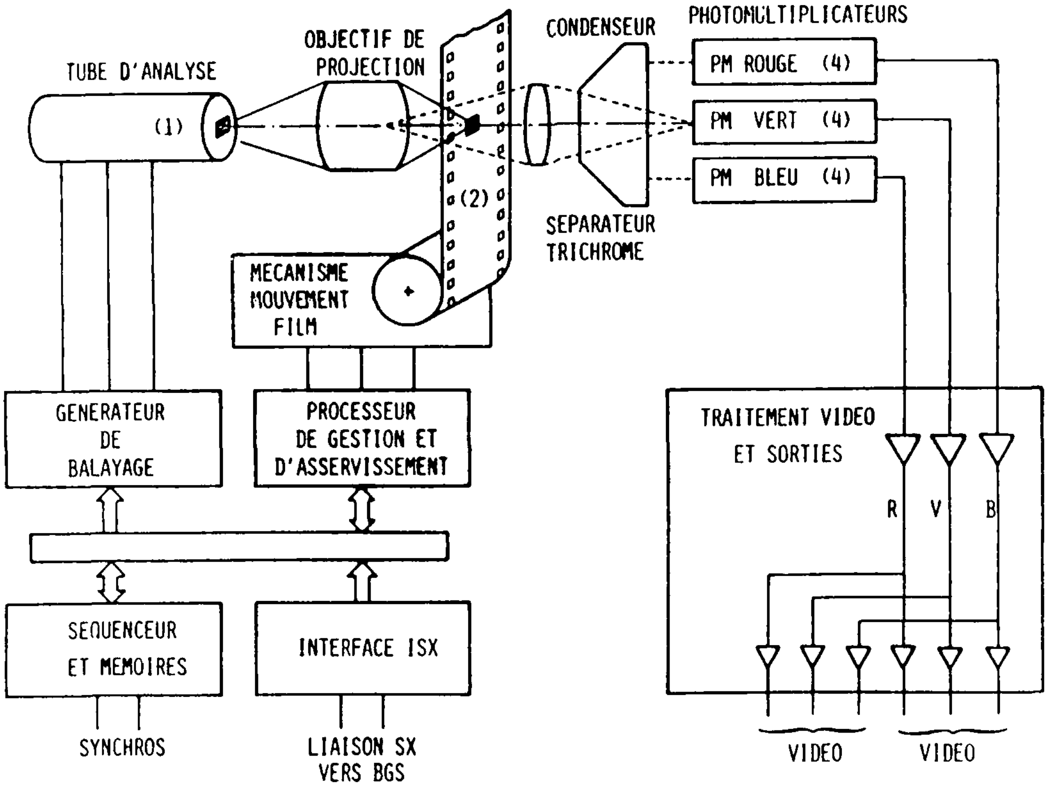

Fig.1 Synoptique boitier analyseur du film

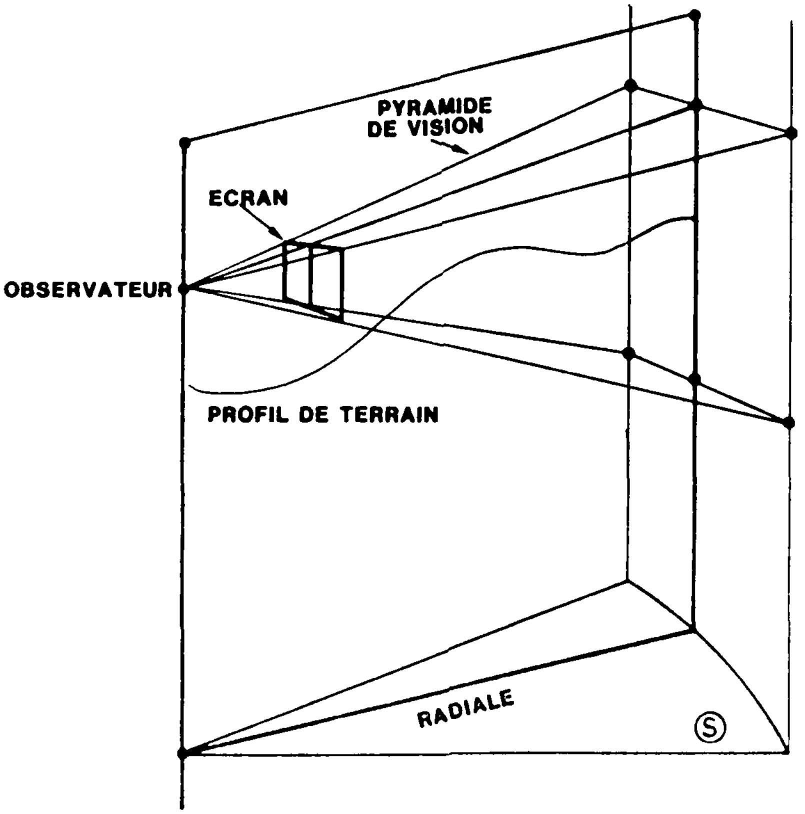

Fig.2 Transformation perspective

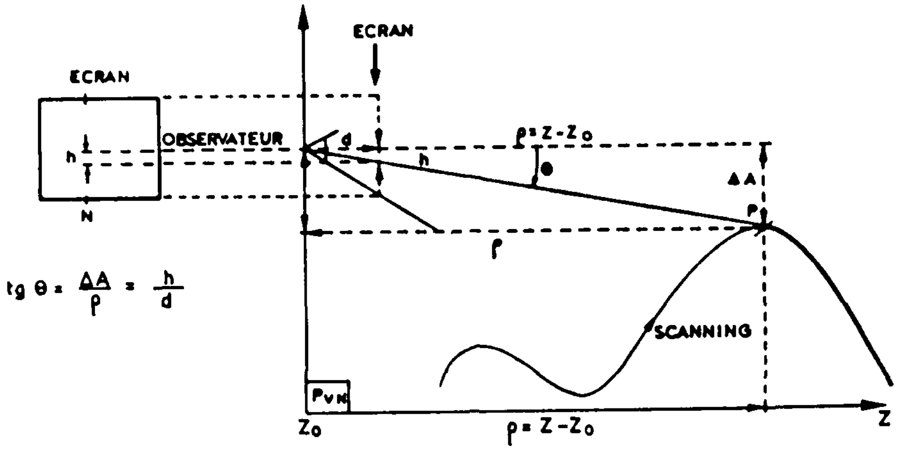

Fig.3 Calcul de la perspective

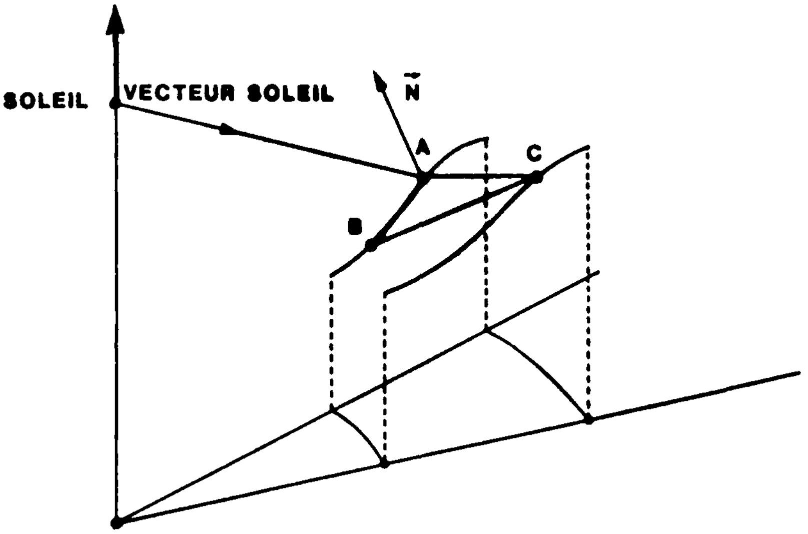

Fig.4 Ombrage

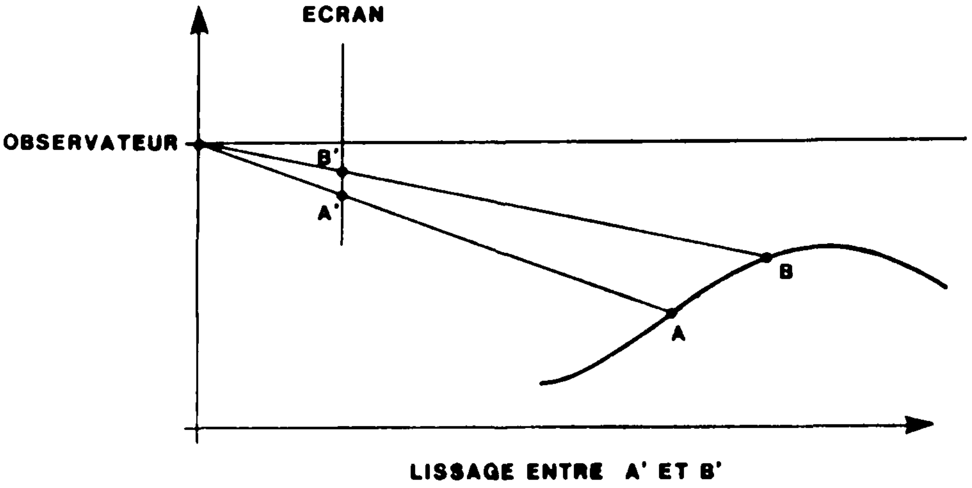

Fig.5 Lissage

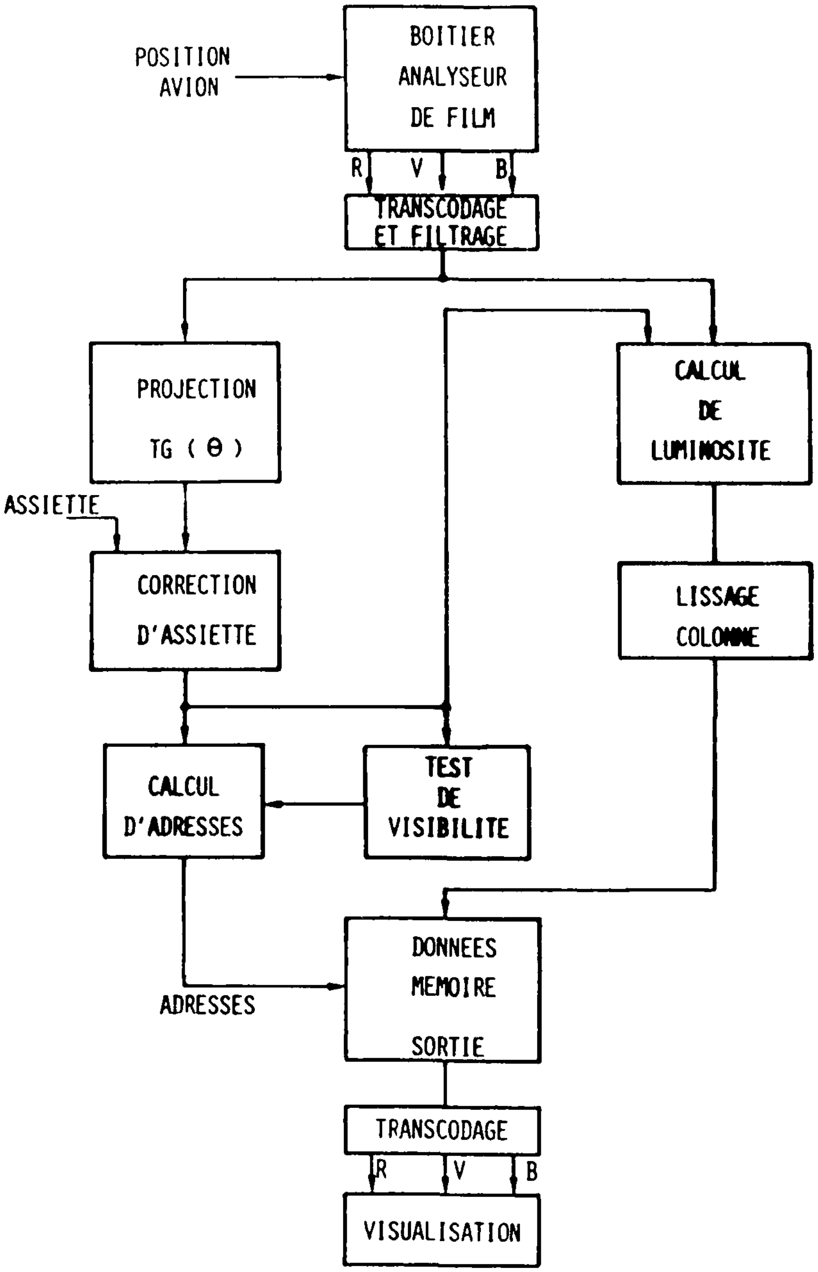

Fig.6 Schéma générale

SYNTHETIC REAL-TIME RELIEF DISPLAY

ALL-WEATHER AIRBORNE MISSIONS

J.N. BOTELLA
THOMSON-CSF
31, rue Camille Desmoulins
92132 ISSY LES MOULINEAUX
FRANCE

Within the context of all-weather airborne missions, it proves to be necessary to provide the pilot with information on the external world, even and particularly when information provided by radar or optronic sensors are failing. The development of altimetric digital data banks induces THOMSON-CSF to examine the display of synthetic relief in a cockpit. The study of various mass storages shows that a colour film has remarkable storage capacities. Altimetric data are stored on a film read by the MERCATOR reader (whose initial function is to read map images). 3D synthesis algorithms are used and they are provided with the exceptional possibilities enabled by the MERCATOR analysis. The philosophy of this study is to show how a unique product, the map reader MERCATOR, designed to display plane images, is used to perform tridimensional displays of relief.

1.0 INTRODUCTION

THOMSON-CSF General Avionics Department, AVS division, manufactures in particular the AIRBUS A310 and A320 EFIS instrument panels, MIRAGE 2000 and Atlantic new generation display units. Colour map readers ICARE and MERCATOR have also been developed. They display the selected map on colour screen and also various navigation and control informations. Next step is to display a synthetic perspective. The system we shall describe is directly stemming from the MERCATOR system whose main elements, we shall refer to this later, are taken up. The purpose of this system is to build a synthetic landscape. It is first necessary to precise the function we want to give to this image.

1.1 FUNCTION OF A SYNTHETIC LANDSCAPE IMAGE

It is possible to use a synthetic real time generated image, head-up displayed in order to complete the landscape with important details which are not visible either for meteorology or light level (night-flight) reasons or blanking caused by the relief. Thus are preserved the sight controls and the pilot gets confidence via the image superimposition. This is reasonable for symbologies such as artificial runways designed to guide the pilot and which may be superimposed on the external landscape via a head-up display. But the elementary graphics of these «objects» are most of the time extremely simple (rectangles) and the used localization devices (radiolocalization approach) are very precise.

It is much more delicate to superimpose a synthetic landscape built from an altimetric data bank and from the navigation system on board. The reason is the failing confidence in the displayed informations. Indeed, a minor error in the aircraft position, or in one of the stored altitude levels, may cause a perspective image to be angularly different from the real image, particularly what concerns the near sight planes. The cause is the principle of perspective display itself : the image of an error (in altitude for example) will be displayed on the screen by an error in inverse proportion to the distance from the observer to the point where the error is located.

Finally, we should not forget the error source due to the vegetation cover.

We thus presently think, that this image type should not be head-up displayed. This image type may nevertheless be of use for the aircraft control in low-head display, taking into account possible error envelope, particularly with the new navigation systems, whose accuracy is a lot ameliorated by automatic updatings. This type of image is also very useful for flight planning. In this purpose, several types of images may be proposed :

- the observer is situated at the aircraft position, the image field-of-view is wide and the sight direction may be selected. A small field-of-view sight (zoom) may be displayed in any direction,
- the observer is situated at aircraft position, but to a higher altitude. In this case, the landscape which the pilot has or should have under the eyes but from a higher position is displayed. The display of the route to be followed or of ground target, is easier,
- foregrounds on synthetic landscape are suppressed, hidden areas are then to be seen,

It will be possible to add other functions designed to enable flight planning.

All these displays may be performed from the present point or for example from a future point corresponding to a mission critical point

1.2 OTHER SYMBOLOGIES

It is not our purpose to describe them, this was the philosophy of other studies ; the particularity of our study is different. Nevertheless, let us recall that it is possible to superimpose on the generated images, graphic figures displaying on 3D dangerous areas (enemy attack and defence systems, the maximum security route, etc... Let us only precise that the storage and access method to the altimetric data which we shall expose, will enable an easier adjustment of these informations.

2.0 MERCATOR

The following is a survey of the moving map display reader system MERCATOR (see figure 1). The MERCATOR is a flying spot colour film analyzer.

The film content (a map, or more generally, any image) is displayed on a colour cathode ray tube. Each position of the spot of the wide spectrum range analyzer tube «lightens» the film point analyzed. The corresponding beam crosses the film, is than discomposed into its 3 components : red, green, blue, by the trichromatic separator. The three photomultipliers are the end of the analysis system. The main interest of a flying spot film analysis, is that simple scanning modifications are performing rotations or zooms of the displayed images. It is sufficient to operate a rotation or a scale factor on the television type scanning of the analyser tube. The only MERCATOR mechanical sub-assembly slaves the film progress.

3.0 FILM MEMORY

3.1 REVELANCE OF THE FILM MEMORY

In the MERCATOR, the film stores *the map under its image form*. The film proves to be a remarkable information storage device as well concerning the volume/weight or the capacity (refer to table I). Table I compares the usual memories to a 17-m film spool.

Second important point : the film is a bidimensional memory. Each point is randomly accessible. The data are sequentially readable along any line. Only requirement is that the flying spot reader follows this line.

To synthetize a landscape enables the full use this surface memory by storing on the film, not anymore a map, but altimetric data.

TABLE I . MASS STORAGES SUMMARY

TYPE	LIMITS
Electronic storages	1 chip = 1 Mbits (thickness with support, estimated to 10 mm) 10 Gbits = 10000 chips and 1.25 kW (average)
Magnetic bubble storages	1 chip 5" x 5" = 4 Mbits (45 x 15 x 5 mm) 10 Gbits = 2500 chips and 1.2 kW (average)
Magnetic disks	1 200-mm disk = 100 Mbits (non formatted) on 2 sides 10 Gbits = 100 disks
Magnetic tapes	The whole tape runs within at least 6 minutes 300 kbits/inch**2 10 Gbits = 3000-m tape (a 15" spool)
Video disk	Militarization to be done 10 Gbits = 1 300-mm disk (1.25 200-mm disk)
Photo film	9.7 Mbits/inch**2 106 bits = 17-m film

3.2 ALTITUDE STORAGE ON A FILM

We *have at our disposal numeric altimetric* files designed by the IGN (Institut Geographique National). These files are grid structured files, i.e. the altitudes on relief are given according to a grid structure drawn on ground. The IGN encodes the altitudes with 16 bits.

We adjust the surface correspondance between each point of the files and the film. Each film pixel is printed so that its pigments carry the altitude information of the corresponding point in the files.

In order to perform such an operation, the altitudes are transcoded in a transparence table for each colour ; red (R), green (G), blue (B). To each altitude corresponds thus a set of three transparences : R, G, B. The film is done so that the triplet is to be found during analysis and so that the altitude is obtained by decoding.

The selected encoding uses four levels for red, eight levels for green and eight levels for blue, 256 altitudes are thus possible.

The analysis spot diameter causes an interpolation effect between pixels ; our code must take this into account for preserving the analysis coherence. This interpolation also will be used.

4.0 RELIEF DRAWING

4.1 IMAGE TYPE

The image type we choose, is adapted to the data read system. The images are smoothed and shadowed. It is also possible to generate only «observed» peak lines. Actually these are points on the ground at the limits of the seen and hidden parts. It is also possible to draw ground cross sections.

4.2 BASIS DESIGN

In the following, we suppose an horizontal sight. The perspective image is built on a screen composed of 512 raws and 512 columns covering a D degrees field.

Let us consider a radial line drawn on the ground (see figure 2). It links the observer's position projected on ground to a point located at the maximum sight distance. Morever, the line belongs to sector S, ground projection of the sight pyramid. The perspective transformation (transformation which projects any point of the ground on the screen). Each point of this radial line is located on a screen column. This and the scanning system of the reader flying spot, enables an easier computing procedure. The spot describes the 512 radial lines required in the film data base, included within a D degrees sector, each radial line being used to build each column of the screen.

To modify :

- observing field,
- observation direction,
- maximum sight distance,

means to modify only the analyser tube scanning.

The perspective transformation itself ends with the computation of the height on screen of each point calibrated on the radial line. It is a simple tangent computation (ref. to figure 3).

4.3 IMAGE DRAWING

4.3.1 SHADOWING AND SMOOTHING

The image final aspect and perspective understanding depends on this operation.

4.3.1.1 Shadowing (see figure 4)

We assume a light source (sun) which illuminates the landscape and thus let it become understandable. The luminance value to be given to each point of the field of view is then computed.

Therefore, the normal vector at the considered point of the ground is evaluated.

Two successive radial lines are required, on which 3 points A, B and C are used (see figure 2). A is the current point. The triangle ABC builds a facet whose inclination is determined by the computation of its lateral inclination (according to AC) and its longitudinal inclination (according to AB).

These data and the sun vector both enable the computation of point A (scalar product of the normal vector to the breakage by the sun vector), supposing that the albedo in the sight pyramid is constant.

In order to simplify the computation, the light source is set vertically at the observation point. The sun vector at each observed point is contained in the vertical plane of the associated radial line.

We are thus able to compute the luminance of the screen transform at each point of the ground.

4.3.1.2 Smoothing (see figure 5)

From one radial line to the other, smoothing is performed naturally by interpolation of the spot between facets, and by direct working on the screen definition (512 radial lines, 512 columns).

Smoothing along a radial line is performed by *interpolation* of the computed luminances.

The obtained result is rather close to a GOURAUD smoothing (bilinear interpolation on luminances at each point of a facet) but the procedure is easier and perfectly adapted to the reading system of the MERCATOR.

4.3.2 HIDDEN PARTS DETECTION

Image synthesis is associated to hidden parts. The selected detection method uses also the particularity of the data read system. It is performed along a radial line (it is a screen column), thus being in a serial position with other processings.

The basis principle is the following : altitude data scanning is performed from the observer in horizon direction. If h is the height of a landscape point on the screen, and d the distance from the point to the observer. A point located at a distance $d1$ is to be seen only if the function $h(d)$ increases in the proximity of $d1$ and if $h(d1)$ is superior to the maximum of $h(d)$ for d included within 0 and $d1$

$$h'(d1) \geqslant 0 \quad \text{and} \quad h(d1) > [\ \mathrm{MAX}\,(h(d))\ |\ 0 \leqslant d < d1\ ]$$

These conditions are easy to wire. The use of this hidden parts reader enables the drawing of the peak lines alone.

4.4 GENERAL DIAGRAM (figure 6)

The blocks corresponding to the above described functions are given in this diagram. Let us precise that the data read is analogue, the whole processing is then digital (wired). The read noise is reduced by filtering. Furthermore an adapted transcoding enables to colour the final image, according to the altitude for example.

The *images generation rate* is adjusted by the analysis tube scanning speed. Present speed is : 25 images/second.

5.0 OTHER GROWTH CAPABILITIES

The flying spot read of altimetric files provides other capabilities.

radar simulation : the data are scanned via a scanning similar to a radar scanning,

detection of intervisibility areas : the areas seen or hidden are determined from any point,

computation of relief profile : the profile can be computed according to any selected path. Sufficient condition is that the analysis tube spot is following this path.

6.0 CONCLUSION

The above described advantages of the system are the following :

chromatic storage of altitudes on a film used as a bidimensional memory,

data acquisition via a flying spot film reader enabling an easy image computation in real time, and small overall dimensions of the assembly.

Tests on a prototype have just begun and will enable us to evaluate the whole design.

Our purpose : a system operating in 1990.

THE WIDE FIELD HELMET MOUNTED DISPLAY

by

Joseph LaRussa
Farrand Optical Company, Inc.
117 Wall Street
Valhalla, N.Y. 10595

SUMMARY

The Farrand Optical Company, Inc. has been instrumental in developing a very wide field of view Helmet Mounted Display. This display provides the pilot with an instantaneous field of view of 60° vertically and 135° horizontally. The central field of view consists of an overlap field of 25° within which full stereopsis is available. It would appear that a new design which the Farrand Optical Company, Inc. is now in the process of designing for Aerospace Medical Research Laboratory (AMRL) would be applicable for night all weather operations where such data as flight path control, computed weapon projectories, synthetic outside world views, expected and unexpected threats and automatic terrain following paths would be displayed.

It is not the intent of this paper to discuss the application of helmet mounted displays (HMD's) to flight operations or to interactive virtual cockpit display systems. For an introduction to such possibilities we would refer you to an article published by Aviation Week and Space Technology.[1] The article was based on discussions with Dr. Thomas A. Furness, Chief of the Visual Display Systems Branch of the Aerospace Medical Research Laboratory (AMRL) at Wright Patterson Air Force Base. AMRL also provided the published illustrations.

This paper then, deals with the parameters that must be considered in designing a wide field helmet mounted display. Briefly, these parameters are size, weight and balance on the head, brightness of the display and see-through ability of the display. The discussion assumes the use of a one inch, high brightness, high resolution CRT input already developed and operational although other formats which may be beneficial to the optical design are currently under development.

The Wide Field HMD was in fact, originally conceived as a simulation device. The Aerospace Medical Research Laboratory (AMRL) first contracted with Farrand to build a Visually Coupled Airborne Systems Simulator (VCASS) for engineering studies. The design was begun in 1978 and the first VCASS was delivered in 1981. This device utilized miniature CRT's on the helmet as image inputs. Meanwhile, Canadian Aviation Electronics (CAE) and Farrand were successful in selling a variation of the same optical design to the Air Force Human Resource Laboratory (AFHRL) as a high resolution, full color, helmet mounted display for simulation. This unit was labelled FOHMD for Fiber Optic Helmet Mounted Display because the input generated remotely is conveyed to the input focal plane of the helmet display by fiber optic ropes.[5]

The system was delivered to AFHRL in January of 1983. A comparison of the two systems follows:

	VCASS (AMRL)	FOHMD (AFHRL)
Instantaneous Field of View	135°H x 80°V to 120°H x 80°V	135°H x 80°V to 120°H x 80°V
Total Field of View	unlimited	unlimited
Interpupillary Adjustment	58 to 72mm	58 to 72mm
Overlap	25° to 40°	25° to 40°
See-Through Ability	9% X B.T.*	9% X B.T.*
Input	high brightness, high res. 1" (19mm format) monochrome CRT	high brightness, full color Light Valve by GE Via Fiber Optic Ropes
Display Brightness	**TB X .01 X .5	30 Ft.-Lamberts minimum
Resolution	6 arc minutes	1.5 arc minutes per TV line in High Resolution inset field 12 arc minutes per TV line in surround

*BT - Beamsplitter Transmission
**TB - Tube Brightness

	VCASS (AMRL)	FOHMD (AFHRL)
Exit pupil dia.	15mm	15mm
Eye relief	39mm	39mm
Weight (less helmet)	N.A.	N.A.

The AFHRL design for simulation utilizes fiber optic ropes to relay the images from the GE color Light Valves to the HMD and as such the simulator version enjoys full color and using two light valves per eye (one for the inset area of interest and the other for the surround) a very high resolution image is achieved. The breadboard version at AFHRL is shown in Figure 1. Here one clearly sees the two fiber optic bundles for each eye, one serving the high resolution inset field and the other feeding the surround field. The mechanical helmet pick-off is also visible. The new or prototype model to be delivered to AFHRL in August 1985 will employ an LED array on the helmet to sense head position and only one fiber optic cable for each eye. The outputs of two GE Light Valves per eye will be combined in the one cable which also employs multiplexing to eliminate the visibility of both the fiber structure and minor fiber breaks and to improve the resolution. A view of this prototype is shown in Figure 2. The Farrand Optical Company has also developed a method of inserting up to two targets in the display for air to air combat.

An evolution of the AMRL prototype for use aboard aircraft or other vehicles might look like the assembly shown in Figure 3. Note that one CRT per eye is used. We are presently limited to a monochrome display because of the available CRT, however the use of CRT's makes the HMD adaptable to on board use. With currently available tubes one can expect a resolution of six arc minutes over an 80 degree field for each ocular. The apparent brightness of the display would be approximately 30 Ft.-Lamberts, adequate for night operations.

The advantages of a wide instantaneous field of view with binocular overlap upon pilot performance in target detection, motion detection and tracking were justified in behavorial studies performed with the AFHRL system.[2,3] Because of the excellence of performance of the optical systems, stereopsis could be provided in the overlap area if the left and right images are generated from two eyepoints. This would be very useful in terrain following operations.

Before we describe the latest advances in the design of HMDs and the problems yet to be overcome, it would be appropriate to review the advantages and disadvantages of methods available to achieve wide instantaneous fields of view. An excellent primer of helmet mounted display design considerations exists in reference 4.

A helmet mounted display must project the view to optical infinity in order to eliminate focus problems with respect to the background. Refractive optical systems may be employed, however they must be bent away from the observer's line of sight if he is to see through the display (see Figure 4).

Because of this requirement, the instantaneous field of view of such a design is limited since this field is defined by the angle subtended at the eye by the closest optical element. Additionally, to produce a large field of view with a small diameter CRT requires a very fast optical system that translates into many elements and a heavy weight. A reflective system is only slightly better since the flat beamsplitter limits the eye relief available and increasing this eye relief reduces the field of view since the spherical beamsplitter must be moved further away from the eye (see Figure 5).

A unique optical system patented by Farrand overcomes all of these problems at the expense of see-through ability. This system has been named the Pancake Window®. It is a reflective system that utilizes polaroids, quarter-wave plates and beamsplitters to achieve very wide instantaneous fields of view (80° plus), and when applied to helmet mounted displays provides very long eye relief (39 mm) and very light weight (20 oz. per ocular). Figure 6 illustrates its application to helmet mounted displays.

When using a spherical mirror as a collimator the focal plane is at half the mirror radius (Figure 7).

Note that the input image is relatively small for the field of view obtained, a decided advantage in terms of being able to use a small CRT. If the spherical mirror were made into a beamsplitter and a plane beamsplitter were added, the configuration would look like Figure 8.

Here the eye relief is very large, but locating a focal surface as shown would prevent the observer from seeing the background through the display. In order to get the focal plane out of the way, use is made of a flat beamsplitter and a relay lens. The flat beamsplitter folds the CRT and relay lens out of the observer's line of sight and the relay lens projects an aerial image to the location of the focal surface (Figure 9).

Because of the relay lens, a real pupil is formed at the eye and it must be large enough to allow for small relative motions between the observer's head and the helmet mounted optics.

Without the patented features of the Pancake Window the observer would see not only the CRT image projected to infinity but he would also see the CRT image directly. The

Pancake Window accomplishes the rejection of the direct input view as follows, (Refer to Figure 10):

Illumination from an image point passes through the first polaroid from left to right and is polarized along a vertical axis. This polarized light passes through the spherical mirror beamsplitter unaffected, but the plane of polarization is rotated 45° in passing through the quarter-wave plate. Passing through the plane beamsplitter does not affect the rotated plane of polarization but in going through the second quarter-wave plate the plane of polarization is rotated another 45° so that the total rotation is 90° and the direct view illumination is blocked from reaching the observer by the last polaroid. If we now consider that portion of the light that was reflected back to the left by the plane beamsplitter, we see that its plane of polarization is rotated another 45° for a total rotation of 90°. This illumination strikes the spherical mirror beamsplitter on the concave side so that it is collimated and re-directed towards the observer. Now passing through both quarter-wave plates, the collimated illumination is rotated another 90° for a total rotation of 180° which allows it to pass through the last polaroid to the observer. The drawback here for see-through ability is that the total transmission is on the order of 9% multiplied by the front beamsplitter transmission, or somewhat like a pair of dark sunglasses. Note that the first polaroid of the Pancake Window® is not in the see-through path. This low transmission may not be important for night operations, however, under conditions of dusk we would like better transmission. We have embarked on two different approaches utilizing holographic techniques which promise to improve the see-through ability to 30 percent transmission.

While the Pancake Window® provided us with the wide FOV, the see-through and the long eye relief capabilities, another Farrand patent on the overlapping monoculars principle, made possible even wider horizontal fields of view. By rotating the optical centerlines of the two limbs outward so that only the right portion of the left eye field of view and the left portion of the right eye field of view overlap, we increase the total horizontal field of view while maintaining an overlap region in the same manner that the human visual system functions. Figure 11 illustrates the overlapping principle. Again we note that because of the excellence of the optical design, significant off-axis angles can be used as a central field providing binocular vision with the possibility of stereopsis, should one wish to generate stereo input pairs.

From an optical design point of view, the remaining areas of desired improvement are larger exit pupils, better see-through ability and lighter weight optics. Our latest designs for AMRL provide for 21 mm diameter exit pupils with the same wide fields of view. Better see-through ability and lighter weight of optical elements will be achieved with holographic Pancake Windows®, which we have manufactured in the past. Expected see-through will approach 30% while retaining a transmission of one percent for the input CRT image. Such a device would also increase the contrast between the CRT image and the outside world because a reflective hologram reflects almost all of the impinging CRT illumination over a narrow bandwidth while preventing transmission of almost all of the background illumination in that same narrow wavelength band. Ideally, the only optical element required would be holographic and on the visor itself, fed by CRT's and relay systems. Such a design would eliminate a great deal of the frontal weight while providing better than 95% transmission for see-through ability and while reflecting and collimating over 95% of the CRT illumination for the observer. This type of system has been manufactured, but the individual fields of view are relatively small (on the order of 40°). Larger fields of view are not practical at present because of wavelength shifts in the reflected images due to the increasing angles of incidence across the field of the image illumination on the hologram.

In the interim between currently applicable technology and the holographic visor, all of the necessary ingredients for night operations exist and have been demonstrated with very wide field of view helmet mounted displays employing Pancake Windows®. In addition, the very important feature of stereopsis can be readily implemented. Next we must address ourselves to the physiognomical requirements which will dictate the optical arrangement within the helmet. Here we are concerned with obtaining a weight balance on the observer's head to relieve strain and to provide comfort for long periods of use. Also, the opto-mechanical arrangement must not interfere with peripheral vision and there must be provided three adjustments to suit all individuals. These adjustments consist of interpupillary adjustment, longitudinal adjustment and vertical adjustment. An example of such a design is shown in Figure 12.

It should be noted that the helmet design lends itself to a completely sealed unit with sufficient internal volume for oxygen, earphones and microphone.

Lastly, one is faced with selecting a helmet pick-off device which is used to orient the projected scene with respect to the observer's line of sight using the vehicle axes as the reference. There exist several such devices, the best known is probably the Polhemus magnetic pick-off which utilizes a magnetic radiator on the helmet and magnetic field sensors around the observer. Most other devices employ infrared radiators usually arranged in a pattern on the helmet and infrared detectors surrounding the observer.

Except for the omission of eye-trackers or oculometers which may be employed for remote control purposes, we believe the foregoing represents the current state-of-the-art in wide field helmet mounted displays.

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4. H. Lee Task, D.F. Kocian, James H. Brindle - "Helmet Mounted Displays; Design Considerations."

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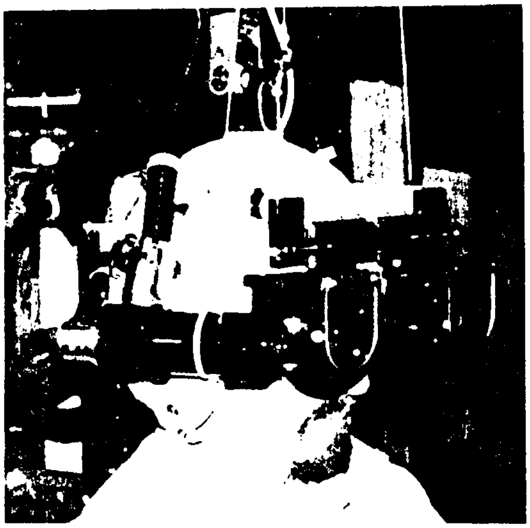


FIGURE 1
AFHRL BREADBOARD

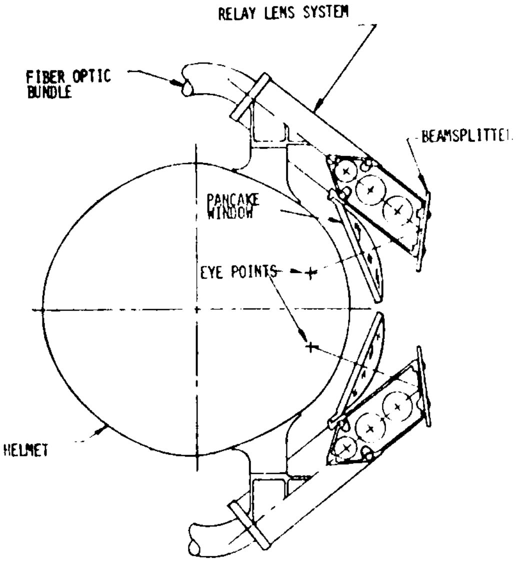


FIGURE 2
TOP VIEW OF FIBER OPTIC HMD
PROTOTYPE FOR AFHRL

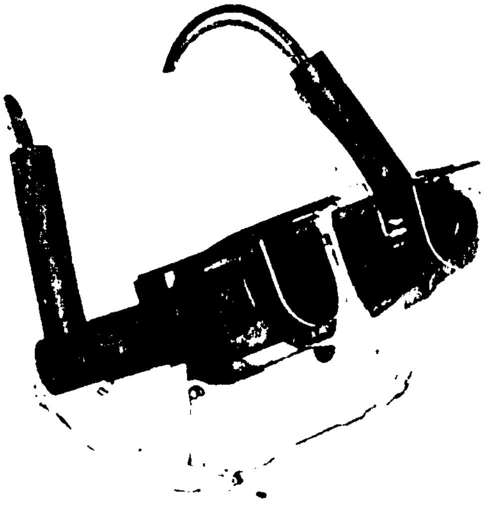


FIGURE 3
CRT INPUTS ON
HELMET MOUNTED DISPLAY

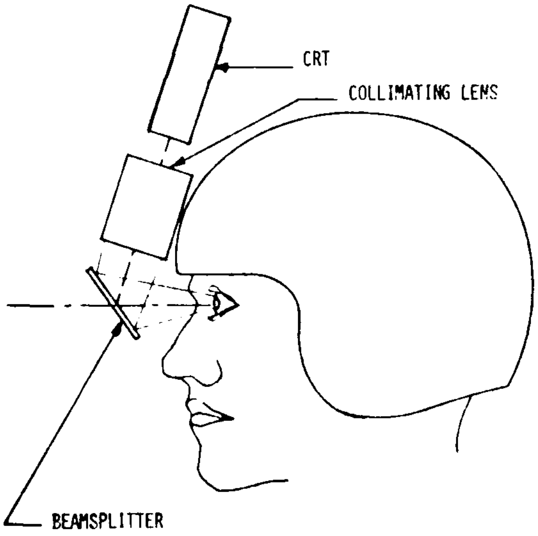


FIGURE 4

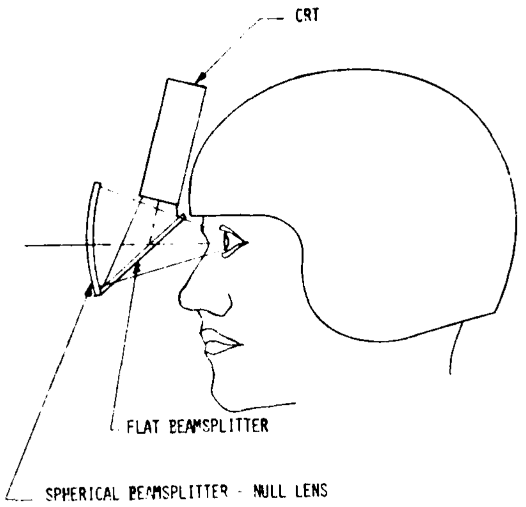


FIGURE 5

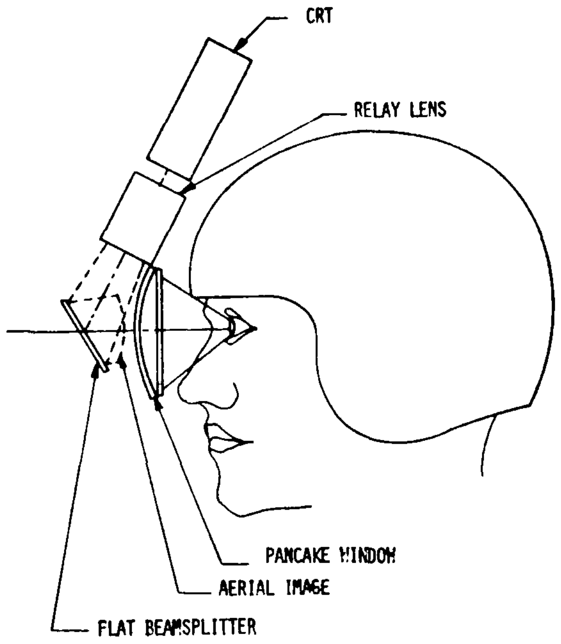


FIGURE 6

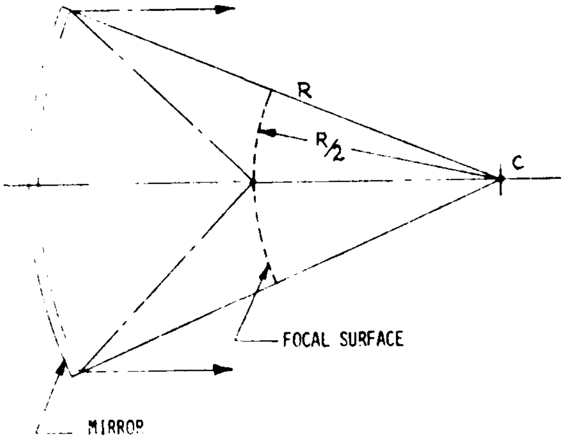


FIGURE 7
SPHERICAL MIRROR
COLLIMATOR GEOMETRY

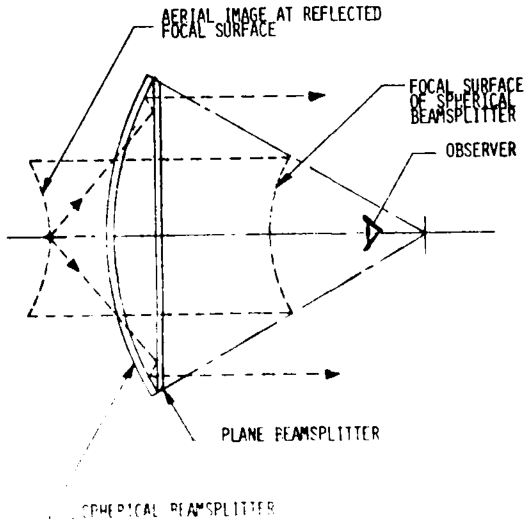


FIGURE 8

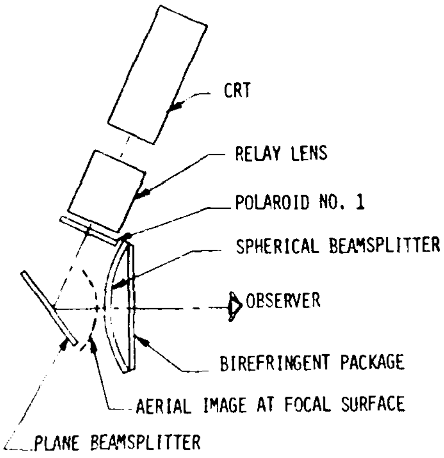


FIGURE 9
PANCAKE WINDOW® SYSTEM

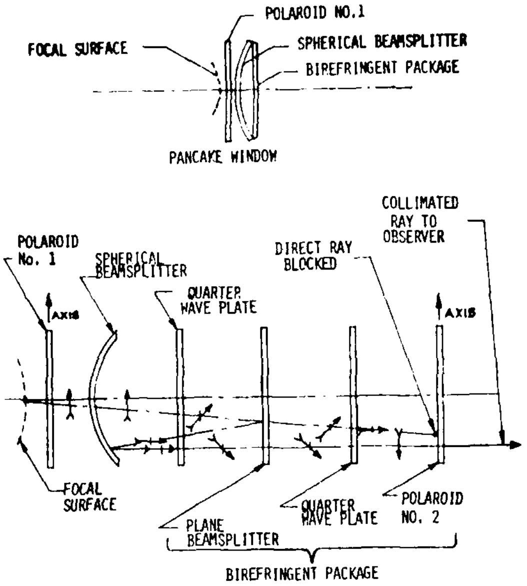
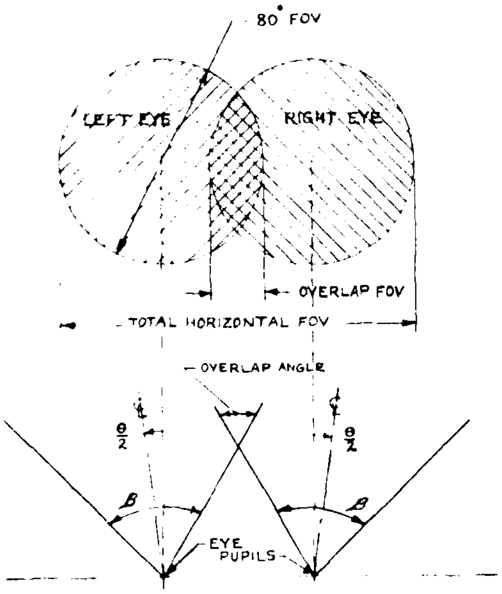


FIGURE 10
STATES OF POLARIZATION
WITHIN THE PANCAKE WINDOW®



θ = DIVERGENCE ANGLE OF OPTICAL CENTERLINES
β = INDIVIDUAL OPTICAL FOV FOR THE OCULARS
TOTAL HORIZONTAL FOV = $2\beta - \theta$

FIGURE 11
OVERLAPPING MONOCULARS PRINCIPLE

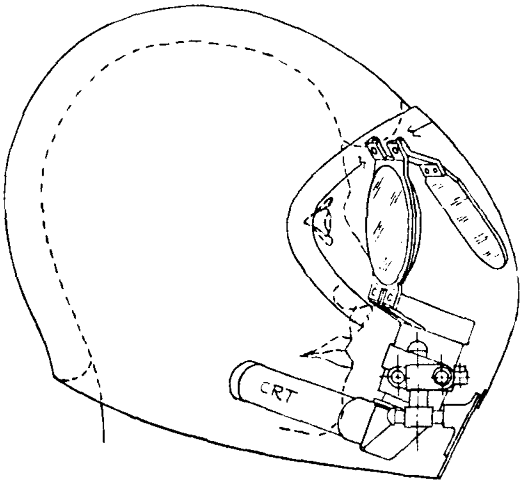


FIGURE 12
CURRENT HMD TECHNOLOGY
(LEFT SIDE OPTICAL SYSTEM SHOWN)

A Solid-state Map Display for Rapid Response Operation

Author D J Powell - Manager Aircraft & Missile Systems,
T E Crayford - Chief Development Engineer,
Guidance Systems Division
GEC Avionics Ltd.,
Airport Works
Rochester. Kent. ME1 2XX

SUMMARY

GEC Avionics have developed a means to provide pilots with a presentation of a moving colour map display on a standard colour CRT. It uses solid-state techniques and derives the display from a digital database. This paper describes the design criteria used in the development of the system and then presents an overview of the system operation. Finally the paper discusses one of the many ways in which the system as a whole may be used in operation.

1. INTRODUCTION

Since the earliest days of aviation, accurate navigation with the aid of maps or charts has been of prime importance to aviators. The use of paper charts within the limited confines of the cockpit area continues to date, due to the combination of the inherent unreliability and inflexibility of existing methods of automatic map presentation to the pilot.

Present day cockpit map displays generally employ optically projected film based systems with a mechanically complex film transport mechanism. It is this electro-mechanical film transport system which is prejudicial to reliability, and the preparation of the film for the area coverage required is a long process which implies inflexibility in an operational scenario.

A number of organisations - including GEC Avionics - have been investigating the feasibility of fully digital map display systems in which the map image is generated dynamically from a digital database. The topographical features in this solution are characterised individually. Such systems will offer great flexibility in the display produced but will require a processing capability which would create an excessively expensive solution for airborne applications. However, at present, the full digital data base is not yet available and even when it is could still have operational restrictions.

This paper describes a map display solution which avoids the pitfalls of preceding types and is especially suitable for rapid response operations. The input data for the system is created by digitally encoding standard operational Tactical Pilotage Charts or indeed any 'Pictorial' data pertinent to a particular mission. The airborne equipment in this solution is comfortably within the bounds of current processing technology and is fully solid state. The digital map database can be prepared rapidly using portable and relatively inexpensive equipment.

In addition to describing the methods used in the preparation and manipulation of the data, the paper discusses how the system can be integrated with other systems and sensors to display information to the aircrew in relation to mission objectives and threat avoidance.

The equipment discussed is currently undergoing flight tests in a Royal Aircraft Establishment Wessex helicopter and further testing in the fast jet environment is planned for later this year.

The digital topographical map display system is thus close to obviating the need for navigational paper charts being used in the cockpit at times other than those caused by system failure, a situation which will always exist in a simplex system.

2. DESIGN CONSIDERATIONS

2.1 General

The GEC Avionics digital colour map development commenced in 1983, the aims of this programme were to:

- prove the real time manipulation of digital map data, i.e. scrolling and rotating the displayed image at rates compatible with fixed and rotary wing aircraft,

- create a digitising facility, using available commercial equipment, which would provide the map database in pixel form from paper charts.

These aims were achieved with laboratory bench demonstrations in February 1984 and the commencement of flight trials in a Royal Aircraft Establishment Wessex helicopter in September 1984. Three months of successful flight trials have accrued together with demonstrations to potential customers.

GEC's drive to develop a new form of map display stemmed from its experience in the earlier electro-mechanical, optically projected film based maps used in the British Royal Air Force Jaguar strike aircraft. To meet its low level role, a number of additional operational and display features were included to facilitate accurate track keeping, steering to waypoints, and track recovery after diversion. Such features have helped to reduce pilot workload in this high stress environment. The value of the map system has been conclusively demonstrated by the experience of more than 500,000 flying hours accumulated with the equipment. This experience has also highlighted the improvements to be gained from an electronic multifunction display of map data.

2.2 Data Storage Medium

Our studies of a colour map reader have considered a number of alternative techniques which can be grouped as:

- analogue - in general using optical film to store the map database and deriving the colour video signal via, for example a vidicon or a flying spot scanner.

- digital - using a digital database and thus being directly compatible with digital processing.

Analogue solutions were quickly rejected as they suffered from the criticisms levelled at previous solutions including the loss of display continuity during frame changes in the north/south direction and scale changing. To these must be added such problems as maintaining spot size/position in a vibrating environment and film susceptibility to temperature and humidity.

With the available alternatives in bulk digital storage media and the rapid growth of memory density achievable, a digital solution was clearly favoured. Four alternative media were considered in detail; two of these were magnetic tape systems and two were semiconductor. The evaluation of these media clearly showed that superior operational and logistic benefits accrue from using semiconductor memory rather than magnetic tape. Because of the widespread and rapidly expanding use of non-volatile semiconductor memory and the rapid development in this area to date, this technology virtually guarantees a further increase in capacity and speed coincident with a reduction in cost per bit of storage.

Although the video magnetic tape medium provides a large data storage capability, around 1 [illegible] at a relativily low price, its environmental performance is limited by the mechanical construction of such parts as the head drum assembly in helical scan recorders and the tape itself. Hermetic sealing of the cassette package, were it practicable, might extend the tapes lower operating temperature but high operating temperatures would remain limited. It was considered that a heater would be necessary in order to prevent condensation which would otherwise rapidly degrade the tape by [illegible]. Regular maintenance of the recorder would also be necessary to prevent the build up of oxide on the heads, with the associated problem of reduced signal [illegible]. These aspects implied low reliability and increased life cycle costs [illegible] semi-conductor solution.

[illegible] Database Generation

Having decided that the GEC Avionics Colour Map System would use paper chart as the primary data source it then became necessary to develop a low cost mechanisation for converting the charts into fixed data for storage. To support the in-service operation of [illegible] aircraft, it is anticipated that there will be a requirement for at least two types of ground facility:

- a Main Ground Station - typically Government Agency controlled and administered, providing the main digital database library for use by local stations.

- Local Ground Stations - these would be available at squadron level or forward deployed and controlled by operational personnel. These local facilities would provide the means of entering mission planning or reconnaisance data as an overlay to the primary data without invalidating the primary data.

Examples of aeronautical charts digitised by the above equipment are shown in Fig. [illegible]. Increasing zoom clearly shows the fixed structure of the digitised [illegible] factor of 2 still presents a useable image. Fig. 7 and 8 show the [illegible] quality provided by our latest digitisation developments and clearly demonstrate the superiority over the earlier images.

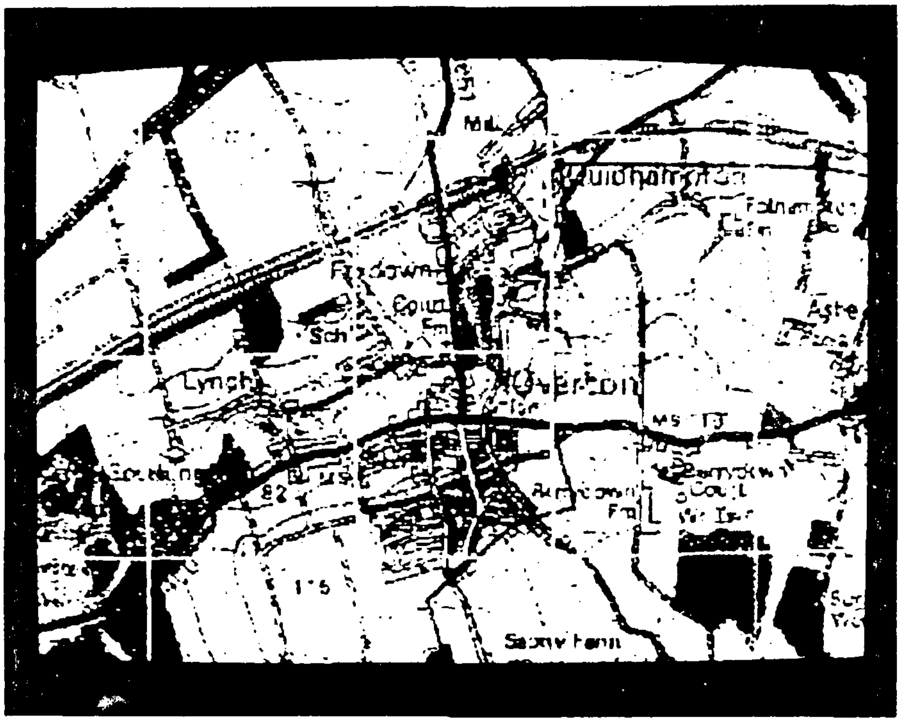


Fig. 1 Early Digitised Map (50,000:1 Scale) Displayed at Zoom Factor 1.0

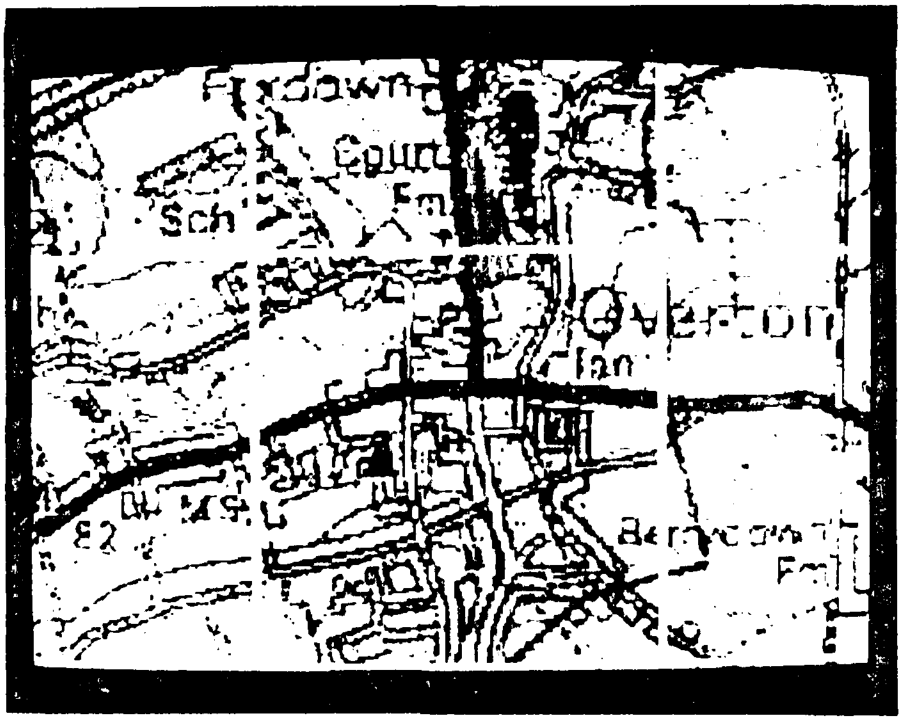


Fig. 2 Part of the Same Area Displayed at Zoom Factor 2.0

Fig. 3 Part of the Same Area Displayed at Zoom Factor 2.8

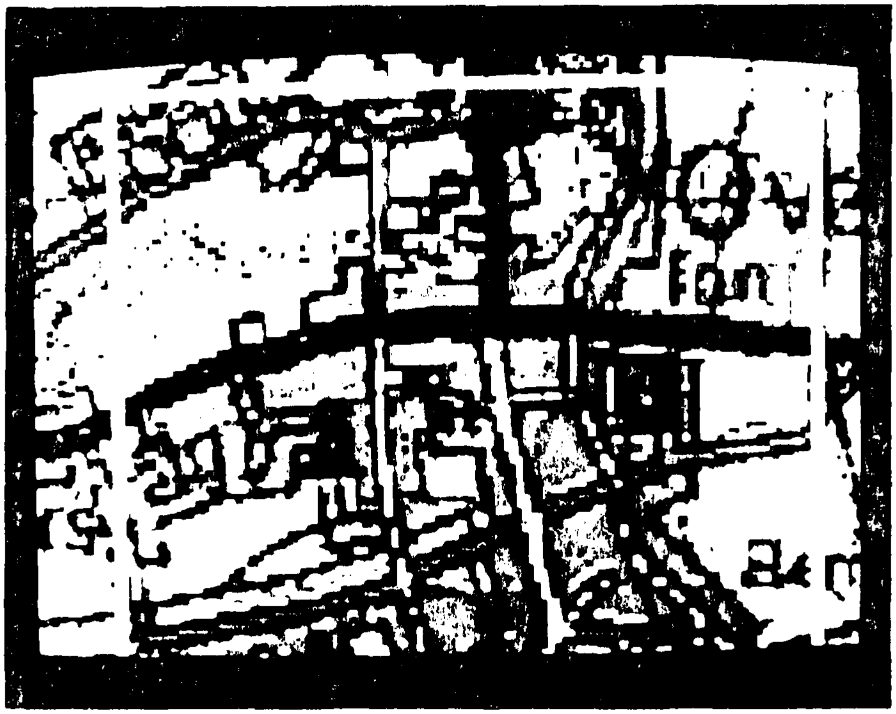


Fig. 4 Part of the Same Area Displayed at Zoom Factor 3.5

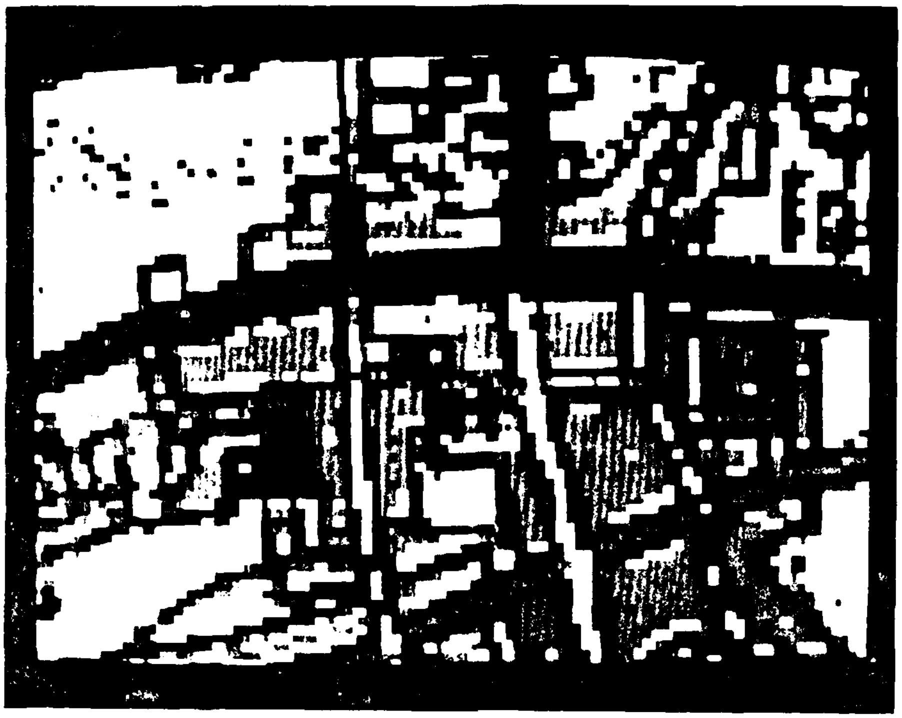


Fig. 5 Part of the Same Area Displayed at Zoom Factor 5.0

Fig. 6 Part of the Same Area Displayed at Zoom Factor 9.0

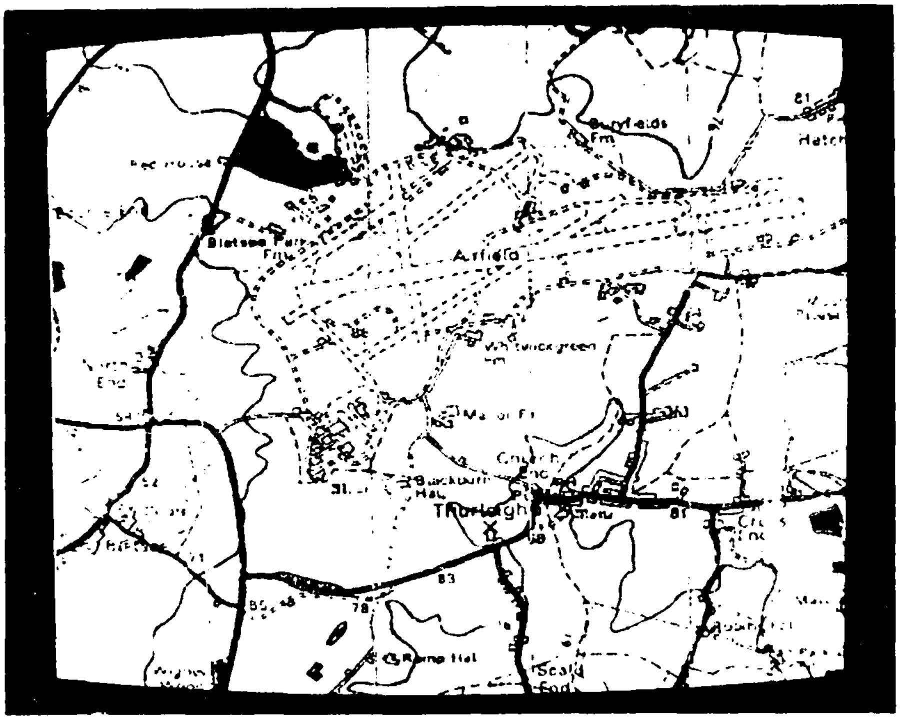


Fig. 7 Latest Digitised Map Displayed at Zoom Factor 1.0

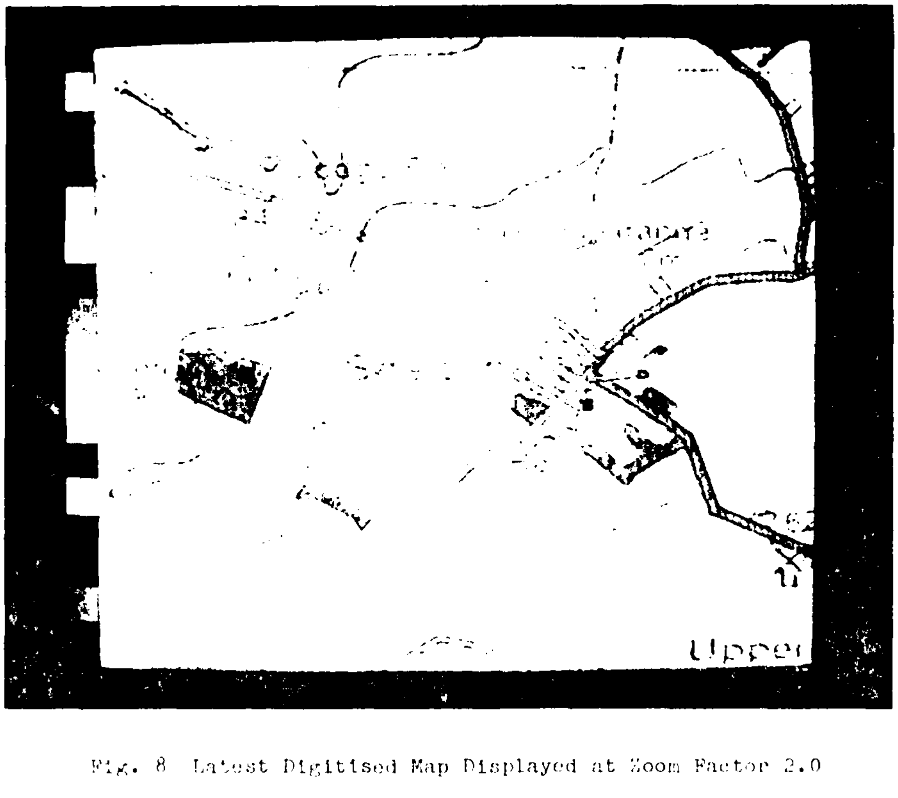


Fig. 8 Latest Digitised Map Displayed at Zoom Factor 2.0

In addition to the generation of pixel data for input to the digital map system, the ground station is capable of converting vector type databases such as PACE or DLMS into a fixed format, thus the services equiped with the GEC Avionics map will have the flexibility of utilising either database without modification of the airborne equipment.

3. THE DIGITAL MAP SYSTEM

The Digital Map System outputs a composite colour video map image together with overlaid navigation symbology. It transmits this image as discrete Red, Green and Blue colour and monochromatic video signals or as either PAL or NTSC format for display on Multipurpose Display (MPD) Units. These composite video images are generated from self contained mass semiconductor non-volatile memory within the map system. Data in this memory is accessed and then further processed to provide correct orientation, scale and positioned according to the aircraft navigation information received. This processing task is performed in accordance with navigation and mode data transmitted to the map system via the aircrafts multiplexed data bus system from the Mission Computer, or from previously loaded mission data stored within the map system. The overlaid navigation symbology is internally generated within the map system in response to the same navigation and mode data received over the bus. The digital memory is derived from either digitised paper charts or from DLMS level 1 or 2 data. Both types of database are preprocessed and loaded into mass memory prior to flight by the purpose built ground support station. In addition to the composite map image the system can display mission/intelligence data as an overlay which is capable of being decluttered from the display during use. This mission/intelligence data is also loaded from the ground support station.

The map system essentially comprises two sections, the memory, and the map computer which interfaces the display computer as shown in Fig. 9.

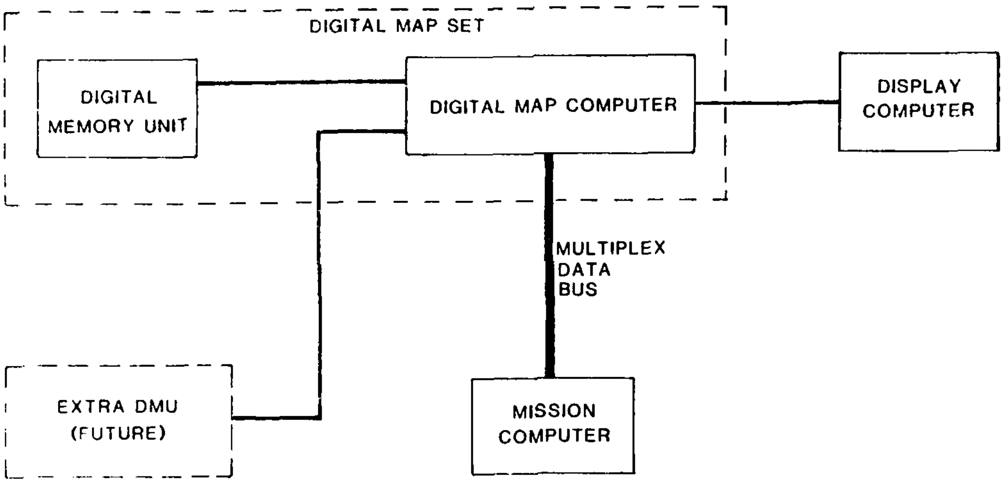


Fig. 9 Map Computer Interface

As currently configured the basic map memory can retain approximately 70 square feet of paper chart plus 256 kbytes of non-volatile memory available for mission and [illegible] [illegible] data overlay. As a convenient means of indexing the map, each sheet is digitised in small squares or tiles. Further non-volatile memory is provided for mission computer initialisation, BIT and mission computer to map message storage. The map computer has a spare input port to interface a further bulk store memory unit should additional area coverage be required. The map computer acts as an interface to the aircraft systems in accordance with the messages received over the data bus. These messages or data are processed in real time to fulfil such functions as:

- the output of pre-loaded aircraft initialisation data to the mission computer.
- the output of video signals to displays, this would include map data overlaid with mission intelligence and self generated navigation symbology.
- the output of video signals of 'pictorial' data.
- the output BIT messages relating to map system performance.

3.1 System Operation

The operation of the map system is depicted in Fig. 10. Aircraft present position and heading is received by the CPU from the mux bus interface together with operating mode and map scale data. The CPU runs through its directory of map areas of the appropriate scale and identifies the map data to be displayed. From information within the directory it calculates the individual map tiles to be extracted from the mass memory to provide the appropriate display. These map tile numbers are transmitted singly to the memory to extract map data in a predetermined manner. The specific data memory location address is determined from the card number and map tile numbers.

The data store card is then read sequentially at the data content location for that particular tile. The first locations give:

(a) the total number of bytes to be read to provide the complete tile data.

(b) the total number of bits of data which should be received by the map scene memory for that tile when it has been processed. This is known as tile sum-check data.

Data (a) is used to control the read of the data store and (b) is the initial data transmitted to the map computer to provide a BIT tile sum-check. The data is read as words of compressed pictorial or compressed pseudo DLMS data and continuously transmitted to the map computer until the data store read is complete.

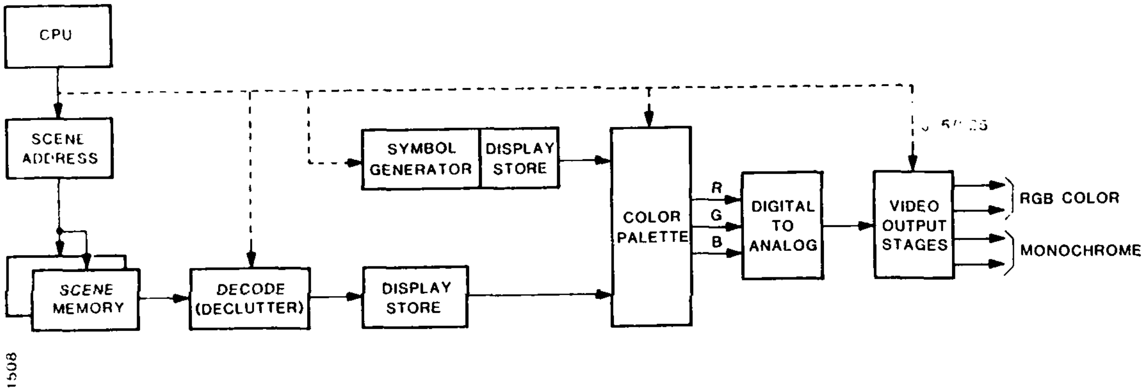


Fig. 10 Map System Block Diagram

The compressed tile data is first error checked, corrected if necessary and then divided into eight bit bytes. This serves two important functions:-

i) to permit the occasional writing error in the mass data store eliminating the necessity of perfectly programming Megabytes of store data.

ii) to detect and correct any data transmission error between the memory and computer should these functions be contained in physically separate units.

The eight bit bytes of compressed map data are then unpacked by decompression circuitry and loaded into a tile store of 128 x 128 x 4 bits for pictorial data, or reconfigured automatically under CPU control to a 64 x 64 x 16 bit tile store for DLMS data. As this tile store is loaded, the decompressed data is sum-checked and on completion, compared with the sum-checked data word received at the start of the tile data block.

There are two such tile stores, one being loaded with new tile data from the memory, while the other is read into the appropriate scene memory bit planes. Each tile block of data is read into the scene memory until 64 such blocks are loaded and the scene memory is ready for use. Addressing circuitry extracts the specific data, actually in display usage, correctly orientates and magnifies the image data before storing in the display memory. The display store is read at display frame rate and the individual display pixels of coded data are passed in sequence through a colour palette decode look-up table where they are assigned digital values for each of the 3 colour guns of the video output. This look-up table is capable of variation in its selection and decode to provide a readily configurable selection of palettes suitable for day and night operation. A final digital to analogue conversion and video output drive stage provides the appropriate RGB video output signals to the display computer.

3.2 Intelligence Data and Symbology Overlay

As a natural extension to the philosophy of digitising standard aeronautical paper charts, it follows that 'pictorial' or other forms of intelligence related data can be rapidly prepared prior to a mission. This data comes in the following forms:

- That which already exists as digital data such as JTIDS, Landsat. and intelligence data transmitted from headquarters via a digital link to forward positions.
- Any pictorial data such as reconnaisance photographs, marked up charts, sketch or data which can be overdrawn on the primary database by a local operator. The facility to overdraw exists within the capability of the local ground station via the use of a bit pad or light pen. This data is then digitised and formatted via the normal process. Information prepared in this way has the correct spacial relationship to the main map.

In addition to the intelligence data which moves coherently with the map display an additional symbol generator is provided which gives the necessary alphanumeric and graphics symbology which is overlaid as a fixed format above the moving map display. This data will typically provide the crew with the necessary navigational data to assist in interpreting the map display. Such symbology will include aircraft track, present position symbol and indications of speed, heading, and map scale together with appropriate range markers.

The symbol generator uses a dedicated CPU (INTEL 8088) and a graphics display controller (INTEL 82720). This converts mode instructions received over the mux bus, into a form that enables the generation of the graphics symbology detailed above into a raster scan format, which is then mixed with the map data video format, to give a composite video display.

Typical intelligence/mission and navigational overlays are shown in Fig. 11, 12 and 13.

Fig. 11 Typical JTIDS Symbology

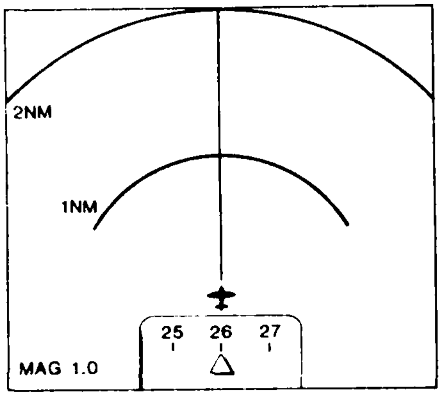


Fig. 12 Typical Track Up Symbology

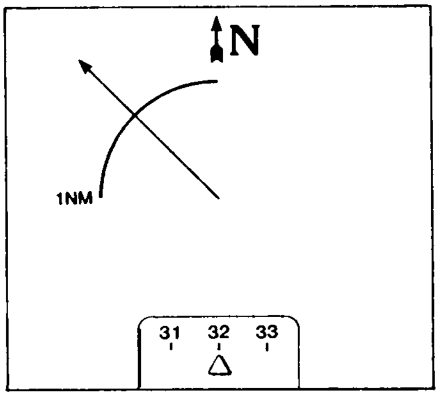


Fig. 13 Typical North Up Symbology

3.3 Area Coverage

To expand on the previously stated 70 square ft of chart coverage, it is first necessary to identify the physical construction of the map memory system. At present the designed EPROM hybrid card module contains 3 Mbytes of compressed map data as a single multilayer circuit board. This equates to 13.5 square ft of paper chart or in more practical terms, four standard US service 250,000:1 JOG sheets (Joint Operations Graphics (Air)). The system is configured to contain eight such cards, of which at present, five are utilised equating to 67.5 square feet of chart. However, as previously stated, with the rapidly advancing memory technology, this coverage should expand to 12 Mbytes per card. (16 JOG sheets) or a total future system capability of up to 400 square feet (i.e. 128 JOGs).

In order to appreciate how the system, as presently configured, would be organised with map data to perform a mission, a typical scenario has been selected to show a 1 hour sortie around the US Nellis Red Flag range with a strike attack in the Tolicha Peak area, see Fig. 14.

The mission has been overlaid on the 500,000:1 Tactical Pilotage Chart (TPC) which completely embraces the Nellis Range area. Actually some 17.5 in x 18.75 in of detailed map coverage is required i.e. 2.3 square feet of chart. However, in this case the complete card module (13.5 sq ft) totalling the whole of the relevant TPC chart (G-18B) is so digitised.

In addition, the area coverage of the mission would also be covered at 250,00:1 JOG(A) 1501 series charts ie 10 sq ft. In this case a single card module would be devoted to JOG sheets NJ 11-8, NJ 11-9, NJ 11-11 and NJ 11-12 which completly covers this area. A further store card module would be devoted to the general 1,000,000:1 low altitude navigation 16 nm/in chart which gives beacons, VOR bearings etc. covering an area of [illegible] nm x 600 nm inclusive of Nellis Air Force Base i.e. 5 sq ft. If in transit to Nellis AFB, two such adjacent charts could be included in one module giving a total coverage of 500 nm x 1250 nm or 600 x 625 nm. This would result in three store card modules being fitted.

If a fine detail map of the Initial Point (IP) to target (Tgt) is required then a further store module card containing US series Topographical Map scale 62,500:1 (15 minute series) Nevada sheet name Tolicha Peak can be carried. Thus a maximum of 4 pre-loaded EPROM cards could be directly drawn from stores for this typical mission which would more than adequately cover the mission and its surrounding environs. With the [illegible] module fitted to the Ground Station, the necessary mission overlay data could be readily loaded into one fitted EEPROM card. Assuming that an absolute maximum of 1 in 10 of the total 500,000:1 map tiles are affected then a total of 208 intelligence tiles are loaded i.e. some 41 kbytes. Thus excluding planning time the unit could be fitted with the appropriate store modules and one EEPROM loaded with mission overlay data in approximately 2 minutes.

4 OPERATIONAL USE OF THE MAP SYSTEM

There are many possible ways of using the map system in operation. This section discusses just one of the potential implementations.

The preparation of aircraft databases from paper charts is a multi-phase process. Paper aeronautical charts are digitised at a central establishment and distributed to operational stations. Here local intelligence data are continually added and updated in readiness for the next phase. This final process adds data which is specific to the particular mission (waypoints for example) and ensures that the assembled database is loaded into the aircraft database module. These processes are described in more detail in the following sections.

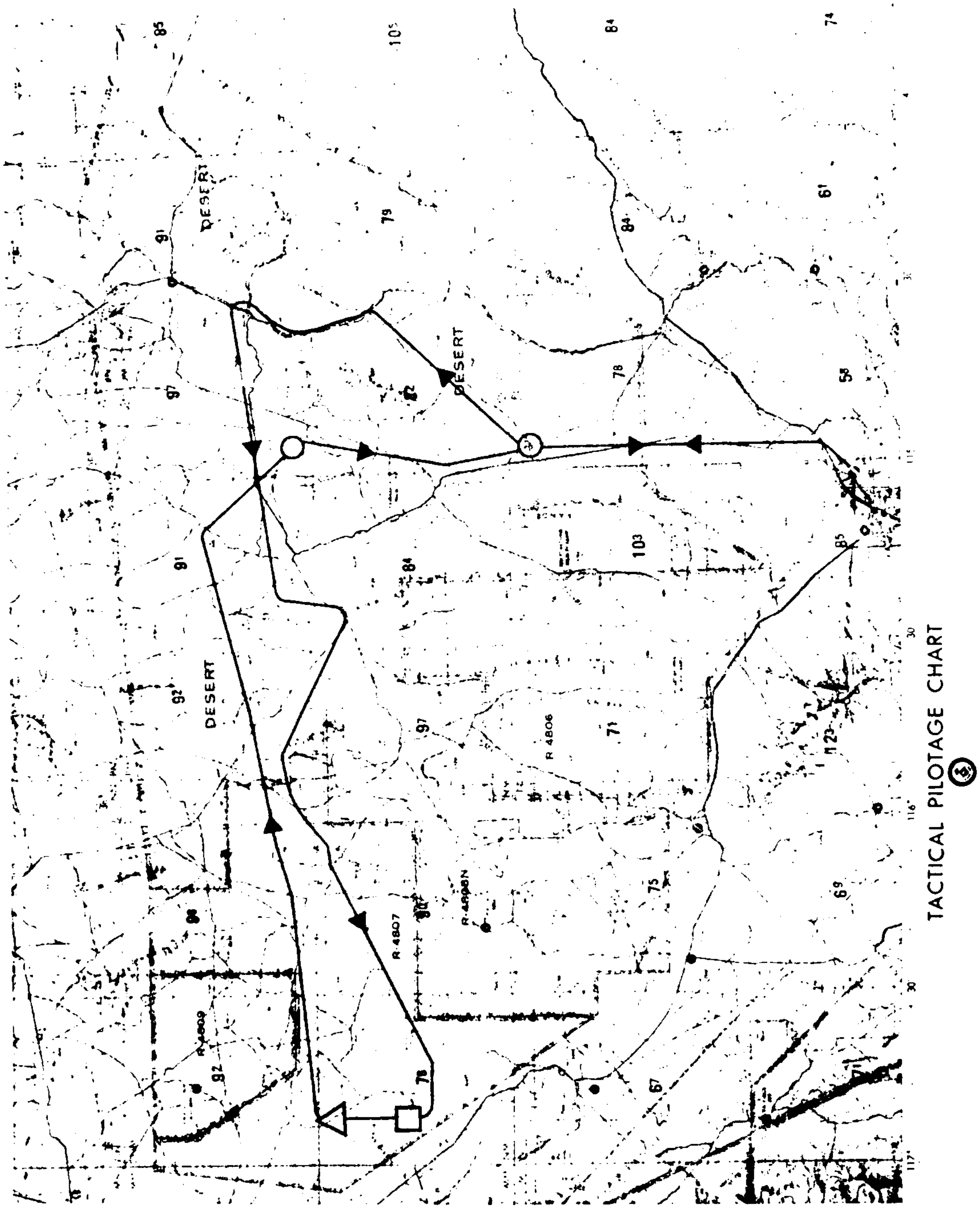


Fig. 14 Typical Scenario

4.1 Chart Digitisation

The digitisation of the paper charts is a two stage process. The first of these is the generation of large, potentially global, areas of map database. This is carried out at a limited number of Main Ground Stations (MGS) which are controlled by a government agency such as the Mapping and Charting Establishment (UK) or the Defense Mapping Agency (US). The charts are digitised using a flying spot scanner or other suitable digitising equipment. These are then processed into a contiguous whole in the correct format for the map system by an integral mini-mainframe computer. Map data of areas of interest are then distributed to Local Ground Stations (LGS) by telemetry or on magnetic discs or tapes etc.

These Local Ground Stations, which are operated at squadron or unit level, extract the map data required for any particular mission from its database. It is important to note that the database held by the LGS covers areas likely to be of local interest. Any further map data required by the station can be obtained from the MGS at short notice.

4.2 Aircraft Database Preparation

The preparation of the database for a particular mission is carried out in a similar fashion to the preparation of conventional paper charts. The database module is loaded with cards which contain the equivalent of sixty (60) square feet of paper chart. These cards are designed so that, once programmed, they may be placed anywhere in the database module. Each memory card could, therefore, be programmed with, say, a representation of an existing paper map sheet. Thus if the cards installed in the database module do not cover the total area of a mission the appropriate cards may be drawn from stores and fitted to the unit.

The LGS has the capability of of entering alphanumeric and graphical symbology into the database. This may be considered a two stage task. First the war situation, including rapidly changing intelligence data, is entered. This data might be entered manually by the Station Intelligence Office or, possibly, automatically from an intelligence gathering system such as Wavell. In practice this would probably be a continuing process and would have little impact on the time to prepare the database for a particular mission. The LGS stores all of the intelligence data relevant to its theatre of operations. In preparing the database for a mission the operator defines the area required. The LGS then extracts the intelligence data pertinent to this area and stores it in non-volatile memory together with a directory of contents.

Finally mission specific data - such as planned track, waypoints, initial points etc. - are added. The area of operations is displayed on a TV screen and the symbology entered using keyboard, light pen, bit pad or "mouse" as required. This is loaded into the database module as an extra level of overlay. Once again it is possible to automate this process to some extent. The operator could, for example, enter waypoints and allow the computer to calculate the best track for radar avoidance. Other criteria for the track calculations could be substituted as required.

Since the data required to be loaded using this process is small - typically taking two or three minutes to load into the memory - the preparation of an aircraft database need take no longer than the preparation of a conventional paper map for a mission. Also once prepared for a single aircraft this can be duplicated merely by loading other database modules in parallel.

A further alternative here is that, since the intelligence and mission specific data are held in electrically erasible read only memories, they may be programmed to the [illegible] in the same time but with the unit in situ on the aircraft thus saving the time required to remove and re-install the unit.

One possible disadvantage of this method is the potentially large spares requirement for the basic map data. Each map sheet that the station is ever likely to use would be programmed and kept in stores in as many copies as might be required. This may be overcome at the expense of the time needed to load the database. In this second method the store cards taken from the database module to be used are first erased and then loaded with the new map data. The time penalty - approximately one hour -may be minimised by allowing the operator to enter the mission specific data into the system while the basic map and intelligence data are being loaded.

In most situations the sixty square feet of map coverage carried by the unit are more than adequate to cater for the needs of all the missions that a station's aircraft [illegible] undertake without changing the basic map data. It is, therefore, expected that the replacement or reprogramming of the map data as described above will be necessary only for missions undertaken in unusual areas or if the battle zone has moved [illegible] the squadron to move it's base of operations.

In the process of database preparation only the actions of intelligence and mission specific data entry normally require manual intervention. Once the operator has defined the required area of cover the loading and checking of the database is automatic. The operator will be prompted if cards need to be changed or erased or if any other action is required.

4.3 Aircraft System

Once loaded the database module is installed on the aircraft either as a plug-in cartridge to the map or as a completely separate unit. On switch-on the processor in the map system scans the directories of the store cards in the database module and constructs a table of where the various data are contained together with the area covered by each map scale in the database. Thus no operator interaction is required in the aircraft to initialise the map system. It is this, together with the extremely powerful overlay facility, that gives the digital map system the flexibility and rapid response to operational demands that a traditional electro-optic map system cannot achieve.

4.4 Possible Enhancements

The basic philosophy outlined so far may be enhanced in many ways. Two such developments recently examined serve to illustrate the point:

1 Use in Aircraft Carriers

By the addition of a simple digitising equipment to the LGS, perhaps a TV camera and X, Y table, the system is capable of digitising single map sheets and processing them into database format in two or three days. This obviously enhances the performance of a carrier-borne squadron which is dependent on communications with land and allows entirely autonomous action provided the basic paper maps are available.

2 Use at Forward Positions

The LGS is capable of preparing a complete database. At the forward post this is unnecessary. All that is required here is the ability to update the intelligence and mission data segments of the database. A subset of the LGS including only the graphics processing and store loading facilities fulfils this function.

5 CONCLUSION

The GEC Avionics map system, then, provides a very flexible solution to the problem of providing the pilot with a moving map display. The expensive components of map database production are few in number and located at central agencies. The databases for individual aircraft are prepared on-site using the latest available intelligence data and includes mission specific data overlays. When installed on the aircraft the pilot is presented with a moving map display capable of continuous scrolling in all axes over the entire database, virtually instantaneous change of presented map scale and a number of selectable and removable overlays. The preparation of the map display, including the mission planning, is all carried out prior to the flight. The aircrew are only left with the tasks of data management and interpretation which considerably eases their cockpit workload. The system thus provides one of the most powerful moving map display systems available today.

APPLICATIONS OF DIGITAL TERRAIN DATA IN FLIGHT OPERATIONS

G. W. Cantrell
Manager, Digital Cartographic Programs
Harris Government Aerospace Systems Division
M. S. 100-1117, P.O. Box 94000
Melbourne, Florida 32951 U.S.A.

SUMMARY

With the availability of a world-wide digital terrain data base becoming a reality, it is now possible to carry and display on a tactical aircraft all of the map information needed for a mission. Along with the map display on a color cathode-ray tube (CRT), current targets and mission-specific data can be shown. The limitations of today's commonly used film readers are eliminated by using a digital data base which contains elevation information; one such data base is the U.S. Defense Mapping Agency's Digital Land Mass System (DLMS). The terrain data can be digitally compressed and efficiently stored so that large area coverages may be achieved. With this information readily available, aircraft mission effectiveness and survivability can be enhanced. The system developed by Harris Corporation for accomplishing this task is called a Digital Map Generator (DMG). The DMG architecture encompasses data storage, data access and reconstruction, data display processing, and data formatting for use by other aircraft subsystems. The Harris Corporation has developed a DMG architecture for application in low-level or nap-of-the-earth tactical missions, as well as long range strategic missions. Mission capabilities are enhanced by using this new DMG to support terrain following/terrain avoidance (TF/TA), autonomous navigation, threat avoidance, and weapons delivery. In addition, the same digital processing approach is usable for pre-flight mission planning. The ability to plan a flight using the actual mission data base gives the pilot the ability to see exactly where he will be at all times and to determine safe corridors for entry and departure, making maximum use of terrain shielding. Similarly, the terrain data may be used for reference during post-mission debriefing, in which the pilot can refer to in-flight annotations made through the DMG subsystem.

DIGITAL MAP SYSTEMS: A SYSTEMATIC APPROACH

In order to exploit the availability of a terrain data base, the full spectrum of data handling and display must be addressed in a systematic way. For instance, there would be no benefit in attempting to develop a digital map system for aircraft operations if the size, weight, and power were not consistent with modern tactical aircraft limitations. Likewise, it would be useless to develop a flyable system without some flexibility and growth potential; and it would be pointless to have a system architecture which requires excessive effort in preparation of the data base. It is necessary, therefore, to tie together all of the aspects of the problem and address them interactively. The key considerations in a decision to employ digital mapping techniques are as follows:

- Availability of source data.
- Methodology for data preparation for aircraft use.
- Aircraft mission requirements.
- Complexity of the on-board equipment.
- Aircraft compatibility in terms of available volume, power and subsystems interfaces.
- Mission enhancement and survivability improvement gained from use of a digital map system.
- Flexibility for future growth.

Availability of source data from agencies such as the Defense Mapping Agency (DMA) is a reality. The DLMS data files already exist for approximately 20 million square miles of the earth's terrain. Limited geographic digital data bases also have been created by the governments of other countries, such as the United Kingdom, for specifically defined areas of coverage. The DMA continues to expand, update, and improve the accuracy of its digital data base. Studies at Harris Corporation and at other locations have indicated that the accuracy and availability of the source data are adequate for use in tactical aircraft operations.

Where source data do not exist, several approaches may be taken to obtain digital terrain data. Of these, the following are the most practical:

- Request through formal channels to the Defense Mapping Agency or similar government agency.
- Use of paper maps through simple two-dimensional digitization.
- Manual generation of an alternate three-dimensional data base (i.e., a data base with elevation parameters in addition to the pictorial information normally shown on a paper map).

Rapid turnaround of data would normally dictate against the first alternative except in the case of high national priority. The second and third alternatives, however, are eminently feasible in a digital map system. Simple color scanning and digitizing of any paper map will produce a data base capable of being used by equipment like the Harris DMG. Manual generation, aided by appropriate computer software, is also possible through use of map-tracing techniques. In tracing a paper map, the contour lines are identified and followed by the tracer, which provides an input to a host processor that converts the data to a DLMS-like format. Thus it is possible, using readily available techniques, to prepare a digital data base in a fairly short period of time, using any available paper maps as the source. In a similar fashion, any other two-dimensional or pictorial source (such as reconnaissance photographs) can be digitized for entry into the data base. The entire source data base may be manipulated digitally to adapt to the needs of using equipment.

A data manipulation and preparation methodology must be developed to allow useful application of the source information. The original source data (such as DLMS data) is normally provided in a format which separates the terrain elevation information from the cultural information, and because of this separation it is easier to compress the data. The process of compression is needed because the volume and format of the source data are too great for practical use in their original form. The compression technology must be selected on the basis of available cost-effective digital storage techniques. The complexity of data compression and reconstruction, which directly affects the on-board system complexity, must also be considered. When all these factors are taken into account, a data compression concept can be selected.

Obviously, aircraft mission requirements will dictate the need for certain functions in a digital map system. It is taken for granted that a color display of the actual map scene is a necessity; still, the matters of display scale, color selection, terrain shape depiction, cultural feature illustration, and similar issues must all be addressed. The availability of color CRT's with adequate brightness for daylight readability is also an issue, but for night missions there is no problem. Recent CRT developments show a potential for daylight readable displays to be available within the next two years in production quantities. Other requirements besides the display will have a bearing on the system design; these include the entire family of uses which other avionics subsystems may find for the terrain data once it is available. Terrain following/terrain avoidance (TF/TA) and general low altitude navigation are certainly the most predominant; but others include use of the terrain elevation information for anticipation of turning maneuvers, shielding from hostile weapons or radar detection, and support of weapon delivery calculations. All of these will be discussed in more detail in following sections of this paper. It suffices to say at this point that the digital map may be considered as a new avionics sensor, and that it opens up a broader range of mission uses and applications.

Another major factor in the evolution of a practical digital map system is the complexity of the on-board equipment needed for the digital map function. On the assumption that multifunction color display heads are coming into common use in most modern aircraft, the display itself is not considered to be a part of an airborne digital map system. The parts to be considered are those elements which store and process the digital terrain data for display or other uses. Design tradeoffs for the airborne equipment must take into account the basic display function while retaining the flexibility for providing data to other aircraft subsystems. Consideration must be given to whether the data should be partially or completely preprocessed before being shipped out to the other on-board using subsystems. Data rates, processing flexibility, and adaptation to existing equipment must all be evaluated. The ultimate decision on a system design concept cannot simply address the added digital map equipment; it must also consider any additions or modifications needed in the remainder of the aircraft subsystems.

Overall mission enhancement is a difficult topic to address in a new system. Analyses must be used to show the benefits of the added investment in terms of overall crew effectiveness, mission success probability improvement, increased survivability, and improvement of other features (such as extended useful life, or broadened tactical capability, of the aircraft). All of these items have been addressed by Harris analysts, who conclude that the addition of a three-dimensional terrain data base in usable form will greatly increase the range of aircraft capabilities while improving the probability of total mission success. In some fields, this effect has come to be known as "force multiplication."

DATA PREPARATION AND STORAGE

Given the current state of the art in digital data storage, it is necessary to compress the rather voluminous source data in order to carry it on board an aircraft in any reasonable volume. A significant advantage in on-board storage can be gained if the source data can be compressed and reconstructed with a high compression ratio and good fidelity. Two types of elevation data compression algorithms are currently under consideration as candidates: (1) frequency domain compression and (2) spatial domain compression. The specific techniques within these two categories may vary, depending on the approach used ultimately to implement the algorithm in data preparation and in-flight data reconstruction. Harris currently uses the frequency domain compression technique with some processing modifications, resulting in a very high compression ratio (256 to 1) and excellent preservation of initial elevation data accuracy. The block truncation technique, a popular data compression approach in the spatial domain, is less efficient in terms of compression ratio, but it is also somewhat simpler to implement in digital processing systems.

The elevation data preparation process typically goes through the following steps, regardless of the compression methodology: (1) Transformation of the source data (DLMS, for example) from latitude/longitude coordinates to x-y type grid coordinates; (2) Partitioning of the transformed data into discrete segments or blocks for convenient processing; (3) operation on the elevation data, using the selected algorithms, to produce a compressed data format ready for data storage; (4) Transfer of the compressed data from computational media (typically computer disk or tape) to the operational storage media for use in the aircraft. The applicable types of operational media will be discussed later.

Most of the above steps are typically performed with the aid of a general purpose computer.

The fourth and final step (transfer to an operational storage medium) must of necessity include provisions for cultural data addition as well as elevation data addition. This may be accomplished simultaneously or in separate steps, depending on the overall data handling approach. The addition of cultural data can also be done in a variety of ways; Harris has chosen a technique which consists of scanning a data block and identifying the points at which a cultural feature (road, river, city, lake, etc.) occurs. Linear features such as roads and rivers are automatically assigned a two-pixel width (in a 500 x 500 pixel display format). Area features such as cities or lakes are scanned by identifying the points at which left-most boundaries occur, and then subsequently the points at which the detected boundary changes. Conversion of these scanned points into a vector format during the data preparation process allows compression ratios on the order of 1000 to 1. The preparation software also provides for the assignment of color codes to cultural features from an essentially infinite selection of allowable colors. Thus the pilot quickly associates a color with a feature; for instance, red for hard-surface roads, yellow for railroads, blue for water, and so on.

The data storage medium to be used in the aircraft may be any type of non-destructive readout (NDRO) digital storage. Currently, the most efficient storage medium (in terms of bits per unit volume and also cost per bit in small volume) is magnetic tape. Tape is also the only near-term viable method for digital storage with proven, long term reliable operating performance history. Various magnetic tape recorders exist in fully qualified, flightworthy configuration. Tape recording suffers from one drawback, however: a discrete amount of access time is needed in order to retrieve a randomly selected data group. *This drawback can be eliminated in practical flight systems* by use of an architecture which allows the digital map system to "think ahead" and retrieve data from tape before it is actually needed for processing. Other upcoming candidates for mass memory are alterable Programmable Read-Only Memories (PROM), optical disk, magnetic disk, and bubble memory. *None of these, however,* is operational and proven in flight configuration except for the bubble memory and erasable PROM's. Storage efficiency, in terms of kilobits per unit volume, for each of these media is approximately as follows:

- Magnetic tape: 1,000 kb/in^3
- PROM : 200 kb/in^3
- Optical disk : 5,000-10,000 kb/in^3
- Magnetic disk: 200 kb/in^3
- Bubble memory: 100 kb/in^3

It is clear from the above table that the optical disk is by far most efficient. It suffers, however, from several drawbacks: it is not available in militarized form today; it requires a relatively large volume and weight in order to achieve its high data density; *and the optical disk memory is normally not* alterable in a tactical user environment. Access time to optical disk, magnetic disk, PROM, and bubble memory contents is much shorter than for magnetic tape (many nanoseconds to tens of milliseconds), permitting a different digital map architecture to be considered. The bubble memory also offers much promise as *densities increase. In its currently available form, a 32 megabit* capacity, the bubble memory is a new but effective product capable of surviving typical military environments. The bubble memory system and the PROM mass memory offer the only alterable storage with no moving parts. The major disadvantage of the bubble memory is the volume of practical systems, *currently on the order of nearly 500 cubic inches for* 32 megabits of storage. The data transfer rate and access times are also slightly lower than that of the disk-based products, but certainly within an acceptable range and much faster than magnetic tape.

PRACTICAL AVIONICS ARCHITECTURES

In order to be useful, a digital map system must be designed so that its architecture is realizable in hardware and software at reasonable cost, with acceptable volume, weight, power consumption, and maintenance characteristics. Two potentially different architectures appear to be the primary candidates:

(1) Centralized processing architecture;
(2) Distributed processing architecture.

Within each of the above categories, there are further tradeoffs related to the scope of general purpose versus dedicated processing, and to the extent of additional processing required in other aircraft subsystems using or accessing the digital map data. Other factors affecting the architecture include the type of data storage medium, the desired display resolution and refresh rate, the speed range of the using aircraft, the number of different operating modes desired, the data compression technique used, and the need for supplemental functions such as alphanumeric or graphic symbology. For the purpose of discussions in this section of the paper, it will be assumed that data compression will be required in order to provide adequate data coverage; use of uncompressed data is therefore a subset of the general architecture.

A general *digital map block diagram* is shown in very simplified form in Figure 1. Its operation is as follows:

- Stored terrain data are accessed by the processing system as required.
- The processing system reconstructs the compressed data.
- *The data formatting system rotates and translates* the input data in accordance with positional or velocity inputs.
- Other special processing readies the data for output to various avionics subsystems such as display, flight computer, navigation, etc.

This basic design applies to all digital map systems. The methodology in data processing to handle the basic digital map functions will depend on one or both of the two basic architectures (centralized versus distributed). A maximally centralized system performs all data manipulations required for all functions and using subsystems in the aircraft.

A maximally distributed system handles only the collection of the terrain data and ships the data out to other avionics subsystems for further special processing. Each architecture has certain advantages, many of which relate to the availability of other processing capability on the aircraft and to the feasibility of moving data around the plane in large volumes at high speed.

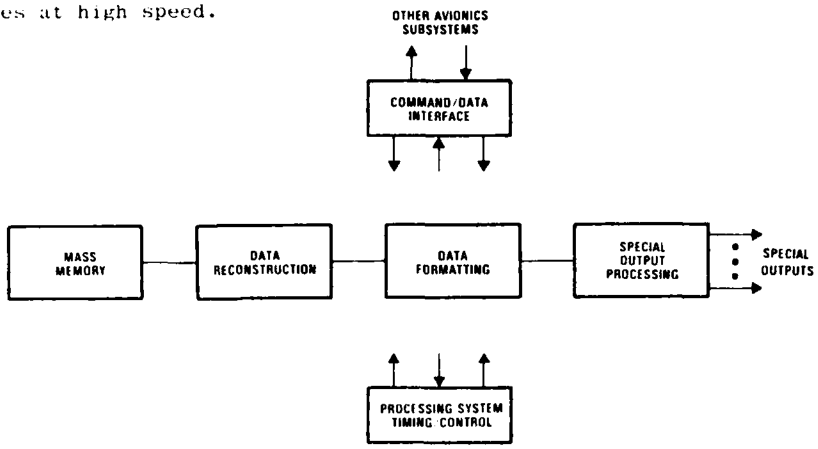


Figure 1. Generic Digital Map System

Most avionics subsystems are designed with adequate growth margin for known and projected processing requirements. The advent of a new sensor such as a digital map with incredible utility and *flexibility, will normally necessitate some* additional (perhaps unforeseen) processing. To distribute the digital map processing load into other (perhaps overworked) aircraft processors is probably a poor solution for two reasons: (1) the spare capacity probably does not exist in current avionics systems; (2) the relatively unprocessed and undigested digital map data will have to be transmitted on some type of very high-speed bus, which currently does not exist in most aircraft. Data rates on the order of tens of megabits per second may be required. It is natural, therefore, that a maximally distributed digital map architecture is not desirable for current aircraft in the world's inventory. A maximally centralized architecture may also be undesirable because it will replicate other processing functions aboard the aircraft and will require too much hardware and software for implementation. It is no wonder that a practical architecture takes advantage of the best features of centralized and distributed processing. Harris Corporation *has developed a digital map architecture through* three evolutionary generations to arrive at a configuration which is optimized for today's avionics, but adaptable to future requirements.

The architectural approach for the Harris DMG is based on the assumption that data may be processed more efficiently at its source if adequate processing power is available. Therefore the architecture, from an external view of the digital map system, appears centralized because data are not distributed outside the box under normal operation. However, inside the DMG the processing is very much a distributed approach. The design utilizes multiple microprocessors operating on a parallel bus with a common shared memory. The internally distributed architecture affords the opportunity to process data at high speeds without the penalty of sending the data to a remote location. This concept also allows *reconfiguration of processor tasking and addition of processors* to the bus without disturbing the existing software structure. The internally distributed, centralized processing architecture will be seen to be particularly effective for growth of the system beyond mere display generation. The system also contains an interface which permits access by other avionics to the terrain data, but it is expected that most applications will be handled internally by the DMG processors. A block diagram of the Harris digital map architecture is shown in Figure 2; a brief description of the system follows.

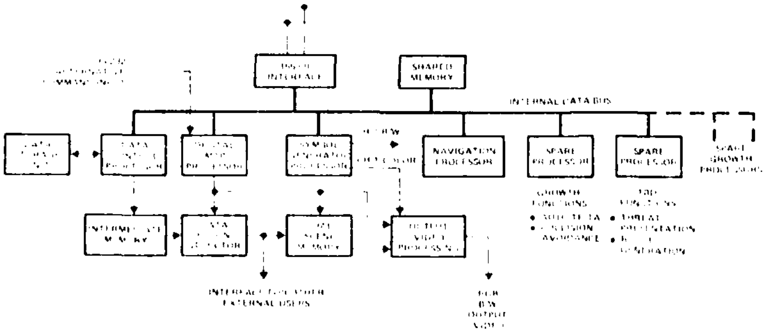


Figure 2. Architecture of the Harris Digital Map System

The data storage unit consists of a pair of 25 megabit tape recorders, which provide the compressed data on request from the data control processor (one of the microprocessors in the system). With a microprocessor-controlled memory interface, a simple software change can be implemented for adaptation to other memory sources. A second microprocessor controls the basic digital map functions, including the timing of reconstruction, the translation and rotation of the map, and the required coordinate conversions. A third identical microprocessor module operates the dual channel symbol generator, providing alphanumeric and graphic symbology based on software/firmware programming. A fourth identical microprocessor module handles the operation of the autonomous navigation algorithm, which will be further discussed in a subsequent paragraph. Spare card slots are prewired to accommodate two more microprocessor modules for growth of the system's capability. All of these microprocessors operate on a high-speed 16 bit parallel global bus, accessing a common global random-access memory (RAM). Each processor also contains its own local or cache memory as a part of its normal hardware complement. Preassigned priorities are arbitrated each cycle, with additional provisions for prevention of one processor from totally blanking out all others. With the global bus design, the system is an internally distributed architecture capable of sharing the overall processing load. External controls and data inputs come into the system through a standard 1553B redundant interface; examples of typical inputs are navigation data and mode control data. Outputs from the digital map also pass through the 1553B interface; examples are the status indicators passed to the flight computer and the display system.

Not directly connected to the high speed internal bus are the other modules: intermediate memory, reconstruction circuits, scene memory, and video output modules. The intermediate memory acts as a buffer between the low-speed data storage unit and the high-speed scene memory outputs. The intermediate memory feeds data into the reconstruction circuits, which are separated into an elevation reconstruction module and a cultural feature reconstruction module. After each reconstruction cycle, the dual scene memory is loaded with new data to update the display in the direction of aircraft movement. Two scene memories are used so that two different scenes may be instantaneously available on request. The final digital video outputs are processed through a color mixing RAM before being converted to analog form for driving the color display. The color mixing RAM is programmed by an initialization data block from the data storage unit, allowing user selection of colors to be changed at any time. Finally, for the other aircraft subsystems which may need direct access to the data, an interface module is available and is operated over a second dedicated 1553B bus.

The flexibility of the Harris digital map design permits an infinite variety of functions and operational modes. Even more modes of operation are possible by making software changes. Some of the major features of the system as currently configured are listed in Figure 3.

- **Display**
  - ***Color or black and white***
  - **Elevation shaded or slope shaded**
  - **Contour lines at selectable intervals**
  - **Cultural features (roads, rivers, cities, lakes, bridges, etc.)**
  - **Interest points (targets, threats, etc.)**
  - **Flight plan points—connected or independent**
  - **Scales from 3 x 3 to 768 x 768 kilometers**
  - ***Terrain color above selected altitude***
  - **Flight instruments**
- **Functions**
  - **Provides elevation or coordinate data on request**
  - **Process Sitan or other navigation algorithms**
  - **Expandable (spare) processing capability**
  - **Symbols/alphanumerics may be flashed and rotated**
  - **Geographic and cultural or point features may be selectively added or deleted ("decluttering")**
  - **Remote area display capability**
  - **Provides real-time tape update capability**
- **Physical/electrical characteristics**
  - **9.6 x 9.8 x 20.5 inches including mounting tray**
  - **Power consumption 370 watts nominal**
  - **Weight 52 pounds**

Figure 3. Primary Features of the Harris Digital Map System

The uses of these features will be covered later. Some of the above features will first be reviewed so that the reader may gain an appreciation of their significance. First, the display itself operates in a variety of modes and colors. Besides the ability to vary the viewed area from 3X3 km to 768X768 km in 2X steps, the DMG can also selectively display classes of cultural features by a process known as "decluttering." For instance, if the pilot wishes only to see major highways, the system can be commanded to delete all other roads. In a similar fashion, various classes of cities, railroads, rivers, and other so-called "linear" features may be displayed or deleted. "Area" features (cities, lakes, forest areas, etc.) are collected in the data base in categories which may also be selectively decluttered. Residential areas, for instance, may be eliminated from urban-type locations so that only industrial areas are shown. Dry lakes and normal lakes are classified differently and may be decluttered. Forests are categorized into various classes (coniferous, deciduous, etc.) and may also be selectively added or deleted.

Besides the indication of "point features" (such as water towers, broadcast antennas, agricultural buildings, and the like) from the basic data source, the digital map system also can display "point symbols" which are specific interest points entered into the data base by the pilot, intelligence officer, or other individual involved in mission planning. These symbols can even be entered via a data link, and may take on a selectable variety of shapes and colors for ease of identification. Representative symbols include waypoints, targets, threats, or any other geographically locatable object which the pilot wishes to keep on file for reference during the mission. Waypoints may be joined by a line showing the aircraft route, and all of the route data may be changed at any time. All of these symbols are produced by the self-contained symbol generator, which also can draw lines or circles of any size. The symbols can also be selectively flashed or rotated, or they may be allowed to remain geographically fixed in one orientation. For aircraft which can provide the appropriate electronic signals to the symbol generator, it will produce synthetic flight instrument displays in raster format. The symbol generator also has a second independent monochrome channel capable of producing a separate display output for use in a helmet-mounted display, heads-up display, or other similar displays.

Colors in the Harris digital map are completely selectable. Many human factors studies have been made to determine the most effective colors and shades; the digital map allows the user to select, through the color mixing RAM, any family of colors considered appropriate. A different set of colors may be chosen for night missions, for instance, in order to accomodate the pilot's night vision goggles or simply to provide minimum disturbance to the naked eye. The color assignments are stored in the mass memory and are easily altered off-line during mission planning and data preparation. Color tables are loaded into the initialization data block, which will be discussed further.

OPERATIONAL MODES OF THE DIGITAL MAP SYSTEM

An efficiently organized man-machine interface is imperative if the digital map system is to be utilized to its full potential. The definition of this interface begins with the major operational modes of the digital map system. These modes, capable of growth to support other functions, are currently as follows:

- Initialization mode
- Terrain data mode
- Aeronautical chart/photo mode
- Built-in-Test (BIT) mode
- Remote map mode

The initialization mode operates as follows. Upon application of power, the digital map goes through an automatic initialization routine, The processors perform a setup of all local hardware and then execute a set of general checks on the health of the system. If fatal errors are discovered during these checks, the errors are logged, the 1553 data bus is enabled, and an attempt is made to report the error over the bus to the external aircraft systems, such as the flight computer. If no errors are found, the symbol generator sub-system displays a "standby" message to alert the user that the system is proceeding to set up the global RAM and other starting point functions by reading in data from the mass memory subsystem (currently the militarized tape recorder). The initialization data block from the tape unit might be comprised of the following contents:

- Mixing RAM Loads (three sets of 4K words)
- Initial Cultural Preselect (256 bytes)
- Initial Mode Command
- 3 Pre-determined Video Modes
- Alternate mode commands
- Tape directory data describing the geographic coverage of tape and map scales on tape
- 32 Flight Plan points and 64 Interest Points (400 words)
- DMG internally used software tables (2048 words)
- 148 words of initialization for use by systems external to the DMG
- 100 data frames (assumes 8192 words)

When all DMG initialization data is received, the digital map system controller retrieves status messages from the Symbol Generator processor and formats a Mode Status Echo message. The Equipment Ready Output Discrete is asserted, indicating that the system is ready for data bus communication. The system is then ready to accept navigation commands and start reconstruction of the requested displays. Upon receipt of navigation data over the bus, the system is placed into the default initialization mode. When the first scene memory block has been reconstructed, the word "STANDBY" is removed from the display. This initialization process, assuming a tape cassette is used, is completed in approximately 30 seconds. If a solid-state mass memory or a disk memory is used, the entire process is completed in less than one second.

The terrain data mode is the normal operational mode for most system operations. In this mode, which is automatically entered upon completion of initialization, the digital map system retrieves and processes the three-dimensional terrain and cultural data stored in the mass memory. Elevation data can be displayed in one of three formats: elevation shading, sun-angle shading, or terrain above a set altitude. Display format is user selectable over the multiplex bus. In the elevation shading format, the intensity of each pixel is a function of the absolute elevation of the terrain being represented.

The intensities are grouped into eight different bands which may be controlled via the multiplex bus using the following three parameters:

- Maximum Altitude - defines the lower limit of the highest elevation band
- Band Interval - defines the elevation interval below the maximum altitude at which shades will change
- Shade Table - eight-entry table allows the user to assign the intensity of the eight shades

Without specific commands, the system will define the elevation shading parameters based on initialization data from the mass memory.

In the sun-angle shading display format, the intensity of each pixel on the display is a function of the slope of the terrain represented by the pixel relative to an artificial sun angle, yielding an artificial three-dimensional appearance to the display. The sun angle is artificially fixed at -45 degrees with respect the map orientation angle (i.e., in the upper left corner of the display) in order to prevent commonly known display illusions. In the sun-angle display format, 16 shade levels are utilized. The shade levels represent differences in slope in approximately 2 degree intervals. The system automatically adjusts for changes in the display scale factor; thus, no external parameters are required in this mode. The third display format is called "terrain above a set altitude." This format is a modification to tbe standard elevation shading format, and its purpose is to provide the pilot with a terrain avoidance display which shows terrain above a chosen altitude in a distinct color. Other areas of the display are the same as for the elevation shading format. The "set altitude" can be fixed or dynamically controlled by the system to correspond to the aircraft altitude plus an externally provided offset. The color chosen is fully programmable.

In each of the three basic elevation formats, black contour lines can be added. The contour lines represent lines of constant elevation in the displayed terrain. The contour lines can be selected or deselected by external bus control. When selected the lines are generated at a real-time 60 Hz rate such that they can keep up with any aircraft translation or rotation. Two inputs are provided to the DMG via the bus to define a reference elevation for contour line location and the interval between subsequent contour lines. Contour lines will be assigned at the chosen elevation and all elevation values above and below that level that are integer multiples of the selected interval. Without specific commands over the multiplex bus, initialization values for the contour lines will be used.

Display color is obtained from the three dimensional cultural data base composed of area, linear, and point features. Within the system, point feature data are processed with all other symbology in the Symbol Generator subsystem. Area and linear feature data are read from the tape in compressed form and reconstructed prior to being written into a scene memory. The system can process up to 62 different area feature types and 64 linear feature types at one time. Each area and linear feature type can be individually selected or deselected via a preselection memory during the reconstruction process. The preselect memory can be loaded from the mass memory or from the multiplex bus. Each memory load specifies selection/deselection as a function of display scale as well as feature type. Thus, one can declutter more and more detail feature data while going to larger area display scales. This capability is extremely important because it allows the pilot to concentrate on only the features of interest, yet it preserves the ability to display any desired features.

The Harris DMG not only provides full compatibility with the DMA Digital Land Mass Level 1 and Level 2 data, but it is also fully capable of being adapted for storing and displaying large amounts of digitized aeronautical charts or reconnaissance photos. This gives the user the ability to display a map scene based on existing standard paper charts, which would be useful to augment the DMA data scene or to provide the aviator with map coverage in those regions where DMA digitized data may not be available. The preparation and digitization of the aeronautical charts into the mass memory is discussed further under the Mission Planning System subjects. Basically, the Harris approach is to use a high resolution red-green-blue (RGB) camera digitizer to scan the charts and generate a data base suitable in structure to process and format into the tape. This technique has been successfully demonstrated at Harris and has proven to offer high quality, faithful reproductions of the material scanned. It also has been shown to be a very time-efficient process providing extremely quick turnaround from initial paper chart to a finished data base, requiring less than 2 hours for a nominal area of coverage. The advantages this provides to the military pilot, in terms of displaying the latest up to the minute chart or photographic information, are obvious.

The Harris DMG can essentially perform the same motion based modes with the aeronautical chart displays as it can with the DLMS generated displays. It can also overlay symbology such as flight plans, intelligence data, etc., and register it to the geographic position of the underlying map scene. Any of the symbol generator overlay data may, of course, be selected or deselected upon command. The basic motion modes supported for the aeronautical chart displays are:

- Real-time translation and rotation synchronized to aircraft motion
- Heading up display, or North, South, East, West up
- Aircraft centered in the display or placed at the lower 20 percent point
- Remote scene look-ahead (stationary view of a command area)
- Slew to any other area within the stored coverage upon command

Another basic mode of operation is the built-in-test (BIT) mode, which allows the digital map to check itself and report on its operating condition. A considerable amount of detail will be presented on this topic because it is considered critical to proper use of the digital map system. The BIT function is incorporated in two primary operating modes. The periodic BIT mode operates continually when the system is in an on-line configuration; that is, periodic BIT executes when the system is operating normally, (for example, during flight). Initiated BIT operates only when commanded, or only when the digital map is in the off-line mode, and is used primarily in the aircraft as a preflight GO/NOGO indication. Periodic BIT has the capability to detect faults during normal (in flight) operation. Both fatal and recoverable faults are detected. Initiated BIT is a comprehensive sequence of tests to verify the integrity of the DMG. The philosophy of initiated BIT is success oriented; that is, interaction of the DMG with the pilot or crew chief prior to flight results in a positive indication that the system is functioning properly (merely an absence of detected faults does not constitute a satisfactory conclusion of initiated BIT). Furthermore, initiated BIT has fault isolation capability where a fault is indicated in the associated major subsystem, the affected minor subsystem, and particular circuit module.

The BIT design concept, for both periodic and initiated BIT, is predicated on the system functions and the associated hardware architecture. The digital map system is a highly integrated array of processing functions. Both general and special purpose processing functions are arranged in basically a parallel pipeline configuration. The generic pipelines are the symbol generator and digital map functions. Parallelism exists between those two functions and with the controlling processors along with the multiplex bus interface. Of course, within the major functions other parallelism exists, such as the two scene memories. The functional partitioning is so organized that a fault in a separable function is uniquely associated with faulty hardware of a particular module. As is described in more detail below, initiated BIT exercises/tests each of the parallel/pipeline functions individually; thus when a fault is detected, isolation is relatively straightforward.

In the digital map system, the firmware controls all built-in test activity except for a minimum quantity of built-in test hardware functions which must be included to cover processor hardware-related faults which could affect the integrity of the firmware or proper firmware execution. The principal hardware functions incorporated as part of BIT are as follows:

- Processor memory parity
- Multiplex bus interface self-checks
- Watchdog timer for processor activity

All memory associated with the general purpose processors has word-wide parity associated with each memory location. Both PROM and RAM memories are included with each processor along with the shared RAM on the global bus. PROM parity is permanently loaded with the firmware. RAM parity is generated by a hardware function as each RAM location is written. When reading memory, whether it be ROM or RAM, parity is checked by a hardware function. If an error is detected, the associated processor is interrupted and the parity error is thus detected. A memory parity error is a recoverable error. The digital map system's action after the occurrence of a recoverable error is described at the end of this section. The multiplex interface self-checks are hardware functions which include the test requirements of MIL-STD-1553B. In the interface, error conditions detected in the message transfer process are loop test error, direct memory access error, Manchester error, parity error, word count low, and word count high. Upon detection of one of these errors, the bus interface chip reports the error to one of the general purpose processors and inhibits updating its buffer status registers. This indicates no message received, which prohibits bad data from entering the system. The error condition is cleared upon reception of the next valid command word. Additional features include a babbling transmitter shutdown function and mode codes to implement transmitter shutdown, override transmitter shutdown, and reset terminal electronics. These features provide additional bus integrity and recovery capabilities. The general purpose processors also have the ability to read and write the status registers of the bus interface. This capability enables the processor to determine if the MIL-STD-1553B ping-pong message buffers are operating properly.

A watchdog timer is implemented in the event that a processor, specifically the DMG control processor, fails passively or "gets lost" in its own firmware. For the watchdog timer not to act, the DMG control processor must periodically reset the timer. If the watchdog timer is not reset, it times out and causes the entire system to reset (comparable to a power-on reset). Timeout of the watchdog timer is treated as a recoverable error/fault. If system recovery actually occurs, it reflects the elimination of the cause which allowed the timer to time out originally. All other periodic BIT functions are controlled by the processors. Prominent functions in this category are:

- Firmware memory checksums
- Mass memory data integrity
- Intermediate memory data integrity
- Reconstruction processor function
- Data path integrity from intermediate memory through scene memory
- Pixel plotter and pixel RAM integrity
- Multiplex bus and interprocessor communications

The firmware memory checksums are performed by each processor on its ROM as available processing time permits. Two successive checksum errors are treated as a fatal error.

Integrity of the mass memory (tape unit) contents is verified by a longitudinal redundancy check (LRC) character at the end of each data block as it is read from the cassette tape. Two tries to read the data are permitted for each time the particular data block is requested before an error is indicated. An inability to read the data block is not considered a system fault if the data are not initialization data or the test pattern (in the initiated BIT mode only). The consequences of the inability to retrieve map data are described in the next paragraph.

Data integrity in the intermediate memory is verified when the memory is read. Each block and subblock (if present) of data has an additional LRC character which is checked as data are read from the memory. In the event an error is detected, a reread is attempted. If the reread fails, the intermediate memory data are again read from the tape unit. If the read of the intermediate memory fails again, a fatal error is indicated. The consequences of the inability to extract map data from the intermediate memory prior to the decision which results in a fatal error are the same as the inability to extract valid data from the tape unit. Map data that is unavailable for placement in the scene memory merely results in the respective geographical map area not being available for presentation. The video will be blank (black) for that geographical area. Such is the case when the map display is positioned at the edge of its on-board data base coverage area. In the particular instance of the inability to retrieve valid data from the tape, a scene memory block will be blanked. If that block comes into view on the display, it will appear as a black area; in the moving map mode, the aircraft can literally fly through the blanked area. Since the inability to read one block of data from the cassette tape cannot generally be considered a system level or catastrophic problem, the described method of operation in that event has been implemented.

The digital map system has two reconstruction processors. The elevation reconstruction processor operates on compressed DLMS elevation data and the cultural reconstruction processor operates on DLMS cultural data and on the compressed imagery generated from aeronautical charts of photographs. Neither reconstruction processor is required to operate continuously. Reconstruction is required only when a new scene memory block must be created. Periodic BIT takes advantage of the idle times of the processor by loading a test pattern in an intermediate memory block and then instructing the reconstruction processors to operate on that data. The reconstructed (test) data are then verified by reading the respective reconstruction scratch pads. Every bit of data is not individually verified; however, representative samples are verified resulting in a high probability of correct reconstruction processor operation. Any failure in the tests of the reconstruction processors in considered a fatal error.

The approach to verifying the proper operations of the symbol generator hardware is similar to that described for the DMG functions above. Tests are initiated in the symbol generator by instructing the pixel plotter to plot a predetermined symbol or shape into one of the pixel RAMs. The appropriate locations in the RAM are chosen so as not to interfere with active symbology. These locations are then read by the processor to verify the proper pixel plotter and pixel RAM functions. Those pixel locations are then cleared prior to that RAM being used for active video generation. The process is then repeated for the other pixel RAM. Any detected fault is treated as a fatal error.

The remainder of the special purpose hardware in the DMG is dedicated to the generation of real-time video. That hardware is not functionally checked during periodic BIT. Two significant factors entered into that design decision. First, digital map data used to support other avionics functions (such as TF/TA, threat assessment/intervisibility, etc.) are extracted from scene memory. Earlier descriptions have shown how map data integrity through the scene memory is verified by periodic BIT. It is important to recognize that automated weapon system functions relying on the digital map data originating in the DMS, such as a coupled flight director function for TF/TA, can be implemented with the assuredness of data integrity verified automatically by periodic BIT. (The particular example was chosen since flight safety is involved.) Second, hardware failures in the video generation circuitry (elevation processor, slope shade processor, etc.) affect only the display quality (i.e., there is not direct coupling to any other function). The consequences of these types of failures is a purely subjective issue. If the display degradation is not noticed by the pilot, the failure is of no consequence. If the problem is recognized, the pilot chooses whether the display is a quality that still provides a useful function. If he decides not, he may discontinue the use of the system.

Communications involving the global subsystem occur among the processors and the bus interface. The global bus protocol, including periodic hardware handshaking between the processors and data flow to and from the bus interface, inherently provides self-test capability. Any breakdown in the communication protocol will result in the DMG control processor allowing the watchdog timer to time out. (The results of this process have been described.) Another example which would result in this situation is appropriate to discuss. If the symbol generator processor fails or "gets lost" in its firmware, it will cease proper communications with the DMG control processor. The lack of communication alone results in the DMG control processor recognizing a problem and, in turn, permitting the watchdog timer to time out. If during reinitialization, the symbol generator processor recovers, operation can proceed normally; otherwise, the watchdog timer times out again and, finally, recovery does not occur. In all instances of an error/fault situation, the status of that condition is made available for multiplex bus transmission, if possible. Furthermore, if possible, error/fault status and, where appropriate, the number of occurrences thereof are entered into non-volatile memory.

All of the preceding discussions of BIT have been on the subject of periodic BIT. As will be recalled, the initiated BIT mode is the other half of the digital map's internal test modes. The initiated BIT function primarily serves as a comprehensive preflight system readiness check. Additionally, initiated BIT provides an automated fault isolation capability which pinpoints a faulty circuit/function to a specific module. The initiated BIT mode will only be entered when the system is so commanded with the appropriate message over the aircraft data bus. The initiated BIT mode may be interrupted at any time. Initiated BIT runs to completion, as is described below, and then remains in that (completed) state until commanded otherwise. Initiated BIT can only be entered from an off-line status where no real-time video can be generated. Some initialization is required prior to entry into the initiated BIT mode. The following typical flight line operational sequence is a good example for descriptive purposes. When the initiated BIT mode is commanded, the processors begin detailed memory tests. Also, early in the process, the system is commanded to move the tape to the test pattern block. The test pattern block is located at the other end of the data blocks from the initialization data. Successfully locating and retrieving the test pattern block verifies proper tape unit operation. The memory tests include local processor memories, the shared global memory and all other read/write memories in the system, such as pixel RAM, intermediate memory, reconstruction scratch pads, scene memories, color mixing RAM, shade tables, etc. The memory testing process takes nearly one minute to execute. When memory testing is completed, the tape will be positioned ready to read the test pattern block. If the tape has not reached that position, then a fault is indicated. The memory testing approach uses alternating bit patterns written and read alternately between different segments of a memory. If a fault is detected, this process allows the distinction to be made between addressing problems and actual memory element problems. This is particularly appropriate for fault isolation where addressing and/or decode functions are not located on the same board as the memory elements (as is the case with the scene memories).

The test pattern is a synthetic digital map block with compressed elevation and cultural data. The elevation data forms a symmetrical pattern designed to exercise the elevation reconstruction processor. The cultural data is somewhat symmetrical and is designed to exercise the cultural reconstruction processor and act as a background for overlaid symbology. The arrangement of the synthetic cultural data is shown in Figure 4. The test pattern is read from the mass memory into intermediate memory. It is then reconstructed at two different scales with different cultural preselect sets into the two scene memories. Since both reconstruction processors are sensitive to reconstructing to different display scales and the elevation reconstruction processor is sensitive to reconstruction differences between the X8 scale and any of the other three scales, the X8 and the X4 scales are used for test purposes. To achieve the necessary display results for test purposes, certain of the memories must contain invariant data unique to the initiated BIT function. These data are loaded into the memories at the conclusion of the respective memory tests. Included are the color mixing RAM values, the cultural preselect primary set (with the secondary set loaded after initial cultural reconstruction) and an initial configuration for each of the scene memories. In the scene memories, elevation values are set to zero and cultural values are all set to area feature values representative of all green area fill or all red fill (where the colors are controlled by the color mixing RAM values). In scene memory A eight blocks each are set to red and green. In scene memory B all 16 blocks are set to red.

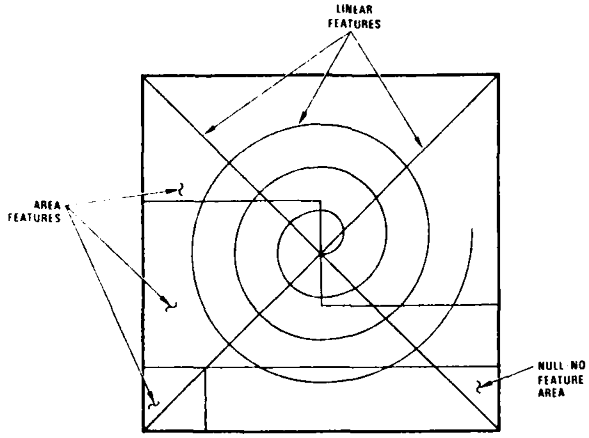


Figure 4. Synthetic Cultural Data Display

One scene memory block of X8 scale is reconstructed and placed in scene memory A as shown in Figure 5. The scene memory block had been "red" before the reconstructed data were entered. Note that the cultural preselect set has the "X" pattern (shown in Figure 4) deselected. This scene memory is then the source of initial video with the resultant display as shown in Figure 5. Note that the reconstructed test pattern has a green border. Any static scene memory addressing errors associated with the video readout functions will result in areas of red appearing on the display. This display will be output for 20 seconds, during which time its simple, basically symmetrical pattern can be verified. The figures presented here do not depict the elevation associated presentation; however, the symmetric elevation pattern is part of the display (except for the final format where symbology is overlaid). In the display of scene memory A, elevation features are sun angle shaded with a low density of elevation contour lines.

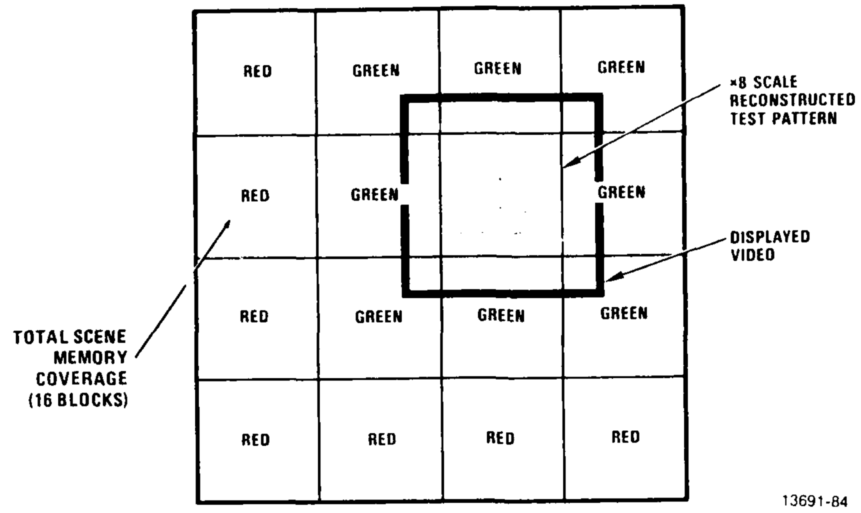


Figure 5. Example of Scene Memory and Display Segment

While scene memory A is being displayed, test pattern reconstruction at the X4 scale is being processed for scene memory B. All 16 blocks of scene memory B are filled as shown in Figure 6. In this reconstruction the spiral linear feature pattern is deselected while the "X" linear feature pattern is selected. After 20 seconds of active display from scene memory A, scene memory B is displayed with the initial display window positioned as shown in the figure.

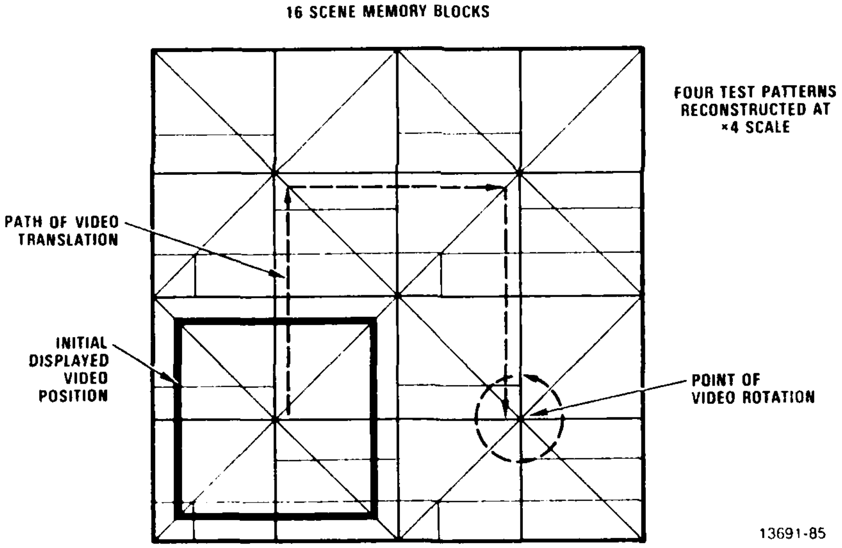


Figure 6. Layout of Scene Memory Translation Rotation Test

The initial elevation presentation from scene memory B is with sun angle shading and with an elevation contour interval more closely spaced (in terms of differential elevation) than was displayed from scene memory A. After ten seconds of a static display, the display center begins to move following the dashed line as shown in Figure 6 (the dashed lines shown in the figure are not on the display). Display translation continues along the straight path segments as shown in the figure. The display does not rotate when translating to the right along the second segment. Translation time for each segment is ten seconds. One-half of the way along the second segment, the elevation display mode changes from sun angle shading to shades of gray with each gray band spanning four of the elevation contour line intervals already present. Again, the display does not rotate when translating along the third segment (it appears to move "backward"). One-half of the way along the third segment, the elevation contour line spacing is increased to coincide exactly with the gray shade band interval. At the end of the third segment, translation stops and rotation begins. The period of rotation is 20 seconds (18 degrees per second). At the end of the rotation period, the elevation shades of gray display mode is altered by shade band base altitude such that no gray shading is present on the display.

The test sequence involving scene memory B exercises the scene memory directory function and the scene memory addressing function. Problems with the scene memory directory will be manifested with portions of the test pattern being misplaced or out of order. If the scene memory had not been loaded properly during the test pattern reconstruction, areas of red will appear. (Recall that all 16 scene memory blocks are displayed during this test sequence.) Both the translation and rotation processes require proper operation of scene memory addressing. If problems are present in addressing, as a minimum, erratic motion will be present during translation and/or rotation. During the rotation, corners of the display area will pass outside of the valid scene memory data area. Again, as a proper function of scene memory addressing, black will appear in those corners when they overlay (geographic) areas outside of valid scene memory data. The variations in the elevation display modes as described verify proper operation of the sun angle shading process, the elevation shades of gray process and the control of the generation of elevation contour lines.

At the conclusion of the preceding DMG test sequence, the symbol generator is commanded to generate an alphanumeric and graphic overlay. The overlay is superimposed on the map display format that remains present at the end of the DMG test sequence. The resultant display arrangement is shown in Figure 7. The overlay (symbolic) format is designed for two primary purposes. The format is a selection of symbols and graphics designed to exercise the various functions of the symbol generator. Additionally, proper symbology registration with the map display is verified.

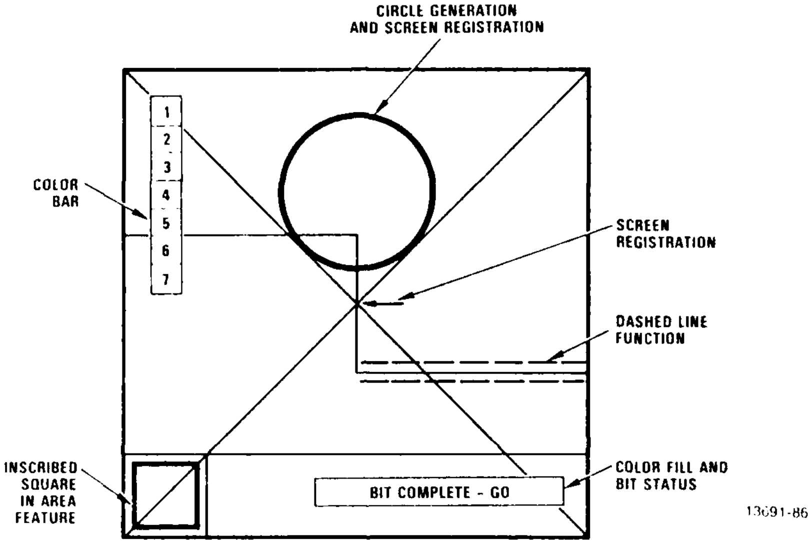


Figure 7. Alphanumeric and Graphic Overlay Superimposed on Map Display

The overlay template is basically self-explanatory. A few notes of explanation will suffice. The inscribed square not only indicates registration, but also verifies the line drawing function of the symbol generator. Similarly, the dashed line function is also verified. The circle drawing function is verified. Proper circle radius is verified by the tangential registration as shown. The arrowhead in the center of the display is a pre-determined symbol shape. The color bar is self-explanatory. The "BIT COMPLETE" legend is inscribed in an occluded rectangle. (Recall from Figure 4 that the area under the rectangle is a "no feature" area - black.) BIT status is also indicated in the rectangle: "GO" for successful completion, and, if possible to display, "NO-GO" for a detected fault. This display format concludes the initiated BIT sequence. The display will remain as active video until the system is commanded to exit the initiated BIT mode. During the initiated BIT sequence, the results of BIT status are continuously available through the multiplex bus interface. Also note that after the memory tests are complete and the system begins the generation of the synthetic display (with the reading of the test pattern block from the tape), periodic BIT is also operating. Therefore, status available over the bus also includes periodic BIT results when periodic BIT is active.

The final element of built-in test involves the video generation circuitry itself. Recall that the digital map system under discussion includes all final outputs necessary to drive a color display, but does not include the CRT itself. Because of the subjectiveness of video picture quality, the test for the video circuits is a simple test pattern approach. The test sequence itself, involving the observer, is structured to easily incorporate fault isolation in the event an anomaly occurs. If the fault is uniquely associated with the video generation circuitry, i.e., the fault is not detected by the digital map system itself, then a straightforward tabular approach is used for fault isolation. The following table exemplifies this approach.

Symptom	Faulty Module
• No video	• Output display
• Elevation parameters incorrect	• Elevation processor
• Sun angle shading problems, but elevation shading OK	• Slope shade processor
• No symbology	• Output display
• Incorrect symbology	• Pixel plotter
• Incorrect colors	• Output display

The remote map mode is the last major mode to be discussed. In this mode, the digital map system is capable of displaying, on command, a scene of a remote area not currently being overflown. The remote display may be automatically programmed, via the multiplex bus, to occur at a specific aircraft position (such as a waypoint) or at a prescribed time. When the command occurs, the system reconstructs the scene from one scene memory while the other memory continues to display the plan view of the terrain under the aircraft. As soon as the remote scene is reconstructed (requiring a few seconds) the remote scene may be displayed on the aircraft CRT. This scene may also be slewed by the pilot's command so that other terrain in the vicinity may be viewed. Since the remote scene is not correlated to aircraft position, it is of necessity a static scene which does not move unless it is commanded via a slew command input. The usefulness of a remote scene display may be left to the imagination; a few typical uses are as follows:

- Display of a target area to refresh the pilot's recollection of details
- Display of the area around a recently located threat to allow the pilot to determine possible evasive action
- Display of an area containing friendly force locations
- Display of alternate destinations or targets.

USEFULNESS OF THE SELF-CONTAINED SYMBOL GENERATOR

A brief discussion of the myriad of uses of the digital map system's symbol generator will give the reader an insight into its unlimited potential. The symbol generator "draws" all point feature symbology and all other alphanumerics on the digital map, as well as a variety of graphics limited only by the capability of the PROM storage library. The symbol generator presents all text and symbols in readable screen-up orientation, but symbols may also be made to rotate if their specific geographical orientation has a unique meaning. For instance, an aircraft symbol on a north-up display would immediately cue the pilot as to his aircraft heading relative to the terrain.

A typical example of an overlay of point symbols and graphics on a digital map display is shown in Figure 8. Approximately four characters of text may be associated with each point feature. The shape of the symbol provides a generic identification. The text is used to provide additional data as required. The color of the symbol and text may be specified independently. A circle centered on the point feature may be specified to indicate an area of influence surrounding the feature. The radius of the circle may be specified. To increase the visibility of the point feature when superimposed on the map, an occlusion zone may be specified around the symbol and text. This zone will block out the map data to provide a featureless background for the symbology, greatly enhancing its legibility. Figure 8 shows occlusion zones around point features and text. Flight plans are indicated by connecting point features together with straight lines. The Symbol Generator organization permits changing the point features in real time. Points may be added to or deleted from the flight plan at any time. Commands to edit the list of point features may be received via the multiplex bus. Also, multiple flight plans may be stored, with selection made at run time. The Symbol Generator gathers data from the multiplex bus once each 50 ms. It ensures that all data transmitted over the bus is displayed even though that data is changing each 50 ms period.

Symbology may be changed in real time to reflect new events. New enemy threat positions, new positions of friendly forces, and other similar data may be entered by the pilot or automatically updated over the multiplex bus by a radio link. This flexibility allows the unchanging basic terrain data base to be brought to the most current state. The ability to add text to a symbol provides an additional cue for the pilot and minimizes confusion. In actual application of one type of digital map system being produced by Harris, the symbol generator will overlay the outlines of restricted air space and the call signs of navigation radios and airports. These are only a few examples of the flexibility inherent in the Harris digital map architecture.

APPLICATIONS OF THE DIGITAL MAP SYSTEM

Digital terrain data availability has already been shown, through the design of the Harris digital map system, to be the source of many modes of visual display of the terrain. The symbol generator in the digital map provides an overlay of text and graphics which further enhance the usability of the display. Display of any two-dimensional information, such as photographic data or copies of ordinary paper maps, is also possible with the digital map. The endless variety of visual presentations presents a challenge to determine which scene display methodology is best for a particular type of mission, or for any part of a mission. Still, generation of a planimetric view of terrain is only one of the many functions of a digital map. This section will cover the other applications as well, concentrating on the revolutionary new capabilities which may be added to an aircraft avionics suite by use of a digital data base and a properly designed digital map system.

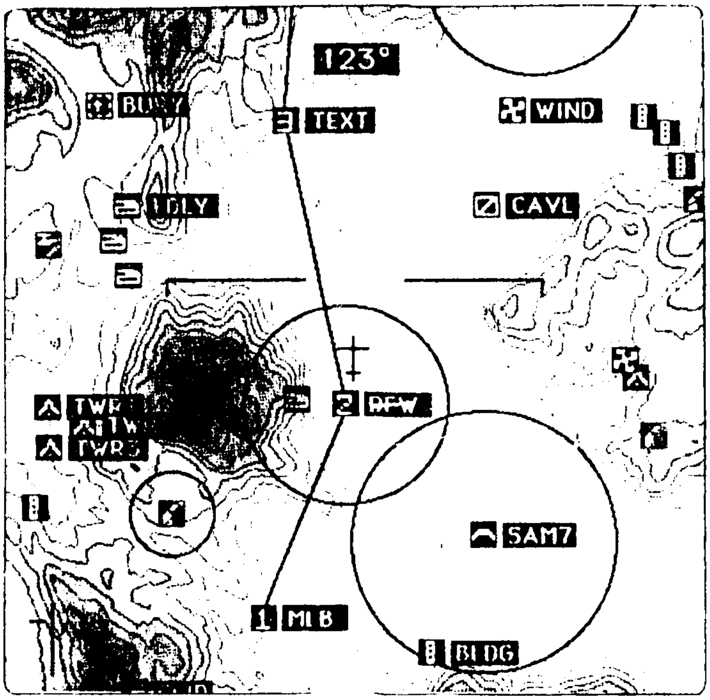


Figure 8. Symbology Overlay on Elevation-Shaded Display

- Review of Visual Display Applications

The various display modes and features have been covered; their potential applications are presented in this section. First the terrain display will be addressed. It is clear that the color display provides terrain information not easily extracted from standard paper maps, and that the ability of the map display to move under the aircraft at the aircraft ground speed frees the pilot from any need to handle documents in the cockpit. From the elevation shading and artificial sun shading, the pilot gains a "feel" for the real texture of the terrain. In night flight, such a display coupled with radar serves to improve the pilot's confidence in his knowledge of the surrounding terrain. Placing the display in the "height above terrain" mode gives an even more graphic indication of relative altitude, as the portions of terrain at and above the pilot's altitude take on a distinctive color. As the pilot climbs or descends, the display patterns shrink or grow to maintain a real-time indication of relative altitude. All "area" features such as lakes, forests, and cities are identified in unique colors readily associated with each feature. Area features are further subdivided in classes which, in the digital processing architecture, can be deleted or decluttered at any time. Examples of such classes are as follows:

• Village	• Fresh lake	• Deciduous forest
• Town	• Dry lake	• Coniferous forest
• City	• Salt lake	• Scrub forest

Data in the DMA data base also allows, for instance, the identification of ridge lines and valleys or drain lines. These features occasionally provide distinctive identification of certain types of terrain.

All "linear" features such as roads, rivers, railroads, and power lines are displayed in selected unique colors. As with the area features, the linear features are classified into many categories to allow selection or deletion. An example of such categories for roads is as follows:

- Four lane highways
- Super highways/expressways
- [illegible], paved
- Unimproved two lane roads
- Trails

[illegible] are accorded a unique code so that they may be quickly located in the display, along with a unique color assignment.

Display scale changes may be selected from a large number of available scales and scale sets as previously discussed in this paper. The pilot may choose to fly normally with a display scale of about 12km x 12 km to 24km x 24km, according to interviews with various pilots. At a nominal ground speed of 400 knots, the pilot flies across these display sizes in one to two minutes. This rate of display movement seems to be in the most satisfactory range. A much large area display may be called up to orient the pilot to the total mission area or to provide additional peripheral information. The use of color plus minimum linear feature widths of two pixels will always provide more information in a large area display than is needed or desired; this is analagous to attempting to shrink a full-size (about 0.6 x 1 meter) tactical pilotage chart to a standard airborne display size of 5 x 5 inches (12.7 x 12.7 cm) and then trying to read all the information on it. Some form of automatic declutter, therefore, is normally advisable, leaving only the key features one would normally seek on a large area display. The system may be programmed to retain only the key linear and area features for very large display areas (usually any display coverage of more than 24 x 24km will benefit from some amount of declutter).

If, in planning the mission, the pilot knows ahead of time that he will be interested in certain terrain display modes and certain key features, he may program the type of display to conform to his specific interests. The display can be programmed to change automatically, based on an elapsed mission time or on passing a preset latitude or longitude. A remote display may also be programmed to occur automatically, as previously mentioned. In a digital map system with the capability to display digitized paper maps or photographic data, a preselected view of the image may also be automatically displayed. The capability to show an actual reconnaissance photo of the target area, for instance, acts as an immediate update of the pilot's memory. The target terrain or photo image may even be overlaid with specific symbols and routes by preprogramming of the symbol generator as well. Where data may become available only after a mission is planned, it is still possible to update the digital map's data base by means of a data link or by manual pilot entry. New targets, threats, vertical obstructions, or any other data may be keyed or linked into the system at any time. New points of interest identified by the pilot during a mission may be entered into the mass memory for retrieval and debriefing upon his return. This operation is normally accomplished by means of slewing a cursor to the point and keying in a "mark point" notation. Many aircraft already have such a capability; if they do not, the digital map system software can accommodate the generation and tracking of a cursor provided that a means of pilot control exists.

The symbol generator capabilities described earlier may be applied to a tactical mission in many ways. The capability to produce any form of alphanumerics permits the display of such items as check lists or special instructions. Messages may even be linked to the aircraft and displayed on the CRT. Other status information or warning information may be displayed, using standard abbreviated notations stored in the symbol generator's memory. The display of approach plates for an airfield may be accommodated by calling up a digitized image of the approach plate; again, this kind of capability greatly reduces the pilot's workload. In aircraft with the capability to transmit basic flight parameter data over the multiplex bus, the symbol generator in the digital map will display an electronic image of selected flight instruments. Harris is currently demonstrating an integrated flight display in one of its digital maps; this display includes the attitude indicator as well as airspeed, altitude, heading, and key steer point data. Other functions and parameters are easily added, as are other flight or engineering instruments. Another use of the symbol generator is for weapons status display; a color graphic display of weapon location and status may be employed to aid the pilot during the mission. As already noted, waypoints displayed by the symbol generator may be linked in a selected order with a route line, and the route or waypoints may be changed at any time during the flight. For instance, a change during flight to an alternate target or a different route could normally entail a lot of effort on the part of the pilot. With the digital map's symbol generator, alternate routes and waypoints may be stored ahead of time or entered in real time to produce an immediate display of the new route. A scale change to a large display area could be made to show all or much of the new route. Other display capabilities of the symbol generator will be covered in the remaining review of applications of the digital map's capabilities.

- Overview of TF/TA Applications

The most promising use of the digital map is not in its ability to display the terrain; if that were all it could do, it would offer little advantage over film readers or simple digitized paper maps. By far, the most exciting application is the use of the elevation dimension to increase mission effectiveness. An immediate benefit can be gained, for instance, in TF/TA flight regimes, where the digital map can provide terrain profile data in addition to, or in place of, a radar system. In this application, the digital data base processed by the system acts as a new sensor, providing terrain elevation to the flight control system through the flight computer. For first time, a pilot can have reason for increased confidence in his position during low-level night attack missions in adverse weather or terrain. The following discussion will present an overview of TF/TA applications; specific aircraft dynamic or control law restrictions are not addressed because the principle of the digital map applies to all cases.

Until the development of the digital map system, the primary sensor in TF/TA flight was the radar system. With the addition of the digital map, the radar may be either relegated to a less critical role or (in the ideal case) eliminated completely. Practical evaluation of the state of the art will lead to a conclusion that total elimination of the radar function is unlikely. In practical near-term application, the digital terrain data will supplement the radar data and provide a secondary input for [illegible] commanding by the flight computer. Where the digital map is used, the radiated radar

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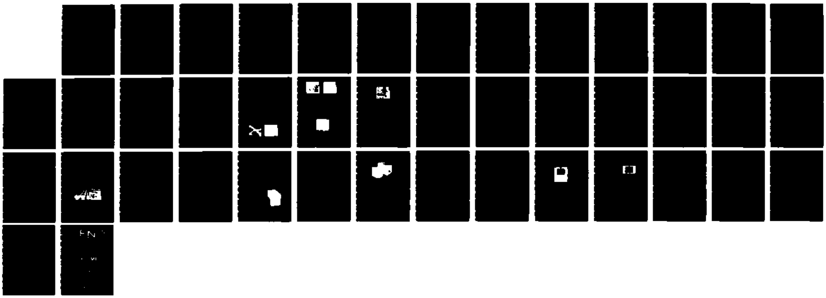
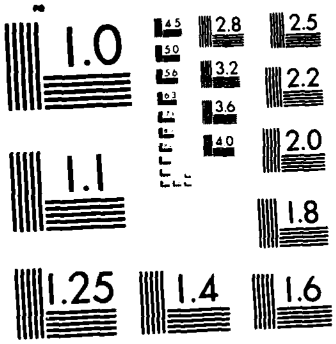




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

power and the frequency of radar scans may be reduced considerably, lessening the probability of electromagnetic detection and thereby increasing survivability.

Several techniques have been suggested by various authors for the application of digital terrain data to TF/TA flight. Any set of algorithms used to define a TF/TA methodology will possess some basic characteristics:

- Access to terrain elevation data at a specified frequency
- Processing of terrain elevation inputs in accordance with TF/TA equations
- Application of the calculated results to the aircraft flight control system.

The obvious purpose of the TF/TA process is to optimize the aircraft path over a nominal course while maintaining a specified terrain clearance. The TF/TA equations all seek to maintain the set clearance by maneuvering the aircraft within a set of geographical and flight dynamics related constraints. The Harris digital map system not only provides the required access to terrain elevation, but also performs the computations in one of its auxiliary processor modules. The results of computation are then passed to the flight computer, where they are combined with results calculated by the radar system in a weighted computation. Of course, other sensor inputs are also used to arrive at a solution to the control equations.

In one TF/TA mechanization, the reference path is established as a line segment between two waypoints. The aircraft enters the path segment at the first waypoint, where the algorithm is activated. The aircraft path is then under TF/TA flight control, with the digital map processor providing the necessary computations. A continuously updated data patch of about 14 x 14km, roughly centered around the aircraft position, is maintained in the digital map memory. Since the elevation of horizontal "posts" or points within this data patch is immediately available to the processor, there are no scan angle conversions involved in determining elevation. The system looks ahead continuously (at a 5 Hz rate) to pick up elevation points within a nominal corridor around the reference path. The decoupled TF/TA algorithm in this example adds a heavy penalty as the aircraft moves away from the reference path and toward the edge of the corridor. Look ahead distances up to about 4 miles (6.4km) are used. Simulations of the algorithm using digital map data have shown that the nominal processing load on the auxiliary processor is well under 50 percent. The decoupled TF/TA algorithms operates by selecting TA (lateral) commands through extraction of an optimum close-in path (about 3km long) from a family of possible choices, based on terrain avoidance and aircraft flight envelope constraints. The TF (vertical) commands are generated by looking ahead along the current heading and determining the elevation of points under the ground track for that heading. The appropriate vertical rate command is issued to maintain the aircraft altitude at the desired level.

The particular advantage of the digital map system is that it provides access to all points in the data base and is not subject to the limitations of terrain shadowing inherent in microwave or optical radar. Since radar cannot see around the hills and cannot always be pointed ahead of a turn, the digital map can provide heretofore unavailable information to improve TF/TA maneuvers. High-g turning maneuvers are especially enhanced, particularly in rugged terrain. Where large, abrupt transitions of terrain contours occur in a horizontal or near horizontal turning plane, the digital map can generate more timely TA signals, reduce the resultant "g" load, and smooth the overall ride. In the same way, the TF maneuver can be smoothed by evaluating transitions between successive points. The profile of a TF flight path is easier to visualize and illustrate. As indicated in Figure 9, a profile involving steep transitions will cause radar-aided TF to contain unnecessary control actions when compared to the profile which can be generated by the digital map. The processing sequence to achieve this benefit contains the following major steps, all performed by the processor module inside the digital map system:

(1) Locate the highest terrain within the area of the projected heading and provide a scaled TF command for a path to fly over it.
(2) Store and compare enroute negative slopes within the scan area to an established maximum negative slope; retain the position of all slopes greater than maximum.
(3) Provide modifications to the basic TF command output when reaching the locations defined in (2) above.

Obviously, the purpose of a second order algorithm incorporating the above steps is to avoid the useless control inputs which would result from forcing the aircraft to begin a downward corrective maneuver, then to have an upward corrective signal follow because of the rising terrain past the negative slope. It is the ability of the digital map system to see this negative slope that provides the clear advantage over radar alone. If the vertical plane profile shown in Figure 9 were turned 90 degrees and the same type of approach were applied to a high-g turn, it is easy to see how the TA algorithm could also be modified for a smoother ride.

Because of inherent small inaccuracies in the existing digital data base, it is unlikely that an aircraft will ever operate autonomously on digital map data in TF/TA flight. However, it should be emphasized that when the TF/TA mode is combined with an autonomous navigation mode using the digital map (to be covered in the following section), true autonomous TF/TA could be achieved with a perfect data base. Even considering the existing imperfections, the DMA DLMS Level 1 data base is quite acceptable for radar-aided digital map flight, and DMA is continuing to improve the quality of the data. Another positive factor is that the relative accuracy of terrain elevation points in the DMA data appears to be consistently better than the absolute accuracy; and it is the relative accuracy which counts most in TF/TA or autonomous navigation. The most likely useful application of digital terrain data in the next ten years is to combine with radar for better low level flight, and to allow the forward looking radar power and repetition rate to be greatly reduced. The algorithmic approach being further investigated by Harris is the use of digital terrain data for distant elevation or negative slope information, combined with low power radar for confirmation of altitudes over terrain at close range. The reduction of radar power and repetition rate means that nearly covert flight is a real possibility. The combination of position update via GPS inputs, terrain-aided navigation, and nearly covert TF/TA will provide a powerful tool which should significantly improve survivability in most missions.

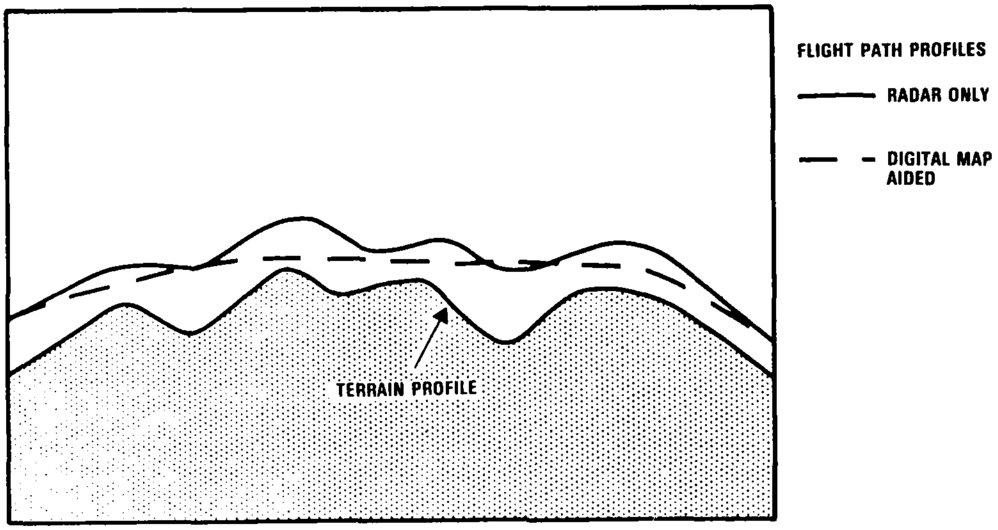


Figure 9. Comparison of TF Flight Paths

TF/TA calculations in support of other aircraft subsystems have been briefly covered. There is also the consideration of TF/TA display to increase pilot confidence as well as to improve mission performance. The plan view TA display showing all terrain above the aircraft altitude has already been mentioned. A perspective view display is also a possibility and will be discussed separately. On either of these displays, additional graphics and alphanumeric notations may be added. Some examples of these displays are as follows:

- A real-time calculation of distance to collision at present altitude can be made by the digital map system's TF/TA processor. In the simplest implementation, the distance to the nearest terrain within a few degrees of current aircraft heading, and at the current aircraft altitude, is continuously calculated and displayed. Combined with the radar information available to the pilot, this additional data provides an improvement in pilot confidence, especially in night missions.
- A vertical elevation profile of the planned mission may be prepared during mission planning and stored in the digital map system for display. The profile would indicate in distinctive colors both the terrain outline and the planned flight path as viewed by cutting a vertical plane through the flight path. During flight, the aircraft's actual position relative to the profile would be indicated by a moving symbol.
- During flight, preselected distinct features capable of being seen by radar and also stored in the digital data base could be compared in position and their correlation shown on the plan view map display. There are many ways to accomplish this; one approach is to use small circles of different colors to indicate the positions of the feature as viewed by the radar and digital map. The congruency of these circles would again improve pilot confidence in his position.

● Overview of Autonomous Navigation Applications

In the third-generation digital map system described in this paper, there are three vacant processor module spaces available for growth functions. Insertion of one processor module and the appropriate software gives the system the capability to perform all calculations necessary for operation of the aircraft in the autonomous navigation mode. The SITAN (Sandia Inertial Terrain Aided Navigation) algorithm developed by Sandia Laboratories has been implemented and will be flight tested in 1985. The SITAN algorithm is a Kalman

Filter approach which utilizes the digital map data, a radar altimeter, and an Inertial Navigation System (INS) to calculate aircraft position. Whereas typical unaided INS positions may vary by several kilometers per hour, the SITAN algorithm has the potential of reducing the position error to less than 100 meters. Considering that the aircraft may not carry a GPS receiver and that the digital map system may be carried for other reasons, the addition of the autonomous navigation capability is essentially a free enhancement with tremendous payoff in improvement of navigation accuracy.

The addition of a standard processor module in an available space in the Harris digital map system provides the capability described above. Figure 10 illustrates the processing flow. The data base for the algorithm resides in the processor module memory, which provides a terrain elevation update for processing at approximately a 3 Hz rate. New data from the terrain data base are added for each 100 meter increment traversed by the aircraft, and "old" data (terrain already behind the aircraft and out of range) are dropped from the memory. This continuously updated elevation information, configured in a 70 x 70 point array with the points 100 meters apart, is summed with radar altimeter data and fed to a Kalman filter array. Once the aircraft position has been acquired (i.e., covariance values are small) the filter array is replaced by a single, more robust filter centered on the aircraft position. This filter then provides a position error estimate to the INS summing junction. Simulations with flight test data have shown that position errors less than 50 meters may be achieved.

Other terrain-aided navigation techniques have been evaluated and analyzed by Harris, and several reports have been published comparing their effectiveness. It is not the purpose of this paper to assess the various techniques, but rather to demonstrate that one fairly well established technique (SITAN) can be handled easily within the architecture of the digital map system. The required code is about 7 kilobytes of local RAM, well within the capacity of the Harris DMG. In the acquisition mode, when the entire filter array is being processed, the loading on the processor module is about 50 percent. In the track mode, where only one filter is operating, the processor loading is well below 50 percent. In fact, it is feasible to utilize the same processor module for both SITAN and TF/TA computations. The system architecture utilizes the same data point array for both types of calculations. If these processes were performed outside the digital map system by other aircraft computers, this kind of efficiency could never be achieved. Nor could the data be easily transmitted and updated at 100 meter intervals without significant replication of digital map system processing by the object computer, not to mention the necessity for sending very high rate data (for which a standard bus configuration does not exist in most aircraft).

● Overview of Threat Analysis and Display Applications

A true optimized path calculation, taking into account all relevant parameters such as threat envelope, threat directionality, threat response time, probability of aircraft detection, and aircraft speed/altitude, is a formidable task which is typically approached only in computer simulations by techniques such as dynamic programming. Such a calculation in real time is beyond the practical capability of any on-board aircraft processor. Ideally, however, this type of processing would be used to minimize exposure to threats and to improve survivability. It is possible, though, to perform some much simpler processing by use of the digital map system, and to combine that processing with previously prepared mission planning data to yield an effective solution to threat avoidance.

The first step in threat avoidance is taken during mission planning. With the aid of a Mission Planning/Evaluation System (MPES) including appropriate software, it is possible to perform analysis of optimum flight routes. The MPES architecture and design concept are covered in a later section. On the assumption that some type of initial planning can be accomplished, the use of the digital map system on board the aircraft begins with the further processing and display of data generated during the mission planning phase. It is reasonable to assume that even rudimentary mission planning has produced the following results:

- Identification of preferred route(s) for the mission.
- Identification of known threats and their lethality envelopes for likely penetration parameters.
- Cataloging of the characteristics and likely locations of other unknown but high probability threats. With this amount of preprocessing, appropirate data is available for storage, further analysis, and display by the digital map system.

Storage of the previously known information described above can be accommodated in the mass memory of the digital map system, and certain shapes and outlines also may be allocated to the symbol generator memory. As the known threat positions are approached, the display of the threat envelope may be called up by the pilot or automatically displayed in accordance with a programmed event. It is not the known threats which present the greatest problem, however, under conditions of a predetermined mission profile. It is the new or unexpected threat, or a significant deviation from the preplanned route, that presents the pilot with a dilemma. It is for this situation that the processing capability in the digital map system may be used most effectively. The recommended implementation is to utilize a spare processor for generation of near real time intervisibility patterns, and to provide the resultant information to the pilot in a form which will allow him to make a decision as to the most appropriate course of action.

Studies and simulations of intervisibility calculations have been made by Harris, with the

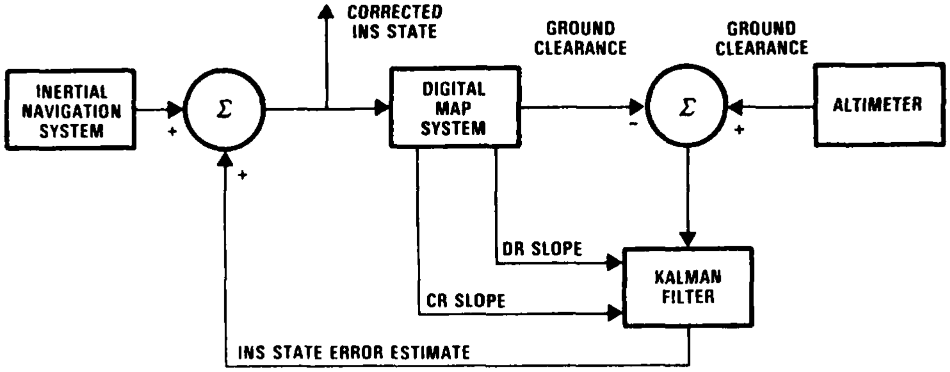


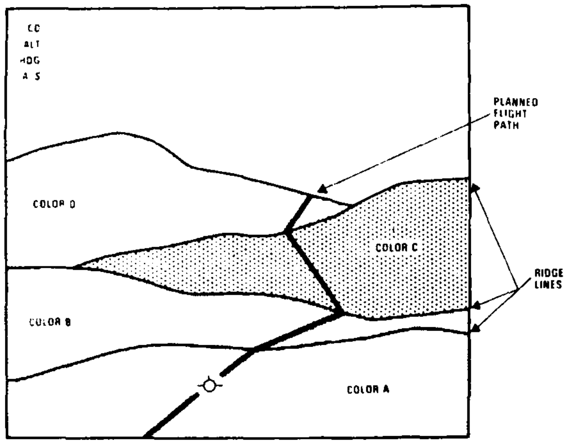
Figure 10. Functional Configuration for SITAN Autonomous Navigation

conclusion that the intervisibility parameter gives an immediate first-order indication of most threats (assuming line of sight is a necessity for a threat to be activated). If a threat location is identified during the mission and entered into the DMG manually or automatically, the complete intervisibility pattern can be calculated and displayed in about 2 seconds. A typical flight scenario would probably disregard any processing of threat patterns within a close range, although this is always a possibility; the more likely application is in the display of a pattern in a remote area, using the remote scene capability of the digital map system. The location of the new threat could be entered as the center of a remote display, and the pattern could be calculated and displayed in static form in the remote scene. In that same scene, the pilot would be able to observe other threats as well as his preplanned route, and he would be able to make a decision as to any evasive action. There is also a possibility of developing an additional penalty term in the TF/TA equation to take into account the added threat, but so far no significant analysis has been done to determine whether this is a practical or effective approach. Other threat display techniques have been considered for the perspective display and will be discussed under that heading.

- Overview of Perspective Display Applications

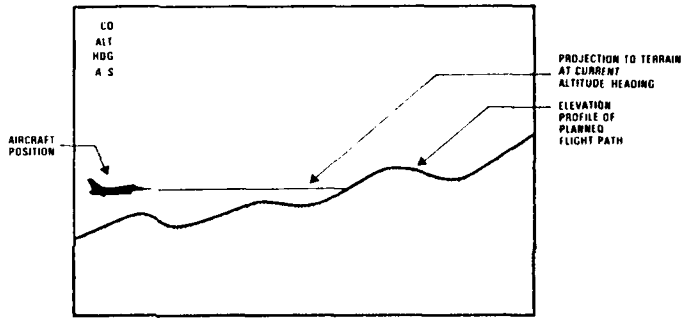
The digital map system is capable of providing all the data needed to display a realtime, pitch and roll compensated scene in perspective to replicate the actual terrain to be seen by the pilot during the mission. At the present time, this capability is not contained inside the Harris digital map system because it is considered to be more applicable to mission planning than to in-flight use. However, some features of the perspective display may become more useful in flight, and their operation and implementation is possible within the digital map architecture.

Since the perspective view is formed by arithmetic operations on the basic digital data base, the source data for generation of the perspective scene already exists. A typical low-level flight at about 100 meters above the terrain will present a rather restricted view (in terms of distance) in all but the most desolate and flat areas. This close-in characteristic may be utilized to generate a very simple perspective view which includes only ridge line definitions and may be easily processed by an auxiliary processor in the digital map system, plus some additional processing hardware that can be added to other available card slots in the Harris digital map system. Figure 11 illustrates a potential display approach, which is much more legible and distinctive when shown in color. The symbol generator defines ridge lines extracted from the data base and paints the visible terrain in different colors related to the terrain distance; lighter colors or shades would be used for the distant terrain. Figure 11 also shows a concept gaining in popularity as a possible means of giving more meaning and usefulness to the perspective display. It includes a broader view of the terrain as if observed from behind and above the aircraft, and it also shows the planned flight path. There remains some controversy as to whether this concept or an out-of-the window type of perspective display is preferable. Either display may also be considered for monochrome projection in a head-up display or a helmet-mounted display.



DISTANT PERSPECTIVE WITH RIDGE LINES

CD - COLLISION DISTANCE
ALT - ALTITUDE
HDG - HEADING
A/S - AIR SPEED

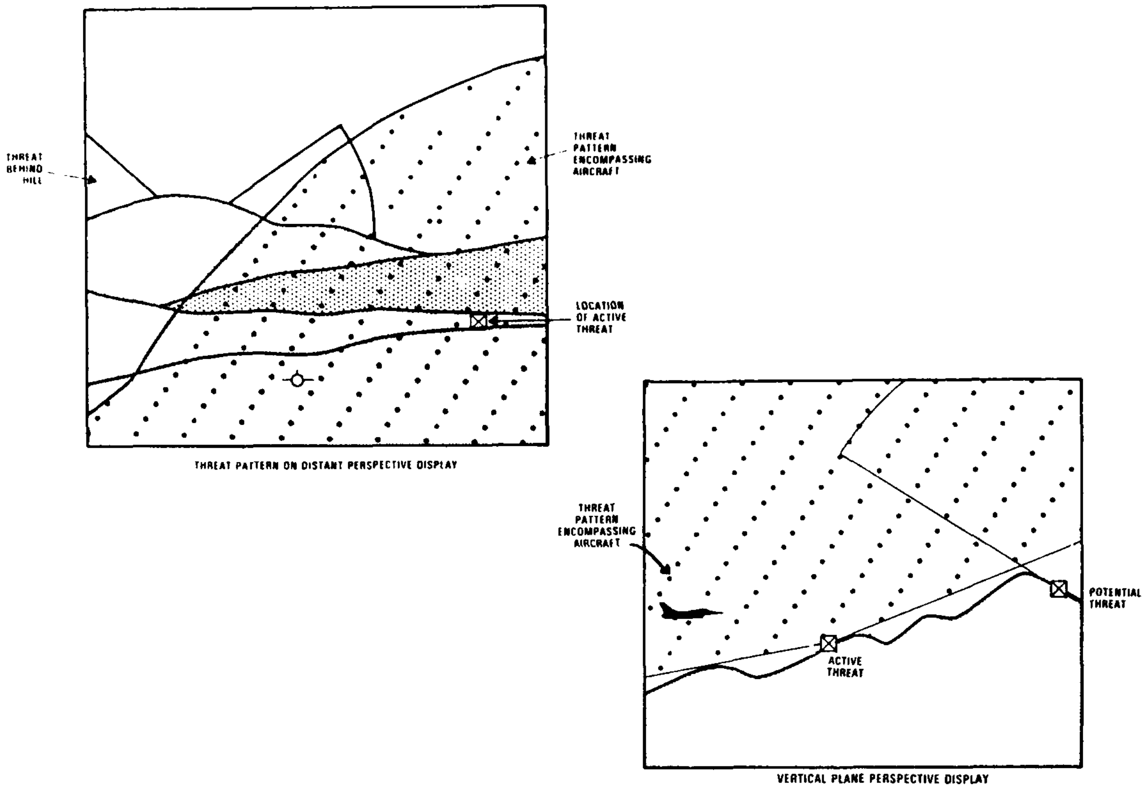


VERTICAL PLANE PERSPECTIVE

Figure 11. Typical Perspective Displays

Harris has developed and demonstrated a full-capability perspective display system which allows the pilot to pre-fly his mission over the exact terrain to be encountered. This system displays the exact terrain shapes and provides realism by means of slope shading similar to the process used in the planimetric view map. With this digital perspective generator (DPG), the preparation of a mission data base also becomes the source of perspective display for the flight. Once the mission has been planned and the route determined, the pilot may actually use the DPG to fly the mission in real time or accelerated time, including all pitch and roll maneuvers, with a completely authentic terrain view for reference. Generated in color with realistic terrain and sky colors, the DPG image promises to be invaluable in pre-flight planning. For most in-flight uses, the DPG is also very desirable because it permits immediate terrain comparison (in daytime) or provides added pilot confidence (at night). A photograph of the display is not included because this paper can only be produced in black and white, and much of the effect of the image is lost when shown without color in a static photo.

Another useful application of the perspective display is the generation of threat patterns. Although threats may be indicated in several ways, any of the display techniques operates from the same type of intervisibility algorithm already discussed. The problem with attempting to display a threat in three dimensions on a two-dimensional CRT is obvious; it is difficult to show depth in the dimension perpendicular to the face of the tube. Some practical threat pattern displays are illustrated in Figure 12. Others are likely to evolve as more uses for the perspective display are discovered.



THREAT PATTERN ON DISTANT PERSPECTIVE DISPLAY

VERTICAL PLANE PERSPECTIVE DISPLAY

Figure 12. Typical Threat Pattern Displays in Perspective

- Overview of Weapons Delivery Applications

The use of the digital map system to support weapons delivery is basically an extension of the TF/TA and intervisibility capabilities of the system. Methods of enhancing weapons delivery include the following:

- Inclusion of weapon delivery maneuvers in the TF/TA flight plan, with different constraints on the flight envelope.
- Calculations of target intervisibility patterns to ensure that exposure to defended targets is minimized.
- Calculation of acceptable delivery envelopes taking into account the masking of the terrain (i.e., a blending of fire control computer and terrain processors).
- Determination of acceptable routes to and from the immediate target area.
- Display of weapon status and storage of weapon-related data.
- Transfer to autonomous weapons of the target terrain characteristics.

It is probably most desirable to develop as much as possible of the the weapon delivery calculations ahead of time, at the time of mission planning. If, however, a change in the mission scenario occurs and an unplanned approach must be executed, the digital map system can aid the success of the mission. In the final phase of the mission, two types of maneuvers can be used as examples of the value of the digital map system:
(1) A high-g turning maneuver designed to minimize the enemy's opportunity to lock on the aircraft;
(2) A pop-up maneuver to permit weapon release, target designation, or the like.

In the high-g turning maneuver, the digital map system provides TF/TA type inputs which allow the execution of a tight turn in near horizontal planes with assurance that no terrain collision will occur. As already mentioned, the data base allows anticipation of terrain profiles which cannot be seen by line-of-sight sensors such as radar or FLIR. The exit maneuver after weapon delivery is also aided by terrain avoidance and collision avoidance data from the digital map. The intervisibility pattern generation capability will also be useful to the pilot in displaying his position relative to the threat envelope from the target area. In pop-up maneuvers, the TF/TA type of function becomes secondary and the intervisibility function becomes primary. With the ability to display the threat intervisibility pattern, the digital map system can provide the pilot with knowledge of the extent of his exposure at the pop-up altitude.

MISSION PLANNING: CONCEPTS, SYSTEMS, AND APPLICATIONS

The last portion of this paper deals with a topic which must actually be considered first in any mission -- the planning of the mission itself. In general, the planning of a mission can be considered to exist in two categories:

(1) Preparation of the topographic data base.
(2) Preparation of mission-specific data.

The preparation of the underlying topographic data can be accomplished well ahead of any mission. In fact, the current operating concept is to maintain a small library of tape cassettes or other source data which cover the general area of interest, and to update each memory unit (tape, bubble memory, etc.) with mission-specific data in the process of mission planning.

Preparation of the underlying topographic data primarily involves the translation and compression of original source material (such as DMA data), and the subsequent transfer of the compressed material to the final storage medium (in the current Harris systems, tape cassettes). If the digital map system has the capability to process aeronautical charts or photographic data, the preparation activity encompasses that source data as well. In some cases, however, a last minute photograph of a target area may become available; if so, the photograph may still be added after preparation of the original compressed data. In fact, given the existence of a basic mission planning system, there is almost no restriction on the lead time for data preparation. Good practice would dictate, however, that the data be prepared in advance if possible. All basic topographic data are compressed for maximum storage efficiency, including aeronautical or photographic data.

Topographical data base enhancement may be needed for source data such as DLMS. Although terrain elevation data is complete, cultural data (particularly linear features such as roads and rivers) are lacking in some cases. Harris has developed a software package which enhances the cultural data base by tracing additional features from a paper map, using a digitizer tablet. This software is an element of an overall mission planning software package which also provides the capability to trace three-dimensional (i.e., terrain elevation/contour lines) information into the data base where no DLMS-type source is available.

Preparation of aeronautical chart data involves a seven-step process which is relatively simple to accomplish. These steps are as follows:

- Digitization
  The aeronautical charts will be digitized using a scanning camera which captures the charts in 16 inch by 16 inch blocks. Each color in the RGB images will be separately digitized. This process will digitize a 12-inch x 12-inch nonoverlapping area. The time to digitize the area is approximately 6 minutes. Note that the overlapping area will be used for distortion correction and mosaicing purposes. The camera resolution will result in 2048 x 2048 pixels in the 16-inch x 16-inch area at a line density of approximately 132 pixels/inch.
- Distortion Correction
  The function of this process will be to correct for geometric distortions resulting primarily from the video camera lens effects.
- Orientation/Rotation
  The function of this process is to align the orientation of the digitized image to "chart-up" operation. This will accommodate slight errors in map rotation and placement on the workstation illuminated surface.
- Map Projection
  The function of this process is to project the digitized chart onto the TM coordinate system for the DMG. Most charts are in UTM or Lambert Conformal projections.
- Mosaicing
  The function of this process is to assemble the digitized areas (subcharts) together to form a contiguous data base. The overlapping border areas of the digitized frames will be used for this purpose.
- Color Normalization
  The function of this process is to normalize the color content of the digitized map areas. This process can be conducted at various levels: within a digitized area, within a map sheet, or within the overall data base.

The preparation of mission-specific data is handled in the Harris system by modifying the initialization block of data in the mass memory (airborne tape unit). The concept of initialization, regardless of the type of mass memory, applies to any processor-based system. In this case, the mission-specific data is added just as are processor setup tables, color mixing RAM loads, conversion tables, and the like. Some of the initialization data, such as software tables, are not directly accessible to the mission planner or pilot because they are transparent to the user. Other tables, such as the color mixing RAM loads, may be readily changed if color assignments are changed. The overall data preparation process, including mission planning and data dissemination, is illustrated in Figure 13, which also illustrates the data cycle through mission debriefing.

To summarize the mission planning effort with respect to mission-specific data, the following list of mission-related tasks is offered as an example of the types of activity which may take place:

- Review and editing of the basic topographical data: addition of interest features, selection of declutter groups, decisions on automation of displays.
- Preparation of mission-specific data: routes, waypoints, threats, targets, alphanumeric notations.
- Preflying the mission in plan and/or perspective view display, and in real time or accelerated time.
- Entry of new data or special data such as checklists, approach plates, emergency procedures, alternate mission prompts, weapon status requirements.

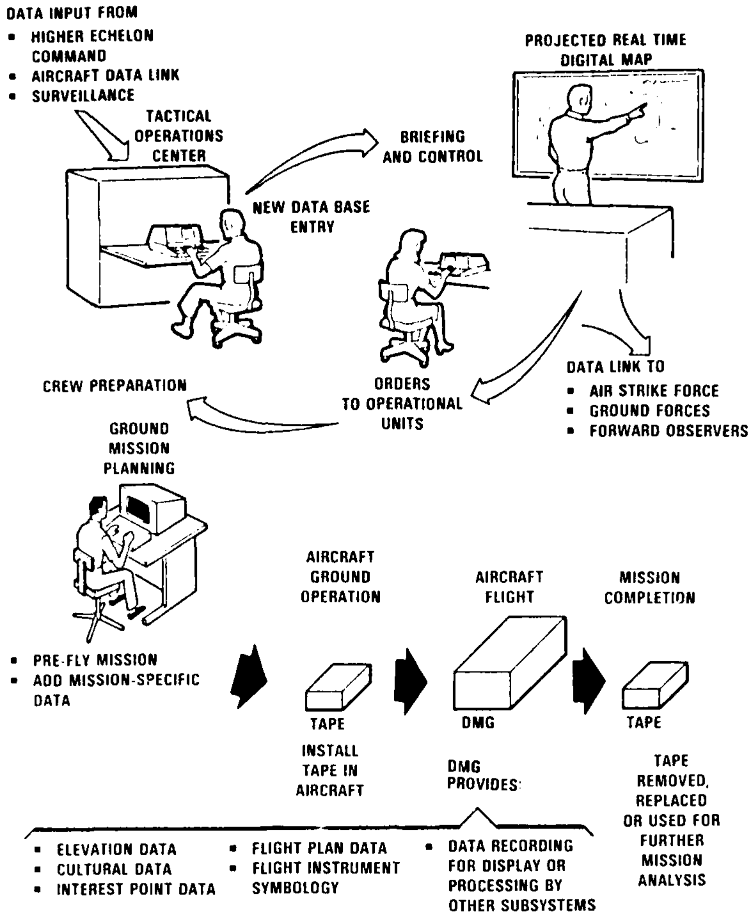


Figure 13. Mission Planning Flow

All of the above tasks can be performed easily and quickly in an appropriate user-interactive environment such as the systems developed by Harris. A typical mission planning/data preparation system configuration is shown in Figure 14.

ACKNOWLEDGEMENTS

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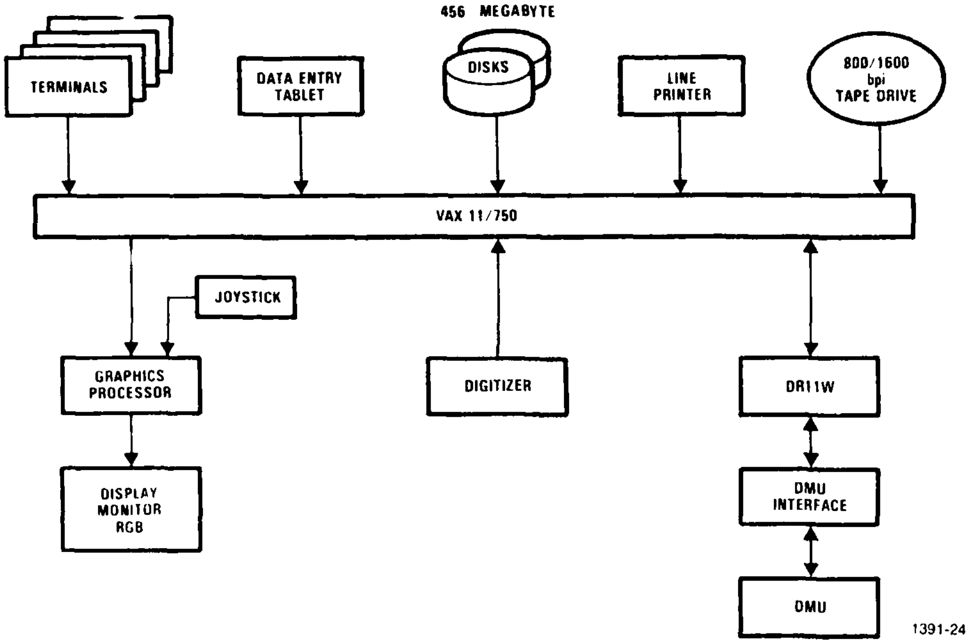

Figure 14. Configuration of System for Data Preparation and Mission Planning

GLOSSARY OF TERMS

BIT	Built-in Test
CRT	Cathode Ray Tube
DMG	Digital Map Generator
DMA	Defense Mapping Agency
DLMS	Digital Land Mass System
GPS	Global Positioning System
INS	Inertial Navigation System
LRC	Longitudinal Redundancy Check
NDRO	Non-Destructive Readout
PROM	Programmable Read-Only Memory
RAM	Random Access Memory
RGB	Red-Green-Blue (refers to video inputs)
SITAN	Sandia Inertial Terrain Aided Navigation
UTM	Universal Transverse Mercator
TF/TA	Terrain Following/Terrain Avoidance

A NEW TECHNIQUE FOR TERRAIN FOLLOWING/TERRAIN AVOIDANCE GUIDANCE COMMAND GENERATION

Richard V. Denton, J. Edwin Jones, and Peter L. Froeberg
10 Jackson Street, Suite 101
TAU Corporation, Los Gatos, California 95030

ABSTRACT

The need for accomplishing relatively automatic low altitude high speed maneuvering flight for key mission phases has long been recognized. A central building block for accomplishing this goal is the computation of the aircraft trajectory according to the mission requirements for the current mission phase. To meet some mission requirements, the automatic trajectory generation can utilize relatively slow techniques (on the order of several seconds) for updating the global route in response to threats or other mission contingencies. Other mission functions require faster trajectory solutions on the order of a second for TF/TA, and often faster trajectory solutions if pop-up threats are included. Further, at some stage, TF/TA trajectory generation must account for aircraft performance constraints and provide the capability for automatic coupling to the aircraft flight control system. This paper presents a new real-time optimization technique that efficiently generates a robust, optimum TF/TA trajectory, and has the structural capability for adding threat avoidance.

The TF/TA technique presented here is based on definition of a performance measure that is systematically optimized in real-time. The approach uses on-board DMA digital terrain elevation data extensively, as updated by real-time sensor inputs. The optimization of the performance measure embodies the real-time trade-off of flying over (TF) versus flying around terrain features (TA). The performance measure is defined to generally penalize large excursions from the nominal (globally-defined) route, while rewarding a trajectory that achieves better terrain masking than contained in the nominal, mission-planned route. (It is the real-time sensor information that necessitates this real-time TF/TA computation, since otherwise much of the computation could be carried out in mission planning.) Direct incorporation of limits on the flight control variables (bank angle, roll rate, normal acceleration, etc.) is included within the procedure.

The TF/TA technique also addresses additional considerations that apply when combining the TF/TA flight trajectory computation with maneuvers through mission waypoints. This involves several subtleties associated with the relative importance of the turning maneuver desired versus the normally applicable TF/TA performance measure.

Finally, the relevance of this work to other advances in trajectory computation is described. This includes the relationship to global trajectory generation, and to integrated TF/TA with Threat Avoidance TF/(TA)^2.

INTRODUCTION

The dense and mobile threat environment that present and future aircraft will encounter gives rise to the need for a low-level, maneuvering penetration, which is made possible by terrain following/terrain avoidance, threat avoidance, and global flight path generation algorithms. Such low altitude tactics can equate to increased survivability and, accordingly, to improved overall mission performance.

Currently deployed systems such as the F-111 and B-1 have a terrain following (TF) capability only; motion is limited to be within a vertical plane with heading as defined by the mission waypoints. More generally, TF trajectories along mission planned curvilinear ground tracks have been considered in some analyses; such trajectories are still essentially TF in nature. In contrast, Terrain Following/Terrain Avoidance (TF/TA) as depicted in Figure 1 addresses an integrated, fine-resolution capability to accomplish simultaneous vertical (pitch axis) and lateral maneuvering to obtain maximum benefits of terrain masking. This TF/TA problem is a real-time flight control problem.

Modern approaches [1,2] to the problem of simultaneous TF/TA have evolved to the concept of separating the trajectory generation and trajectory following functions. The trajectory generation function calculates a reference TF/TA trajectory that is "optimum" with respect to some combined vertical/horizontal performance measure. The trajectory following (or tracking) function determines appropriate guidance commands for the aircraft flight control system to capture and track the desired trajectory.

The tight coupling of TF/TA with the flight control system is one way of distinguishing TF/TA from recent global route generation developments as described in references [1,3,4,5,6]. Such global flight planning techniques result in ground track resolution of a mile or so; because they are obtained relatively "open loop" from the flight control system, they require further processing to obtain actually flyable trajectories. TF/TA can be thought of as the means for processing the global route, accounting for real-time sensor information, lateral and vertical maneuvering degrees of freedom, and current aircraft state information, to obtain the desired three dimensional flyable trajectory. In considering both lateral and vertical degrees of freedom in an integrated manner, TF/TA is thus substantially more involved than generation of a TF profile starting from the global route ground track as input.

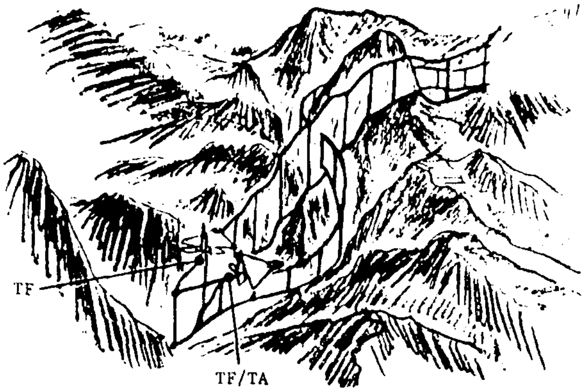

Figure 1. Terrain Following (TF) and Terrain Following/Terrain Avoidance (TF/TA) Trajectories

The work in this paper may be viewed as a sequel to a previous AGARD presentation [1], which described the main concepts and techniques associated with global flight planning. The goal in this development was to explore the applicability of similar mathematical techniques to the higher resolution TF/TA problem solution. These techniques involve use of dynamic programming optimization, which is attractive in that the "best" tactical solution is found automatically. This is in contrast to other techniques such as gradient searches which, being more sensitive to the particular initial conditions, may sometimes result in solutions that are not the tactically "best" solution [7]. In mathematical terms, "best" solution is the globally optimal solution according to the tactical performance measure being used, while other solutions that may exist correspond to local optima in the performance measure. Needless to say, it is a non-trivial exercise to establish that the "best" mathematical solution corresponding to a given performance measure indeed corresponds to the "best" real world tactical solution.

Although dynamic programming techniques typically have the globally optimal solution feature described above, which has been extensively exploited in global route determinations [1], such techniques have traditionally not lended themselves to a detailed coupling with the flight control variables, as is necessary on the TF/TA temporal quantization scale of approximately one second. Such a quantization scale is necessary in obtaining truly flyable TF/TA trajectories that are then fed through to the flight control system via a pitch-roll decoupler. The innovation in this development was to achieve this high fidelity coupling using dynamic programming. Thus, flyable three-dimensional trajectories are obtained efficiently without the need for any additional smoothing to assure that all flight constraints are met. The dynamic programming path generation algorithm described here has been given the name "Dynapath."

As mentioned already, a combined vertical/horizontal performance measure must be selected for the TF/TA computations. The Dynapath Algorithm is well suited to use of performance measures that may also include threat templates associated with nearby SAM or other threats. This has important implications for the manner in which TF/TA is integrated with threat avoidance. Specifically, the Dynapath technique provides a framework for adding maneuvers to account for threats in the immediate proximity of the flight path.

In providing a general framework incorporating threat considerations, the Dynapath technique has applicability to several development programs. For example, it would be useful in supporting the AFTI/F-16 Automated Maneuvering Attack System (AMAS) in integrating terrain considerations with the target attack maneuvers. The Terrain Following/Terrain Avoidance/Threat Avoidance Program within the Air Force Wright Aeronautical Laboratories will also need a capability such as described in this paper. Finally, similar capabilities are necessary for Nap-of-the-Earth flight* and contour flying by helicopters such as in the Army LHX Program.

SYSTEM CONTEXT AND TF/TA PROBLEM DEFINITION

A block diagram of the Dynapath Algorithm interfaces is shown in Figure 2. The solution is for a patch in front of the aircraft as shown in Figure 3 and corresponds to an optimum value of the performance measure in the vicinity of the global reference path. Referring to Figure 2, the global reference path is an input that has been calculated on a relatively coarse scale as described in several references [1,6]. The global path incorporates global mission considerations (mission destination, minimum exposure to threats, timing and fuel constraints, etc.). The Dynapath Algorithm utilizes this global reference path, terrain information, and various other parametric inputs to compute the optimal TF/TA trajectory solution over the current patch. The trajectory solution

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*Nap-of-the-Earth flight involves additional complexity as well due to an expanded set of control variables in modeling the helicopter motion in the NOE altitude/speed regime.

is then converted via Horizontal and Vertical Command Generators to consistent inertially referenced commands ($p_x, \ldots\ p_y \ldots$) that are fed to a pitch-roll decoupler. The pitch roll decoupler provides the interface to the flight control system; it serves the tracking function of always guaranteeing adequate authority to the vertical channel to maintain altitude, while assuring that lateral deviations from the commanded trajectory are minimized.

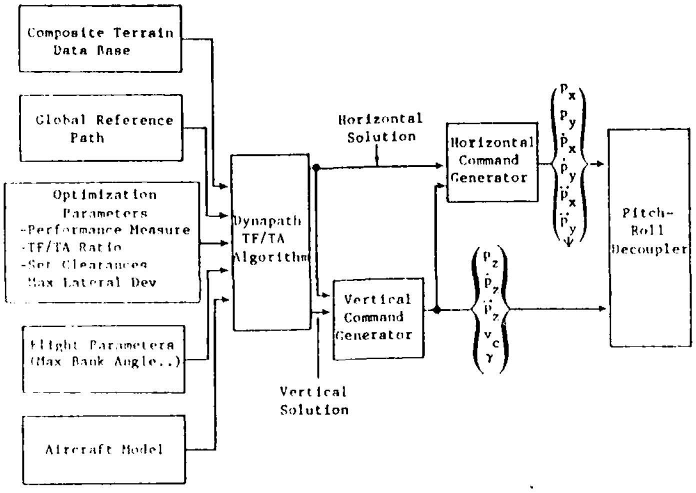

Figure 2. Block Diagram of Dynapath Interfaces

Some of the key parameters referred to in Figure 2 are as follows:

Horizontal Set Clearance - In seeking out lower altitude corridors, there is a minimum acceptable horizontal terrain clearance at the current flight altitude.

Vertical Set Clearance - The flight altitude above ground level (AGL) must be above the set clearance altitude, from flight safety considerations. In this work, set clearance was simply taken as a constant bias above the local terrain value. The constant bias is a user input.

Maximum Lateral Deviation - A maximum lateral deviation from the reference path can be specified. A large value can result in significant computational requirements, while too small a value constrains the trajectory to essentially terrain following behavior.

TF/TA Ratio - This adjusts the relative weight between TF flight and TA (lateral maneuvering) flight.

Flight Parameters and Aircraft Model

- Ride Level - The range of normal g's that are permitted relate to ride comfort. The normal load factor limits indicated in Table 1 are incorporated into the algorithm explicitly.

- Flight Path Angle Limits - The angle between the aircraft vector and the x-y plane can be limited asymmetrically as shown in Table 1. These limits are used in the vertical command generator.

- Roll Acceleration, Maximum Bank Angle - These are used explicitly in generating the TF/TA trajectory. The roll acceleration is important in establishing the appropriate time quantization used in the trajectory computations.

- Aircraft Model - A point mass model was used that parallels the one used in the FDA [illegible].

The TF/TA problem for the current aircraft location is portrayed in Figure 3. This figure illustrates that at low altitudes the actually sensed terrain may only extend out for the next [illegible] seconds or so of flight time. Simulations have shown that this limited sensor range does not provide sufficient anticipation for achieving adequate TF/TA performance, in that the aircraft can find itself in a "box canyon." This problem is avoided in the TF/TA system concept by combining the relevant DMLS terrain elevation data base [illegible] shown in Figure 3 with the available sensor information. The combined data base then supports the TF/TA trajectory determination to result in an adequate [illegible] capability.

In anticipation of the DLMS terrain data, we are adopting a relatively aggressive posture with respect to the successful near-term implementation of this technology in an actual system. Thus, it is worth a minor digression to address the "box canyon" issue in somewhat more detail. Figure 4 portrays a situation where the patch length being used is simply too short. The extreme case of a short patch length is when the guidance computations are based on the immediate sensor range, which is very limited at low altitude. When the performance measure rewards solutions that search out low altitude corridors, for example, the apparently best solution can lead inadvertently into a box canyon. When the aircraft reaches the end of the box canyon, it is then forced into a fly-up maneuver that results in excessive exposure. With a longer patch length, which involves use of the DLMS terrain data, box canyons can often be avoided. Thus, the performance is improved.

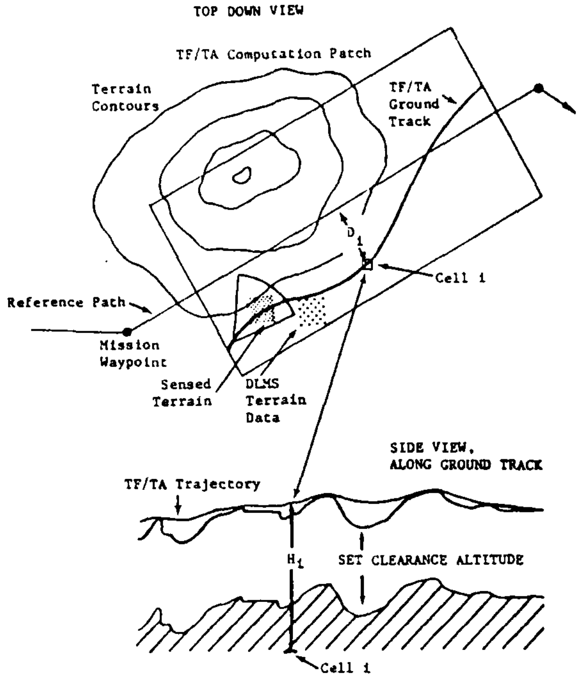

Figure 3. TF/TA Calculation for Current Patch

On the other hand, the improved performance carries its own price in terms of both added system complexity and increased computational requirements. The performance/computational tradeoff for the Dynapath Algorithm is sketched in Figure 5, and shows that computational requirements can increase drastically for only marginal improvements in performance. Benchmark studies [7] have shown that extending the anticipation beyond the immediate sensor range (i.e., using DLMS elevation data) brings significant performance enhancement, while the marginal return drops off once one has an overall patch length corresponding to approximately 30 seconds of flight time.

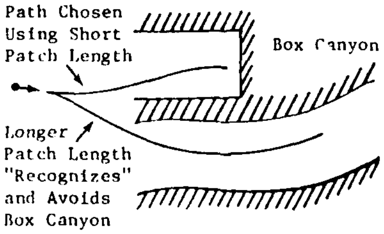

Figure 4. Look-Ahead Effects

Returning now from the digression, the Dynapath TF/TA algorithm designed in this study applies to a single computational patch that was shown in Figure 3, where the patch may include a waypoint within the patch. (In the latter case, a turn is executed as part of the patch calculation.) During the time that the TF/TA trajectory calculation for the current patch is being carried out, the aircraft is flying a previously computed trajectory with predicted initial conditions for this current patch calculation. By the time the aircraft enters the patch, the trajectory calculation has been completed and stored in a buffer. This trajectory is then flown, while calculations for the next patch proceed, etc.

In practice, only the first 5 seconds or so of a given patch solution is used, so that individual patches overlap one another. Flying only part way into a patch assures that there is always an adequate look-ahead distance (for adequate patch length of at least 30 seconds or so). The upper limit for calculating the trajectory for a single patch is then the patch update rate, or 5 seconds. However, this limit does not take into account the new information that is made available due to the real-time sensors. Such information may require an immediate maneuver. Depending on the manner in which such requirements are taken into account in the system operation, the TF/TA processing may need to be accomplished in much less time--in some cases in less than a second.

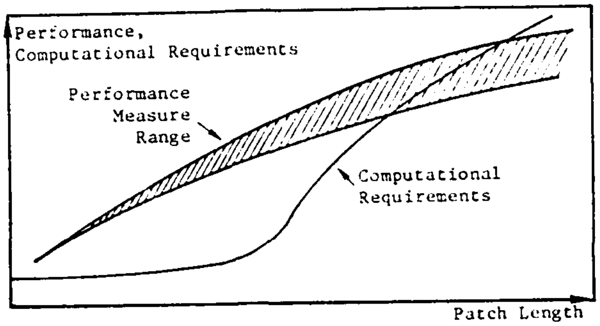

Figure 5. Associated Computational Impacts for Improved Look-Ahead

The TF/TA performance measure used in this study is given in Eq. (1):

$$J = \sum_i (\omega D_i^2 + H_i^2) \tag{1}$$

where ω = TF/TA ratio
D_i = Lateral deviation from reference path
H_i = Altitude above a uniform reference altitude
i = (x,y) cell location, with cell dimensions of order of 300 ft on a side

This measure uses the global trajectory as a baseline for developing the fine-tuned trajectory, in that lateral deviations from the global path are penalized, while flight at higher altitudes is also penalized. In evaluating all possible trajectories using this penalty function, the best trajectory generally seeks out low altitude corridors ("valleys") in the neighborhood of the global reference trajectory. The relative weight ω between these penalties is called the TF/TA ratio. A large value for this ratio results in essentially TF flight along the reference path, while a small value permits large deviations (TA flight) in the search for low altitude corridors.

The general philosophy behind this performance measure is that low altitude corridors afford terrain masking from threats, and thus represent good candidates for improvement over the global reference trajectory. However, recent testing [7] has shown that threats and terrain masking should be incorporated explicitly for best performance. Otherwise the TF/TA trajectory may go through a threat region unnecessarily. Mathematically, inclusion of threats can be achieved by adding to the TF/TA performance measure a term $\beta\,(P_k)_i$, associated with the threat danger P_k in cell i.

Having defined the performance measure, the actual optimization problem is:

Find the trajectory in inertial coordinates that corresponds to a global minimum of the performance measure, subject to the following constraints:

- Initial boundary conditions (aircraft position in (x,y,z) and velocity vector) given
- Final boundary conditions unconstrained so long as aircraft exits at rear of patch
- Satisfy the aircraft equations of motion with various associated parameter ranges as shown in Table 1.

Table 1. Parameter Ranges Used for Tactical Aircraft

PARAMETER	RANGE
Vertical Clearance Setting	50 ft to 1000 ft
Horizontal Clearance Setting	50 ft to 1000 ft
Mach Number	0.5 Mach to 1.2 Mach
Flight Path Angle	-15 Deg to +30 Deg
Ride Level	
● Hard (Normal LF)	0 g to +3 g
● Medium (Normal LF)	+.5 g to +3 g
● Soft (Normal LF)	+.75 g to +3 g
Normal LF Rate (Pitch Jerk)	-1.5 g/sec to +3 g/sec
Maximum Lateral Excursion from Nominal Path	-2.5 NM(Left) to +2.5 NM(Right)
Roll Acceleration	-75 Deg/sec^2 to +75 Deg/sec^2
Bank Angle	-75 Deg to +75 Deg

SOLUTION APPROACH - THE DYNAPATH ALGORITHM

To solve the TF/TA problem, an integrated application of dynamic programming (DP) and tree searching was devised. The tree structure handles the dynamics of the aircraft and the dynamic programming reduces the number of possible trajectories. So, basically, the problem is solved by a forward running DP algorithm where the state transitions are handled by a tree structure.

Two versions of the Dynapath Algorithm were developed. In one version, the aircraft is free to move in all three dimensions subject to aircraft equations of motion and all contraints in carrying out the TF/TA optimization described in the last section.

The second version involves the determination of the lateral (ground track) first, followed by a determination of the vertical commands. In this version, the ground track is found by essentially assuming that the aircraft can fly perfectly in the vertical set clearance surface. This surface is a surface above the terrain surface but displaced by a constant set clearance bias. The TF/TA tradeoff is made under this assumption, resulting in the lateral ground track. The vertical command generator then relaxes the assumption that the aircraft flys perfectly at the set clearance altitude, and treats the set clearance altitude as a minimum altitude constraint.

The approximation of flight, initially, on the clearance surface leads to fewer computations. Depending on the terrain statistics in the scenario, it is expected to give results that are almost always the same as those of the first version. It is this second version that will be discussed further in this paper.

The Tree Structure

For any location of the aircraft, a tree describing its potential future positions can be generated by quantizing in bank angle as the control variable. The number of bank angle quantization levels, possible restrictions on transitions between levels, and the solution time step are interrelated, so care is needed in setting these parameters. For a tactical aircraft a solution time step of one second was chosen to afford adequate sampling of the underlying terrain data. Five equally spaced bank angle quantizations ranging from full bank in one direction to full bank in the other were used, and a consideration of roll acceleration for the tactical case restricted transitions to be between adjacent levels.

In the implementation, it turned out that a convenient parameterization of possible controls was in terms of the inverse turn radius (i.e., curvature) associated with coordinated turns:

$$\rho = \frac{1}{R} = 0, \pm \frac{g}{v^2} \tan(\phi_{max}/2), \pm\frac{g}{v^2} \tan(\phi_{max}).$$

A tree is constructed by using all possible values of ρ to exhaustively generate every branch of the tree to a depth of N seconds. An example tree is given in Figure 6. This is a tree of N=3 stages, or time steps. Of course, the branch lengths and turn radii have been exaggerated to better demonstrate the tree structure.

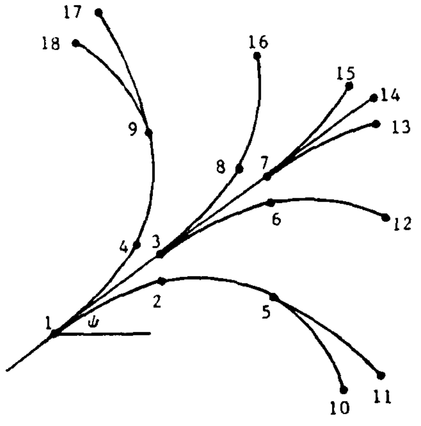

Figure 6. An Example Tree

At each node k of the tree, the following information is stored:

S_k =
- Position (x,y)
- Heading ψ
- Parent: node that has generated node k
- Cost: cumulative cost up to and including the present node (for the performance measure being used)
- Curvature control used to arrive at node k (quantized in five values, for simplicity referred to in terms of controls -2, -1, 0, 1, 2 with negative controls being a right turn)

At tree generation time, branches can be discarded according to any one of several possible criteria. In this problem we have chosen to set a maximum lateral deviation from the reference flight path and an absolute maximum deviation from the reference path heading. The use of such criteria to accomplish pruning is denoted as "constraint pruning."

Dynamic Programming Overlay

The above description applies to a single tree. In actual operation, the Dynapath Algorithm grows many trees, selectively prunes them, grows more, etc., until there is virtually a uniformly dense forest of only the best trees. From this forest the single best tree corresponding to the optimum in the performance measure is selected. It is the dynamic programming overlay that accomplishes this selective pruning.

The end nodes of the initial and later trees are classified into a dynamic programming "overlay," as shown in Figure 7. This is shown as a rectangular grid that is oriented along the reference track. (Other grid geometries have also been used during the development; the particular shape of the grid can be altered if desired.) Subdivisions are indicated as a two-dimensional spatial classification of the space according to the zone and division dimensions. The subdivisions in turn are divided according to an angular classification into one of n possible cells (possible azimuth directions). Thus, the end nodes of a tree are classified according to a cell of dimensions x, y and ψ. An important consideration in this development was that memory of the actual (x,y) location of an end node within a cell be retained. As a result, the classification of an end node within a cell does not introduce any quantization artifacts.

For a given tree, a DP state is associated with each end node of the tree. The DP state for an end node "k" contains a label designating the trunk (source) of the end node, the cumulative cost to that end node, as well as state and control information. We note that many end nodes may have the same source, namely, the end nodes for a given tree. Also, dynamic programming states will be selected on the basis of the best cumulative cost at the end nodes, but do not require storage of the full set of controls and states in traversing from the tree source to a given end node. In short, the DP states "leapfrog" from end nodes to trunks without storing the intervening branches. However, note that storage of the immediately preceding two curvature controls ρ is all that is necessary to smoothly restart generation of a new tree from any given end node.

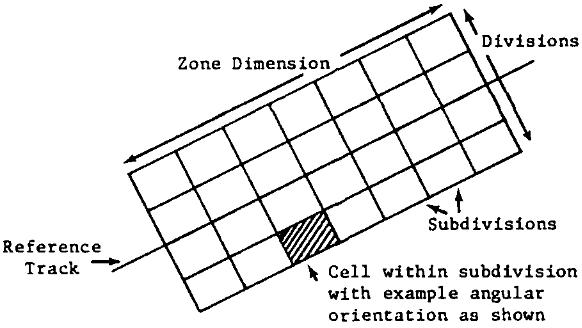

Figure 7. Dynamic Programming Overlay

Optimization Procedure

Starting from the initial position and heading in the patch, an initial N stage tree is generated. The value of N is typically seven or eight, i.e., seven to eight seconds of flight time. The initial tree corresponds to approximately 2000 nodes. Constraint pruning of this tree and subsequent trees will occur according to criteria such as the maximum lateral deviation from the reference track being exceeded.

In parallel with the pruning, the dynamic programming selection proceeds. As a tree is generated, the cell corresponding to each end node is computed. If the cell is empty the end node including its cost is registered as being in the cell. If the cell is already occupied by an end node, the cost of the current end node is compared with the previously registered cost and the end node with lower cost is kept. This forms the basis for the dynamic programming (DP) operation for selecting the best trees.

Many trees are used by this technique in propagating to the end of the patch. Once the end nodes of the last trees are past the last zone in the patch, the optimal path is determined by selecting the end node with the lowest cumulative cost. (Additionally, various patch end node boundary conditions such as a maximum lateral deviation or heading with respect to the reference track can be imposed.)

The optimum path is retrieved by tracing through the DP structure until arriving at the initial tree. This is possible because we have kept track of the source at every stage. We note that the full set of controls--in one second quantizations--is available for the first tree due to the way the solution is constructed and stored. For subsequent trees, the retrieved solution is sampled on a coarser time scale corresponding to the source-to-end-node time. This was done for memory storage efficiency and in recognition that only the first five seconds or so of a patch will actually be flown before the patch is updated. However, the optimal solution is of course based on the uniform one second quantization over the entire patch length due to the manner in which the DP solution is constructed. Indeed, DP state memory has been designed to permit retrieval of the precise path, if desired, with very minor computational increase.

Vertical Trajectory Generation

Prior to generation of the vertical and horizontal commands, the vertical trajectory must be generated. To achieve this, there was a requirement in this development to simply emulate the operation of the ADLAT terrain following algorithm. Since the horizontal path (ground track) is known from the above sections, actual ADLAT software could be used to generate this vertical trajectory along the ground track.

However, the ADLAT software involves a large number of aircraft-specific coefficients. Although use of this software is straight forward, it was felt to be unnecessarily cumbersome for a simple emulation of ADLAT. Thus, the same techniques used in generating the ground track were used for this emulation.

Vertical and Horizontal Command Generation

The trajectory parameters were combined with a point mass aircraft model similar to that used in Ref. [2] to generate inertial axis motion. The heading ψ and flight path angle γ are known at one second intervals from the trajectory determination. Thus, all inertial commands as indicated in Figure 2, as well as bank angle ϕ, can be specified in terms of γ, ψ, and the horizontal and vertical controls used at each time step.

RESULTS

The Dynapath Algorithm has been implemented on a VAX 11/750 in FORTRAN. Lateral path examples are shown in Figures 8 and 9. The terrain altitude in these figures is coded in gray levels, with dark corresponding to lower altitudes and light to higher altitudes. The terrain is not real terrain, but rather, has been designed to test out features of the algorithm. (Unfortunately, the full dynamic range in gray levels has been lost through the photo reproduction process.) The computed ground track in Figure 8 starts on the left side of the patch and makes a sharp turn to exit in the lower right hand corner of the patch, corresponding to the lowest altitude corridor. Here the maximum bank angle was 60°, and for the aircraft speeds involved the sharp maneuver was possible. For this patch computation the boundary conditions accepted the lowest cost trajectory that exited anywhere at the end of the patch.

Note that the path has several kinks (discontinuities in the first derivative), in apparent contrast to the assertion made earlier regarding smooth trajectories. Here, the kinks are due to the display of only the dynamic programming states after the initial tree. The dynamic programming states are from a source to an end node, and do not include the intervening branches. The straight lines connecting the sources to end nodes then result in the kinks. Since only the first part of the track is actually flown, the downstream kinks do not matter. As noted already, the actual path - without kinks - can be retrieved if desired.

Figure 9 shows the same scenario but for a maximum bank angle of 30° instead of 60°. Here the turns are necessarily less sharp, which prevented a maneuver to reach the lower right hand corridor. Instead, the less deep upper right hand corridor was optimal for the given aircraft constraints.

Figure 8. Patch Calculation, for 60° Maximum Bank Angle

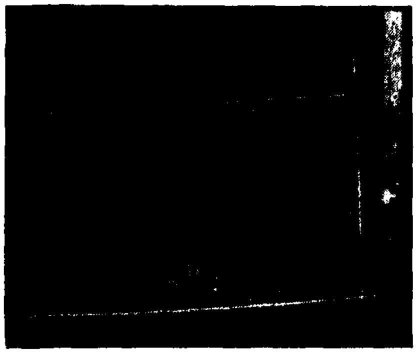

Figure 9. Patch Calculation, for 30° Maximum Bank Angle

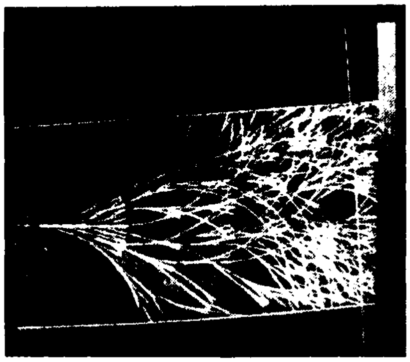

Figure 10. Achieving Global Optimality - 60° Maximum Bank Angle Case

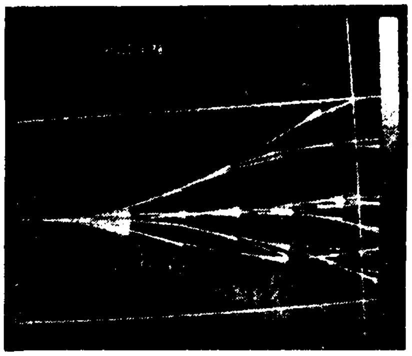

Figure 11. Achieving Global Optimality - 30° Maximum Bank Angle Case

Global Optimality

Figures 10 and 11 suggest how global optimality is actually achieved in this TF/TA approach. Figure 10 shows the complete set of trees that is generated when the maximum bank angle is 60°. These trees have been selected using the dynamic programming overlay, the trees are successively pruned, from which new trees are generated, etc., to the end of the patch. The optimal path is then selected. When the maximum bank angle is only 30°, then the number of possibilities is much smaller as shown in Figure 11. Although the entire region is covered, the coverage is much less dense than when the aircraft maneuverability is larger as in Figure 10.

Vertical Profiles

For the lateral ground track that is found, the vertical profile is then computed. It is based on an emulation of ADLAT, where the vertical set clearance is a constant bias above the terrain. Figure 12 shows a typical example, where the trajectory follows the general terrain features while staying at or above the set clearance. The aircraft cannot dip lower into the troughs because this would violate either the maximum dive angle of 15° or the maximum negative g load used in this example.

Notice the following interesting distinction from ADLAT operation. Whereas ADLAT operation imposes the somewhat arbitrary boundary condition that the flight must be at a 0° flight path angle at the top of each hill in the terrain, this boundary condition is not imposed in the optimal control implementation. Generally, the condition of 0° flight path angle will result at pushover in the present approach if the terrain is symmetric in its altitude profile on either side of a hill. However, if there is a systematic upwards or downwards slope to the terrain, then the flight path angle at pushover will be non-zero accordingly.

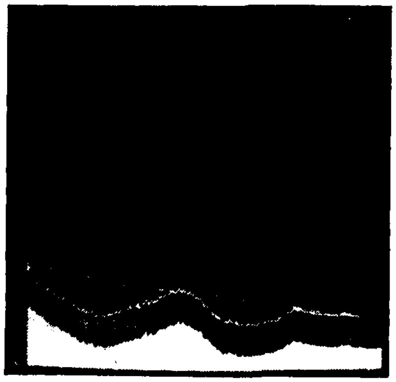

Figure 12. Typical Terrain Following Profile, Along Ground Track

Trajectory About A Waypoint

Figure 13 shows a case where the waypoint exit direction is shown as a straight line with an arrow, and the entry is from the left. The performance measure used in this example has two terms. The first term rewards a close approach to the waypoint without actually requiring flight over the waypoint as a hard constraint. The second term is an altitude penalty implemented as an H^2 contribution. As a result of this second term, the ground track is not perfectly along the suggested waypoint exit direction. Rather, the path deviates slightly to the right to gain the advantage of the low altitude corridor. Other examples could be shown for paths about waypoints, but they are all fairly similar.

Figure 13. Waypoint Example

Thus, trajectories about waypoints can be developed as a fairly straightforward extension beyond the normal TF/TA patch calculations. The interesting feature of this extension is that a desired motion around waypoints, the aircraft maneuvering dynamics, and terrain proximity considerations are all treated in an integrated manner.

The previous AGARD paper [1] indicated how threat and target masking, combined with target illumination constraints, can be combined with a curvilinear weapon delivery profile that enhances survivability. The above techniques for treating trajectories about waypoints can also be used to address the complex curvilinear weapon delivery problem. Here also, terrain features are an integral part of the weapon delivery profile and are directly incorporated through the real-time optimization process.

CONCLUDING REMARKS

The Dynapath TF/TA Algorithm appears to have achieved the original goals of being computationally and memory efficient in optimizing the TF/TA performance measure. The three dimensional TF/TA trajectory requires no smoothing before handoff of the associated commands to the pitch roll decoupler; in short, the trajectory is flyable.

Two versions of the algorithm were implemented in computer code, although only the version reported in this paper has undergone simulation testing in the Air Force to date.

In a system context, the Dynapath Algorithm must interface with a fast-response processing algorithm associated with the immediate sensor range (cf. Figure 3), as well as with the broader considerations associated with threat avoidance such as in Tactical Flight Management [6]. It presently appears that the interface with a fast processing sensor range algorithm can be achieved in several ways. Indeed, it may even be possible to use the Dynapath algorithm itself for this near-term processing function.

In an airborne implementation there is typically interest in parallel processing architectures to accelerate the processing. The Dynapath Algorithm lends itself to an implementation using such parallel architectures. As a result, we believe a subsecond processing time requirement is a realistic goal for this algorithm.

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ACKNOWLEDGEMENTS

This work was supported by the AFWAL Flight Dynamics Laboratory under contract F33615-83-C-3617. Lt. Daniel E. Russ of AFWAL/FIGL was the Air Force Project Engineer. This activity contributed to the Low Level Survivable Penetration Program in AFWAL/FIGL directed by Mr. Walter W. Harrington.

UTILISATION D'UN LIDAR A LASER CO$_2$
POUR LE VOL ET LA PENETRATION A TRES BASSE ALTITUDE

Bernard STEPHAN
Responsable du Secteur Capteur Optronique
S F E N A
Aérodrome de Villacoublay
BP 59
78141 VELIZY-VILLACOUBLAY
France

RESUME

Présentation d'un senseur optique à laser CO$_2$ du type télémétrique permettant l'acquisition des distances porteur-terrain en champ large. Les données acquises en temps réel par un calculateur de type UMP 7800 permettent de générer et d'entretenir une carte du terrain environnant le porteur en coordonnées géographiques. Cette carte rend possible l'élaboration d'une trajectoire optimale de navigation à très basse altitude, optimisée pour l'évitement de terrain. Ce senseur a été expérimenté sur le site de Villacoublay en 1984 et subit actuellement des essais en vol au C. E. V. Les résultats des expérimentations au sol, en analyse statique et dynamique, sont présentés.

1. INTRODUCTION

Le senseur étudié et réalisé par la SFENA a pour vocation de permettre à un avion d'armes d'effectuer du suivi et de l'évitement de terrain à très basse altitude dans des conditions de sécurité satisfaisantes. Il est constitué principalement d'un télémètre hétérodyne à compression d'impulsions, d'un dispositif de balayage et d'un calculateur permettant de traiter en temps réel les informations de distance et de direction de visée.

Ses avantages par rapport à des radars centimétriques sont ceux liés à l'utilisation du laser :

- très forte directivité du rayonnement d'où une grande résolution spatiale ;
- discrétion d'utilisation et insensibilité au brouillage ;
- compacité compatible avec un montage en pod.

Le choix du laser CO$_2$ (10,6 μm) apporte les avantages dus à la longueur d'onde :

- meilleure transmission atmosphérique que celle des rayonnements visibles et proches infrarouges ;
- bonne cohérence spatiale ;
- bon rendement électro-optique du laser ;
- sécurité oculaire accrue.

2. DESCRIPTION DU CAPTEUR OPTIQUE

La configuration optique retenue est celle d'un interféromètre de MACH-ZENDER modifié (figure 1). Elle utilise notamment :

- un laser CO$_2$ guide d'ondes de QUANTEL d'une puissance de 5 Watts ;
- un modulateur acousto-optique (M. A. O.) qui permet de superposer à l'émission laser une modulation linéaire de fréquence ;
- une combinaison afocal dioptrique-afocal catoptrique qui réduit la divergence d'émission à 0,5 mrd ;
- un système de balayage du type diasporamètre à prismes tournants ;
- un détecteur HgCdTe refroidi à 77 K.

Les émissions du capteur sont déclenchées à partir des informations de codage du système de balayage. Celui-ci génère une figure invariante dans le repère du porteur, inscrite à l'intérieur d'un cône dont l'angle au sommet est de 40°. La fréquence de répétition des émissions est fixée par le nombre de gravures déposées à la périphérie des prismes et par la vitesse de rotation du diasporamètre. Elle est de 10 kHz au maximum, avec une période d'image de 200 ms. La trace de la figure de balayage correspondant à ces conditions expérimentales a été reportée en figure 2.
Le signal émis, après réflexion sur la cible et focalisation sur le détecteur, est converti, par détection hétérodyne, à une fréquence intermédiaire dans la bande 96-150 MHz puis comprimé par des composants à ondes acoustiques de surface.

Le capteur optique délivre donc les informations suivantes :

- des impulsions d'environ 100 ns de large, permettant la détermination de la distance porteur-terrain ;
- les tops de déclenchement issus du diasporamètre pour identifier la direction d'émission dans le repère du porteur ;
- des tops de recalage périodiques pour surveiller le fonctionnement du diasporamètre.

3. DESCRIPTION DE LA CHAINE DE TRAITEMENT

L'acquisition et le traitement des mesures issues du capteur optique ainsi que l'acquisition des informations nécessaires à ces opérations sont assurés par une unité de traitement numérique articulée autour d'une unité centrale de type UMP 7800. La planche 1 montre l'architecture de cette unité.
Outre la détermination précise des distances porteur-terrain, elle permet d'élaborer et d'entretenir en temps réel une carte altimétrique du terrain environnant le porteur en coordonnées géographiques.

Ces tâches sont assurées par un module microprogrammable de gestion automatique des échanges, associé à un module de comptage et à une extension comprenant notamment les cosinus directeurs des directions de visée. La carte terrain élaborée par le capteur LIDAR a les caractéristiques suivantes :

- dimensions de l'espace enregistré : $(10240\ \text{m})^3$;
- systèmes d'axes géographiques (Nord-Est-Verticale) ;
- résolution horizontale : 40 m ;
- résolution verticale : 10 m ;
- volume de mémoire nécessaire : 36 kmots de 16 bits.

Cette carte, centrée en permanence sur le porteur, est découpée en blocs de 320 m de côté. Dans chaque bloc sont mémorisées les 32 informations les plus récentes. Les informations anciennes sont éliminées automatiquement par une gestion circulaire du contenu des blocs.

Cette architecture permet d'obtenir une bonne connaissance du relief par accumulation d'images successives et autorise à la fois l'indépendance, l'asynchronisme ou la simultanéité des processus d'acquisition et d'exploitation de l'information. A partir de cette carte de terrain, de la trajectoire de navigation définie au cours de la préparation de mission et des limites d'évolution de l'avion, il est possible :

- d'élaborer une trajectoire optimale de navigation à très basse altitude optimisée pour l'évitement de terrain, ainsi que les commandes successives permettant à l'avion de suivre exactement cette trajectoire ;
- de calculer la courbe de dégagement et de la faire suivre à l'avion si un obstacle est détecté tardivement.

4. PERFORMANCES ET RESULTATS EXPERIMENTAUX

Dans sa définition actuelle, le capteur LIDAR offre les performances suivantes :

- champ d'analyse : cône de 40° d'angle au sommet (valeur typique) ;
- échantillonnage angulaire variable du centre au bord du champ (valeur maximale 1,5° pour 40° de couverture totale sur une image, 0,75° sur une période mécanique) ;
- précision de la mesure de distance : inférieure à 20 m ;
- période de renouvellement des mesures : 200 ms à 1 s ;
- nombre maximum de points analysés par image : 2000.

Les essais en statique (axe de visée pointé dans une direction déterminée sur le site de Villacoublay) ont donné les résultats suivants :

- détection de pylônes métalliques à 6,6 km de distance (réflexion spéculaire) ;
- détection de terrain herbeux (diffusion pure) à 2 km de distance sous incidence rasante:
$$\frac{S}{N\text{moyen}} = 13\ \text{dB}$$
- détection d'immeuble à composante spéculaire modérée à 4,2 km de distance :
$$\frac{S}{N\text{moyen}} = 30\ \text{dB}$$
- détection d'arbres à 3,5 km : $\frac{S}{N\text{max}} = 10\ \text{dB}$

Ces résultats ont été obtenus dans des conditions atmosphériques favorables (atténuation atmosphérique inférieure à 1 dB/km). Le tableau de la planche 2 montre l'évolution théorique de portée du capteur en fonction des conditions atmosphériques.

Une analyse statistique effectuée sur des échos provenant du terrain à 1,5 km de distance a montré que pour un rapport signal à bruit moyen de 16 dB, environ 80 % de ces échos seront détectés avec un seuil à 10 dB au-dessus du bruit.

La figure 3 représente les points de la figure de balayage ayant donné lieu à au moins un écho. Cette acquisition correspond à un temps d'analyse de 9,6 s, conduisant à 31680 émissions (période d'émission : 300 μs). Elle fait apparaître un taux global de détection de 42 % pour des obstacles étalés entre 8 m et 2234 m. Compte tenu du nombre important de télémétries en direction du ciel et de la présence d'une fenêtre temporelle limitant la portée à 2234 m, on peut prédire que la probabilité de détection du terrain sur plusieurs images successives, ici huit, est de l'ordre de 80 %, tous obstacles confondus.

Ces acquisitions ont été traitées hors temps réel par un calculateur HP 9836 et présentées en découpage par des plans verticaux perpendiculaires à l'axe moyen de visée. Ces découpes ont été lissées par un filtrage médian sur trois points pour éliminer les points isolés de type pylône et arbres afin d'en faciliter l'interprétation.

Les résultats obtenus, superposés à une photographie du site de Villacoublay, sont présentés en figure 4.

CONCLUSION

Les resultats expérimentaux acquis en 1984 sont conformes aux objectifs de performances fixés au système LIDAR.

Le capteur, intégré dans une configuration compacte, subit actuellement des essais en vol sur hélicoptère au C. E. V. avec soutien du STTE.

Parallèlement des travaux d'étude sont menés pour accroître les possibilités du système. Parmi les fonctions envisagées on peut citer :

- la détection de mobiles ;
- la navigation Doppler ;
- l'aide à la conduite de tir.

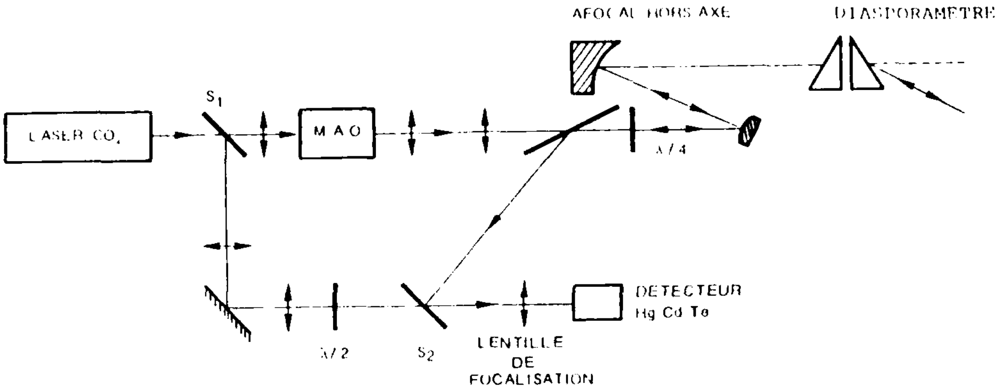


Figure 1 : schéma de la configuration optique

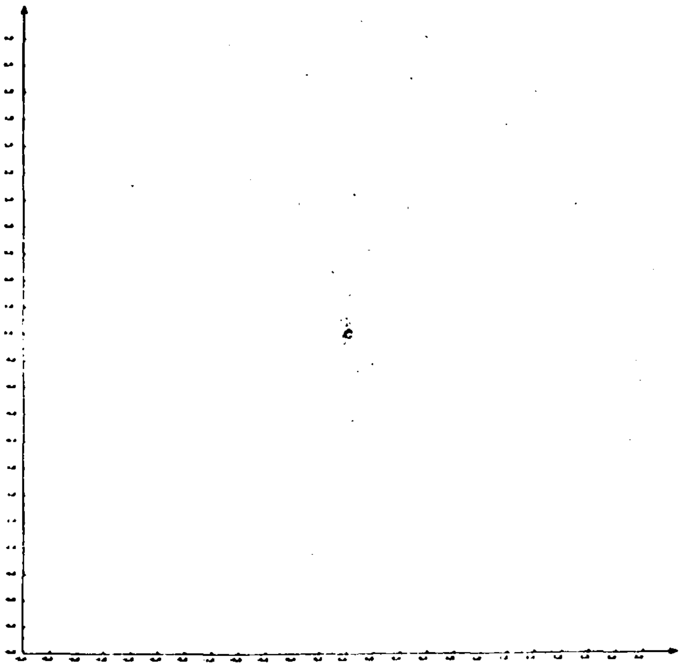


Figure 2 : balayage de type cycloïdal

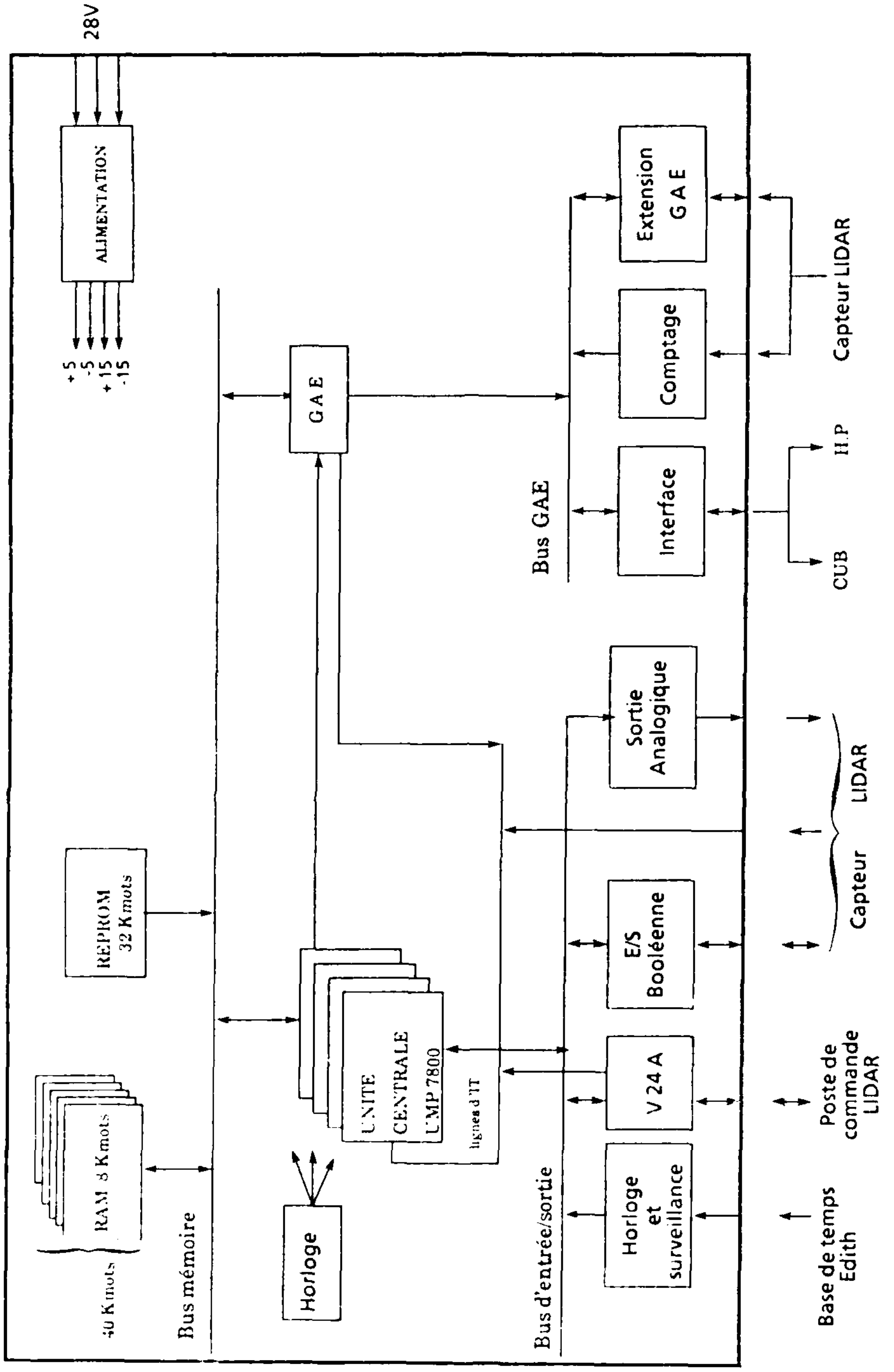


Planche 1 : Architecture de l'ensemble de traitement du système LIDAR

Atténuation atmosphérique dB/km	Evolution de la portée	Conditions atmosphériques typiques
1	5 km	Visibilité optique supérieure à 10 km
3	2,6 km	Visibilité 1 km, avec ou sans précipitations (< 2,5 mm/heure)
10	1,1 km	- précipitations de 20 à 30 mm/heure (forte pluviosité) ou - brouillard léger ou - fort crachin (diamètre de gouttes important) - visibilité optique de l'ordre de 500 m
20	650 m	- très *fortes précipitations* (>80mm/heure) ou - brouillard modéré (visibilité $\simeq$ 300m) ou - crachin modéré

Nota : la portée calculée suppose que l'on *télémètre le même* obstacle dans les mêmes conditions pour obtenir un rapport signal à bruit identique en ne modifiant que les conditions atmosphériques.

Planche [illegible] : Evolution de la portée en fonction des conditions atmosphériques.

```
Enregistrement M02 du 01/03/85  ===>  13386 mesures

Nombre d'images analysées                          --->   0008
Nombre d'émissions effectuées                      ---> 031680
Nombre de mesures effectuées                       ---> 013386
Taux global de détection (mesures/émissions)       --->   42.3 %
Nombre d'axes de visée par image                   --->   3960
Nombre d'axes de visée couverts                    --->   2065
Taux de couverture du champ                        --->   52.1 %
```

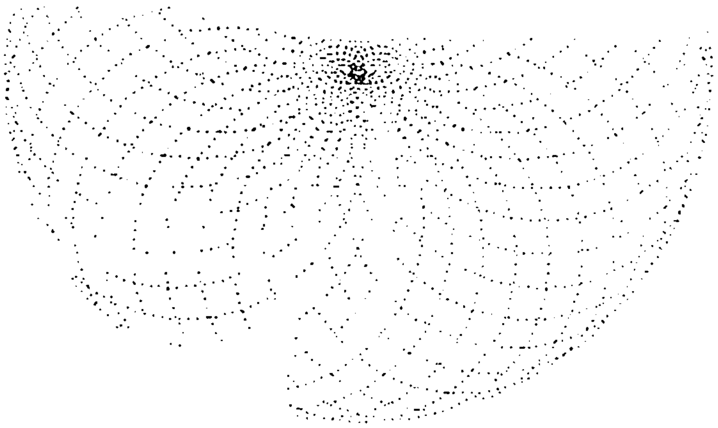


FIGURE 3 : POINTS DE LA FIGURE DE BALAYAGE AYANT DONNE LIEU A AU MOINS UN ECHO

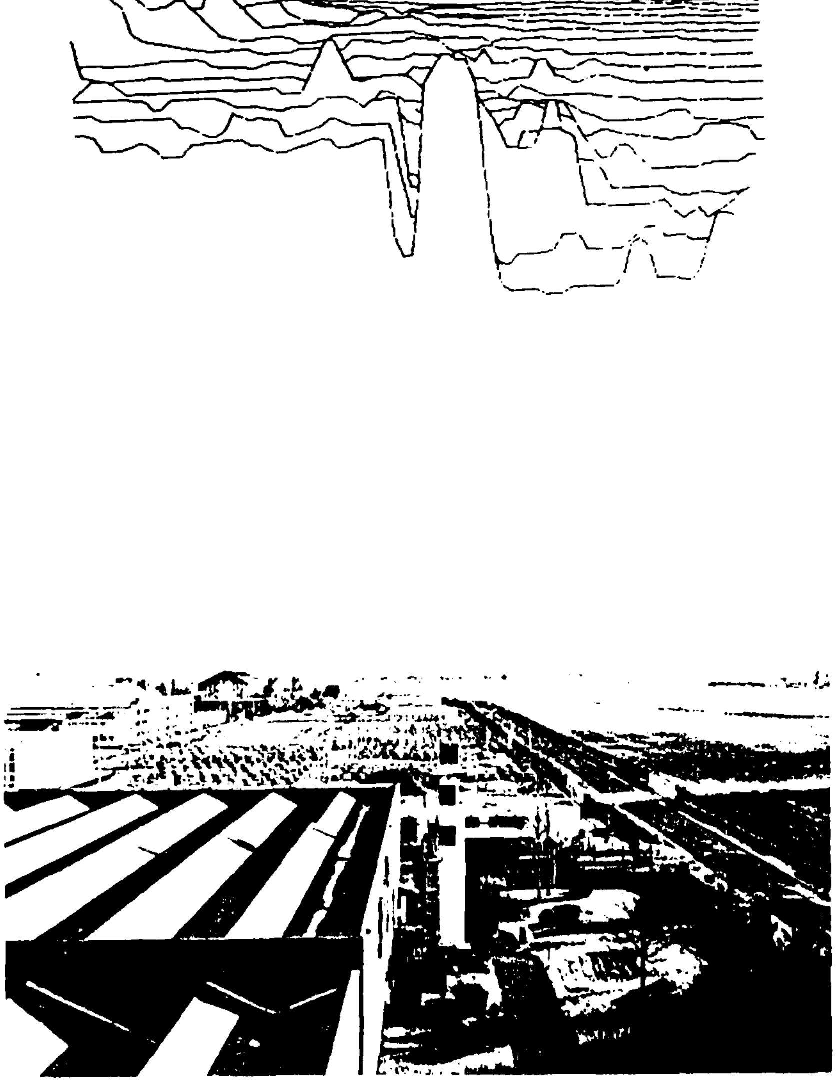


FIGURE 4 (a) DECOUPE DES DONNEES ACQUISES PAR LE CAPTEUR LIDAR
(b) PHOTOGRAPHIE CORRESPONDANTE DU SITE DE VILLACOUBLAY

UN SYSTEME DE NAVIGATION ET DE GESTION DE LA MISSION POUR LES HELICOPTERES MILITAIRES MODERNES

par

J.L.Roch
Crouzet S.A.
Division Aérospatiale
25 rue Jules Védrines
26027 Valence Cedex
France

RESUME.

L'évolution des exigences des hélicoptères militaires modernes entraîne une évolution de leur système de navigation qui, de simple senseur de position, devient un véritable organe centralisé de gestion de mission.

Après un rappel des besoins opérationnels modernes, et des systèmes de navigation autonome encore utilisés aujourd'hui, on trouvera une présentation du système de navigation et de gestion de mission NADIR MK2 développé par la Société CROUZET pour satisfaire ces nouvelles exigences.

1. INTRODUCTION.

Le besoin d'une navigation de haute qualité a toujours été présent pour l'accomplissement des missions dévolues aux hélicoptères militaires.

Ainsi, selon les différentes phases d'une même mission, et selon les diverses missions realisées, on retrouve des caractéristiques majeures qui s'appliquent au système de navigation, telles que la précision, la fiabilité, la redondance d'informations, l'autonomie, l'automatisation.

Aujourd'hui, les capacités et les performances croissantes des hélicoptères induisent un accroissement du nombre de missions spécifiques pour un même type d'hélicoptère, la complexité croissante des systèmes d'armes un accroissement de la charge de travail de l'équipage, dans un environnement menaçant.

Les technologies modernes utilisées dans les systèmes de navigation pour hélicoptères permettent désormais de satisfaire ces besoins et d'assurer de hautes performances tout en limitant le poids, le volume et le coût des équipements. Des fonctions nouvelles sont introduites. Peu à peu, le système de navigation se transforme en organe de gestion complète de la mission.

2. LES BESOINS OPERATIONNELS.

Les besoins opérationnels en matière de navigation peuvent être répertoriés selon trois types de vol :

- vol de croisière,
- vol tactique,
- vols spécifiques des missions navales.

2.1. Vol de croisière.

Cette phase de vol est commune à toutes les missions navales ou terrestres, mais son importance varie selon la mission. Elle constitue par exemple l'essentiel du vol pour les missions de transport tactique ou d'évacuation sanitaire.

Durant cette phase, les premières qualités demandées au système de navigation sont certainement la précision de positionnement et l'autonomie, c'est-à-dire l'indépendance vis-à-vis des aides à la radio-navigation, qui pourraient être faussées ou détruites en cas de conflit.

Ainsi, pour les missions de transport tactique par exemple, chaque hélicoptère peut naviguer indépendamment des autres et déposer ses troupes en toute sécurité au point de ralliement choisi.

La navigation autonome doit pouvoir être recalée aisément au passage à la verticale de points de report caractéristiques, ou à partir d'informations de radio-navigation lorsqu'elles sont présentes. Le vol est ainsi constitué d'une succession de segments rejoignant ces différents points pour former un plan de vol que le système de navigation doit gérer, chaque point étant repéré par un code alphabétique ou numérique.

Enfin, l'économie du carburant constitue un objectif important de l'équipage durant cette phase où le profil du vol doit être optimisé en fonction des conditions de vent, de l'horaire prévu et de la masse embarquée.

2.2 Vol tactique.

Les phases de vol tactique se retrouvent dans les missions de type "Aéromobilité terrestre" telles que la reconnaissance, l'identification de cible, les missions Air-Sol et plus particulièrement les missions anti-chars. Durant une telle phase de vol, l'hélicoptère vole au ras du sol, effectue des évolutions serrées ou des vols stationnaires entre les arbres. La trajectoire est fortement perturbée et l'équipage est concentré sur les tâches de pilotage d'une part, et sur l'éxécution de sa mission propre d'autre part.

Cette phase de vol peut comprendre l'éxécution d'une mission offensive avec attaque d'objectifs au sol ou en vol au canon, à la roquette, au missile.

Les conséquences pour le système de navigation sont :

- maintien d'une bonne précision de positionnement, à basse altitude et dans un environnement difficile ;
- sécurité indispensable de l'information de position ;
- Minimisation de la charge de travail de l'équipage : le système doit libérer l'équipage de tout souci concernant sa navigation ;
- d'autres fonctions sont également souhaitables, pour fournir une aide maximale à l'équipage, par exemple :
  - calcul continu du vent, même à très basse vitesse,
  - aide à la gestion des fréquences radio,
  - prédiction de conditions marginales telles que le survol de zones interdites, l'approche d'une limite de puissance disponible, l'attente d'une réserve de carburant préaffichée, etc ...
- enfin lorsque la mission comporte l'utilisation d'un armement, toute puissance de calcul disponible à bord de la machine peut être utilisée pour optimiser l'efficacité de l'armement : cela peut être le cas du calculateur de navigation.

2.3. Profils de vols maritimes.

Les missions navales incluent :

- les missions de recherche et sauvetage (S.A.R.) ;
- les missions anti-surface (A.S.F.) ;
- les missions anti-sous marines (A.S.M.).

De telles missions exigent des caractéristiques spécifiques du système de navigation, du fait qu'elles sont effectuées au-dessus de la mer et souvent à partir d'une frégate ou d'un porte-avions.

On retrouve des caractéristiques déjà citées, notamment l'autonomie, mais également des nécessités telles que :

- la redondance d'informations pour assurer une sécurité maximale aucun repère n'étant disponible au-dessus de la mer ;

  la mémorisation de figures spécifiques aux missions navales appelées "patterns" qui permettent le quadrillage systématique d'une zone de recherche ;
- l'utilisation de coordonnées grille (x, y), en référence à un centre grille ;
- l'entretien de la position de buts "mobiles", c'est-à-dire affectés d'une vitesse (par exemple : le porte-avions) ;

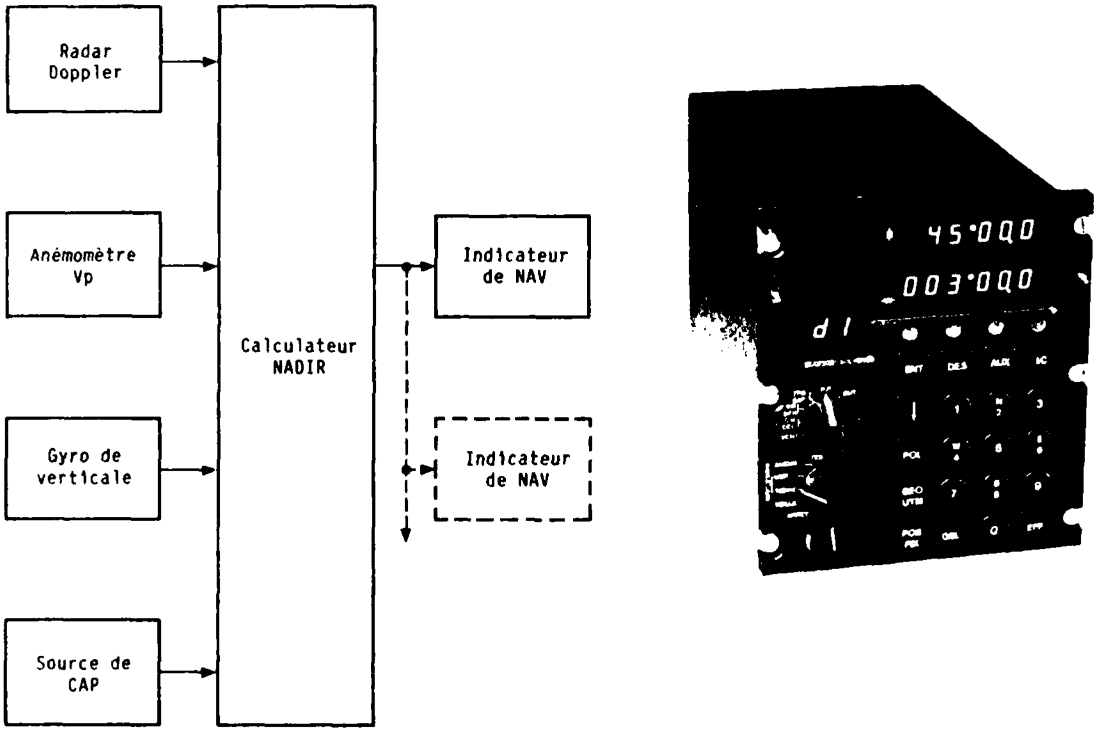
- l'exécution de corrections fonction de l'état de la mer (vent de surface) ;
- le couplage aux divers organes du système d'armes, en particulier :
  - le pilote automatique, pour une conduite automatique de l'hélicoptère vers un but ou le long d'une trajectoire pré-déterminée,
  - le radar de recherche pour d'une part permettre à celui-ci l'entretien d'une situation tactique, et d'autre part introduire en but de navigation tout écho particulier choisi par l'opérateur radar,
  - le système de lancement de missiles,
  - le système de détection (SONAR, système de bouées acoustiques, MAD).

3. LES SYSTEMES DE NAVIGATION ACTUELS.

Les hélicoptères militaires actuels sont généralement dotés d'un système de navigation autonome comprenant les éléments suivants :

- un radar doppler léger, adapté aux besoins des hélicoptères ;
- un calculateur de navigation léger, disposant d'une face avant permettant l'insertion d'ordres et la visualisation d'informations installé directement sur la planche de bord ;
- un anémomètre compensé fournissant la Vitesse Propre (TAS) de l'hélicoptère nécessaire pour la détermination du vent ;
- une source de cap de type gyro-compas ;
- une référence de verticale gyroscopique ;
- un (ou plusieurs) indicateur de navigation.

Il en est ainsi du système de navigation conçu autour du calculateur NADIR de CROUZET et installé sur les PUMA et GAZELLE "HOT" de l'ALAT Française.



SYSTEME NADIR

Un tel système possède des qualités telles que :

- navigation autonome, de bonne précision (de l'ordre de 2 % de la distance parcourue sur terre, dans 95 % des cas) ;
- faibles poids, consommation, volume ;
- aide appréciable fournie à l'équipage :
  - guidage vers un but,
  - simplicité d'utilisation,
  - gestion d'un plan de vol (limité à 9 buts),
  - exécution possible de certaines fonctions spécifiques aux missions navales telles que patterns, coordonnées géographiques polaires ou grille, buts mobiles, couplage au pilote automatique et au radar de recherche.

Toutefois, face à l'évolution rapide des systèmes d'armes et de l'avionique des hélicoptères, ainsi qu'à la diversité des missions envisagées pour un même hélicoptère, un système de navigation tel que celui décrit ci-dessus s'avère souvent insuffisant.

4. LA GESTION DE MISSION.

Le système de navigation des hélicoptères évolue aujourd'hui vers une définition plus complexe répondant aux besoins des utilisateurs, et à l'évolution de l'avionique :

- nécessité d'une redondance d'informations de navigation pour assurer la sécurité de la mission et de l'hélicoptère ;
- gestion d'un plan de vol plus complexe ;
- automatisation poussée de la navigation ;
- introduction de fonctions nouvelles permettant d'optimiser le profil du vol :
  - gestion carburant,
  - aide à la sélection des fréquences radio,
  - anémométrie tout domaine de vol,
- nombre croissant d'interfaces avec les autres équipements du système ;
- disponibilité d'une puissance de calcul importante pour assurer des fonctions spécifiques à la mission ;
- intégration des différentes fonctions dans un même équipement, afin de diminuer les coûts recurrents du système.

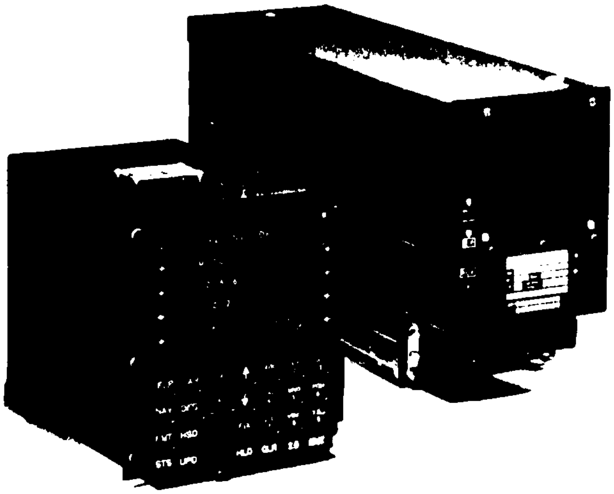
5. UN SYSTEME CENTRALISE DE NAVIGATION ET DE GESTION DE MISSION.

Pour répondre à l'évolution de la fonction navigation sur les hélicoptères militaires modernes, CROUZET a développé le NADIR MK2, calculateur de navigation et de gestion de mission.

5.1. Description.

NADIR MK2 est composé :

- d'un Poste de Commande et de Visualisation (PCV) de faibles dimensions, doté d'un large écran à tube cathodique et d'un clavier à touches fonctionnelles d'un côté, alphanumériques de l'autre ; le PCV est en outre capable de se connecter à un Dispositif d'Insertion de Données (DID) automatique sur sa face avant ;
- d'un Elément Principal (EP) de taille réduite (4 MCU, 6 kg) mais néanmoins doté d'un calculateur très puissant. La technologie utilisée permet de couvrir l'ensemble des besoins actuels et de conserver une très importante provision d'espace pour l'introduction de fonctions nouvelles.



NADIR MARK 2

Le coeur du système est une unité arithmétique puissante conçue par CROUZET pour servir comme module de base, à différents équipements. Ce calculateur, baptisé ALPHA 732 présente les caractéristiques suivantes :

- fonctionnement et échange de données sur 32 bits en virgule fixe et 24 + 8 bits en virgule flottante ;
- puissance de traitement de la classe 1 Mop/s ;
- capacité d'adressage largement suffisante par l'ensemble des besoins identifiés : 2 x 512 K mots de 32 bits ;
- Utilisation d'un langage de programmation de haut niveau, le PASCAL.

Un atelier logiciel a été développé pour la production et la mise au point de programmes complexes, nécessitant l'intervention de plusieurs équipes de programmation pouvant travailler en parallèle et sur des sites différents.

5.2. Fonctions.

Le système NADIR MK2 peut assurer les fonctions suivantes :

- gestion d'une navigation multi-senseurs.

  Outre les informations en provenance du radar Doppler, le système reçoit également celles provenant de senseurs de radio-navigation :

  - courte distance : VOR/DME ou TACAN,
  - longue distance : OMEGA ou LORAN C, bientôt NAVSTAR GPS.

  Le système assure en parallèle l'entretien des positions calculées en fonction de chacun de ces senseurs, ce qui assure la redondance nécessaire à la sécurité de la mission.

  De plus, la navigation autonome peut être recalée sur l'une de ces positions, ce qui, lors des vols de croisière de longue durée, borne l'erreur due à la dérive du doppler, accroissant ainsi la précision globale du système en tout lieu et quelle que soit la durée du vol.

- Automatisation du pilotage et des procédures de navigation :

  - couplage au pilote automatique,
  - suivi automatique d'une route, d'un pattern de recherche, exécution d'une transition automatique sur naufragé, ralliement d'un but mobile,
  - appel de points de report (way points) repérés par un code alphabétique,
  - procédures d'utilisation simples et fonctionnelles, fondées sur le principe du "menu" présenté à l'opérateur,
  - Recalage manuel de la navigation ou à partir des informations de radio-navigation.

- Réelle gestion du vol :

  - Plan de vol alphanumérique de 140 buts dont 20 peuvent être "mobiles", et pouvant être ordonnés en 10 routes différentes.
  - Gestion du carburant : calcul continu de la masse de carburant restant, de la consommation et de la distance franchissable. Alerte automatique en cas d'insuffisance de carburant pour rejoindre la base avec réserve. Vérification du temps et du carburant nécessaire pour suivre une route, compte tenu du vent présent sur les différents segments.
  - Gestion du profil de vol : calcul continu de la vitesse optimum de croisière, détermination de la masse maximum décollable, de la réserve de puissance disponible en fonction des données moteurs
  - Gestion de la mission : aide à la gestion des fréquences de radio-navigation et de radio-communications, alerte à l'approche d'une zone de menace.

- Intégration des fonctions anémobarométriques :

  - Fourniture des informations d'altitude, vitesse air, vent, température, densité, etc..., à l'ensemble du système d'armes.
  - Extension du calcul de ces paramètres à l'ensemble du domaine de vol de la machine.

- Gestion système :

  - Sorties vers P.A., indicateurs de navigation, visualisations électroniques (EFIS), indicateur cartographique, etc...
  - Echanges d'informations avec le radar de recherche, le SONAR, le système de détection acoustique, etc...
  - Liaisons numériques de type ARINC 429 disponibles.
  - Possibilité d'assurer la gestion principale d'un Bus 1553 B.

- Gestion d'armement :

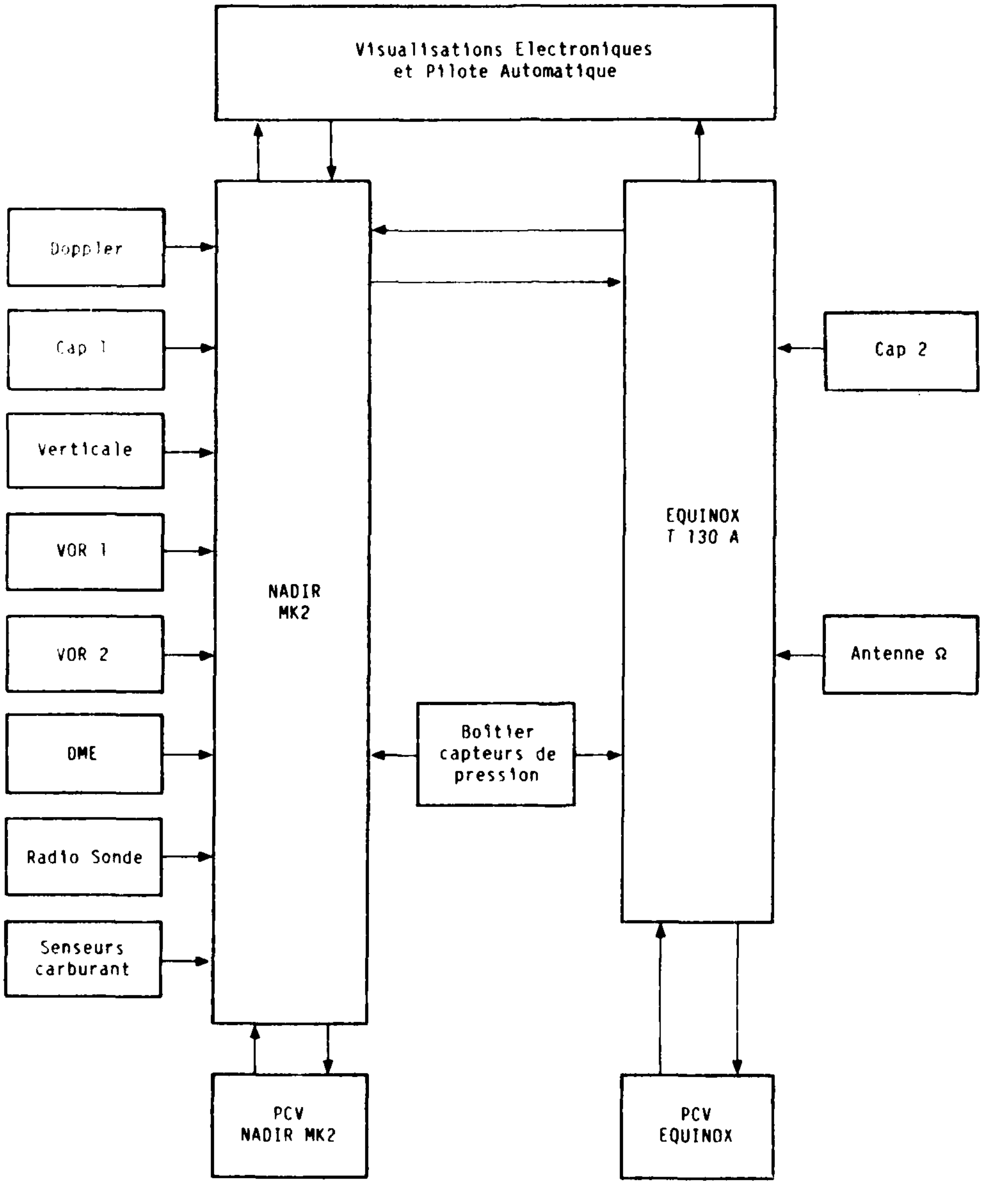
  - Conduite de tir canon Air/Sol, Air/Air et roquettes.

  - Entretien de la configuration et de la masse en fonction des armements tirés.

Toutes les fonctions de gestion de la mission identifiées ci-dessus peuvent être assurées par NADIR MARK 2. De nombreuses fonctions sont basiques et communes à l'ensemble de la famille ; d'autres sont optionnelles.

Toutefois, l'extensibilité est une caractéristique inhérente à la conception de cet équipement, et les provisions retenues, tant au niveau du matériel que du logiciel lui assurent la capacité de traiter de nombreuses fonctions supplémentaires.

Un exemple d'intégration est celui du DAUPHIN SAR de l'Aérospatiale où NADIR MARK 2, qui constitue le calculateur principal de navigation, est associé au système de Radio-Navigation OMEGA EQUINOX 130 A de CROUZET. L'ensemble est couplé aux indicateurs électroniques et au pilote automatique, de sorte que le calculateur EQUINOX 130 A puisse assurer la navigation secours de la machine, ce qui confère à l'hélicoptère un maximum de sécurité.



<u>**SYSTEME DE NAVIGATION DAUPHIN SAR**</u>

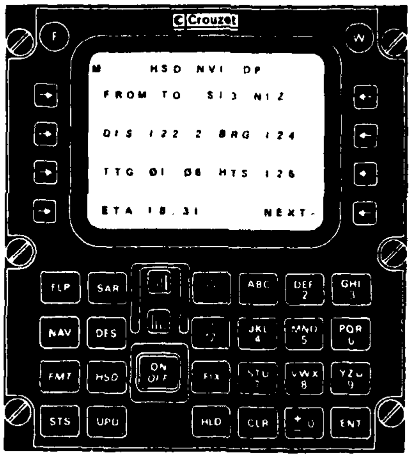
5-3 Utilisation.

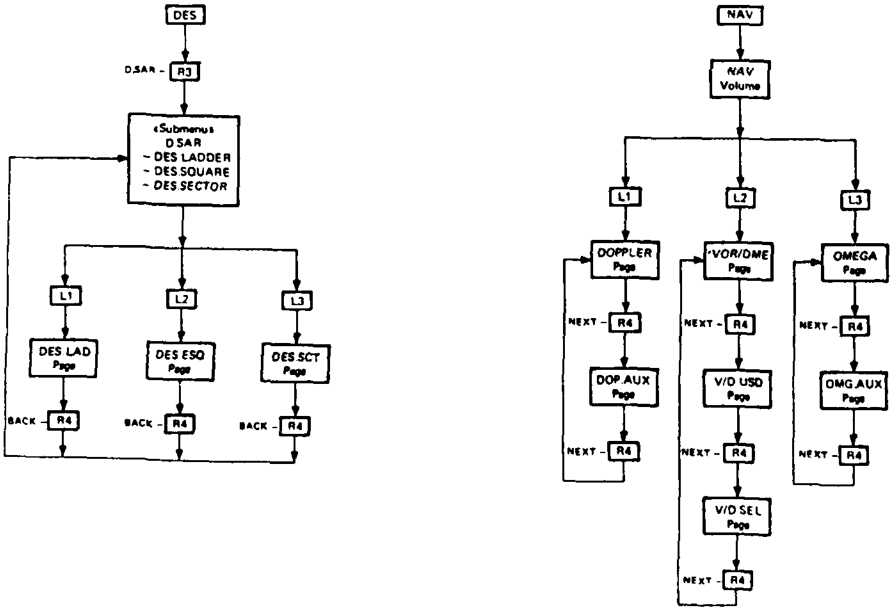
Les procédures de dialogue avec le PCV utilisent le principe du "menu", c'est-à-dire d'une liste d'informations proposées au choix de l'opérateur. Toutes les données sont classées en volumes, eux-mêmes subdivisés en "pages".

L'accès à l'information désirée s'effectue par sélection successive du volume, puis de la page concernés.

Cette procédure simple permet l'échange d'une très importante quantité d'informations entre l'homme et la machine.

Elle permet un apprentissage rapide de l'utilisation du système.

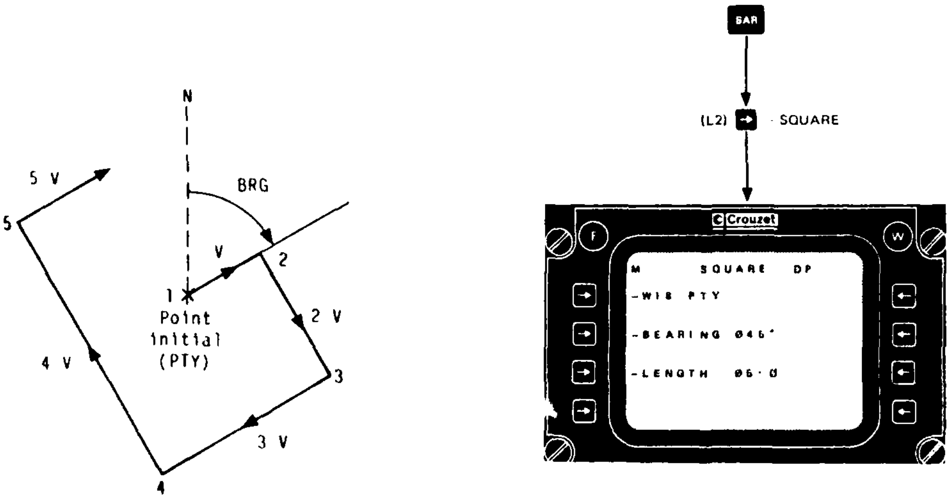




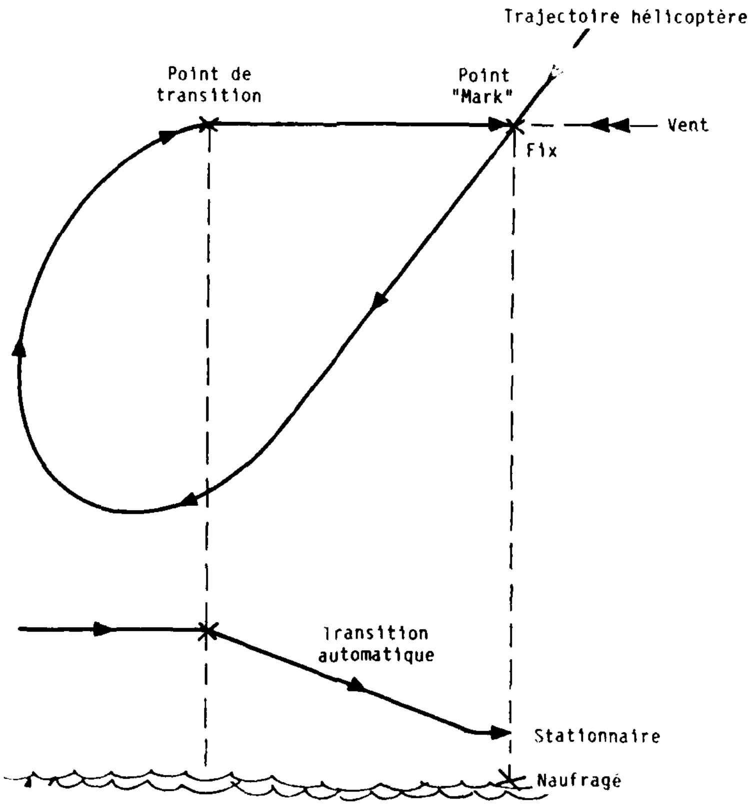
EXEMPLES D'ORGANISATIONS DE VOLUMES

Exemples de trajectoires automatiques

L'exécution de "patterns" de recherche peut être réalisée automatiquement : le calculateur de navigation, qui mémorise ces courbes paramétrées, guide l'hélicoptère à travers le pilote automatique, le long de trajectoires prédéterminées.



PATTERN "CARRE EXPANSE"



ACQUISITION AUTOMATIQUE DE STATIONNAIRE FACE AU VENT

6. CONCLUSION.

Ainsi, à l'origine simple capteur de l'information de position du véhicule, le système de navigation des hélicoptères se transorme en un organe centralisateur d'informations, intégrant de nombreuses fonctions nouvelles destinées à fournir une aide maximale à l'équipage. Il devient un véritable organe de gestion complète de la mission, dont les fonctions devraient encore s'accroître en nombre dans les années futures.

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