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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.410

EFFICIENT CONDUCT OF INDIVIDUAL FLIGHTS AND AIR TRAFFIC

or

OPTIMUM UTILIZATION OF MODERN TECHNOLOGY

(guidance, control, navigation, communication, surveillance and processing facilities)

FOR THE OVERALL BENEFIT OF CIVIL AND MILITARY AIRSPACE USERS

André Benoît
Symposium Chairman and Editor

Papers presented at the 42nd Symposium of the Guidance and Control Panel,
held in Brussels, Belgium, 10–13 June 1986.

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Air traffic management
Navigation, guidance control
Aircraft trajectories
Zone of convergence
Control in TMA
Flight management systems
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PREFACE

This Symposium marks a step forward in the progress made by the Guidance and Control Panel of the Advisory Group for Aerospace Research and Development (GCP/AGARD) towards providing a forum for those responsible for the selection of technological options suitable for meeting the air traffic control and management challenges of the future.

The computer has already been of great service to the air traffic controller. It has relieved him of a series of mainly logistical tasks, enabling him to concentrate his attention on the safe conduct of navigation.

We have now reached a stage where we can look forward to the development of a ground-based computer capable of talking direct to an onboard computer to guide aircraft safely from departure to destination with a level of safety as high as that achieved today and with near maximum efficiency in terms of economics and capacity.

The use of satellites for highly accurate surveillance, navigation that is virtually independent of local facilities, and reliable communications with aircraft anywhere in the sky over the planet, together with the tremendous power of the next generation of computers or, more generally, processing facilities suitable for taking guidance decisions in the most complex configurations, tend to confirm that the above expectation is no longer a mere dream. Clearly, it is not our intention to suggest that both stations (ground-based and onboard) will operate without human intervention. But does the presence of either one person (the pilot) or two persons (the pilot and the controller) necessarily prevent the overall control system from operating automatically? In other words, what level of automation do we envisage and, regardless of present legislation, what role may we expect the human to play in the ground/air/ground control loop?

The density of air traffic continues to grow, but the available capacity seems unlikely to keep pace. As a result, the complexity of air traffic management and control will increase and the computer will have to take guidance decisions. In the initial phase it will offer them to the human controller who will then decide whether or not to implement them. If the computer proves itself to be reliable, the controller will begin to accept its guidance systematically. The consequences are easy to predict. A second phase will follow, in which the computer will simply present what it intends to send to the unit(s) concerned (either adjacent centre(s) and/or aircraft) and request their agreement. This procedure could in due course become no more than a courteous formality. At that stage, what role will the human controller play?

It is in an attempt to answer this question that this Symposium will investigate the latest perspectives on a number of fundamental issues by examining the possibilities offered by new technologies. Particular attention will be focused on the use of more powerful data processing facilities, the introduction of satellites for integrated navigation communications and surveillance and the potential role of automatic two-way air/ground data links. The fields covered will include advanced surveillance radar, advanced landing systems, the management of air traffic (particularly in extended terminal areas), the potential and limitations of automation, including the possible applications of intelligent knowledge based systems, and new onboard equipment that will clearly necessitate a fresh look at the relationship between air traffic control and individual aircraft.

Dr. André Benoît
Symposium Chairman

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Le Panel tient à remercier les Délégués Nationaux de la Belgique près l'AGARD de leur invitation à tenir cette réunion à Bruxelles, Belgique, et de la mise à disposition de personnel et des installations nécessaires.

ACTIVITIES IN AIR TRAFFIC CONTROL

Over the past 15 years, the Guidance and Control Panel of the Advisory Group for Aerospace Research and Development to the North Atlantic Treaty Organization has devoted part of its activities to the fascinating field known historically as Air Traffic Control. The Panel's contributions listed below cover, in particular, the air and ground components considered as parts of a single system, the methods, techniques and technologies applicable to or usable for the management of the flows of aircraft or the control of individual flights, the ever-increasing level of automation and the essential role of the human acting on-line in the control loop.

"Air Traffic Control Systems".
Guidance and Control Symposium, Edinburgh, Scotland, 26-29 June 1972.
AGARD-CP-105, April 1973.

"A Survey of Modern Air Traffic Control"
AGARDograph AG-209, Vols. I and II
July 1975.

"Plans and Developments for Air Traffic Systems".
Guidance and Control Symposium, Cambridge, Mass., USA, 20-23 May 1975.
AGARD-CP-188, February 1976.

"Air Traffic Management. Civil/Military Systems and Technologies".
Guidance and Control Symposium, Copenhagen, Denmark, 9-12 October 1979.
AGARD-CP-273, February 1980.

"Air Traffic Control in Face of Users' Demand and Economy Constraints".
Guidance of Control Symposium, Lisbon, Portugal, 15 October 1982.
AGARD-CP-340, February 1983.

"Efficient Conduct of Individual Flights and Air Traffic
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Guidance and Control Symposium, Brussels, Belgium, 10-13 June 1986.
AGARD-CP-410, this document.

"Computation, Prediction and Control of Aircraft Trajectories"
AGARDograph AG-301, in preparation.

OPENING ADDRESS

by

Major General H.Robyns de Schneidauer
Chef d'Etat-Major Adjoint Logistique
de la Force Aérienne Belge
National Delegate to AGARD

Ladies and Gentlemen,

Let me introduce myself, I am Major General ROBYNS, Deputy Chief of Staff Logistics of the Belgian Air Force. On behalf of Lieutenant General LEFEBVRE, Chief of Staff of the Belgian Air Force, I have the privilege and the pleasure in my capacity as Belgian National Delegate to AGARD to welcome the Guidance and Control Panel for its 42nd symposium and the 2nd one organized in Belgium.

The interest shown by Belgium in the activities of the GCP from both points of view of the scientists community on one hand as well as of the users community on the other hand, is illustrated by an active contribution to the programme of this symposium. Dr. BENOIT of EUROCONTROL (scientist) will chair the first session entitled "Looking to the future" and LtCol COUPEZ (user) Commander of the BAF traffic control center/radar post will chair the last session of this meeting entitled "Contribution to system automation".

I am also particularly pleased and proud to note among this distinguished audience the presence of the honorary dean of AGARD Prof. HAUS, Belgian member of your panel since the very beginning of its existence in 1965.

Several AGARD conferences have already been organized in Belgium, nevertheless I see that, once more, a very large attendance is reached, and it gives me great pleasure. I dare not guess whether you are mainly attracted by the subjects of this symposium or by the charms of Brussels and Belgium, or even by a combination of both.

Anyhow, I think that Belgium is a proper place to hold a meeting dedicated to "The efficient conduct of individual flights and air traffic".

Indeed, as you all know, the Belgium Airspace is a very complicated one, not only as a consequence of its limited dimensions, but also because of the amount and variety of air traffic criss-crossing, and because of the different control centres that have to co-operate, and co-ordinate their action in the same small area.

Throughout the whole world modern technology is in continuous development, and already in the last decade of this century, we will have to define the philosophy according to which more and more powerful technical tools will have to be applied in the best possible way, in order to guide and control air traffic in such a manner that optimal use of airspace is obtained for all categories of users.

The important impact of technology upon operational flying in the future is well underlined by several interesting contributions to this symposiums' programme where I remark items such as advanced surveillance and landing systems, automatic data link between airborne and ground based stations, space based capabilities, air traffic and flight management systems and proceeding automation in air traffic control. All of these features will contribute to safeguard the classic objective of establishing a safe, orderly, expedite and economical flow of air traffic.

There is a continuous need for advanced technology that will offer many advantages; among others it will permit aircraft to operate more independently, it will meet the requirement of proceeding as direct as possible from departure to destination field, it will allow optimization of automation in order to modify the methods of separation of aircraft and to obtain a better regulation of air traffic in busy areas, it will establish data communication channels for exchange of information between control and flight management systems.

Let me end up with just one more non technical reflection; notwithstanding the emerging technological possibilities, it is anticipated that during the next decades the responsibility for safety in the air will remain with the ground based air traffic control, possibly backed up by airborne traffic warning systems; this option, anyway, has among others, already been taken in the United States of America. It is clear that technological development and progress alone cannot yet provide a solution to the problem of efficient and safe management of air traffic and that, up to now, the important role of men - call the controllers or airspace managers - is highly confirmed, as long as these human beings are strongly assisted by automatic systems in their decision making process.

In conclusion I think that many attractive challenges continue to be present in the air traffic world and I am sure that this 42nd AGARD guidance and control panel meeting will bring a most valuable contribution to sound and suitable solutions for the future problems by giving the participants the opportunity of sharing their experience and knowledge, so that safety and economy in the air will be maintained for many years to come.

I wish you all a pleasant stay in Brussels and a very successful meeting.

CP 410

CONTENTS

Page

PREFACE iii

GUIDANCE AND CONTROL PANEL OFFICERS AND PROGRAMME COMMITTEE iv

ACTIVITIES IN AIR TRAFFIC CONTROL v

TECHNICAL EVALUATION REPORT†
by B.Furcolo

OPENING ADDRESS
by H.Robyns de Schneidauer vi

Reference

KEYNOTE ADDRESS:
Belgium moves ahead in air traffic control
by A.Vandenbroucke K

SESSION I: LOOKING TO THE FUTURE

Chairman: Dr A.Benoit, BE

LE CHOIX DES FUTURS SYSTEMES DE LA NAVIGATION AERIENNE CIVILE
par O.Carel 11

FANS – A U.S. PERSPECTIVE
by S.B.Poritzky 12

LA NAVIGATION AERIENNE ET L'AVION A L'HORIZON 2000
par V.Vachiery 13F
AIR NAVIGATION SERVICES AND AIRCRAFT AROUND THE YEAR 2000
by V.Vachiery 13E

SESSION IIa: GLOBAL POSITIONING SYSTEM

Chairman: Dr M.Pelegrin, FR

GPS: OVERVIEW AND PRESENT STATUS
by P.Hartl, W.Schoeller and K.-H.Thiel 21

INERTIE – GPS: UN MARIAGE DE RAISON... A L'ESSAI
par P.Lloret et B.Capit 22

GPS AS THE SOLE MEANS NAVIGATION SYSTEM IN US NAVY AIRCRAFT*
by G.Lowenstein, J.Phanos and E.R.Rish 23

SESSION IIb: AUTOMATIC AIR/GROUND/AIR DATA LINK

Chairman: Dr M.Pelegrin, FR

COMMUNICATION, NAVIGATION, AND SURVEILLANCE SERVICES FOR THE AVIATION INDUSTRY USING SATELLITE TECHNOLOGY
by R.A.Pickens 24

POSSIBLE CONTRIBUTIONS FROM THE SSR MODE S DATA LINK TO THE CONDUCT OF EFFICIENT AIRCRAFT OPERATIONS
by M.E.Cox 25

---

* Not available at time of printing.
† Published separately as AR 236.

Reference

SESSION III: ADVANCED SURVEILLANCE RADARS
Chairman: Prof. P.Murino, IT

SPACE-BASED MULTIFUNCTION RADAR SYSTEMS: FUTURE TOOL FOR CIVILIAN AND MILITARY SURVEILLANCE
by G.Galati and G.Losquadro 31

MONOPULSE SECONDARY RADAR: PRACTICAL REALIZATION AND ACHIEVEMENT; MODE S, THE RADAR OF TOMORROW
by F.Delille 32

A PRACTICAL EXAMPLE OF MOVING TARGET DETECTION (MTD) PROCESSING FOR AN AIR TRAFFIC CONTROL RADAR WITH WEATHER CHANNEL
by C.Bruno 33

SESSION IV: ADVANCED LANDING SYSTEMS
Chairman: Prof. G.Schaenzer, GE

MICROWAVE LANDING SYSTEM (MLS) AREA NAVIGATION: COMPUTED CENTERLINE EXPERIMENTS AND SYSTEM ACCURACY ANALYSES IN AN RF ENVIRONMENT
by J.H.Remer and B.R.Billmann 41

MLS: ITS TECHNICAL FEATURES AND OPERATIONAL CAPABILITIES
by R.Seifert 42

ADVANCED ATC: AN AIRCRAFT PERSPECTIVE
by L.Credeur, D.H.Williams, W.E.Howell and C.R.Spitzer 43

SESSION V: AIR TRAFFIC MANAGEMENT – AUTOMATION – ADVANCED TMA
Chairman: Prof. W.Hollister, US

STRATEGIC CONTROL TO IMPROVE EFFICIENCY OF AIR TRAFFIC MANAGEMENT
by L.Bianco 51

A TIME-BASED CONCEPT FOR TERMINAL-AREA TRAFFIC MANAGEMENT
by H.Erzberger and L.Tobias 52

PHILOSOPHY OF APPLYING AUTOMATION TO AIR TRAFFIC CONTROL
by L.F.Page 53

COMPUTER ASSISTED ARRIVAL SEQUENCING AND SCHEDULING WITH THE COMPAS SYSTEM
by U.Völckers 54

CONTROLE DU TRAFIC DANS LES TMA MODERNES; TECHNIQUES DE LA PROCHAINE GENERATION
par A.Benoît, S.Swierstra et R.De Wispelaere 55F
NEXT GENERATION OF CONTROL TECHNIQUES IN ADVANCED TMA
by A.Benoît, S.Swierstra and R.De Wispelaere 55E

SESSION VI: FLIGHT MANAGEMENT AND OTHER ON-BOARD SYSTEMS
Chairman: J.L.Hollington, UK

EXPLOITING THE CAPABILITIES OF FLIGHT MANAGEMENT SYSTEMS IN SOLVING THE AIRPORT ARRIVAL PROBLEM
by J.F.Meredith 61

APPLICATION OF FLIGHT PERFORMANCE ADVISORY SYSTEMS TO US NAVY AIRCRAFT
by M.J.Friedman, L.J.Cowles and R.C.Carson, Jr 62

Paper 63 withdrawn

Reference

DESIGN CRITERIA FOR MULTI-LOOP FLIGHT CONTROL SYSTEMS
by G.Schaenzer 64

SOME EXPERIENCES IN INTEGRATING AVIONIC SYSTEMS ON THE CIVIL FLIGHT DECK
by P.England, R.Harlow and N.Cooke 65

SESSION VII: CONTRIBUTIONS TO SYSTEM AUTOMATION
Chairman: J.J.E.Coupez, BE

Paper 71 withdrawn

SEMI-AUTOMATIC CROSS-CHECKING BETWEEN DIFFERENT COPIES OF THE SAME FLIGHT PLAN
by S.Ratcliffe 72

THE APPLICATION OF INTELLIGENT KNOWLEDGE BASED SYSTEMS TO AIR TRAFFIC CONTROL
by W.S.Nicol, G.C.Dean, A.Jackson and W.A.Stretton 73

ROUND TABLE DISCUSSION RTD

CP-410

BELGIUM MOVES AHEAD IN AIR TRAFFIC CONTROL

by

ir. A. VANDENBROUCKE

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INTRODUCTION

It is a personal privilege and a great pleasure to be given the chance to speak to your at the AGARD symposium, which this year is concerned with the efficient conduct of individual flights and air traffic. I like to think that the reason that I was selected by AGARD for this keynote address is that we are doing something appropriate to this symposium and interesting to you, the attendees. What I am going to talk about is an exciting new program for us, the Régie des Voies Aériennes/Regie der Luchtwegen (RVA/RLW). One that has been in preparation for quite a while, but has now left the runway for good.

Also, by way of introduction, I want to tell you that the RVA/RLW, which is under the responsibility of the Ministry of Communications, has jurisdiction over the public airports, airways, facilities, and air traffic control services within Belgium.

Rather than going directly to the details of the subject matter, I would like to set the stage. Belgium is a small country by world standards, but its location bestows on it great international significance. Belgium is the home of the EEC, SHAPE and NATO and about 10 million people. With its substantial and diverse population, Belgium is a nation at the crossroads of Europe and therefore transportation is an essential fact of life. Transport movement at ground and sea level is structured to follow the motorways, railways and waterways. Transportation in the airways cannot be structured with physical constraints because it is uniquely three-dimensional and an order of magnitude faster than surface transportation. With the dynamics of modern aircraft and the limited airspace, the difficulties of providing the efficient conduct of air traffic are magnified. Increases in air traffic add an element of criticality to the situation.

How will Belgium meet the challenge of providing efficient conduct of individual flights and air traffic within the country's unique airspace ? The answer lies in an optimum utilization of modern technology in a new Air Traffic Control System called CANAC, which is an acronym of Computer Assisted National Air Traffic Control Center.

CANAC BACKGROUND

Before I go into a description of CANAC I would like to tell you a little about its historical background.

It was determined in the mid 1970's that the Belgian operating facilities were no longer compatible with the needs and evolution of current air traffic. In 1976 the RVA/RLW addressed this problem by instituting a plan to modernize the Belgian air traffic capabilities. This plan included the installation of a new en-route radar station at St. Hubert, the provision of an interim automated radar data processing and display system (called the "TEMPO ACC") and the replacement of the obsolete en-route radars at Brussels airport by a new radar station at Bertem. The implementation of CANAC to replace the "TEMPO ACC" will now complete this modernization plan.

CANAC OVERVIEW

The CANAC project will fulfill the goal of a Belgian national air traffic control center which integrates the control of en-route and terminal air traffic. In general, CANAC is a consolidation and modernization program for the processing and display of radar and flight plan data, and for a highly reliable ground-to-ground and ground-to-air voice communication capability.

Two major subsystems are to be procured to replace aging equipment. These are an Air Traffic Control (ATC) Automation System which will process and display radar data and aircraft flight data, and a Voice Communication Switching System which will provide air traffic personnel with a modern, reliable means of voice communication. Other procurements include a new ATC building, a reliable power source and a security system.

The ATC Automation System will be used for both the Area (en-route) Control Center and Brussels National Airport Approach Control Unit. These control units will share the computer hardware and software, thereby minimizing the total cost of the CANAC system.

The objectives in acquiring CANAC include :

- Relieving controllers and assistants of routine tasks associated with the collection, collation, sorting, updating, coding, processing and distribution of data.
- Simplifying and accelerating the exchange of data needed for coordination between operating positions in the new center and between other air traffic positions in military and adjacent centers.
- Improving the display and the update of flight data to air traffic personnel.
- Reducing the communications volume and consequently the mental effort normally associated with air traffic handling.
- Standardizing to a larger extent air traffic procedures in most of our air traffic units and with our military and international partners.

AUTOMATION SYSTEM DEFINITION

The CANAC Automation System will be part of the total air traffic services provided by the RVA/RLW. It will have the capability to interface with up to six radars (fig. 1). The initial implementation will include the processing of signals delivered by the en-route radars of Bertem and St. Hubert.

Both radars are of a very recent technology. The radar of St. Hubert is in use since 1980 and the Bertem site has just recently been put into service. The ASR-7 terminal area radar at the Brussels National Airport will also provide radar service to the CANAC APP positions. The input of military data to CANAC is from the Semmerzake Radar Operated System (SEROS) in the Military Air Traffic Coordinating Center. And, the Message Switching System (MSS) interface is used for Aeronautical Fixed Telecommunications Network (AFTN) data. Future interfaces will include the Maastricht Automatic Data Processing and Display System (MADAP), the Benelux Air Traffic Flow Management Unit (ATFMU), the Distributed Airport Information System (DAISY), and adjacent Flight Information Regions.

By using very advanced technologies and suitably sited radars, a much safer and expeditious movement of air traffic will be assured in the en-route airspace of Belgium and Luxembourg, as well as in the terminal area of the Brussels National Airport.
Fig. 2 illustrates the radar coverage in the Belgian FIR.

The CANAC system will completely fit into the integrated concept of the security of the airspace above the Benelux/North Germany area that is now being developed between the four involved countries and Eurocontrol. This concept will, by way of automatic computer-to-computer data exchange, integrate five ATC centers; four national centers (Amsterdam, Brussels, Bremen and Düsseldorf) for the lower and terminal airspace, and the Eurocontrol Center of Maastricht for the upper airspace.

Fig. 3 shows a general block diagram of the CANAC Automation System.

The proposed design of the automation system makes maximum use of off-the-shelf equipment. There will be multiple threads of data processing equipment with provision for automatic reconfiguration to standby equipment for both radar and flight data processing. Manual assignment of these threads to software development and training functions is also provided for. Situation data displays will be of proven design. Close coordination between the contractor and an RVA/RLW task force will assure that the air traffic consoles will be of a good ergonomic concept.
Software will also make use of off-the-shelf designs, particularly for support programs. Much of the application software will be done in the ADA language. This is the language that has been adopted as a standard by the United States

Department of Defense. The software development capability will provide for verification of changes to the operational and support programs prior to use in the CANAC system. The training function will provide for controller familiarization and in-depth training using live as well as simulated data.

The automation system is composed of five functional parts (fig. 4). These parts are data processing and peripherals, display and input/output, digital data communications, software development and training, and remote devices.

The automation system will perform five basic functions within CANAC. These are :

- To provide air traffic services to civil and military flights operating as general air traffic within the Belgian airspace ;
- To provide for the training of personnel ;
- To provide for the maintenance and development of air traffic control software ;
- To augment the air defense system by exchanging the required data ; and
- To provide coordination with adjacent facilities.

The automation system will have the following capabilities

- Processing and storing flight data received from the Air Traffic Services Reporting Office, CANAC operating positions, and the Message Switching System, as well as storing the flight plans of regularly scheduled air carrier flights ;
- Modifying the flight data base in response to flight update information, calculating arrival times over posting fixes, and updating track information ;
- Receiving Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR) data from the radars, processing and assigning SSR codes to flights, and processing and displaying the PSR and SSR data on aircraft ;
- Initiating tracks on flights, maintaining association between flight plans and tracks, processing and displaying plot and track information, and assisting control personnel in the handoff of aircraft between CANAC sectors and between the CANAC and adjacent facilities ;
- Receiving, storing, and displaying Notice to Airmen data ;
- Exchanging information with other air traffic control and air defense facilities ;
- Performing real-time quality control as well as system and incident analysis recording ; and
- Providing simulation, training, and software development capabilities.

VOICE COMMUNICATION SYSTEM DEFINITION

The Voice Communication Switching System is a computer based electronic stored-program controlled system designed specifically for air traffic control. It will be used to connect called and calling parties; to ensure uninterrupted communications between (and among) the connected parties; and to disconnect the parties when calls have been completed. It will consist of switching, signaling and transmission functions. The switching function will identify and connect users to a suitable transmission path. The signaling function will supply and interpret the necessary control and supervisory signals to perform the switching function. All switching and signaling functions will be performed utilizing multiple stored-program digital processors (or microprocessors). The transmission function will deal with the media over which calls and control signals are routed. These functions will be integrated into a highly reliable and easily maintained system utilizing modern, state-of-the-art integrated circuit technology.

The system is composed of : a Ground-to-Ground switch which interconnects positions within the air traffic control facility (intercom) and connects those positions to positions at other air traffic control facilities (interphone); and a radio control function which connects the ATC facility positions to Air-to-Ground equipment.
Régie des Telegraphes et des Telephones and RVA voice-grade circuits will interconnect the equipment. The system will be designed such that it may be introduced into the existing system without interruption to, or degradation of, air traffic services; moreover, its implementation will require no significant changes to existing procedures. In order to achieve reliability, the system will provide redundancy for alternate transmission routing and equipment backup. The system will have internal diagnostic features, self-contained monitoring and testing, and provisions for trunk restoration.

Capabilities included in the Voice Communication System :

- Direct access - Intercom and interphone connections shall be established between parties by the depression of a single pushbutton.
- Indirect access - Intercom and interphone connections shall be established by dialing a selected party through the use of a 12-key dial pad.
- Incoming call queueing and common answer - Incoming indirect access calls to a position shall be queued for answering in a random order.
- Override - A calling party shall have the ability to override a busy control position to establish an intercom or interphone connection.
- Call forwarding - Incoming intercom and interphone calls to a control position shall be automatically forwarded to another position.
- Call transfer - Incoming intercom and interphone calls shall be manually transferred to another position.
- Hold - An intercom or interphone call shall be capable of being held by either the called or calling party.
- Radio control - The system shall provide radio transmitter and receiver selection and control capability.

Voice recording and software development/training functions will also be provided.

FACILITY

CANAC represents totally new system equipment for automation and communications. As befits such an undertaking, a new building is being constructed to house CANAC. This facility will be located within the land area of the Brussels national airport.

Basically, the CANAC building will consist of two main wings : the operational wing and the administrative wing. The operational wing requires two levels. The lower level will include a computer raised floor and a mezzanine (low-ceilinged cable floor) for the electronic data processing equipment, telecommunications equipment and other support functions. The upper level will include a false floor and a double-height false ceiling and will house the en-route and approach operations rooms, the Belgian Air Force offices, and the current operations/on-the-job training/extension area.
The administrative wing consists mainly of administrative and housekeeping functions, and will consist of four levels.

PROGRAM MANAGEMENT

CANAC is the largest air traffic control system project to be undertaken in Belgium. Its degree of sophistication and complexity creates the need for careful program management.

The approach being used for CANAC provides a four-phase division of acquisition activities : System Definition Phase ; System Development Phase; System Testing and Deployment Phase ; and System Operation/Evaluation/Transition Phase.

The automation system is being procured as a single system. The system is being developed by a single prime contractor, Thomson-CSF (France), and that contractor will have the responsibility for installation (hardware and software), checkout, system testing, and training. The Mitre Corporation provided support during the definition phase and will continue to provide system engineering support to the RVA/RLW during development, installation and testing. As required by the RVA/RLW, Belgian industry and in particular Tractionel Information Systems (TRASYS) will participate in the development of CANAC thereby allowing transfer of software and ATC technology. The RVA/RLW will have the responsibility for integrating personnel and procedures into the prime contractor supplied system and to ensure that the final automation system is operationally certified for air traffic control.

The Voice Communication Switching System is being procured as a single system and developed by one prime contractor, Nerion (Norway). The installation of this Communication System will be coordinated with the installation of the ATC Automation System.

The System Definition Phase of the CANAC project has been completed. The activities in this phase included : preparation of system specifications; preparation of Requests for Proposal ; evaluation of proposals; and negotiations and placing of the orders.

During the system development phase which has recently begun, the components of the system will be procured or assembled at the prime contractors' facilities. Also during this phase a significant amount of application software will be developed to meet our specific operational requirements.

During the system testing and deployment phase, tests will be conducted in accordance with the prepared system acceptance test plans. The tests will include the evaluation of system performance in terms of specified functional capability, reliability, compatibility with the external environment, and the adequacy of the specified support functions.

The final phase will provide operational assessment and phaseover to operational status. This phase provides the opportunity to fine-tune the system, refine the certification requirements and standards, and develop the procedures to be used during operations. The operational proficiency of controller personnel on the new system is also further developed during this time. The evaluation period is completed when the total system has been demonstrated to be ready for certification.

The phaseover of the system to operational use will be accomplished in accordance with a carefully prepared phaseover plan.

SCHEDULE

Now that CANAC has definitely "taken off", it is interesting to look at the program schedules. Looking back at the system definition phase, the project has been underway for a few years. This time has been spent determining all requirements to be specified and in preparing procurement documentation. Some delay has also crept into the process as air space control responsibilities had to be resolved. These activities are now behind us, and Belgium is catching up the lost time. Some of the major milestones for the automation system include : final design review, January 1987; factory acceptance tests, September 1988; delivery, December 1988; site acceptance, June 1989 and system phaseover, December 1989. The total time from contract award to phaseover is 42 months.

CONCLUSION

In conclusion, I would like to emphasize that CANAC is involved in three major integrations.

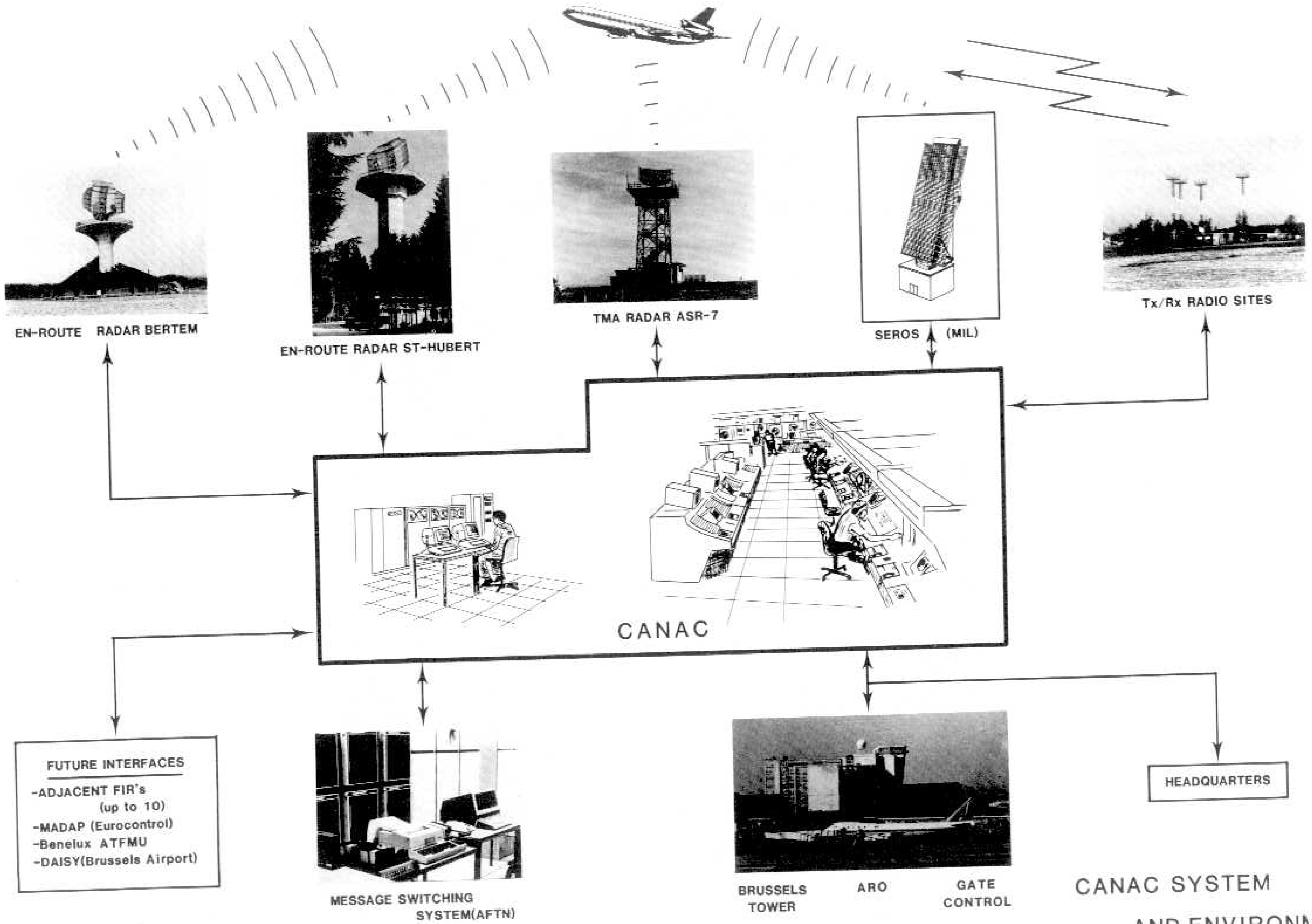
1. The integration of en-route and terminal control capabilities into one shared system ;

2. The integration of military control positions within a civil facility ;

3. and finally, the most important, the integration of information among 4 national centers and Maastricht.

To enhance a little on this third integration, CANAC will have, inherent in the system, the capability of controlling traffic to FL 300 (and beyond). This capability, in coordination with the data exchange provided in the third integration, greatly facilitates the possibility of backing up adjacent facilities in time of center failures. The RVA/RLW is presently engaged in on-going discussions aimed at the realization of a mutually supportive Western European ATC service.

Now that the "green light" has been given to CANAC, and to the activities of this symposium, I hope you will find the presentations on air traffic activities which follow to be most interesting. I also hope that you will find an opportunity to explore the ancient heart of Brussels. And, while wandering among the many 17th century buildings, if a jumbo jet climbs out over the city you may get a true sense of the progress we have made and will continue to make as we move towards the 21st century.



CANAC SYSTEM
AND ENVIRONMENT

Figure 1

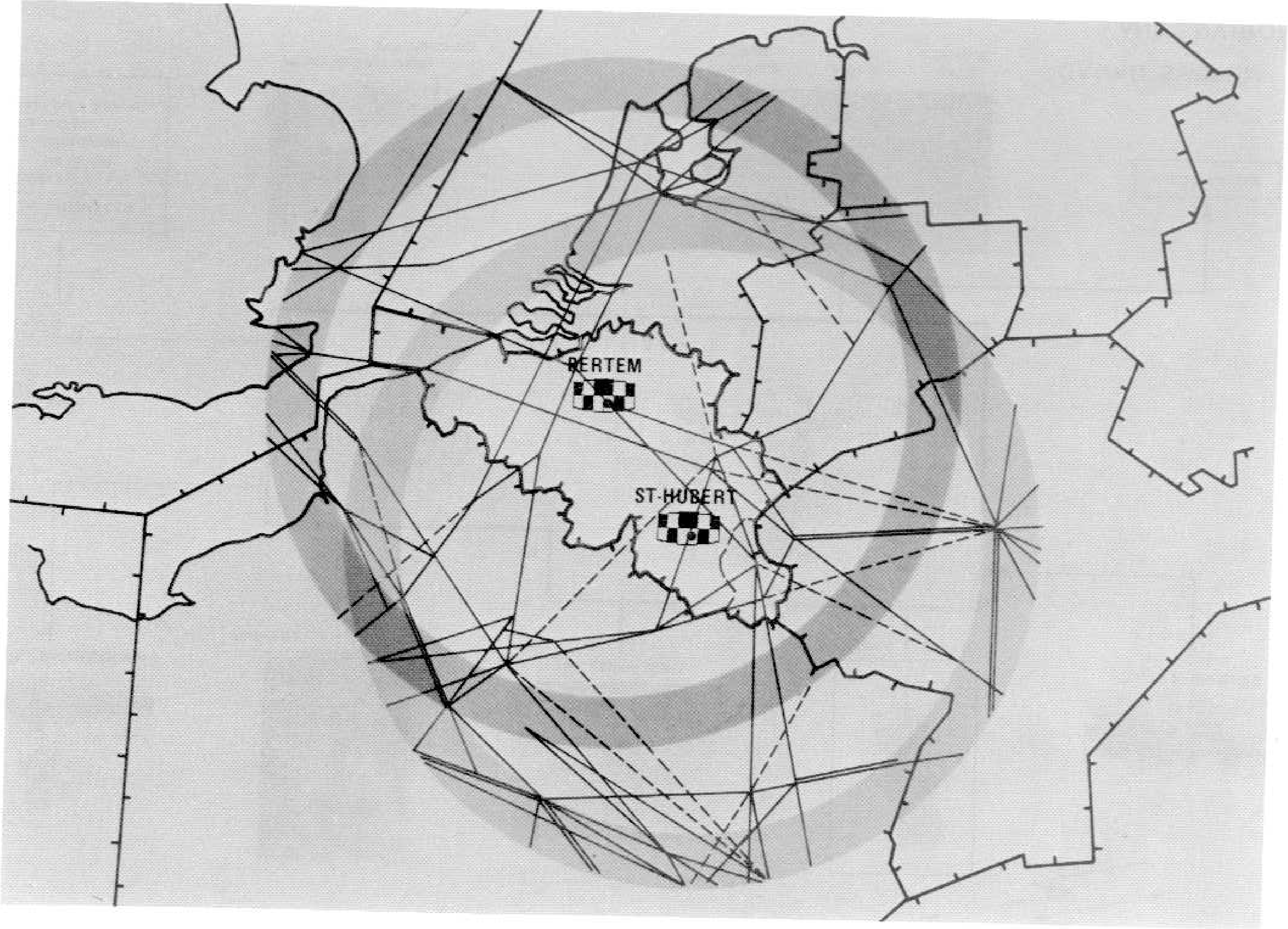


Fig.2 Radar coverage

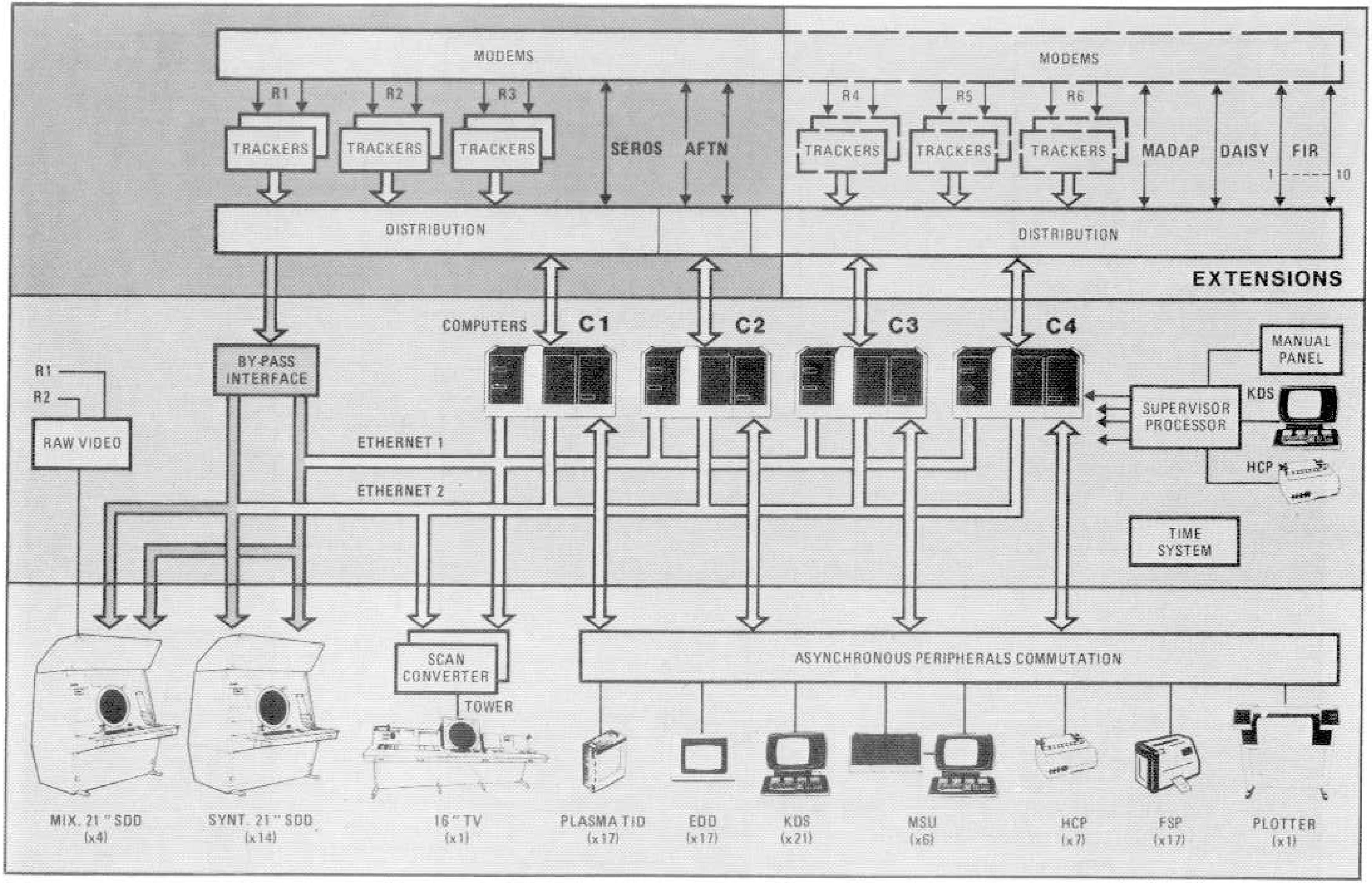


Fig.3 CANAC — general configuration

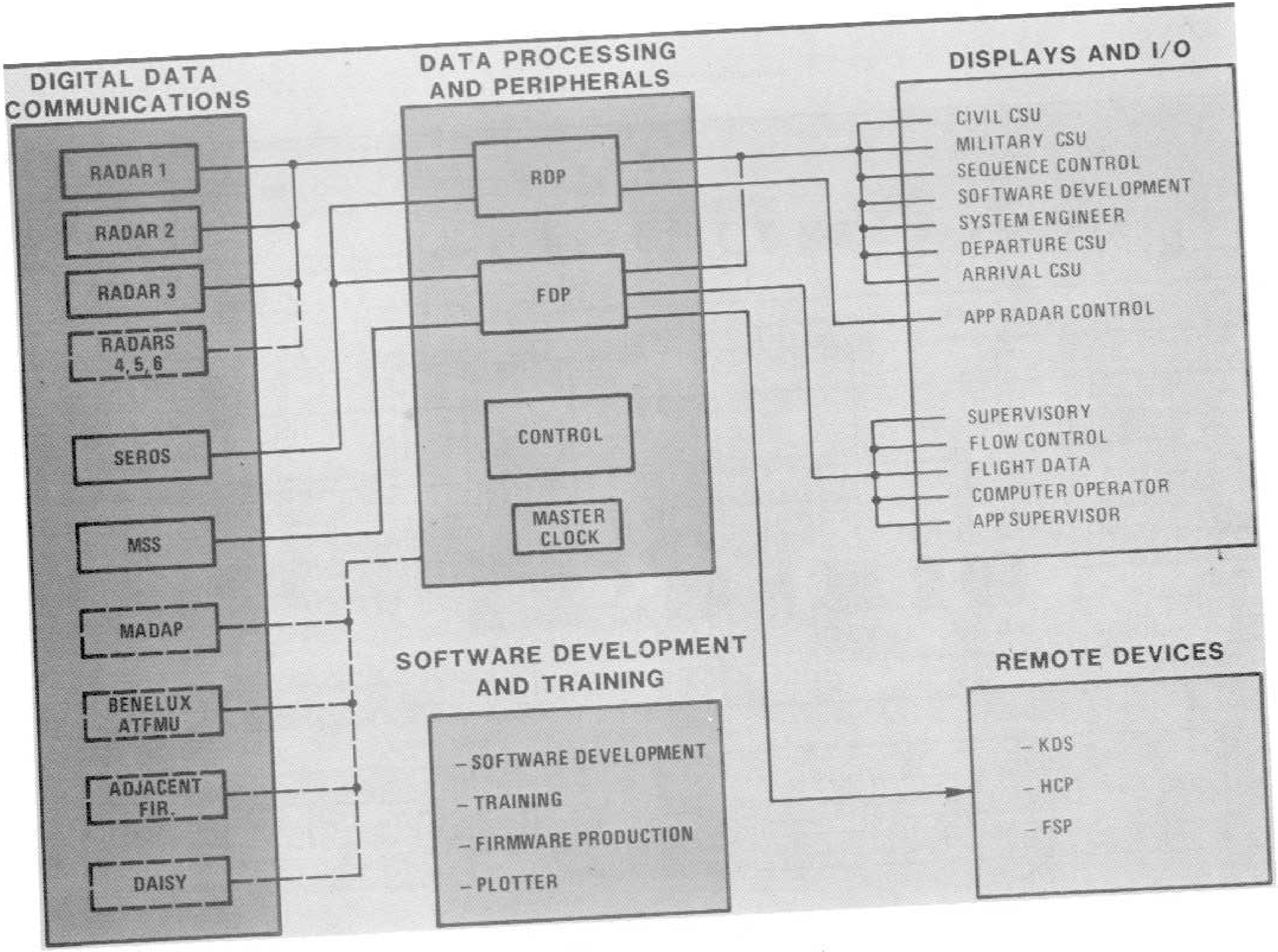


Fig.4 CANAC automation system functional diagram

CP-410

LE CHOIX DES FUTURS SYSTEMES DE LA NAVIGATION AERIENNE CIVILE

par

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Résumé

L'organisation de l'Aviation Civile Internationale a crée un comité spécial FANS chargé des futurs systèmes de navigation aérienne. L'exposé décrit la création de ce comité et traite avec plus de détail de sa principale réunion, FANS-2, en avril 1985. Il évoque aussi les travaux plus récents de ce comité. Les concepts de "surveillance dépendante automatique" (ADS), de "performances de navigation requises" (RNPC) sont décrits. L'absence de discussion à FANS sur Navstar est regrettée. Enfin l'évolution très rapide de la situation dans le domaine des communications mobiles aéronautiques par satellite est décrite. Cette évolution pourrait se faire si vite que l'OACI n'arrive pas à la contrôler, ce qui serait regrettable pour l'efficacité du transport aérien.

1 - INTRODUCTION

L'objet principal de cet exposé est de décrire l'action de l'**Organisation de l'Aviation Civile Internationale (OACI)** dans la mise en place des futurs systèmes de la navigation aérienne et plus particulièrement des travaux du comité spécial FANS (Future Air Navigation Systems). L'auteur de cet exposé est le membre de ce comité désigné par la France. L'exposé tentera de faire le point sur l'état des forces qui agissent en ce domaine, à l'OACI mais aussi hors de l'OACI. La situation évoluant de mois en mois, cette partie de l'exposé risque d'être rapidement désuète, malgré nos efforts pour ne pas tomber dans l'anecdote.

Un pays, les Etats-Unis, joue un rôle fondamental dans le développement de l'aviation civile et le choix de ses systèmes. Le représentant des Etats-Unis au comité FANS se trouve avoir une forte personnalité, à la mesure des intérêts qu'il doit promouvoir.Il est l'auteur de l'exposé qui suit celui-ci, exposé que nous suivrons avec une grande attention.

2 - L'ECHEC D'AEROSAT

L'aviation civile a failli utiliser des satellites. En France, le Centre National d'Etudes Spatiales (CNES) a commencé à considérer la question dès 1966, il y a vingt ans. Le projet de satellite aéronautique auquel participait l'Agence Spatiale Européenne, les Etats-Unis et le Canada s'appelait AEROSAT. L'OACI, faisant suite aux voeux de nombreux Etats, a créé sur ce même sujet un groupe de travail le groupe ASTRA. Les études économiques justifiant le satellite Aérosat on été faites avec le plus grand sérieux. Elles étaient cependant basées sur diverses hypothéses malheureuses = le trafic d'avions supersoniques Concorde au dessus de l'Atlantique, était surestimé, la place qu'allaient prendre les avions gros porteurs en particulier le 747 était sous estimée. La navigation des avions, à l'époque effectuée par des navigateurs semblait exiger une espèce de super radar, or la diffusion des centrales à inertie, du Loran C, de l'Oméga, ont changé le problème. Bien entendu les experts n'avaient pas prévu le basculement de l'économie mondiale dans les difficultés qu'elle connait depuis le milieu des années 70. Le projet Aérosat avait beau avoir fait l'objet d'expérimentations et du développement techniques passionnants, il était abandonné en 1976, laissant chez tous les directeurs de l'aviation civile impliqués, un grand ressentiment.

3 - L'INERTIE NATURELLE DE l'AVIATION CIVILE

L'aviation civile n'a pas beaucoup de goût pour les nouveautés, ou plutôt, la nécessité impérative de normaliser les systèmes de l'aviation civile à l'échelle mondiale rend très difficile et très coûteux tout changement. Les périodes de transition entre systèmes anciens et nouveaux sont longues. Le coût de l'emport d'un double équipement (l'ancien et le nouveau) pendant cinq à dix ans est exorbitant. On voit aujourd'hui comme il est presque impossible de changer de systèmes d'atterrissage, de passer de l'ILS au MLS. Les compagnies aériennes qui de loin accueillaient avec plaisir la nouvelle des futures performances du MLS, s'aperçoivent, que vu de près, le MLS apporte d'innombrables dépenses, modifications des avions, des pilotes automatiques, des procédures d'utilisation des avions, de l'entraînement des équipages, des homolagations et certifications des matériels et des procédures, en échange d'avantages futurs trop ténus pour justifier le coût de la transition.

Notons que l'OACI a défini un autre système dont l'introduction ne va pas sans difficulté : le mode S du radar secondaire. Tout ceci ne plonge pas dans l'enthousiasme les responsables de l'aviation civile. L'introduction de services satellitaires n'ira pas sans difficulté.

4 - LA CREATION DU FANS

Le nouveau départ des réflexions sur les satellites aéronautiques est venu à l'initiative d'INMARSAT en 1982. L'agence INMARSAT est une agence internationale dont le siège est à Londres et qui vend des communications téléphoniques entre navires en mer et réseau commuté terrien. Elle met en oeuvre des satellites, MARECS et MARISAT, lancés il y a longtemps (1977 pour le plus ancien). Avant de commander des satellites de seconde génération en 1983, Inmarsat a demandé l'avis de l'OACI, qui a répondu évasivement, et à l'association internationale des compagnies aériennes, l'IATA qui a déclaré ne rien vouloir de plus que l'OACI. Cependant, à partir d'une initiative américaine, l'OACI décidait de revenir à l'étude des satellites. Elle souhaitait que ce travail de réflexion ne cherche pas a imposer des satellites plutôt que toute autre solution éventuellement moins coûteuse. Elle désirait que les problèmes de l'aviation civile soient vus de façon globale en considérant l'ensemble du système. Pour éviter de tomber entre les mains de savants, elle décidait qu'il fallait créer un groupe de responsables de haut niveau hiérarchique. Certains états, dont la France, n'ont pas suivi cette dernière recommandation. Le **Comité spécial sur les systèmes de la navigation aérienne du futur** (FANS, Future Air Navigation Systems) est donc composé de membres éminents provenant des pays suivants :

Arabie Séoudite, Argentine, Australie, Brésil, Canada, Danemark, Espagne, France, Allemagne Fédérale, Islande, Inde, Irak, Italie, Pays Bas, Japon, Tanzanie, Royaume-Uni, Etats-Unis, URSS.

L'IATA est le plus important des "observateurs" du groupe c'est à dire des associations représentées à FANS qui ne sont pas des Etats. Mais on trouve aussi l'IFALPA (syndicat des pilotes de ligne), l'IAOPA (pilotes privés), l'IFATCA (contrôleurs de la circulation aérienne), des agences opérationnelles importantes comme l'Agence Spatiale Européenne, l'ASECNA (Association pour la sécurité de la navigation aérienne en Afrique et à Madagascar) et INMARSAT, envoient des représentants aux travaux de FANS.

Au lieu d'en faire un banal groupe de travail, le conseil de l'OACI a donné à FANS Le titre rare de "Comité Spécial", c'est à dire que FANS rend compte de son action au conseil de l'OACI qui en est l'organe exécutif, plutôt qu'à la Commission de navigation aérienne, qui ressemble plus à un comité technique.

Le comité spécial FANS s'est réuni deux fois. Il a choisi pour président, un personnage célèbre pour sa science de l'OACI, sa sagesse, son autorité et son humour, le directeur de la navigation aérienne hollandaise, M.Ian Smit.

A FANS-1 en 1984, le groupe a fait connaissance et a essayé de rédiger son propre mandat de façon un peu détaillé comme on le lui demandait. Le domaine que s'attribue le FANS n'est pas l'ensemble de la navigation aérienne mais plutôt les moyens radioélectriques qui unissent les avions à la planète, c'est à dire les moyens de **communication**, de **navigation** et de **surveillance** du trafic, ensemble que nous appellons élégamment par leurs initiales : le système C.N.S.

5 - COMMUNICATIONS, NAVIGATION, SURVEILLANCE

Le contrôle de la navigation aérienne vise à assurer un service public, l'acheminement de tous les avions vers leur destination en veillant à trois objectifs, sécurité, régularité et économie.

Le besoin de **sécurité** est évident. Un vol d'avion de transport public sur un million se termine tragiquement. Tous les quatre ou cinq ans, un avion de transport public est détruit en vol par une collision avec un autre avion. Cette sécurité, encore imparfaite, exige une minutie scrupuleuse de la part d'innombrables agents. La sécurité peut parfois être abordée de façon scientifique et on peut passer par le calcul des probabilités du taux d'erreur par bit d'une transmission de message à un risque opérationnel inadmissible. Certains risques sont cependant difficiles à aborder = que deviendraient une flotte d'avions en vol si par la panne d'un ou deux satellite, toute communication entre eux et le sol était perdue ?

La **régularité** est l'exigence d'assurer le transport avec la même efficacité quel que soit l'environnement : météorologie, densité du trafic aérien etc.... Sur l'Atlantique Nord que tout le monde veut traverser dans le même sens à la même heure, ce problème est important. Nous y reviendrons.

L'**économie** du transport aérien comprend bien sûr le meilleur choix des éléments du système de contrôle qui ne doit pas être plus complexe que nécessaire. Mais c'est aussi, depuis toujours, la nécessité de ne pas maintenir les avions en l'air inutilement soit par des procédures d'attente, soit par des cheminements trop longs. Depuis peu, l'économie vise aussi à permettre aux avions de choisir un profil du vol et des vitesses qui permettent d'économiser le maximum de carburant. Cet objectif n'est pas très facile à assurer et il ne doit guère y avoir que sur le Pacifique Sud qu'on puisse laisser l'avion suivre une trajectoire ascendante économique. Rappelons que le coût des moyens au sol CNS sont de plus en plus souvent imputés aux exploitants d'aéronefs par le moyen de redevances diverses.

Face à ces objectifs, le système CNS n'est lui même qu'un moyen entre les mains de ceux qui gèrent l'espace aérien. Il est clair qu'on peut envisager divers types de compromis techniques entre les performances des communications, navigation et surveillance. Par exemple le contrôle peut tirer ses informations sur les positions des avions de diverses sources : le plan de vol de l'avion, les comptes rendus de position communiqués par les pilotes ou les moyens de surveillance radar. Des systèmes peuvent fonctionner avec de bonnes navigations et de mauvaises communications comme sur l'Atlantique Nord, ou au contraire en surveillant attentivement des avions qui obéissent passivement au contrôleur comme dans certaines approches.

6 - FANS-2

La principale réunion de FANS fut sa seconde réunion **FANS-2** qui fut tenue du **10 au 26 avril 1985** au siège de l'OACI, à **Montréal**. L'ordre du jour était le suivant :

- étude d'éléments concrets sur les besoins non satisfaits, actuels et futurs,
- examen des besoins de spectre de fréquence en vue de préparer la défense de l'aéronautique à la réunion mondiale de l'U.I.T sur les communications mobiles de 1987 (CAMR/MOB 97 en français, WARC en anglais)
- élaboration de scénarios réprésentant des situations typiques dans le monde,
- étude préliminaire des performances des systèmes nécessaires pour répondre aux besoins non satisfaits,
- échanges de vues sur les aspects institutionnels de la gestion des systèmes internationaux CNS,
- activités futures.

Cet ordre du jour découlait de la façon dont FANS avait rédigé un plan de travail à FANS-1. La plupart de ces tâches étaient infaisables à court terme. La réunion FANS-2, à partir de cet ordre du jour pas très satisfaisant, a pu dégager quelques idées fortes et intéressantes. D'autre part, certaines de ces idées ont avancé depuis FANS-2 au cours de trois réunions officieuses tenues à Montréal (novembre 1985), Washington (mars 1986) et Brunswick (avril 1986).

7 - LES INSUFFISANCES DU SYSTEME ACTUEL

Le groupe FANS s'était donc chargé lui-même de trouver dans le monde de l'aviation d'aujourd'hui, des "**insuffisances**" (shortcomings) des "**besoins non satisfaits**". Nous avons quelques doutes sur ces objectifs. Il est inutile de se plaindre de certains faits : par exemple qu'il n'y ait pas assez de moyens en Afrique, car on y trouve les moyens compatibles avec le petit nombre de vols qui la survole. En revanche, on peut essayer de trouver des domaines où un progrès au coût abordable, améliorer considérablement une situation. Ceci n'est pas si facile : voir le MLS.

La liste des insuffisances dressée par FANS-2 est assez longue. Elle commence par un point qui peut orienter tout le reste de l'affaire. L'aviation civile est gênée par les contraintes dues à la propagation optique des ondes radio aux fréquences utilisées aujourd'hui. Cela implique de multiplier des moyens au sol et nuit à la souplesse de l'utilisation de l'espace aérien. Si ce point est considéré comme fondamental, il faut passer aux satellites. Mais combien d'avions ou d'hélicoptères évoluent à basse altitude? Espérons que le comité pourra creuser un peu plus cette question.

Les autres insuffisances notées par le groupe sont :

- le manque de moyens au sol dans bien des régions, faute de justification économique (trafic aérien faible) ou faute de possibilités techniques (océans, zones polaires),
- le découpage des espaces aériens qui complique les opérations aériennes (mais qui est souvent dû à des questions de défense nationale),
- le maintien de techniques dépassées et coûteuses (les communications HF par exemple),
- le manque de moyens d'échange de données codées avions/sol (notons que l'OACI travaille activement aujourd'hui à définir un moyen, le mode S du radar secondaire, qui pourrait jouer ce rôle là où la couverture radar est assurée),
- le manque de souplesse dans le choix des cheminements (obligation de voler suivant une succession de tronçons de voies aériennes en ligne brisée),
- le manque de moyens de guidage et de surveillance sur la surface des aéroports (rappelons le drame de Ténériffe : aucune solution simple aujourd'hui qui puisse s'appliquer à un aérodrome de ce genre. Ce point a le défaut de ne pas se résoudre avec des satellites),
- la nécessité de diminuer les espacements verticaux entre avions dans l'espace supérieur (au-dessus du niveau 290). C'est dans ce domaine que tout progrès peut entraîner d'importantes économies de carburant. Cet objectif connu mais difficile, est déjà traité par d'autres groupes de l'OACI et d'EUROCONTROL.

8 - LA "SURVEILLANCE DEPENDANTE AUTOMATIQUE" (ADS, Automatic Dependant Surveillance)

Le comité spécial FANS, sous l'impulsion de Sieg Poritzky, Etats-Unis, a considéré qu'il y avait beaucoup à gagner par l'introduction de la **surveillance dépendante automatique** (ADS). L'ADS serait un système dans lequel tous les avions d'un espace aérien communiqueraient automatiquement leur position au centre de contrôle qui a la charge de cet espace aérien. Le message avion/sol codé consisterait principalement dans les coordonnées géographiques de l'avion telles qu'elles sont mesurées par le système de navigation de l'avion. La précision de la navigation des avions a considérablement évolué avec les possibilités offertes aux avions riches par les centrales à inertie, mais aussi dans certains pays par le Loran C (mais la France, par exemple n'est pas couverte en Loran C), par l'Oméga, et même par les VOR et DME classiques dont les informations peuvent être traités par des calculateurs de navigation embarqués. Dans les zones sans couverture radar, ou plutôt là où l'établissement d'une couverture radar serait d'un coût excessif devant les moyens des opérateurs d'avions, l'ADS serait une amélioration indiscutable. C'est d'abord le cas de l'Atlantique Nord, où le trafic n'est pas immense (40 avions gros porteurs dans chaque sens, chaque jour) mais où il est très concentré dans l'espace et dans le temps. Toute amélioration de la souplesse du contrôle amènerait des économies de pétrole en permettant de rapprocher les avions les uns des autres sur les itinéraires optimaux. La mise en oeuvre de l'ADS pourrait être facile à adapter à chaque cas. On pourrait demander des points de report plus ou moins fréquents suivant la densité du trafic.

Cette notion a un peu avancé au cours de la récente réunion FANS de Washington. Il est admis maintenant que le message ADS comprendra toujours les trois coordonnées de l'avion (longitude, latitude, altitude-pression) et un facteur de qualité, qui donnerait une idée de l'erreur possible de l'estimation de position ou de la probabilité d'erreur grave. Le sol pourrait réclamer s'il en a besoin d'autres paramètres en envoyant un ordre codé. Citons parmi ces paramètres les éléments du vecteur vitesse de l'avion, ou les coordonnées des deux prochains points tournants (waypoints).

La surveillance indépendante automatique existe déjà aujourd'hui dans le plan vertical avec le report de l'attitude du mode C du radar secondaire.

Il est possible que l'ADS, si elle s'avère efficace, remplace le radar secondaire dans des endroits isolés. Il n'est guère imaginable que l'ADS remplace tous les radars secondaires. Le suivi des avions en zones terminales exige un renouvellement fréquent (toutes les 5 secondes) de l'information de position et une précision importante qui n'est pas en rapport avec ce qui permettrait une collecte de données. J'admets cependant que ce point mériterait d'être considéré de plus près .

9 - LA DEFENSE DES FREQUENCES AERONAUTIQUES

L'aéronautique dispose de deux bandes de fréquence pour les liaisons aéronautiques par satellite, il s'agit des bandes **1545 MHz à 1559 MHz et 1646 MHz à 1660 MHz**. Ces bandes sont restées en friche depuis qu'elles existent (à un client près ; VOLNA, URSS). Cet état d'abandon est scandaleux au moment où la communauté des télécommunications ne sait où trouver la bande nécessaire aux innombrables véhicules terrestres qui seront, paraît-il un jour, équipés de liaisons téléphoniques ou des moyens de messagerie .

Les grandes décisions sur cette bande seront prises à Genève en 1987. FANS a repris à son compte le plus clair d'un document américain qui prouve que les deux fois quatorze mégahertz de la bande L aéronautique suffiront à peine à deux types de communication, les communications de la **circulation aérienne (ATC)** qui mettent en jeu la sécurité de l'aviation, et les besoins des **opérations des compagnies aériennes (AOC**, Airline Operationnal Control) qui sont importantes pour l'économie du transport aérien. Ce calcul exclut un usage qui semble appelé à se développer, **le téléphone public** mis à la disposition des **passagers (PPC**, Passenger Public Correspondance). Ce calcul se base sur de nombreuses hypothèses difficiles à justifier= par exemple l'efficacité des vocodeurs de l'avenir (faudra-t-il 64 kilobits par seconde pour passer une voix numérisée, ou 16 kilobits comme avec le codage Delta, ou 8 kilobits comme cela semble possible en 1986 ou moins?), la directivité des lobes des satellites, le trafic aérien, etc... Mais qui peut prévoir mieux ?

Depuis FANS-2, il y a plus d'un an, les questions évoluent un peu, pas dans le sens que souhaiteraient les aviateurs. D'une part, tous les prestataires de service de communications aéronautiques par satellites, comptent bien que le téléphone des passagers passera par les mêmes équipements, et donc la même fréquence que l'ATC et l'AOC. D'autre part, certains experts aimeraient bien que l'on autorise les véhicules terrestres à partager les moyens satellitaires de l'aviation. Enfin, l'aviation civile découvre avec étonnement en 1986 un client de la bande L aéonautique que tous les autres spécialistes connaissaient depuis longtemps, il s'agit du système soviétique VOLNA que le secrétariat de l'IFRB et que les Etats ont laissé s'étendre dans toute cette bande et qui avec ses 8 satellites actifs et ses 13 satellites prévus limite les possibilités futures de l'aviation civile.

Nous espérons personnellement que dans chaque pays, les responsables de l'aviation civile sauront convaincre leur PTT qu'ils ne peuvent renoncer à la seule voie ouverte au progrès des communications de l'aviation, cette bande L aéronautique.

10 - LA NAVIGATION ET LE CONCEPT DE RNPC

Pour se débarasser, dans la mesure du possible, des questions de radionavigation, et pour permettre l'introduction de nouveaux moyens, notamment de NAVSTAR-GPS, il était naturel d'essayer d'étendre à tous les espaces contrôlés la notion actuellement utilisée sur les voies de l'Atlantique Nord, de MNPS (Minimum Navigation Performance Specification). Rappelons qu'une liste des moyens dont un avion doit obligatoirement être équipé est en général publiée par les états. En France, il faut, entre autres moyens, avoir un VOR à bord pour voler en IFR et l'emport d'un DME est obligatoire par exemple dans les espaces contrôlés de la région parisienne. Ce type de réglementation est un peu dépassé lorsque les avions sont équipés de centrales à inertie de qualité. Sur l'Atlantique, à la suite de calculs précis sur la probabilité de collision entre avions volant sur des voies parallèles, une norme a été définie. Les opérateurs d'aéronefs doivent prouver aux autorités de l'aviation civile de leur pays, qu'ils tiennent cette norme (erreur de navigation et erreur de pilotage) s'ils veulent avoir accès à l'OTS (Organised Track System). Les pays chargés du contrôle de l'OTS vérifient avec leurs radars que, sur la portion d'OTS à portée de radar, les dispersions des trajectoires sont bien conformes à la réglementation MNPS.

Il serait intéressant d'étendre ce concept aux autres espaces aériens, mais il devient difficile de faire des calculs de probabilité lorsque les voies aériennes se recoupent de façon complexe. La solution la plus simple consiste à définir quatre ou cinq niveaux de qualité de navigation. Pour avoir accès à un certain espace aérien, les autorités locales exigeraient une qualité donnée, ce serait le **RNPC (Required Navigation Performance Capability ou qualité de navigation requise)**. Les opérateurs d'avions devraient prouver à leurs autorités qu'ils tiennent ce niveau avec l'équipement de bord qu'ils ont choisi. Ce type de logique permettrait à ceux qui ont fait les frais d'un système précis et sûr de débarquer, enfin, leurs radiocompas ou leur récepteur VOR. C'est aussi la porte ouverte à NAVSTAR et autre systèmes à satellites, à condition qu'ils suivent les specifications. Ces spécifications comprendront la précision, bien sûr, mais aussi le rythme mimimum de renouvellement de l'information, la détection des pannes, le temps maximum pour détecter une panne, l'obligation de se référer à un géoïde normalisé, etc...

Il est difficile de savoir comment on peut fixer de façon universelle l'**intégrité** d'un système de navigation, c'est à dire la certitude que des informations erronées ne seront pas utilisées comme bonnes. Le concept a été lentement muri pour l'ILS et l'atterrissage tout temps. Mais le problème se pose différemment pour un système à satellites multiples. Quelques experts de la FAA et quelques consultants aux Etats-Unis connaissent un peu mieux la question et je rends hommage à la FAA qui est actuellement isolée dans sa défense de l'intégrité face aux sectateurs de GPS. Les débats sur ce sujet se passent surtout dans le groupe de travail **SC 159 de RTCA** (Radiotechnical Commission for Aeronautics). Hélas, l'OACI est aujourd'hui absente de ces débats et il semble même que certains membres du FANS souhaitent tenir FANS en dehors de ces questions de navigation. **Il me semble anormal de maintenir l'OACI hors de ce débat.** La définition du concept de RNPC est excellente. Elle rejoint d'ailleurs des travaux déjà entrepris dans d'autres organismes comme le comité NAVSEP d'EUROCONTROL. Dans divers pays, dont la France, on voit circuler des projets de textes exigeant des valeurs diverses de dispersion des erreurs de navigation et de pilotage (erreur technique de vol). Cependant, il ne semble pas admissible que des pays différents réagissent différemment à des propositions d'équiper un avion de GPS (ou de tout autre système). Dans ce cas, ou bien les Etats recopient ce qu'ont faits par exemple les Etats-Unis (c'est déjà le cas dans de nombreux domaines), ou le cas est discuté dans un forum international, et l'OACI est là pour ça. Ces discussions de l'OACI coûtent un peu en frais de mission, mais elles ont prouvé qu'elles constituent un filtrage très efficace des erreurs, des négligences, ou des caprices dont nous sommes tous capables quand nous rédigeons un texte dans l'isolement.

Pour rester dans le domaine des réflexions d'un membre du FANS qui ne sont pas celles de tout le FANS, je voudrais exprimer à la fois mon admiration pour un système aussi extraordinaire que GPS et ma méfiance pour ce même système avec la constellation (18 satellites opérationnels plus trois rechanges sur orbite) insuffisante qui est prévue aujourd'hui. Diverses solutions existent pour améliorer le système, elles posent des problèmes d'organisation, de financement mais pas de problème technique. Citons la possiblité d'intégrer dans un même récepteur des satellites GPS américains et des satellites étrangers et surtout **la possibilité d'ajouter une fonction GPS sur des plateformes en orbite géostationnaire.** Il serait dommage que la situation reste bloquée.

11 - PREMIER ESSAI DE DESCRIPTION DU SYSTEME CNS FUTUR

Le comité a rédigé en une cinquantaine de lignes une première et prudente description du système CNS futur. En voici un concentré :

- **Systèmes de navigation à satellites** de plus en plus répandus et fournissant longitude, latitude mais aussi temps universel et altitude géocentrique,
- **atterrissage de précision par MLS** (notons le silence prudent sur la survie du DME associé au MLS),
- **altitude barométrique**, mais applications possibles de l'altitude géocentrique (détection d'erreurs de l'altitude barométrique par exemple),
- développement de la **surveillance automatique dépendante** (reports de position automatique de l'avion vers les centres de contrôle),
- **communications de données air/sol par satellites**, avec possibilités de communications vocales,
- possibilité d'utiliser l'équipement de bord destiné aux liaisons par satellite pour effectuer des liaisons directes avion-sol dans les zones terminales.

Cette description laisse de nombreuses questions sans réponses, citons pêle mêle :

- les communications en HF vont peut être, enfin, disparaître mais FANS espère-t-il aussi se débarasser de la VHF pour que toutes les communications soient concentrées dans l'unique bande L aéronautique ? Dans ce cas la bande L n'est-elle pas trop étroite ?
- Imagine-t-on que le radar secondaire puisse disparaître un jour ?
- Existera-t-il un système embarqué d'anti collision comme l'A-CAS, basé sur les signaux au format du radar secondaire?
- Fermera-t-on un jour les NDB, les VOR ?
- Si on garde le MLS, a-t-on vraiment besoin de garder le DME de précision qui en est un élément, surtout si le DME en route doit disparaître avec les VOR ?

On peut aussi se poser des questions sur le rôle que joueront les échanges vocaux dans l'avenir et bien d'autres questions importantes. Le groupe FANS a donc du pain sur la planche.

12 - VERS FANS-3.

La prochaine réunion FANS aura lieu, on le sait depuis peu, du 4 au 20 novembre prochain (1986).

Entre FANS-2 qui date d'avril 1985 et FANS-3 le groupe s'est donné diverses tâches dont voici la liste :

- poursuite de la réflexion sur la surveillance dépendante automatique,
- réflexions sur les besoins de communication air-sol, voix et données, et sur ce qui peut être commun à des systèmes utilisés simultanément dans une phase transitoire (par exemple, ACARS-HF, mode S du radar secondaire, et transmission de données par satellite),
- développement du concept de RNPC (probablement par le groupe RGCSP de l'OACI),
- avenir de l'anti-collision embarquée, possibilité d'étendre sa portée à 40 milles nautiques,
- liste des insuffisances des moyens actuels dans chaque région de l'OACI,
- problème de la circulation à la surface des aéroports,
- suivi de l'évolution de la question des séparations verticales au-dessus du niveau 290,
- localisation des avions accidentés,
- amélioration de la description du système futur,
- suivi du sort des bandes de fréquence 1545 à 1559 MHz à 1646,5 à 1660,5 MHz,
- recueil de documentation sur les systèmes de satellite applicables au CNS,
- mise au point de "scénarios", c'est-à-dire de quelques cas typiques d'espace aérien et de la façon dont chacun évoluera de la situation actuelle au système futur,
- étude de la façon dont devraient être gérés les systèmes futurs CNS, notamment par satellites (agence internationale existante ou à créer, rôle du privé,etc...)
- évolution des traitements des données dans les centres de contrôle et adaptation de ceux-ci à la surveillance dépendante automatique,
- recueil de renseignements économiques divers et études économiques éventuellement nécessaires.

Ces tâches sont un mélange bureaucratique d'axes de recherches importantes, de détails, de tâches possibles et de tâches impossibles. Il était difficile de faire mieux dans le temps d'une réunion. Parmi ces points, certains avancent un peu : la mise au point de l'ADS est celui qui va le mieux.

L'étude de scénarios qui décriraient la situation de l'aviation civile aujourd'hui et dans vingt-cinq ans va lentement. Les espaces aériens typiques que décriraient ces scénarios seraient l'Atlantique Nord, la circulation en route au-dessus de l'Europe, une zone terminale typique, la TMA de Francfort, les espaces aériens de l'Afrique de l'ASECNA et du Brésil. En novembre on aura peut être une description de l'état présent, ce qui n'est pas d'un intérêt gigantesque. Certains organismes souhaitent avoir le temps de simuler sur des ordinateurs la circulation aérienne du troisième millénaire. Il serait très intéressant de disposer de tels travaux mais on peut douter qu'ils soient achevés en temps voulu.

Restent deux sujets qui ont avancé un peu et dont nous voudrions parler pour conclure ce sont ceux liés à l'organisation d'un service de communications aéronautiques par satellites. Au FANS, ce sujet est partagé en deux, l'un traite de la normalisation technique des signaux, l'autre de la façon dont il faudrait gérer les organismes de communications aéoronautiques par satellite. En fait, du technique au politique, la frontière est peu visible .

13 - LES COMMUNICATIONS PAR SATELLITE

Le système vers lequel nous dérivons est un système de communications en bande L qui comporterait les fonctions suivantes :

a) communications pour le contrôle de la circulation aérienne (ATC, Air Traffic Control) codés et éventuellement voix,

b) communications techniques internes aux compagnies aériennes (AOC, Airline Operationnel Control), codes et éventuellement, voix,

c) communications publiques des passagers (PPC, Passenger Public Correspondance) c'est à dire le téléphone public.

La bande disponible est de deux fois 14 mégahertz, de 1545 à 1559 MHz pour la voie descendante, de l'avion au satellite et de 1646 à 1660 MHz pour la voie montante.

Le marché semble exister dans les trois domaines, ATC, AOC et PPC.

Le besoin ATC existe sur l'Atlantique Nord où on pourrait certainement faire un meilleur usage de l'espace aérien si l'on pourrait mieux surveiller les avions. Le même besoin se développera un jour sur le Pacifique Nord. Notons que les Etats responsables de l'Atlantique Nord, au comité FANS se gardent bien de promettre quoi que ce soit aux futurs utilisateurs de communications satellitaires.

Le besoin AOC, crée un demande croissante. L'Europe s'équipe graduellement du système d'échanges de données codées en VHF, ACARS que la SITA met en oeuvre hors des Etats-Unis.

Le besoin de téléphoner des passagers existe certainement, mais pas à tout prix. Il existe sûrement un public prêt à payer quelques dollars la minute (disons de 2 à 5 dollars), il est moins sûr qu'il en existe un pour payer de 15 à 30 dollars la minute, ce qui, d'après certains, serait le coût d'une communication par satellite. Les compagnies aériennes recevront une part du chiffre d'affaire PPC, ce qui ne constituera sûrement pas une affaire merveilleuse, mais le fait de fournir ce nouveau service sera un argument commercial en faveur des compagnies équipées.

Face à ce marché qui semble s'ouvrir, divers prestataires de service se présentent : ARINC, coopérative américaine de compagnies aériennes, qui assure des services de communications aéronautiques fixes et mobiles, est en train de s'organiser et a créé un comité pour définir un matériel embarqué. La SITA, autre coopérative fournissant des services analogues, hors des Etats-Unis, a aussitôt proposé un service analogue en s'unissant à INMARSAT et à l'Agence Spatiale Européenne. Les services des postes et télécommunications de divers pays se mettent en mouvement. British Telecommunications, met bientôt en service expérimental le téléphone public sur certains avions de British Airways en utilisant les satellites d'INMARSAT. Aux Etats-Unis, divers organismes privés de communication, Mobilesat, Skylink, Omninet entre autres, se manifestent.

Tout peut avancer si vite que FANS et l'OACI en soient réduits à entériner les choix techniques de ces divers organismes. Un conflit technique peut exister entre les choix des prestataires de service qui se basent sur les signaux faibles des satellites d'INMARSAT (qui ont le mérite d'exister et l'inconvénient d'être un peu dépassés) et d'autre part ceux qui utilisent des satellites qui n'existent pas encore. Notons que dans la vague où l'on se trouve, toutes les parties intéressées, compagnies aériennes et administratives, souhaiteraient que le service mis en place soit modulaire et permette de servir à la fois des avions équipés de l'antenne omnidirectionnelle la plus simple (et qui se contenterait de passer quelques données codées), et les avions équipés de réseaux d'antennes à déphaseurs pointant en permanence un lobe de 7 à 12 dB de gain sur le satellite et capables de transmission de paroles en duplex. Pour que le service de communication par satellite soit d'un usage souple, il est important, et tout le monde l'admet, qu'il conviendra d'utiliser pleinement le concept OSI (Open Systems Interconnexion) défini par l'ISO.

Le développement continu de la technique jouant aussi bien pour les systèmes anciens que les nouveaux il est possible que les choses évoluent mal, comme le MLS qui coûtera 2 à 3 fois le prix d'un ILS équivalent. Il est possible qu'au contraire, ces techniques deviennent indispensables, comme l'est devenu le radar secondaire.

14 - CONCLUSION

L'aviation civile internationale par son organisation traditionnelle, l'OACI et son comité FANS participe à la mise en place d'une nouvelle génération de moyens de communication , de navigation et de surveillance. La gestation de cette nouvelle génération de moyens et de concepts inédits se fait à la vitesse la plus grande que permet une organisation internationale, ce qui n'est pas très rapide.

Beaucoup de choses pourraient être obtenues dans le domaine de la navigation avec les systèmes tels que GPS et les compléments à GPS ou dans le domaine des communications codées entre calculateurs de bord et calculateurs au sol par satellite. Les divers partis en présence défendent chacun leurs intérêts comme il est naturel. La somme des égoïsmes particuliers étant rarement égale à l'intérêt général, il n'est pas certain que les systèmes qui verront le jour seront globalement les plus intelligents ni les plus économiques. Le comité FANS où tous les débats sont permis entre les Etats et les organisations pourrait être le lieu où des conceptions unifiées seraient définies. Et j'espère bien que ce sera le cas.

Cependant, certains jouent pour que les choix se fassent ailleurs.

CP 410

FANS -- A U.S. PERSPECTIVE

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SUMMARY: This paper traces the development of a worldwide effort to establish aviation requirements for CNS systems for the future, with special emphasis on satellite technologies. Beginning with the air traffic services modernization efforts underway in several countries, the paper reports on the evolution of the ICAO Future Air Navigation Systems (FANS) Committee, the U.S. Radio Technical Commission for Aeronautics (RTCA) effort to support the development of a U.S. view and the realities which must be faced in considering the definition of new systems and new approaches. The paper describes the activities of FANS to date, the approach being taken to achieve a worldwide minimum satellite communications system standard, and efforts to achieve agreement on automatic dependent surveillance.

At its first meeting, the International Civil Aviation Organization (ICAO) Future Air Navigation Systems (FANS) Committee agreed that one of its objectives is "to identify needs and subsequently to consider the satisfaction of those needs by: i) systematically identifying world aviation needs for the next 25 years; ii) considering potentially applicable technologies which may cost effectively satisfy the identified needs; and iii) laying the groundwork for any required international standardization by appropriate bodies of ICAO and other organizations."

The order is not an accident, but a recognition of how easy and tempting it is to get fascinated with a new technology mousetrap and then find an application for it. It should be the other way around; a need or a requirement should be expressed first, then new solutions must be thoroughly tested against other, perhaps less costly, alternatives. Even more important is agreement on what a requirement really is. Said straight out, a requirement for a new system or a new capability is a need we have identified, for whose solutions we are willing to pay--no more and no less. This point is all-important because our industry has changed in the last few years. Until not so long ago, any new technologies that promised benefit were eagerly embraced by the industry and by Government. As the industry has matured, it has become more money-conscious and more skeptical. In today's market, a new technology must have clear and obvious benefit--and soon--if it is to be viewed seriously, especially if the investment required is either unknown or prospectively high.

What is the atmosphere in which the U.S. is looking at new technologies and FANS? The National Airspace System (NAS) Plan and similar modernizations in other countries will provide major improvements. At the end of our U.S. modernization, it is reasonable to assume that:

- The air traffic control process, through the Advanced Automation System, will be far more flexible, and more automatic, than it is today, and will be far along to permitting automatic creation and transmission of conflict-free clearances.
- Information available on weather and winds will be improved dramatically.
- Information flow will be enhanced through use of digital data link communications.
- Dynamic knowledge of system capacity and airport capacity will have become good enough to permit a great deal more strategic planning than exists in the system today, and the system will be more capable of rapid, dynamic adaptation as the situation changes.
- Cockpit systems will simplify and optimize the interaction of pilots with automatic systems and digital communications devices.

Well, then, what is left to do? As seen from the U.S. perspective, many people in the Radio Technical Commission for Aeronautics (RTCA) Special Committee 155 (SC-155), "User Requirements for Future Communications, Navigation, and Surveillance Systems, Including Space Technology Applications," believe that among the challenges remaining at the end of the NAS Plan will be:

1. lack of sufficient airport and heliport facilities in major city areas,
2. lack of surveillance information in much of the airspace over oceans and unpopulated areas,
3. lack of instrument approach capability to many paved and lighted airports, and, perhaps most important,
4. lack of low-altitude communication, navigation, and surveillance (CNS) coverage in most areas of the world.

A growing view is that the most effective way to reduce or eliminate such CNS deficiencies is through the use of satellites as one important ingredient in improving information flow. It may well be that easy and convenient information flow, satellite and otherwise, is the key not only to the evolution of CNS, but also to the provision of improved ATC and weather service.

In thinking about new technologies to aviation, world realities must be faced squarely. The major modernization programs are concentrated in a relatively small area of the world. Yet new capabilities, which might be nice to have in areas where sophisticated air traffic control services already exist, may be essential in parts of the world where few services now exist. And the need for standardization demands that at least subsets of the same basic systems serve all.

The second meeting of the ICAO FANS Committee was exceptionally candid in discussing this problem. They said:

> "The fact that services are less than adequate in many parts of the world results not only from lack of financing, but in many instances also from a lack of trained technical personnel and engineering, maintenance, and operations disciplines in those parts of the world."
>
> "There appears to be little likelihood that the present air navigation situation will improve within the near future unless new approaches are adopted."
>
> FANS-2 said, "it seems inevitable that the full implementation of the present ICAO Regional Air Navigation Plans is unlikely to be accomplished," and that FANS "must now extend consideration to the application of alternative technologies, functional concepts, and associated institutional arrangements."

The gauntlet is down. The needs of the future can be met by the introduction of better data and information flow, more automation in high-density operations, and improvement in the basic CNS services, but can we agree to make it happen?

RTCA Special Committee 155, in its examination of needs, concluded in its interim report that there is a need in the future for C,N&S services to be available anywhere in the world from the surface to 70,000 feet plus. The only viable way that has emerged to date to deal with that requirement, if it is real, is by the use of satellite services.

But why haven't there been energetic applications of satellite services for aircraft before now? The reason is that it has up to now been too expensive, and the need has not been sufficiently pressing.

It is not that anyone seriously doubts the technical capability of satellite services to do what they promise. That has been proved again and again.

After the demise of AEROSAT, FAA became a partner in an international committee to undertake an international requirements study. The findings of that body (the Aviation Review Committee, under the chairmanship of Roy Cox from the United Kingdom Civil Aviation Authority), were interesting. Among their conclusions:

- o The greatest savings in efficiency improvements in the areas studied would result from reduction of vertical separation above Flight Level 290.
- o Lesser savings would flow from an improved navigation performance standard combined with improved data link communications (either HF or satellite service), with automatic dependent surveillance capability.
- o Implementation of improved navigation performance standards and an airborne separation assurance device would be valuable.

Their findings were surprising to many because they did not tout satellites as the end-all and be-all, but they were realistic--especially one which said that in order for oceanic air traffic control satellite services to be viable financially, aviation would need to share satellites, possibly even space-based transponders, with other users who might pay a large share of the satellite capital costs.

While the Aviation Review Committee could not produce a ringing endorsement of satellite services, they were uneasy with their finding. It appeared to them "unthinkable that civil aviation should enter the next century without satellite systems at least providing cost-effective aeronautical mobile communications."

FAA believed then and believes now that satellites will have a future role to play in communications and probably in surveillance and navigation.

An FAA study shows aviation may require all of the spectrum currently allocated to Aeronautical Mobile Satellite (R) services, and perhaps more. This work was subsequently supported by RTCA SC-155, and tested by FANS and COM/OPS. It was agreed that the satellite spectrum long protected for civil aviation would be required by civil aviation.

In order to justify its conclusion, ICAO FANS-2 postulated prospective satellite applications as part of the future system. It did so tentatively and nervously, but, as you have heard, a first-blush tentative system concept was hammered out at FANS-2. Its basic elements are as follows:

- Satellite navigation will prove to be a highly reliable, high-integrity, and high-accuracy system. Three-dimensional information will be available, along with a standard system time service.
- The accuracy and integrity of the system is likely to be such that it can serve all navigation functions with nearly instantaneous failure warnings in oceanic, en route, and terminal operations. MLS will be used for precision approach and landing operations; it is, however, possible that the satellite system may eventually be able to provide information adequate to support Category I-type approaches. Services will be provided and separation standards will be implemented based on navigation performance requirements suited to the applications. Other suitable navigation systems may be available and used.
- Barometric altimetry will remain an important element in the system, but the geocentric altitude available from the satellite navigation system could serve as a crosscheck on vertical position.
- A satellite navigation system will be of sufficient integrity to serve as a source for automatic dependent surveillance, in which navigation position information is transmitted to the ground either directly or via satellite relay, to serve as a surveillance system for all airspace, with appropriate built-in redundancy and failure protection.
- The committee considered, however, that automatic dependent surveillance may not be fully satisfactory for all circumstances. Therefore, in addition a cooperative independent surveillance service, based on satellites, is likely to be needed. There are several ways to achieve this capability. In some cooperative independent surveillance concepts the navigation satellite geocentric altitude will serve as an integrity crosscheck on the aircraft barometric altimetry system.
- A satellite communications relay will be used extensively to provide automatic dependent surveillance position information, along with additional information, as required and available, such as aircraft identification, state and intentions, meteorological information, etc., and information concerning ATC services. The communications services (voice and data) between aircraft and the ground system will utilize satellite relay in over-ocean and remote land areas, at altitudes below line-of-sight in both low-density and high-density airspace, and for other purposes.
- In some airspace, such as terminal areas, the bulk of communications may be such that a direct ground-to-aircraft and aircraft-to-ground communications system may be preferable to a satellite-based communications system. In order to permit use of common avionics, spectrum in the 1 545-1 559 MHz and 1 646.5-1 660 MHz bands is needed for such a terrestrial-based communications system.
- Aircraft operators will continue to require spectrum for operational control communications.

It is the job of FANS now to flesh out this concept, to change it, to test it, and to see what can be done to practically evolve towards it. It is a job not in the first instance for ICAO, but for the States and organizations involved in it, and for the aviation communities in our countries. In the U.S., that means the major groupings of aviation interests, as well as organizations like RTCA and others.

I want to say a few words about the Global Positioning System (GPS). Satellite navigation is a significant part of the tentative concept developed by FANS-2. Work on satellite navigation has been underway a long time in several places. In a way, GPS is a special case because, unlike other satellite services which are still vying for sponsorship, GPS is happening. It represents a major investment by the U.S., available to the world, to achieve a dramatically improved global navigation capability.

In the FAA assessment to which I referred, we asserted that because of the major benefits it offers, satellite navigation will eventually replace most ground-based navigation systems for en route operations and for nonprecision approaches. We assumed that the full accuracy capability of GPS will become available to civil users, and that the remaining issues of coverage, reliability, and integrity will be resolved--by one of several available means.

A part of FAA's program is to support the utilization of GPS in the National Airspace System. We hope to investigate CNS system technology alternatives and emerging technologies with civil aviation potential and, importantly, to study the integration of satellite technologies with ground-based services.

ICAO and RTCA both are looking at the need for services and the technology possibilities out to 25 years or more from now. But why bother? Isn't it simply a blue sky exercise, when laissez faire *will get us there as well? We have not been good* at predicting the future, particularly inventions not yet invented. We are not good at predicting our business for 10 years ahead, much less 25 or 30.

So why not let a few people with their heads in the clouds (no pun *intended)* think about the future, and get on with our near-term business, especially in an industry which isn't sure where next year's dollar is coming from? Let me suggest some reasons why the work is important, beginning with what I consider to be important truths:

1. Technologies are marching forward rapidly, not only in the computer and data *processing world, but also in satellite* and terrestrial communications technology. There is truth to the fear expressed at FANS that if we do not move rapidly to determine our needs, the new technology will pass us by and we will take the leavings from what the industry wants to offer.
2. Satellite system implementation is moving so rapidly in a number of countries that if aviation cannot state its requirements and develop technical standards, we will be condemned to a variety of complex, unworkable, nonstandard systems.
3. Integrated CNS systems, talked about for 25 years or more, will be difficult to achieve, for a variety of reasons: (1) the problems perceived in the three areas (C,N,&S) have never meshed in time, (2) we have seldom had the courage to change more than one technology at a time, and (3) the benefits of integrated systems have never been clear to the aviation community.
4. *The transition to new* technologies will not happen, either singly or in an integrated way unless the benefit is clear. One such benefit which must be offered is the possibility of simplification of the avionics suite, particularly in general and business aviation. The new technology offers a chance of getting there.
5. New technologies have traditionally taken from 12 to 18 years, and sometimes longer, to move from conception to implementation, in spite of sometimes Herculean efforts to speed up the process.
6. Regardless of their neatness or their technical sophistication, implementation to new technologies simply will not happen unless the transition and implementation path is clear.
7. The level of implementation of systems around the world is and will remain widely *divergent. The needs* of 15-20 percent of the world's geographic area are wildly different from those of the other 80-85 percent. The true test of new CNS technology is that it must be implementable in a time- and capability-phased fashion, and in a way in which Country A can move forward without Country B moving at the same time. *The concept we need is one which can* be embraced at different levels by both the highly developed and less-developed States, with a clear indication that benefit will accrue.

There are a hundred reasons why FANS may not make progress, *and even more reasons* why even the best-designed system concept may fail for political, institutional, or economic reasons, or because States will not choose to agree. Yet the opportunity exists to make progress in the near term and gain a far better system in the long term.

There are some things we need to do now, certain practical actions to put ourselves *into position to utilize* the new capabilities when the need is clear. There are some barn doors we need to close before the horses run away. Some of them are the near-term activities: reduction of vertical separation standards above Flight Level 290; harmonization of traffic information to controllers on aircraft position and intent; movement toward *beneficial use of airborne* collision avoidance systems; the introduction of the SSR Mode S data link; and improvements in emergency aircraft location.

But, I want to emphasize improvements in data and voice communica*tions capability* and automatic dependent surveillance.. Data link applications are being developed at VHF, at HF, and for satellites. The Mode S data link is coming closer to application in air traffic control and data link use is growing rapidly in the airlines. Satellite data and voice communication schemes abound. Work is underway in a number of countries and by a whole host of proposers in the United States.

Unless there is rapid movement by the aviation industry to establish requirements and communications standards to the degree they are needed, we face the possibility of a variety of satellite communication schemes becoming available for sale to aviation users--with no real standardization. It is essential right now to establish the necessary communication *systems standardization, to* accommodate airline operational needs and automatic dependent surveillance, but, of course, to go further--to build a foundation for the functions beyond which will need to be accommodated. Both satellite and nonsatellite methods of communications by data and voice will need to be considered.

Since ADS, first over oceans and probably later in domestic areas, represents near-term ATC system payoff from new technology, we need to reach agreement on approaches and technical standards for it. Whether we choose to implement sooner or later, such preliminary agreements can help define systems which are valuable both as safety improvements and money makers.

We need to develop an airborne system architecture to achieve the most effective and safest communications protocols and automatic dependent surveillance messages in aircraft. We must move toward less dependence on particular transmission media to perform the functions we need.

We need to correlate improvements in communications, navigation, and surveillance with improvements in ATC services (i.e., separation standards, tactical operations, etc.), to establish clearly the benefit of implementing new CNS technologies.

The FANS Working Group of the Whole met in Montreal on November 4-8, 1985, and made some important progress. Even though it was only a Working Group and not a formal FANS meeting, it was attended by most of the active members of FANS except that, unfortunately, the members from the U.S.S.R., Tanzania, and Iraq were unable to be present.

Several views were pervasive throughout that meeting:

- Civil aviation must take early and persuasive action to stake its claim to satellite spectrum and to show clearly that it intends to use it.
- The first practical application of ATC satellite services is likely to be over-ocean automatic dependent surveillance and related direct pilot-controller data link communications, and action is needed to bring automatic dependent surveillance into being because of increasing traffic and a continuing significant number of large deviations from track in oceanic operations.
- Since automatic dependent surveillance must have a commonly agreed-to signal format compatible with terrestrial and aircraft systems in order to have a chance worldwide, it is likely to be the service which lays the basis for international satellite signal standards, protocols, and formats.

The Working Group considered all of its work program, but I want to report on only a couple of items. In the discussion of automatic dependent surveillance, the Working Group took several important steps. A definition for automatic dependent surveillance was agreed upon, as well as certain fundamental views:

1. There is operational benefit and anticipated cost/benefit in the application of an effective high-integrity automatic dependent surveillance service.
2. Effective application of automatic dependent surveillance requires complementary direct two-way pilot-controller communications.
3. The technical capability of satellite communications to support automatic dependent surveillance and other ATC related aeronautical air/ground communications exists and has been demonstrated in several test programs.
4. Advantage should be taken of the present navigation systems to implement automatic dependent surveillance.
5. The need will exist for various position reporting intervals.

In addition, the Working Group agreed on a series of tasks which need to be performed to achieve operational automatic dependent surveillance service.

Perhaps the most important effort started was the task of minimum air/ground communications system standardization. Starting with the premise that automatic dependent surveillance will lead the way toward the communications standardization, but that functions beyond automatic dependent surveillance must be catered for in the standard, the group agreed that this item represents a high priority.

The task is to assure:

1. Interoperability sufficient to permit aircraft to use various satellite systems which might be available in various regions.
2. Interoperability with related terrestrial aeronautical systems.
3. Achievement of the simplest common standard avionics.

It was agreed that work needed to be done by working parties prior to FANS-3 "to consider the technical aspects of communications standardization and to avail the group of expert advice on satellite and other techniques which impact on the need for standardization and delineation of system architecture."

As baseline material for this meeting, the tentative future CNS concept and the digital data flow and spectrum needs agreed by FANS-2 were used, as well as the automatic dependent surveillance concept developed in the Working Group meeting.

The Working Group of the Whole discussed a series of CNS system studies and experimental programs, with contributions from England, the European Space Agency, Japan, and the United States. The group recognized the importance of coordinating satellite experiments and demonstrations to assure common purpose and to avoid future differences of view which could come to plague FANS.

The Working Group agreed on definitions and a series of traffic scenarios against which future system concepts might be evaluated. Six scenarios were selected for consideration--a complex en route airspace structure, a remote continental airspace, an oceanic airspace structure, a high-density and a low-density terminal area, and special scenarios, such as the Gulf of Mexico, polar regions, and others. The FANS Member from the Federal Republic of Germany chairs this effort.

The first of two subworking group meetings was held March 17-21, 1986, to move FANS work forward, primarily on satellite communications systems standardization (FANS Work Program Item b) and Automatic Dependent Surveillance (Item a).

The group agreed that rapid progress would need to be made on both communications system standardization and Automatic Dependent Surveillance. Confirming conclusions of the November 1985 meeting, the groups working on these tasks again agreed that events were moving so rapidly in the satellite world that early decisions and recommendations on aviation's needs are needed if aviation is to have an impact on satellite developments.

Further, many states and international organizations feel that Automatic Dependent Surveillance is of potentially great value for both safety and efficiency, and that decisions with respect to it need to be made at the earliest possible time.

Two other considerations were noted by the group--the stated intention of at least one major international carrier to implement operational control communications via satellite data link in the very near term, and general recognition that such early implementation, while entirely welcome, would have a major impact on international standardization. As noted by the U.K. Member:

> "There are no natural stages at which everyone re-equips so successive generations of equipment must co-exist with each other. It is, therefore, essential that the initial systems and the standards on which they are based, must have the capability to grow to meet the ultimate requirements."

The view expressed by the U.S. Member was that a system concept can be developed which meets all foreseen requirements without disadvantaging any one user element, and that the need for ICAO now is to develop a system concept which can evolve from relatively simple applications to the more complex applications; a concept in which all elements of aviation can eventually participate--from general aviation to air carrier and military, in areas from the lowest density remote areas to oceanic use, to high density domestic en route and terminal airspace. It is in the interest of international aviation to move as rapidly as possible toward achievement of this kind of concept. This means that the initiatives by air carriers to move out should be applauded and supported, but that every effort should be made to provide such services in the context of a broad and universal system concept. This view was widely shared by working group.

During its week of work, the participants were able to make important progress in two areas:

o Minimum Communications System Standardization.

1. It was agreed that the ISO Open Systems Interconnection model system be used for the design of future digital communication systems to be standardized by the international civil aviation community.

2. It is essential that an early initial satellite communications system framework that will accommodate all user classes and all anticipated user services be developed. This framework should provide for international ADS service, potentially as the first ATS application of satellites, but it was recognized that some international airlines plan to use satellite data communication for operational control purposes in the near term.

3. The international system must provide for data and voice communications.

4. This system is to operate in the L-Band Aeronautical Mobile R satellite spectrum segments (1544-1559 MHz and 1645.5 and 1660.6 MHz). The bands will be used for ground-to-aircraft and aircraft-to-ground, respectively (for satellite-based and terrestrial communication systems, as envisaged in the tentative FANS-2 Future System Concept).

5. There must be avionics interoperability among candidate satellite systems and related terrestrial systems on a global basis.
6. The potential future capability of providing cooperative independent surveillance when and where such functional capability is needed should be a part of the system structure (that is, a functional capability like that envisioned for RDSS should be available within the system concept as part of the integrated system).
7. The system envisions the use of digital modulation for transmission of voice communications. Where both capabilities exist, voice and data communications must be available simultaneously, and full duplex capability for voice and data must be a part of the system.

The Working Group agreed on a series of objectives which must be met by the system design and, after examination of a variety of system elements, agreed on a series of ten which require international system standardization.

o <u>Automatic Dependent Surveillance (ADS)</u>.

The Working Group reiterated and strengthened a number of basic agreements reached at the November 1985 meeting. Among them:

1. There is operational benefit and anticpated cost/benefit in the application of an effective high integrity ADS, including ancillary direct pilot/controller communications.
2. The technical capability of satellite communications to support ADS and other ATC related aeronautical air-ground communications exists and has been demonstrated.
3. ADS can be successfully and usefully implemented with existing navigation systems, although future availability of navigation capability providing better performance will be helpful.
4. ADS service must be designed to a global standard and must serve all classes of aviation users in a variety of environments.
5. The Working Group refined its definition of Automatic Dependent Surveillance.
6. The group recognized the operational potential to support system efficiency improvements through an increased level of tactical control and to support reductions of separation minima. The group, again, agreed on significant separation reduction as an objective to be supported by Automatic Dependent Surveillance.
7. It agreed on a series of application and functional objectives for Automatic Dependent Surveillance. It agreed on a series of system characteristics of Automatic Dependent Surveillance and identified further work to be done.
8. The group agreed on a table of minimum and extended Automatic Dependent Surveillance system message elements, their content, and the range of communications services required to accomplish them.
9. The group identified a series of criteria for reliability, redundancy and continuity, service, and identified further effort to establish the necessary figures.

The work will continue in a June 1986 meeting in Paris, preparatory to FANS-3 in November.

I said earlier that ICAO FANS, at its first meeting, agreed on the need for world aviation to move rapidly to establish its requirements and to lay the basis of system standardization for aviation. If the energies of the satellite industry are to be harnessed on our behalf, if aircraft avionics suites are to be kept simple and efficient, if basic worldwide system improvements are to be achieved, and if future international controversy over systems is to be avoided, the opportunity is now.

LA NAVIGATION AERIENNE ET L'AVION A L'HORIZON 2000

par

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RESUME

Le système des services de la circulation aérienne des années 2000 devra pouvoir faire face à l'augmentation constante du trafic et présenter un minimum de contrainte au niveau des coûts d'exploitation des aéronefs.

Il devra prendre totalement en compte les méthodes de conduite du vol et, en particulier, la possibilité de suivre, de façon précise, un profil de vol déterminé.

Depuis 1980, un Groupe de travail de l'Agence EUROCONTROL est chargé de la mise au point du concept futur et de la formulation du programme de recherche correspondant.

L'exposé qui suit passe en revue les objectifs, les obstacles, les principes essentiels et les caractéristiques associés à la mise en oeuvre et à l'exploitation du système ATS futur.

Il fait ressortir la nécessité d'une concertation intense entre les avionneurs, les équipementiers, les exploitants du transport aérien et les responsables des services de gestion du trafic aérien.

1. INTRODUCTION

Assurer l'écoulement du trafic avec souplesse, sécurité et dans les conditions économiques optimales constitue la mission du Contrôle du Trafic Aérien. Les moyens nécessaires à l'exécution du Contrôle du Trafic Aérien au cours des dernières décennies ont évolué progressivement en un système complexe dont les composants principaux sont le radar de surveillance, les communications, les systèmes de navigation et le traitement informatique. Ce système a pu s'adapter à l'évolution de l'avion sans qu'une concertation étroite s'établisse entre les concepteurs d'avions et ceux de l'ATC.

Jusqu'alors, le "SOL" établit la situation "AIR", prévue et instantanée, à partir de données totalement indépendantes de celles qui sont utilisées pour la conduite du vol, exception faite de l'altitude Mode C du radar secondaire.

Le traitement informatique des données plan de vol et radar, ainsi que l'assistance automatisée à la prévision et la gestion des courants de trafic sont désormais largement répandus avec des degrés de raffinement divers. On voit, par ailleurs, s'accroître le nombre d'avions modernes équipés de systèmes de gestion de vol (FMS). Néanmoins, les systèmes "SOL" les plus avancés travaillent toujours à partir d'une description de performances "avions" qui ne correspondent à la réalité que de façon approximative. Ceci a des conséquences directes sur un certain nombre d'aspects fondamentaux, tels que la détermination des normes d'espacement et les procédures utilisées pour en assurer le maintien, en route, comme dans les zones terminales.

Les transporteurs aériens exercent sur les autorités responsables du Contrôle, une pression légitime pour obtenir un service adapté à l'augmentation constante du trafic et présentant un minimum de contrainte à la rentabilisation des investissements consentis au plan de l'avion.

Il est clair qu'il ne pourra leur être donné satisfaction dans l'avenir que par la mise en oeuvre de concepts qui prennent totalement en compte les méthodes de conduite du vol et, en particulier, la possibilité donnée à l'aéronef de respecter, de façon précise et dans les quatre dimensions, un profil déterminé.

2. LES OBJECTIFS

S'il est besoin de se convaincre de la distance qui sépare le système actuel de celui que désirent les usagers, il suffit de passer brièvement en revue les phases de préparation et d'exécution d'un vol telles qu'elles devraient de dérouler.

2.1. Plan de vol

Au stade de la préparation du Plan de Vol, le Commandant de bord devrait avoir le libre choix de la route, du profil de vol et de l'heure précise de départ. Il devrait disposer automatiquement des données Météorologiques et de l'Information Aéronautique. Il devrait obtenir avant le départ la "clearance" pour la totalité de la route et du profil requis.

2.2. Décollage et montée

Les opérations de mise en route des moteurs, roulage, alignement et décollage devraient s'enchaîner sans discontinuité. La montée sans restrictions au niveau de croisière optimal devrait être la règle générale.

2.3. Phase en route

Elle devrait pouvoir s'exécuter comme prévu, sans altérations de niveaux et de caps, et en maintenant au minimum les interventions du pilote liées au contrôle du trafic (changements de fréquence, communications, manipulations de clavier, etc.).

2.4. Descente et roulage

La descente devrait s'effectuer selon le profil optimal jusqu'au toucher des roues et la distance pour rejoindre le parking, être aussi courte que possible.

Comme on peut le constater, l'écart est grand par rapport à la réalité.

3. LES OBSTACLES

3.1. Lorsqu'on essaie d'imaginer le système futur, on se trouve confronté à plusieurs aspects, parmi lesquels :

- les aspects qui sont tributaires d'accords intervenus ou à intervenir dans le domaine international (normes ARINC, OACI, dates de protection des systèmes, organisation de l'espace aérien, etc.). La lenteur du processus peut être facteur de ralentissement dans l'introduction de technologies pourtant disponibles à court ou moyen terme ;
- les aspects qui ressortent du rôle de l'homme dans le système et de l'adéquation de certaines techniques ou méthodologies (reconnaissance de la parole, présentation 3 D, utilisation de systèmes experts, etc.) ;
- le fait que le système ne peut progresser que de par évolution et l'énorme difficulté qu'il y a à synchroniser les phases d'évolution au sol et à bord ;
- les contraintes résultant de l'organisation de l'espace (cohabitation civile/militaire) et de la capacité des aéroports.

3.2. Ceci tendrait à montrer la nécessité de définir des objectifs plutôt ambitieux que modestes - afin de ne pas se laisser porter par les événements - et qui servent de guide aux actions relatives aux sujets mentionnés plus haut, c'est-à-dire sur le plan

- des instances internationales,
- des axes de recherche, développement et expérimentations,
- de la mise en oeuvre.

3.3. L'analyse des hypothèses les plus probables quant aux caractéristiques des systèmes de navigation, de surveillance et de communications à l'horizon 2000 permet de mieux cerner les problèmes :

- Navigation précise
- Localisation précise
- Communications automatiques air/sol et sol/sol
- Couplage étroit entre l'avion et le sol.

4. LES MOYENS DE NAVIGATION

Il a été largement fait écho aux travaux du comité spécial de l'OACI - Future Air Navigation Systems (FANS). Ce comité a introduit la notion du concept RNPC (Required Navigation Performance Capability). Il a postulé que la navigation par référence satellite s'avèrera hautement fiable, de haute intégrité et de haute précision.

La liste des systèmes condidats éventuels (NAVSTAR/GPS, GLONASS, GRANAS, NAVSAT, GEOSTAR et d'autres sans doute à venir), ainsi que la nature des questions qui restent ouvertes laissent présager qu'il faudra un certain temps avant que la situation se décante.

En tout état de cause, le système actuel, essentiellement basé sur l'utilisation du VOR/DME, évoluera vers un système de navigation de surface (double DME et/ou satellite). Ceci aura un impact direct sur l'organisation de l'espace aérien.

5. SYSTEME DE SURVEILLANCE

L'amélioration du système de surveillance se manifestera dans les domaines suivants :

- Précision de la mesure de position et des vitesses horizontales et verticales.
- Fiabilité des données d'identification.
- Possibilité de détecter les erreurs grossières de navigation.

La mise en oeuvre du radar secondaire/Mode S pourrait permettre d'atteindre ces objectifs.

Par ailleurs, le comité FANS étudie un concept de "Surveillance Automatique Dépendante" (ADS), dans lequel l'aéronef transmet à l'usage du contrôle des données du système avionique soit périodiquement soit sur demande du sol. Ceci ferait appel à des satellites de communications et son application serait initialement limitée à des zones non couvertes par radar.

On peut également noter que la liaison de données du Mode S fait actuellement l'objet de spécifications préliminaires pour échange air/sol, sol/air. Des essais de communications aéronautiques par satellite ont déjà eu lieu ou sont envisagés (par exemple, PROSAT). L'utilisation d'une liaison de données est partie intégrante du système ADS. On ne s'attend toutefois pas à ce que un ADS remplace un système coopératif indépendant (du type Mode S) dans les zones à haute densité.

La notion d'un système coopératif indépendant de surveillance est également évoquée par le Comité FANS. Il présenterait, par rapport à un réseau de radars au sol, des avantages indéniables (couverture, précision, maintenance).

Dans tous les cas, la disponibilité de moyens d'acquisition de données d'identification et de position précises est assurée.

6. COMMUNICATIONS

6.1. Communications de données Air/sol :

Qu'il s'agisse de liaisons de données Mode S ou satellites, on voit enfin se matérialiser la possibilité de disposer d'une transmission automatique de données Air/Sol et Sol/Air. Le besoin de disposer au sol, en plus de l'altitude et de l'identification, d'informations connues à bord a été exprimé depuis des décennies. Les limites à la précision de la prédiction de trajectoires se trouveront repoussées de façon significative.

Il devrait également être possible d'avoir accès, depuis le bord, à des bases de données au sol (Météo, SIA) et de transmettre vers le bord certaines instructions ATC depuis le sol.

La mise en oeuvre de liaisons de données air/sol-sol constitue un de ces domaines où la nécessité d'harmoniser les programmes d'équipement au sol et à bord revêt une importance primordiale.

6.2. Communications verbales air/sol :

Dans un environnement où une grande partie des communications de routine sont acheminées sur les liaisons automatiques, il restera impératif de pouvoir utiliser les communications verbales pour la résolution de problèmes particuliers.

6.3. Communications sol/sol :

Les liaisons automatiques centre à centre devraient se développer de façon considérable. Le système ATC repose de plus en plus sur l'interrogation de bases de données distribuées et partagées entre plusieurs entités fonctionnelles, avec les problèmes associés de mise à jour et de maintien de la cohérence. Un problème particulier réside dans la création d'un futur réseau Mode S (fonctionnement intersite).

7. LES SYSTEMES INFORMATIQUES

L'évolution attendue du volume de trafic va nécessiter un accroissement correspondant de la capacité du système ATC. C'est surtout en augmentant le rôle de l'assistance automatisée dans le processus de prise de décision que ceci sera possible. Il est clair que, comme dans bon nombre de domaines, l'informatique va occuper une place prépondérante. Les développements prévisibles de la technologie des ordinateurs et des moyens d'entrée/sortie (visualisation, dialogue, etc.) laissent un vaste champ libre à l'imagination.

Il faudra néanmoins garder à l'esprit les sujets de préoccupation majeurs, tels que :

- la nécessité de disposer de systèmes fiables et "tolérants à la faute",
- les rapports homme/machine,
- la compatibilité des systèmes entre eux.

8. L'AGENCE EUROCONTROL

Depuis 1980, l'Agence EUROCONTROL travaille à la mise au point d'un concept du futur système des services de la circulation aérienne (ATS) et à la formulation d'un programme de recherche correspondant. La période d'application s'étend de la fin du siècle aux années 2020. La présente communication est évidemment largement inspirée de la réflexion du groupe de travail qui élabore le concept et dont les considérations dépassent la région EUROCONTROL proprement dite. Ce groupe a mis en relief un certain nombre de principes pour le développement et la mise en oeuvre du système futur, ainsi que les fonctions ATC essentielles. Dans ce qui suit, l'accent sera mis sur les aspects qui associent étroitement l'avion et le contrôle du trafic.

9. LES PRINCIPES

On trouvera, en annexe, la liste de ces principes. Cinq d'entr'eux méritent une attention particulière.

9.1. Responsabilité du contrôleur et du pilote en milieu automatisé :

Des progrès dans l'automatisation et dans l'assistance par ordinateur sont indispensables pour le système futur. Il faudra trouver le juste équilibre par rapport aux tâches et au rôle de l'élément humain. Ceci concerne les tâches de surveillance du trafic et, plus particulièrement, les mécanismes de prise de décisions.

9.2. Fonctions de gestion du trafic :

Elles devraient, pour l'essentiel, être exécutées par l'organisation au sol. On n'exclut pas, toutefois, à long terme, la notion d'un transfert partiel de responsabilité vers le "bord".

9.3. Responsabilité pour la navigation :

La responsabilité de la navigation incombe au pilote, exception faite en cas de guidage radar.

9.4. Exploitation des possibilités de l'équipement de bord :

Il devrait être pleinement tenu compte de la nécessité d'exploiter les possibilités des équipements de bord modernes afin d'assurer des conditions optimales d'économie du vol compatibles avec l'efficacité globale du système.

9.5. Organisation de l'espace aérien :

Le système futur devrait être basé sur un concept de contrôle de zone par opposition à un concept de réseau de routes fixés, ceci dans le but de permettre un maximum de souplesse et d'économie des opérations.

10. RESUME DES ORIENTATIONS

Le concept à l'horizon 2000 repose donc sur les éléments suivants :

- On dispose d'un système de navigation précis, dans l'espace et dans le temps, et, de systèmes de gestion et de conduite de vol performants (FMGS).
- Le sol est en mesure d'élaborer des données précises sur les positions instantanées et prévues des aéronefs, avec ce que cela implique au plan de la capacité de traitement des sytèmes informatiques (temps réel, prévisions à court, moyen et long terme).
- On dispose d'un système de communications de données air/sol-sol/air qui permet la réalisation d'un couplage étroit entre l'avion et le contrôle.
- L'organisation de l'espace aérien est basée sur un concept de navigation de surface.

Le précision du système de navigation et l'efficacité des systèmes de gestion de vol devraient permettre au pilote de proposer à l'ATC des trajectoires directes et optimales qu'il est, par ailleurs, certain de suivre de façon stricte.

En retour, les possibilités de l'ATC d'évaluer la situation générale également avec une grande précision devraient permettre l'établissement du dialogue préalable au choix de la trajectoire. L'objectif global est d'augmenter la capacité du système de contrôle tout en respectant les impératifs de sécurité et d'économie. Les moyens consistent à accroître l'assistance automatisée à la prise de décisions du contrôleur. Ceci suppose bien entendu que les fonctions automatisées constituent un ensemble cohérent, qu'on puisse concevoir les algorithmes appropriés pour leur exécution et que des solutions acceptables soient trouvées au plan des relations homme/machine. Il faudra également résoudre les problèmes de transition à des niveaux croissants d'automatisation avec leurs implications sur les aspects "fiabilité".

11. FONCTIONS PRINCIPALES

Les améliorations principales au système ATS sont attendues dans les domaines suivants :

- harmonisation des fonctions stratégiques et tactiques,
- productivité du contrôle,
- gestion des vols à l'arrivée.

11.1. Harmonisation des fonctions stratégiques et tactiques

L'efficacité du contrôle dépend, d'une part, de l'aptitude à prévoir les situations de trafic, à agir sur ces situations par des mesures de planification et, d'autre part, de la possibilité de décider de mesures tactiques qui cadrent, autant que possible, avec la situation prévue.

Pour la période d'application du concept, les techniques d'intelligence artificielle devraient permettre de reproduire des situations de trafic organisées, susceptibles d'être rationalisées en fonction de conditions spécifiques rencontrées (auto-apprentissage, méthodes heuristiques, etc.).

11.2. Productivité du contrôle

On distinguera deux aspects importants, participant à l'amélioration de la productivité du contrôle :

- l'identification de situations de conflits potentiels réels,
- la mise en place de dispositifs d'alerte aux conflits.

Trois types de niveaux sont envisagés : Conflits à moyen terme (15/20 minutes), à court terme (type filet de sauvegarde - 2 minutes) et immédiat (30 secondes - type ACAS et ses dérivés).

La fonction d'alerte aux conflits pour les deux premiers niveaux est exécutée au sol.

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

Il s'agit de combiner l'exploitation maximale de la capacité d'atterrissage et l'utilisation de profils optimaux de trajectoires. C'est un domaine où des travaux de recherche et d'expérimentation se déroulent depuis plusieurs années (COMPAS, Zone de Convergence, etc.). Les performances des FMGS, des systèmes de prédiction basés au sol et les perspectives d'utilisation des liaisons automatiques de données laissent entrevoir des solutions.

Il convient de garder à l'esprit les éléments suivants :

- L'ATC sera toujours confronté à un environnement mixte au plan des capacités de l'équipement de bord.
- Il faudra donc concevoir, évaluer et valider, des algorithmes et des procédures adaptables à un large éventail de configurations géographiques et de trafic.

11.4. La prédiction de trajectoires

L'obtention d'améliorations significatives dans les domaines qui viennent d'être passés en revue passe par la nécessité de disposer d'un système de prédiction de trajectoires de haute qualité. Ceci implique la possibilité pour l'aéronef de suivre, de façon stricte, une trajectoire prédéterminée.

De plus, il ne sera pleinement tiré bénéfice du concept de navigation de surface que dans la mesure où le système au sol sera assuré de disposer de techniques éprouvées. La nature, le taux de renouvellement, la précision et, aussi, la source des données qui sont requises au sol pour la prédiction de trajectoire diffèrent selon le niveau d'alerte de conflit considéré et selon la partie du vol, à laquelle on s'intéresse (en route, zone terminale, etc.).

On peut identifier un certain nombre d'axes d'études additionnels à ceux qui ont été évoqué plus haut, tels que :

- les possiblités d'acquisition au sol et à bord des données météorologiques à jour,

- l'amélioration de la connaissance du vecteur d'état de l'avion,
- les performances de tenue de trajectoire dans les quatre dimensions des appareils qui voleront pendant la période considérée.
- le couplage des systèmes de suivi et de prédiciton de trajectoires à bord et au sol.

12. SYSTEME DE DEMONSTRATION DE TECHNOLOGIE ATC D'AVANT-GARDE

12.1. Tout système fondé sur la stricte observance des trajectoires prévues demande des données de haute qualité concernant le vol, ainsi qu'une bonne connaissance des intentions du pilote et, partant, une étroite coopération air/sol. Par ailleurs, les divers éléments de l'ATC sont de plus en plus interdépendants.

Il en résulte que l'évaluation spécifique à un composant particulier (FMGS, Mode S, etc.) doit être nécessairement complétée par une évaluation au niveau du système. On voit donc apparaître le besoin de moyens de simulation représentatifs du système ATS dans son ensemble. Ces moyens de simulation devraient faire appel aux technologies les plus avancées qui ne sont pas nécessairement celles que la réalité imposera dans les premières années de la mise en oeuvre du concept. Dans ce sens, de tels systèmes constitueraient aussi bien des moyens de simulation que des moyens de démonstration.

12.2. Ceux-ci préfigureraient le système futur dont l'organisation au sol pourrait s'envisager comme suit :

Entrées dans le système :

- transmises par le data link air/sol. Des propositions de trajectoires dérivées du FMS et des données de position dérivées du système de navigation,
- dérivées du système de surveillance indépendant : des données de position pour l'ensemble du trafic,
- les plans de vol.

Sorties du système vers l'avion (transmises via le data link air/sol) :

- des propositions ou amendements de trajectoires,
- des instructions de guidage et d'évitement.

L'architecture du système au sol, décrite dans la Figure 1, pourrait se concevoir comme étant répartie entre cinq sous-systèmes :

- le calcul des trajectoires 4-D et la "négociation" de la trajectoire avec le pilote ;
- la fonction stratégique ;
- la fonction ATC tactique ;
- la surveillance de la conformité entre la situation prévue et la situation réelle ;
- les positions de travail avec leurs moyens de présentation et d'entrées/sorties.

12.3. Les systèmes de démonstration de technologie ATC d'avant-garde comporteraient donc :

- la représentation réaliste de l'avion que l'on supposerait doté des équipements les plus perfectionnés,
- un système global de localisation complété par une liaison de données air/sol,
- la représentation des fonctions les plus avancées du système au sol,
- des positions de supervision et d'intervention faisant appel aux techniques les plus modernes de communication homme/machine.

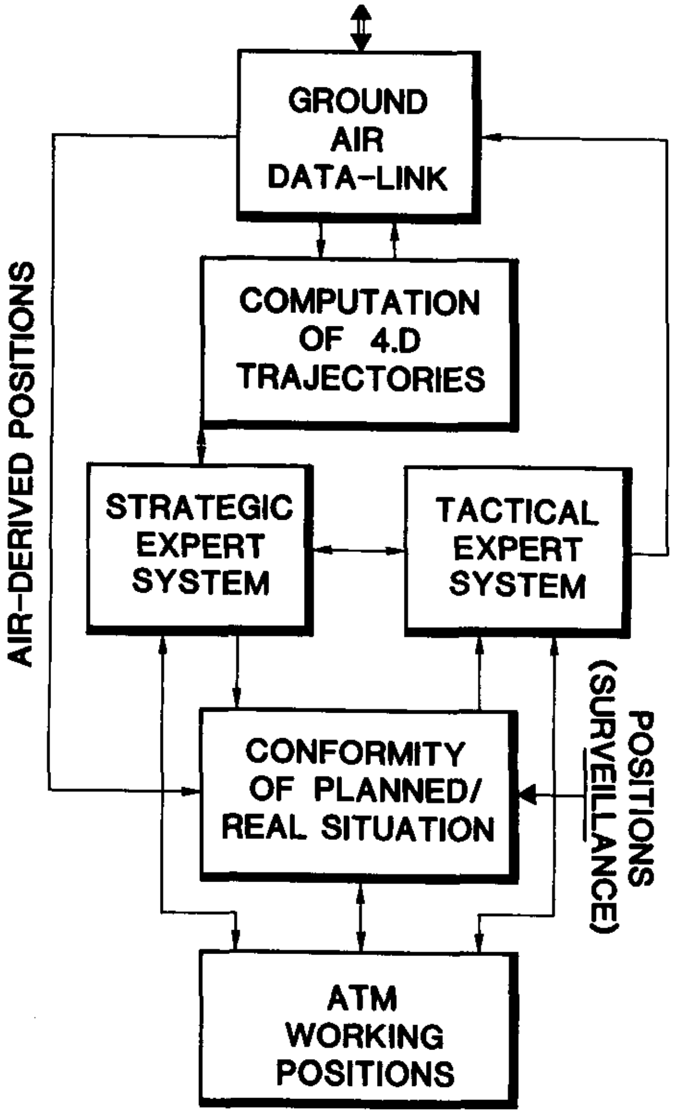

Figure 1

13. CONCLUSION

Il reste un travail considérable à faire pour raffiner le concept ATS des années 2000. On voit néanmoins s'en préciser les grandes lignes :

- navigation précise
- couplage étroit entre l'avion et le contrôle
- localisation précise
- communications automatiques.

Les travaux de recherche et d'expérimentation s'intensifient dans tous ces domaines. Ils devront être marqués, sous peine d'échec, par une concertation intense entre les avionneurs, les équipementiers, les exploitants du transport aérien et les responsables des services du contrôle du trafic aérien.

ANNEXE I.

LES PRINCIPES

Les principes essentiels devant guider le développement et l'exploitation du système sont les suivants :

1. Conformité à la réglementation OACI
2. Continuité et sécurité des opérations.
3. Redondance appropriée pour la Navigation, la Surveillance et les Communications.
4. Equilibre des responsabilités humaines (pilote et contrôleur) en milieu automatisé.
5. Le système dessert l'ensemble de l'espace et la totalité du trafic.
6. Utilisation de la notion de spécifications de performances minimales.
7. Décisions basées sur l'analyse coût-efficacité et l'appréciation opérationnelle/technique.
8. Fonctions de gestion du trafic essentiellement assurées par les services au sol.
9. Aptitude à faire face aux demandes.
10. Equilibre entre la gestion des flots de trafic et les fonctions ATC.
11. Eviter la ségrégation de l'espace.
12. Le pilote est responsable de la navigation (sauf guidage radar).
13. Pas de règles de priorité systématique.
14. Harmonisation fonctionnelle des services.
15. Compatibilité dans les échanges de données.
16. Exploitation maximale des possibilités de l'équipement de bord.
17. Organisation de l'espace aérien basée sur un concept de contrôle de zone.

CP 410

AIR NAVIGATION SERVICES AND AIRCRAFT AROUND THE YEAR 2000 *

by

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SUMMARY

The Air Traffic Services System for 2000 and beyond shall have to cope with the constantly increasing traffic demand and cause the minimum constraint vis-à-vis the costs of operating the aircraft.

It shall take wholly into account the methods by which the aircraft are conducted, and, in particular the ability to adhere accurately to a predefined profile.

Since 1980 a working party of the EUROCONTROL Agency is in charge of the development of a future system concept and the formulation of a corresponding research programme.

The present communication reviews the objectives, the difficulties, the main principles and the characteristics associated to the development and implementation of the future ATS concept.

It points at the necessity for close consultation between aircraft manufacturers, avionics manufacturers, aircraft operators and the authorities responsible for Air Traffic Management.

1. INTRODUCTION

The role of Air Traffic Control is to ensure the smooth, safe and economically-optimum flow of air traffic. During the last 20 or 30 years the facilities needed for air traffic control have gradually evolved into a complex system whose main components are secondary surveillance radar, radar communications, navigation systems and data processing. In fact, the air traffic control system has been able to adapt itself to the advances that have taken place in aircraft design without any significant dialogue having developed between aircraft designers and ATC planners.

Today, with the exception of the Mode C altitude read-out on the secondary radar, the ATC ground system establishes both the forecast and the instantaneous situation in airspace from data which is completely separate from that used for the conduct of flights.

The utilisation of flight plan data processing and radar data processing as well as the automated assistance in the forecasting and management of traffic flows is, with various degrees of refinement, fairly wide-spread. Also, an increasing number of aircraft are being fitted with flight management systems (FMS). Nevertheless, the most advanced ground systems are still working on the basis of a description of aircraft performance which corresponds only loosely with reality. This directly affects some of the basic features of air traffic control, such as the determining of standard separation minima and the procedures employed to maintain such minima both en route and in terminal areas.

Air carriers exert on the ATC authorities a legitimate pressure to obtain an air traffic control service which is suited to the traffic demand (constantly increasing) and causes the minimum constraint vis-à-vis the profitability of the investments in aircraft.

In this connection, it is clear that the only way to satisfy air carriers will be through the implementation of concepts which take wholly into account the methods by which flights are conducted and, in particular, the possibility for the aircraft to follow accurately a specific profile in the four dimensions.

2. AIMS

To be convinced of the gulf between the current system and the one the users wish to see, it is necessary only to look at the different phases of preparing for and performing a flight as they ought to be.

(*) *Translated from French*

2.1. Flight plan

When preparing his flight plan, the pilot-in-command should be able to choose without any restriction the route, the flight profile and the precise time of departure. MET data and Aeronautical Information should be available to him by automatic means. He should also be able to obtain before departure a clearance for the whole of the route and profile to be flown.

2.2. Take-off and climb

Engine start-up, taxying, line-up and take-off should follow one another without any break. Unrestricted climb to the optimum cruise level should be the general rule.

2.3. En route phase

This should take place as planned, with no change to the flight levels and headings, and keeping the ATC-related tasks of the pilot, such as changing frequency, RTF communications, operation of key-pad(s), to a minimum.

2.4. Descent and taxi

The descent should follow the optimum profile until the moment of touch-down and the distance to the ramp parking position should be as short as possible.

As can be seen, the difference between the above and the way flights are currently conducted is large.

3. THE DIFFICULTIES

3.1. In attempting to visualise the future ATC system, various factors have to be taken into account. Among these are the following:

- A number of aspects of ATC depend upon existing or future international agreements, e.g. ARINC standards, ICAO, dates for the protection of systems, airspace organisation. The slowness of the process involved in such agreements can be a factor delaying the introduction of technologies which are in fact available in the short or medium term;
- Factors connected with the role of the human being within the system and the suitability of certain techniques or methods, e.g. speech recognition, 3-dimensional presentation, the use of expert systems;
- The fact that the system can progress only by means of an evolutionary process and also the great difficulty involved in synchronising the evolutionary phases in the ground ATC system with those of ATC-related aircraft systems;
- The constraints resulting from airspace organisation, especially the cohabitation by both civil and military, and airport capacity.

3.2. The above tends to show the need to define aims which are ambitious rather than modest - in order not to be influenced too much by events - and which can be a guide to the action to be taken in connection with the subjects mentioned above, i.e. with regard to

- international authorities
- the main lines of research, development and experimentation
- implementation.

3.3. If the most likely assumptions as to the characteristics of the navigation, surveillance and communication systems in use in the year 2000 are submitted to analysis, it is easier to identify the areas in which the problems involved lie, namely, accurate navigation, accurate position-finding, automatic air/ground and ground/ground communications, and close coupling between the aircraft and ground control.

4. NAVIGATIONAL FACILITIES

The work of the ICAO Future Air Navigation Systems (FANS) Special Committee has been made widely known. The Committee introduced the concept of Required Navigation Performance Capability (RNPC) and postulated that the use of satellites for navigation would prove to be highly reliable, of high integrity and highly accurate.

The number of navigation systems that could be adopted, viz. Navstar/GPS, Glonass, Granas, Navsat, Geostar, and no doubt others still to be developed, together with the nature of the questions which still remain to be decided is probably and indication that it will be some time before the situation becomes clear.

In any event, the current system, based essentially on the use of VOR/DME, will evolve towards an area navigation system (RNAV) using dual DMes and/or satellites. This will directly affect airspace organisation.

5. THE SURVEILLANCE SYSTEM

Improvements in the surveillance system will occur in the following areas:

- Accuracy in determining aircraft position and horizontal and vertical speeds;

- Reliability of the data providing identification;

- The possibility of detecting gross navigational errors.

The introduction of Mode S secondary radar could make it possible to achieve the above aims.

Moreover, the FANS Special Committee is studying an "Automatic Dependent Surveillance" (ADS) concept whereby an aircraft periodically, or upon request from ATC, transmits avionicsystems-derived data to the ground system for air traffic control purposes. This method would make use of communications satellites and its application would initially be restricted to those areas not covered by radar.

It may also be noted that work on the preliminary specifications for the air/ground and ground/air exchange of data via the Mode S data link are currently in hand. Various trials of aeronautical communications via satellite have already taken place or are envisaged, the Prosat system for example. The use of a data link is an integral part of the Automatic Dependant Surveil-lance system. It is not however, expected that the ADS system will replace an independant co-operative system of the Mode S type in areas of high-density traffic.

The idea of an independant co-operative surveillance system is also mentioned by the FANS Special Committee. This would provide undeniable advantages in the matter of coverage, accuracy and maintenance as compared with a network of ground radars.

In all cases, the availability of facilities for the acquisition of accurate identification data and position data is assured.

6. COMMUNICATIONS

6.1. Air/ground data communications

Whether by means of Mode S or satellite data links, the possibility of having automatic air/ground and ground/air data transmission can at last be seen. The need for ATC to have further data from aircraft in addition to altitude and identification have been expressed for decades. The limitations on the accuracy of flight path prediction will be reduced to a significant extent.

It should also be possible for the aircraft to have access to a number of data bases, such as those relating to MET and AIS, which are stored in ground systems, and for certain ATC instructions to be transmitted to the aircraft form ground stations.

The installation of air/ground and ground/air data links is one of those areas in which the need to harmonise aircraft equipment programmes and ground equipment programmes is of prime importance.

6.2. Verbal air/ground communications

In an environment in which a large part of the routine communications takes place via automatic links, verbal communication will still remain essential in order to resolve special problems.

6.3. Ground/ground communications

Automatic centre-to-centre links will probably increase to a considerable extent. The ATC system relies more and more on the interrogation of distributed data bases which are shared between several functional bodies, along with the associated problems of updating and of maintaining consistency. A special problem occurs in the setting-up of a future Mode S network with inter-site operation.

7. DATA PROCESSING SYSTEMS

The expected increase in the volume of traffic will bring about a corresponding increase in the capacity of the ATC system. But it is especially by increasing the part played by automated systems in the decision-making process that this increased capacity will become possible. It is obvious that, as in any other fields, data processing is going to occupy a predominant place. The foreseeable developments in computer technology and in input/output facilities (e.g. displays, dialogue, etc.) are such as to leave a wide field open to the imagination.

A number of major subjects of preoccupation must however, be borne in mind; subjects such as:

- the need to have reliable systems which will be "fault-tolerant";
- the man/machine relationship;
- compatibility between systems.

8. THE EUROCONTROL AGENCY

Since 1980, the EUROCONTROL Agency has been working on the development of a future system concept for air traffic services and the formulation of a corresponding research programme. The time-scale of this concept extends from the late 1990s to the decade 2020/2030. Quite clearly the present document is largely inspired by the thinking of the working group which is developing the concept and whose considerations go beyond those of the EUROCONTROL area properly speaking. This group has emphasised a certain number of principles for the development and implementation of the future system together with the essential ATC functions. In the paragraphs that follow, stress will be placed on the aspects which associate aircraft and ATC closely.

9. PRINCIPLES

A list of these principles will be found in Annex 1. Five of them deserve special attention and are referred to below.

9.1. The responsibilities of controller and pilot in the context of automation

Progress in automation and in computer-provided assistance are essential for the future system. It will be necessary to find the correct balance as regards the tasks involved and the role played by the human beings concerned. This applies to traffic monitoring and, more particular, the mechanism involved in decision-taking.

9.2. Air traffic management functions

The basic functions of the ATS system will be performed by the ground organisation. However, the idea of a partial transfer of responsibility in the long term to the airborne side is not excluded.

9.3. Responsibility for navigation

With the exception of radar vectoring, responsibility for the navigation rests with the pilot.

9.4. Exploitation of the capabilities of airborne equipment

Full account must be taken of the need to exploit the capabilities of advanced airborne equipment so as to provide optimum flight economy compatible with overall system efficiency.

9.5. Airspace organisation

The future system should be based on an area control concept instead of a fixed route network concept. This is so as to allow the maximum of flexibility and operating economy.

10. GUIDE-LINES

The concept for the year 2000 depends therefore on the following features:

- The availability of a navigation system which is accurate in space and time and of reliable Flight Management and Guidance systems (FMGS);
- ATC is able to obtain accurate data on the instantaneous and forecast positions of aircraft, together with what this implies in the matter of data processing system capacity with respect to real time and to short, medium and long-term forecasting;

- The availability of an air/ground and ground/air data communication system which enables a close coupling between the aircraft and ATC to be achieved;

- Airspace organisation is based on an area navigation concept.

The accuracy of the navigation system and the efficiency of the flight management systems should enable the pilot to propose to ATC the direct and optimum routes and flight profiles that he is certain he can follow very closely.

In return, the ability of ATC to evaluate the general situation also with great accuracy should allow a dialogue to be established prior to the 'route and flight profile being chosen. The overall aim is to increase ATC system capacity, while at the same time complying with the overriding needs of safety and economy. The means for doing this consist in increasing the automated systems in decision-making by the controller. This of course supposes that the automated functions form a consistent whole, that appropriate alogirthms for performing them can be worked out and that acceptable solutions can be found as regards the man/ machine relationship. It will also be necessary to resolve the problems connected with transitions to increasing levels of automation together with their implications for reliability.

11. MAIN FUNCTIONS

The main improvements in the ATS system are expected to take place in the following areas:

- Harmonisation of strategic and tactical functions;

- ATC productivity;

- The management of arriving flights.

11.1. Harmonisation of strategic and tactical functions

Efficient air traffic control depends, firstly, on the ability to forecast traffic situations and, when necessary, to use planning measures to modify these situations and, secondly, on the ability to decide on tactical measures that are the most appropriate to the forecast situations.

During the period of application of the future ATS system concept, artificial intelligence techniques should make it possible to reproduce planned traffic situations which can be rationalised in accordance with the specific conditions involved, e.g. selfteaching, heuristic methods, etc.

11.2. Controller productivity

It is possible to discern two important aspects connected with an improvement in controller productivity. These are:

- the identification of genuine potential conflict situations;

- the installing of conflict-alert systems.

Three timescales are envisaged: medium-term conflicts (15 to 20 minutes); short-term conflicts (of the 'safety net' type: 2 minutes); immediate conflicts (30 seconds, i.e. of the ACAS type and its derivatives).

The alerting function of the first two of the above is carried out by the ground system.

11.3. Improvement in the management of arriving flights

This involves combining the utilisation of the maximum landing capacity and the utilisation of optimum flight path profiles, and is an area in which experimental and research work has been in progress for several years, e.g. COMPAS, Zone of Convergence. Given the capabilities of flight management and guidance systems, ground-based prediction systems and prospect of automatic data links, various practical courses of action can be foreseen.

The following, however, have to be borne in mind:

- ATC will always be faced with a mixed environment where the capabilities of airborne equipment are concerned;

- It will therefore be necessary to design, evaluate and validate algorithms and procedures which are adaptable to a wide range of geographical and traffic configurations.

11.4. FLIGHT-PATH PREDICTION

Significant improvements in the areas dealt with above are dependent on the availability of a high-quality flight-path prediction system. This implies that aircraft are able to follow accurately a predetermined flight path.

In addition, the full benefit of the area navigation concept can only be obtained insofar as the ATC system is provided with tried and proved techniques. The nature, renewal rate, accuracy and also the source of the data required by the ground system for flight-path prediction differ according to the conflictalert timescale and also according to the phase of the flight concerned, e.g. en route, terminal area.

It is possible to identify a certain number of lines of research which are additional to those mentioned above, namely:

- The possibility of the acquisition of updated MET data by airborne equipment and ground equipment;
- Improved knowledge of the vector state of the aircraft;
- The ability of the aircraft during the period under consideration to keep to the predetermined flight path in the four dimensions;
- The coupling of the flight control systems and flight path prediction systems in the aircraft and on the ground.

12. ADVANCED ATC TECHNOLOGY DEMONSTRATION SYSTEM

12.1. Any system based on the strict adherence to planned flight paths requires high-quality data concerning the flight together with a good knowledge of the pilot's intentions and consequently close cooperation between the aircraft and the ground systems. Moreover, the various components of the air traffic control system are increasingly inter-dependant.

As a result, an evaluation which is concerned specifically with a particular component of the system, e.g. FMGS, Mode S, must of necessity include an evaluation at the system level. There is therefore an evident need for simulation facilities which are representative of the ATS system as a whole. These simulation facilities should use the most advanced technology available (these are not necessarily the same that actual conditions will dictate at the start of the implementation of the concept). In this sense, such facilities would be simulation systems as well as demonstration systems.

12.2. The above foreshadows the future system the ground organisation of which could be envisaged as follows:

System input:

- Transmitted via the air/ground data link: proposals regarding the future flight path derived from the Flight Management System and position data derived from the navigation system;
- Obtained from the independant surveillance system: position data for the whole of the traffic;
- Flight plans.

System output to the aircraft (via the air/ground data link):

- Proposals concerning, or modifications to, flight paths;
- Instructions for vectoring and avoidance.

The architecture of the ground system described in Figure 1 could be seen as having five sub-systems, as follows:

- Calculation of the four-dimensional flight paths and the "negotiation" of the route and flight profile with the pilot;
- The strategic function;
- The ATC tactical function;
- The monitoring of the actual situation to check compliance with the forecast situation;
- The working positions with their display and input/output facilities.

12.3. The advanced ATC technology demonstration system would therefore include:

- the realistic representation of the behaviour of aircraft which would be presumed to have the most advanced equipment;
- a global position-finding system supplemented by an air/ground data link;

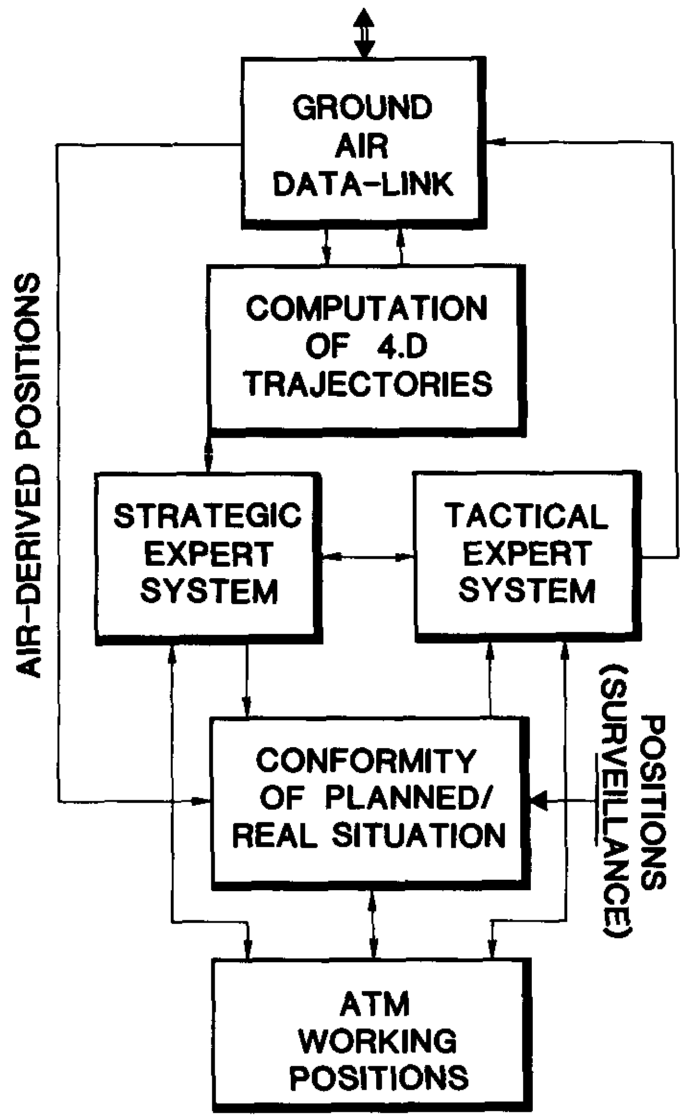

Figure 1

- the representation of the most advanced functions of the ground system;
- supervisory and executive control positions which include the most advanced types of man/machine communications facilities.

13. CONCLUSION

A considerable amount of work still remains to be done in order to refine the ATS system concept for the year 2000 and beyond. It is nevertheless possible to discern the broad lines of future developments:

- Accurate navigation;
- Close coupling between each aircraft and ATC;
- Accurate position-finding;
- Automated communications.

Studies, tests and trials in all the above fields are increasing. However, to avoid the risk of failure they will need to be accompanied by frequent consultation between the aircraft manufacturers, equipment manufacturers, aircraft operators and the authorities responsible for air traffic control.

PRINCIPLES

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

1. Adherence to ICAO rules.
2. Continuity of safe operations.
3. Provision of adequate redundancy in navigation, surveillance and communications.
4. Responsibilities of controller and pilot in the context of automation.
5. The ATS system to serve the whole of the airspace and the totality of the traffic.
6. Utilisation of Minimum Performance Specifications.
7. Cost-effectiveness analysis and operational/technical judgement for policy decisions.
8. The air traffic management functions of the system should be essentially ground-based.
9. Capacity for coping with demands.
10. ATFM capability and relationship with ATC.
11. Avoidance for airspace segregation.
12. Responsibility for navigation.
13. Priority rules.
14. Functional harmonisation of services.
15. Compatibility in data exchanges.
16. Maximum exploitation of advanced airborne equipment capabilities.
17. ATS airspace organisation based on an area control concept.

CP 410

GPS: OVERVIEW AND PRESENT STATUS

by

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ABSTRACT

Due to various reasons the interest in the practical use of GPS has considerably increased during the last two years. The test phase has demonstrated its outstanding performance. With the differential method the relative accuracies achieve values that open its use even for the precision approach of a/c landing. The development of new techniques allows also the 3-dimensional attitude measurement and angular rate determination. Diverse civilian groups will use GPS in the future; in particular motor car drivers, geodesists, civil engineers etc. This review paper describes the present state of development and discusses the various practical applications.

KEYWORDS: Global Positioning System, GPS, NAVSTAR, navigation receivers, positioning, tracking, attitude and velocity measurement, angular rate determination, differential method, radio navigation.

1. INTRODUCTION

The NAVSTAR GLOBAL POSITIONING SYSTEM GPS (NAVSTAR = NAVigation System with Time And Ranging) is under development by the U.S. Government. It is managed by the U.S. Air Force Space Division, but will be used by many other organizations as well. GPS will revolutionize navigation. This technique will open many new fields of practical application in the military area as well as in the civilian domain. This becomes quite obvious considering its capability to provide for an unlimited number of users worldwide continuous navigation information, independent of weather conditions, three dimensionally, in one unified coordinate system and with a precision much better than any other system can offer.

For civil users the system will be available in Standard Positioning Service (SPS). Most probably this service will be of an accuracy of 40 m CEP (CIRCULAR ERROR PROBABILITY) which is equivalent to 100 m, 95% level of confidence (2d RMS). The final decision of the DOD regarding an intentional degradation of the performance of the SPS, which uses the C/A-ranging code (Coarse and Acquisition Code) is not yet known, or has not even been made. The Precise Positioning Service (PPS) with the P-code (Precision Code) for military users will offer 15 m SEP (SPHERI CAL ERROR PROBABILITY), 0.1 m/s rms velocity accuracy and 0.1 μs timing accuracy. No other navigational aid has comparable performances, as can be seen from table 1.

If it is sufficient to determine a position relative to a neighbouring one, the performances improve considerably. Even with SPS it is possible in the "Differential Mode" to achieve accuracies which are sufficient for aircraft instrument landing. Approximately 2 m rms error horizontally and about 0.5 m vertically can be expected. Furthermore, it is possible to use GPS-signals for precise three dimensional attitude and angular velocity measurements as well. Thus, the system can deliver the three dimensional components of the position, velocity, attitude, angular rate and time. This means, it is the most universal navigational system with superior performance compared with other existing systems. It is obvious why the DOD policy considers GPS its future radio navigation system and intends to terminate the operation of its other radio navigation systems as soon as GPS is fully operational /1/.

As regards the time schedule the deployment of the operational satellites should have started already, according to the original dates given in table 2. A delay due to the launcher problems can be foreseen. However the final operational capability might well be achieved by the end of this decade because the launch of the 18 operational satellites and the three active spares could be done relatively fast considering that sets of 3 satellites are orbiting in the same plane and could be launched as triplets. With seven launches the complete space segment would be available. Presently, we can consider the system to be still in the test and evaluation phase, as far as the segment configuration is concerned: Seven satellites can be used for navigation. They are orbiting in 2 planes of 63 degrees inclination. This present orbit configuration is shown in fig. 1. For Brussels the visibility during the months of June/July is demonstrated in fig. 2. In fig. 3 the ground tracks of the 7 satellites are drawn and the contour line of the visibility for a receiver in Belgium is indicated.

2. SYSTEM DESCRIPTION

The three main elements of the GPS are

- the satellite segment (termed NAVSTAR),
- the ground control segment, and
- the user segment.

The NAVSTAR satellites are equipped with atomic clocks and L-band transmitters for two carrier frequencies, L1 = 1.57542 GHZ (=154 x 10.23 MHz) and L2 = 1.22760 GHz (=120 x 10.23 MHz). The L1signal is QPSK-modulated with

- the pseudorandom noise sequence (PN-sequence) for the C/A-code with a chiprate of 1.023 MHz and 1 msec period,
- the P-code with a chiprate of 10.23 MHz and a period of 267 days, but a restart every week, and
- the data stream for the information about the ephemeris, the time correction and the satellite's state.

The L2-signal carries the information of the P-code and the data stream. The C/A code is used for the acquisition phase and for the civilian applications. The L2-carrier signal and its P-code are mainly necessary for the determination of the total electron content of the ionosphere, in order to calculate the propagation delay of the upper atmosphere.

All PN-sequences are unique and almost orthogonal to each other. In this manner the signals of the set of satellites can be discriminated from each other, although they are transmitted with the same center-frequencies (Code multiplexing). The PN-coding can be used for measuring the time delay between transmission of the signal from the satellite and its reception at the user's receiver by means of correlation techniques. The precision is a function of the SNR and of the integration time. It is normally in the order of 1/10th to 1/1000th of a chip length, which is roughly 1 μsec for the C/A-code and 0.1 μsec for the P-code. The corresponding measurements expressed in wavelengths of the P-code (= 29.31 m), and of the C/A-code (= 293.1 m) are in the meter and submeter ranges and well below (for the static cases of geodetic applications). The operational control segment consists of a master control station, three ground stations and two monitor stations. It monitors the satellites by means of telemetry and telecommand, determines the precise ephemeris and clock errors and updates the corresponding data dissemination message of the NAVSTARs. The user segment comprises the large community of military and civil users. Various receivers have been developed and more different types will be in the future, to meet the needs of the "customers". Officially 4 types of receivers have been developed for the military application during phase II, namely

- MANPACK version for 0 - 6 m/s^2 acceleration, with one channel,
- LOW DYNAMICS version for 6-25 m/s^2 and one channel,
- MEDIUM DYNAMICS version for 25-50 m/s^2 with two channels, and
- HIGHLY DYNAMIC version for more than 50 m/s^2 and 4 channels.

The number of channels indicates how many satellites the receiver can operate simultaneously. If the number of channels is less than 4, then the signal reception for a 3-dimensional tracking requires time-sequential operation, which causes at least 4 x 30 sec for one position determination. This disadvantage is compensated by the low cost of the one-channel receiver over a four channel version. As a compromise various time - multiplexing receivers have been developed or are under development. They are both fast and cost effective. Table 3 lists some examples of existing types of receivers. They are suitable for position and - in most cases - also for velocity determination. None of them is used yet for the attitude measurement. They are partly designed for the static or near static operation, in particular those for use in the geodetic community. Such receivers apply small bandwidths and can achieve accuracies in the dm level and well below by long term integration. Various other types of receivers will appear on the market in the near future.

2.1 POSITION DETERMINATION

The final orbit configuration of 18 NAVSTARs is shown in fig. 4. There are 6 distinct 12 hour orbits (20.160 km altitude) with inclinations of 55 degrees to the equator and 60 degrees separation to each other. Each orbit contains a set of 3 satellites, equally spaced 120 degrees from each other. At the equator, the satellite of one plane is 40 degrees apart from the neighbouring satellite of the adjacent plane; fig. 5. Because of its "12 hourorbit", the satellite passes over the same points of the earth every 23 hr 55 min 56.6 sec. The difference to the 24 hours is due to the difference between the solar and the siderial day, which is one day per year, as is well known. Thus, a satellite appears every day at a given point of the earth 4 min. 3.4 sec earlier than the previous one.

This regular configuration of the 18 satellites guarantees that at least 4 satellites are "visible" at any point in the world at any time. Each GPS satellite continously transmits ranging signals. They consist of ranging codes of "pseudorandom noise sequence" (PN-sequence) type and of data providing satellite ephemeris and clock bias information.

The basic ranging concept is shown in fig.6. We assume, that 4 satellites are in view of the user. Each satellite transmits its own characteristic PN-codes (C/A and P). The satellite clocks are synchronized to the same GPS-time. They transmit the ranging information at the same instant, according to their own atomic clocks. The transmitted PN-sequence of each satellite is known as a function of time a priori. It is, therefore, possible for the receiver to identify the various signals and their delays. This is done by correlation methods and time comparison. The time of arrival of the beginning of the PN-code is measured by correlation techniques.

Of course very precise clocks are necessary for this "one-way"ranging method. An uncertainty of 1 microsec would already reflect in a 300 m range uncertainty! The satellite clocks are stable enough, as they are cesium clocks, which will be monitored from ground. Any bias in a satellite clock will be indicated in the disseminated data stream mentioned above. On ground, the requested accuracy of the receiver clock cannot be maintained without some additional support. It is for this reason, that ranging to 3 satellites is not sufficient; 4 satellites are used for 3-dimensional positioning and estimation of the user's clock bias. The four unknowns can be solved for in the set of 4 equations:

$$R_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} + T \cdot c$$

$$R_2 = \sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} + T \cdot c$$

$$R_3 = \sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} + T \cdot c$$

$$R_4 = \sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} + T \cdot c$$

where x, y, z and T are the unknowns of the user position and clock bias. The x_i, y_i, z_i values are the position coordinates of the i-th satellite at the transmission time. The R_i values are the so-called pseudo-ranges. As "measurement values" they contain the actual range value and the range equivalent time offset. This set of nonlinear equations can be linearized under the assumption that some coarsely estimated values x_n , y_n , z_n , T (n = "nominal values") exist a priori. The difference between the actual and the nominal value is the corrective value

$$\begin{aligned} x &= x_n + \Delta x, \\ y &= y_n + \Delta y, \\ z &= z_n + \Delta z, \\ T &= T_n + \Delta T. \end{aligned}$$

This leads to the following equations:

$$R_{ni} + \Delta R_i = \sqrt{(x_n + \Delta x - x_i)^2 + (y_n + \Delta y - y_i)^2 + (z_n + \Delta z - z_i)^2} + (T_n + \Delta T) \cdot c$$

If we ignore the second order terms then we can write

$$\frac{(x_n - x_i)\Delta x}{R_{ni} - T_n \cdot c} + \frac{(y_n - y_i)\Delta y}{R_{ni} - T_n \cdot c} + \frac{(z_n - z_i)\Delta z}{R_{ni} - T_n \cdot c} + \Delta T \cdot c = \Delta R_i$$

These coefficients are the cosines of the angle between the LOS (line of sight) to the i-th satellite and the j-th coordinate and are symbolized by α_{ij}. The corresponding matrix is

$$A = \begin{Bmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} & 1 \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & 1 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & 1 \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & 1 \end{Bmatrix}$$

Then we can write in vector form

$$A \cdot x = r \qquad x = A^{-1} \cdot r$$

and the corresponding vectors are

$$x = (\Delta x \quad \Delta y \quad \Delta z \quad c\cdot\Delta T)^T$$

$$r = (\Delta R_1 \quad \Delta R_2 \quad \Delta R_3 \quad \Delta R_4)^T$$

The relationship between the pseudo- range measurement errors, corresponding errors in the user position, and the user clock bias are given by covariance matrices:

If

$r = A\cdot x + n$, n = measurement noise

with covariance $E\,(n\cdot n^T) = \sigma_r^2$

then

$$E\,(r\cdot r^T) = A^{-1}\,E\,(n\cdot n^T)\,A^{-T} = \sigma_r^2\,(A^T\cdot A)^{-1}$$

The diagonal elements of $(A^T\cdot A)^{-1}$ are weighting factors of position and time error. They describe the influence of the geometry to the actual geometric error:

- GEOMETRIC DILUTION OF PRECISION

  $\mathrm{GDOP} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2 + \sigma_{tt}^2}$

  GDOP * 1 σ_r = 1 SIGMA TOTAL ERROR

- POSITION DILUTION OF PRECISION

  $\mathrm{PDOP} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2}$

  PDOP * 1 σ_r = 1 SIGMA ERROR IN THE 3 SPACE COORDINATES

- HORIZONTAL DILUTION OF PRECISION

  $\mathrm{HDOP} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2}$

  HDOP * 1 σ_r = 1 SIGMA ERROR IN THE 2 HORIZONTAL COORDINATES

- VERTICAL DILUTION OF PRECISION

  $\mathrm{VDOP} = \sqrt{\sigma_{zz}^2}$

  VDOP * 1 σ_r = 1 SIGMA ERROR IN THE VERTICAL COORDINATE

- TIME DILUTION OF PRECISION

  $\mathrm{TDOP} = \sqrt{\sigma_{tt}^2}$

  TDOP * 1 σ_r = 1 SIGMA ERROR IN THE RANGE EQUIVALENT CLOCK BIAS.

We can interprete these factors of dilution with the satellite geometry. In /3/ it is shown, that the volume V of a tetrahedron (fig. 7) is reciprocal of the value of PDOP.

2.2 DILUTION OF PRECISION AND POSSIBLE SYSTEM IMPROVEMENTS

The instantaneous configuration of the GPS-satellites relative to the position of the user is of considerable influence to the actual accuracy of the point fix. This is well known from the navigation tasks of terrestrial radio navigation systems, where the angle of intersection of the two lines of position plays a similar role; fig. 8. In the case of a three-dimensional position determination with the additional time parameter, one can discriminate various measurements of "dilution of precision", as shown in chapter 2.1.These values are represented by the corresponding traces of the covariance matrices.

Fig. 9 shows the GDOP and PDOP for the final GPS-satellite configuration for various latitudes. It becomes apparent that there are critical dilutions in particular at about a latitude of 50°. In this area even during periods of good navigation the error is about 4 to 12 times larger than in other regions of good navigation. 72 areas of bad performance exist on earth at various times, four of them are very serious and repeat at the same location twice a day, lasting about 30 minutes.

Various methods can be applied to overcome this problem, which stems from the fact that instead of the originally planned 24 satellite GPS -configuration only an 18 satellite system will be realized.

- One can use a very precise clock at the receiver: Low cost compact rubidium standards are now on the market which can avoid a considerable amount of the degradation caused by clock instability.
- It is also possible to integrate GPS with other navigational aids.
- For example one can apply the GPS-navigation to the horizontal coordinates and make use of other navigational tools for the vertical component.
- One could complement the GPS configuration with a few geosynchronous satellites, which could also be of benefit for telecommunication.

2.3 IMPROVEMENT BY DIFFERENTIAL TECHNIQUES

The GPS-error budget for absolute positioning is given in table 4 for both cases; SPS with the C/A code and PPS with the P-code for actual positioning and ionospheric correction with the two carrier frequencies L1 and L2.

The budget shows, that in particular, three error sources are dominant: The errors of the ephemerides, of the clock and - in the SPS case - the ionosphere. In addition, it is important to acknowledge that dilution errors will occur as a function of the position of the user and time. This latter point will be discussed in the next chapter where we consider the other error sources and the possibility to reduce their contributions to the overall position accuracy. This can be effected in two different ways:

- One can reduce the individual errors. The orbital tracking and the GPS-time will be improved in their accuracies within the first years of operation. Various precise tracking schemes and time transfer methods are under development and test, which can lead to error reduction by a factor 5 or even better.
- The other way, which is being practiced is the differential method.

This improvement addresses to relative measurements. It compares the satellite positioning results of two locations, one of which is fixed and well known in its coordinates, the other one is unknown. The known location serves as the reference, the other one is the user's position, static or dynamic.

The basic principle is shown in fig. 10 for the simplest case. One of the receivers is located in the user's vehicle, the other at a surveyed place; for example close to the runway. This reference receiver measures the pseudo-ranges to the GPS-satellites.

These measurement results are compared with the nominal calculated distances. The deviations define the corrections to be made due to satellite ranging measurements. Although they are only the exact values for the reference point, one can assume that they are also a very good approximation correcting the actual measurement of the other receiver, provided that it is not very far from the reference point.

Two requirements must be fulfilled and three methods are possible. As regards the requirements, it is necessary that at the reference as well as at the user point a similar GPS-receiver is installed. In addition, there must be a possibility to transmit the corrective information, for example by means of a microwave data link from the reference point to the user point.

We can discriminate between the three following methods:

- At the reference point, only the 3 coordinate corrections for x,y,z are determined and are sent to the user. He should apply them to his own positioning results. If the user is close to the reference point, one can assume that the selected GPSsatellites are the same for both positions and that the biases are also approximately the same.

- In the second case, all pseudo-range data for a given set of 4 satellites is measured at the reference point. The information, including the identification of the satellites, is transmitted to the user. The user should apply the same set of NAVSTARs and can be sure that he can compensate, to a very large extent, the bias errors. The improvement will be better than in the first case.

In the third case the receiver at the reference point will not just select the most advantageous set of four satellites, but will apply all visible ones and will send the proper corrective values to the user, who can then also make benefit of the total information.

If an aircraft should land on a runway, where close to the touchdown point such a receiver is located, one should come to accuracies at the touch down point, which are almost exactly the correct values. At the most, a few meters of random errors might remain; the bias might disappear completely.

This method can be used for areas of a few tens of kilometers in diameter. The larger the distance, the smaller the correlation of the propagation effects for two positions. In general, one can assume that even for areas of one or two hundred kilometers radius, the improvement of the overall accuracy is remarkable. For SPS one could achieve precisions, which are of a few meters.

For very precise measurements, for example in the domain of geodetic applications, one could apply 4 receivers at four wellknown positions within a square of some hundred kilometers width for example. One could then determine the satellites' ephemerides and their time uncertainties extremely precise and use this corrective data within the square to determine other, unknown coordinates with a fifth receiver extremely accurate.

2.4 VELOCITY DETERMINATION

The velocity of the user with respect to NAVSTAR is determined by the range difference per time interval. Instead, one can also measure the range rate by means of the Doppler frequency shift.

There is some difference in the results of the pseudo-range vs. Doppler measurements, if the ionospheric delay is significant, because of the frequency dispersive character of the plasma. The phase velocity v_p for the Doppler effect is larger than the vacuum light velocity c, whereas the group velocity of the ranging differences is determined by the group velocity v_g, which is lower than c. The product $v_g v_p$ is equal to c .

With the two frequencies L1, L2, it is possible to determine the total electron content TEC and to correct for the deviations of these velocities. It is also possible to correct the phase velocity directly, if the two carrier frequencies and their Doppler effects are received and properly processed.

3. PRESENT STATE OF GPS-RECEIVER TECHNIQUES

3.1 TYPES OF USERS

The original intention of DOD was directed towards the development of receivers for military application. Meanwhile, many other civil applications and receiver types are also becoming of great interest:

- Receivers for motor-cars might share the largest portion of the whole market. One can imagine that the millions of cars being produced yearly can lead to a mass fabrication of integrated GPS-receivers, which cost only 500 to 1000 Dollars. This presumes of course a receiver concept with a simple frequency conversion technique, early digitization, channel multiplexing and µP- VLSI-technique.
- Reduction of costs, volume, power and mass also offers new applications in civil engineering, civil air, land and sea transportation.
- The geodetic application of the GPS-technique will revolutionize this discipline and its work. The accuracies in the range being in dm, cm and subcm region for baseline measurements with differential methods, allow to operate efficiently, without need for line of sight conditions between the baseline points. This makes the surveying technique fast, computer compatible and relatively economical.

  In most cases the C/A-code receivers will be sufficient. In geodynamic applications, where over large distances precise measurements are needed, one must have L1- and L2 frequency receivers to take into account the ionospheric delay. In addition various difference methods must then be applied to eliminate the influences of biases; fig. 11. Most of the geodetic measurements are based on carrier beat phase measurements. Some of the receivers operate with the knowledge of only the C/A code or are fully independent of the code information. These "codeless" receivers apply the phase measurements of the various clocks and carriers; table 5. In this manner it is assured, that GPS can be used for geodetic applications, even if the DOD decides to restrict the use of GPS by more intensive use of encryption and message degradation.

3.2 CLASSIFICATION OF GPS-RECEIVERS

The classification of the receivers can be done in various ways, namely with regards to the

- types of detected signals
- types of techniques, and
- technology applied.

3.2.1 CHARACTERIZATION BY THE DETECTED SIGNALS

In order to understand this classification, let's first consider the transmitted signal. In fig. 12 one can see that each satellite contains 6 navigational signal sources, namely the

- carrier with frequency L1,
- carrier with frequency L2,
- C/A ranging code modulated on carrier L1,
- P ranging code modulated on carrier L1,
- P ranging code modulated on carrier L2.
- data (navigation information)

In addition, the message about the NAVSTAR type, the ephemerides, the time bias, etc. is modulated onto the L1 as well as onto the L2 carrier.

In principle, one needs N sets of correlators, if one wants to receive the signals of up to N NAVSTARs simultaneously. As mentioned above, N = 4 is the minimum number for the threedimensional case. For economic reasons, one can also operate with less than N sets of correlators, one set being the minimum. However in this cases the signals must be either received in time sequencing, i.e. one after the other, each one for a period of a complete measurement procedure, or one can apply the time multiplexing technique, where only for very short time slots samples are taken from each satellite signal and the signal processing is performed in parallel and is finished for each signal just before a next sample is taken.

The basis processing on board can be described by the equations and the block diagram of fig. 12. The ranging codes are typical PN-codes, characterizing the individual satellite. If they are known a priori to the user, then it is possible to generate a replica in the receiver and to correlate it with the noisy received signal. By aligning the local code replica to the incoming signal, one can achieve a correlation peak. It indicates both the existence of this PN-code in the received signal and the accurate synchronization of the received signal with the internal generated replica. The internal PN-code allows the measurement of the precise propagation delay, i.e. the pseudorange equivalent time delay. Thus, the receivers task is the detection of the NAVSTAR signals by inversion of the procedures of fig. 13 and to determine the time delay by proper alignment. Depending on the type of receiver, this is done for C/A-code, or C/A- plus P-code etc.

For simplification, the procedure is shown only for one carrier frequency and for the C/A - code in fig. 14. This block diagram is, therefore, valid for the SPS - receiver. For the PPS receiver the procedures must be extended to the P - codes.

Thus, we have assumed that the PN-sequences are known to the user. As mentioned above, it is not possible for the civilian user to apply the encrypted PPS information. Therefore, the scientists looked into the possible use of the system by developing "codeless receivers". This is justified for the geodesists because for some of their applications it is not sufficient to apply the orbital information, which is disseminated via the satellites. They need more precise data. In order to acquire it, they can measure the actual satellite position as a function of time by the evaluation of the satellite signals received at 4 very precisely known positions by means of phase sensitive receivers. With this information and with a good estimation (a priori knowledge) regarding the position of the points to be measured, it is possible to use just the phase information of the various signals, in order to extract unambiguously the exact.coordinate values for points in question by means of a fifth receiver.

There are three types of codeless receivers:

- The simplest form is the "squaring receiver". Here, the received signal is squared and the carrier signal and its Doppler shift information can be detected; fig.15. The system can operate similar to the TRANSIT - receivers.
- The "delay-and-multiply receiver" can detect the fundamental (clock-) frequencies of the PN-codes. By measuring the phase shifts, one can achieve the same accuracies as in the correlation process, however it requires more time to compensate the increased noise influence. With combination of the squaring procedure and the delay and multiply technique, it is possible to

measure with two receivers the length of a baseline to fractions of a carrier - wavelength, i.e. 2/100 to 1/1000 of 19 cm. One can achieve values of cm and sub - cm accuracies in this manner.
- The "VLBI - type of receiver" ignores any a priori knowledge of the signal structure of the GPS and applies the methods in use by the radio astronomers to track radio stars. This technique is, of course, unnecessarily expensive, but operates successfully.

3.2.2 CARRIER PHASE RANGING

It should be emphasized, that for geodetic/static application the phase information of the carrier is used for the precise ranging. If one assumes, as mentioned above, that the ranging resolution is proportional to the wavelength and amounts to approximately 1/20 to 1/1000, then it becomes obvious that values of cm can be achieved. The problem of ambiguity due to carrier wavelength (λ = 19 cm) must however be solved. Recently, carrier phase positioning for taxing and flying was demonstrated by G.L. Mader /6/. The accuracies achieved were in the order of 5 cm.

3.2.3 RECEIVER TECHNIQUES

There are two different types of techniques in use:

- The analog systems, and
- the digital systems.

The original correlation receivers were based on analog techniques. The basic concept is shown in fig. 16. After preamplification and filtering, the signal is transposed into a first and second IF. Then the signal is correlated by the C/A-code (PNdespreading). The carrier is reconstituted by means of a COSTAS LOOP and finally the message is demodulated. In parallel to the despreading of the C/A-code, the same procedure can be done - with 10 times higher chiprate - for the P-code.

Due to the weak signal level, it is necessary to amplify the input signal by about 140 dB. The despreading allows to narrow the signal bandwidth to a few kHz afterwards, in order to improve the S/N factor. For static applications the final ranging loop bandwidth can be in the order of one Hz or less.

Due to the advances in the IC-techniques, it is becoming more and more common to apply digital techniques for most of the functions of the GPS-receiver. The basic concept is shown in fig. 17. Various concepts are possible. They all try to down - convert the microwave input signal as soon as possible, in order to be able to convert then immediately to the digital representation. Various A/D conversion concepts are possible. One, two and more bits per sample are in use. As regards the down - conversion, either the zero frequency or a low IF-frequency is feasible.

Most of the receivers apply time-multiplexing, in order to receive the signals from many satellites with relatively modest expense and without any delay. The sampling rate must be 20 msec /N, if N satellites should be received . This allows to pick up from any channel every message bit, as the bitrate of the message is 50 Hz. The N - channels can then be processed in parallel without loss of information. Only the S/N - ratio decreases by the factor of N. Thus, multiplexing combines most of the advantages of parallel receivers, but is almost of the cost of a one - channel receiver.

3.3 ADVANCES IN TECHNOLOGY

The advances in the receiver technology are very remarkable. We want to show this only by means of a few examples:

- TRIMBLE-Model 400 1/4 offers an ATR ARINC short module (7 x 12 x 2.25 inch) for 25 m position accuracy, 0.1 m/s velocity determination, which should be able to sample sequentially 4 satellites. Without a control head, this equipment shall cost 4.000 Dollars/unit in excess of 1000 units and shall demonstrate that technology is already presently available, which could lead to low cost units of the order of 1.000 Dollars apiece in mass production.
- COLLINS ROCKWELL has received a contract for the development of a pocket sized receiver, called SUNS (Small Unit Navigation System), which can demonstrate the possibility to produce very tiny instruments for a wide range of users.

- Almost all important motor car companies are about to support developments for navigational systems to be used like radio sets in the future. It is to be expected, that mass production involved will considerably drive the whole navigational instrumental world.

4. GPS APPLICATION TO ORIENTATION MEASUREMENTS

In most cases, GPS-receivers are used for positioning and velocity determination. Another very interesting application is its use for angle determination.

The basic principle is quite simple and is based on the interferometer techniques as shown in fig. 18. Here we assume that the baseline b is very small in comparison with the distance R to the satellite. The two lines of sight from the antennas are in good approximation parallel to each other. Therefore, we can assume the range difference to be

$$\Delta R = b \cdot \sin \phi$$

$$\Delta\phi = \frac{2\pi \cdot \Delta R}{\lambda} = \frac{b \cdot 2\pi}{\lambda} \cdot \sin \phi$$

As long as the baseline is approximately normal to the line- of - sight to the satellite, it is possible to achieve good angular definition. More precisely, it means that the angle can be measured as a function of the phase difference. We have seen above that the wavelength L1 is 19,029 cm (of L2 it is 24,421 cm). If the phase difference of the signals of both antennas can be determined to about 1 degree accuracy, then this means roughly 19/360 = 0.05 cm , i.e. half a mm. With a baseline of 5 m one can then achieve a resolution of 0.0001 rad, for 25 m one fifth of this value. The influence of the satellite's position accuracy is very modest, as can be seen from fig. 19.

There are many applications of the angular information. In an aircraft the heading information can be gained with relatively small baselines. Ships can use the three dimensional orientation for heading and for measurement of the pitch, yaw and roll variations, which is important, for example, for sea surface sounding etc. For geodesy, artillery alignment, for plate tectonic monitoring, for civil engineering tunnel planning and the like, the extremely high attitude measurement accuracy (fractions of an arc sec over baselines of several kilometers) will become increasingly important.

These extremely high values are, of course, only achievable in the static case, or can be calculated a posteriori in smooth flight, for example for photogrammetrical work (recording of direction and attitude of flight information). However even a resolution of some fractions of a degree might be of interest for cases, where nowadays a compass, a gyro or an INS is used. The importance is two-fold: The GPS-technique can be applied globally, over the poles as well as in areas of large magnetic deviations. Very important may become a new integrated navigational system approach. The possibility of updating with threedimensional information the position, attitude, velocity, angular velocity and in addition the time information allows to simplify the classical instrumentation. The simplified instrumentation may, however, also help the GPS-technique to bridge problems of shadowing effects, multipath, jamming etc. Also extremely high acceleration, which can cause tracking lag, can be avoided. It is, therefore, of particular interest for military applications to look into new concepts of integrated systems.

5. CONCLUSIONS

GPS will become a universally applicable navigational aid, which can improve any of the existing systems and can in many cases replace them. New "user groups" are envisaged at the military as well as the civil side.

GPS is considered an extremely important step towards better navigation and improvement of transportation, earth science and civil engineering. There are new possibilities for further improvement of the GPS performance and accuracy by geostationary supplementary telecommunication/navigation satellites and by support of the GPS-receivers with simplified conventional navigational tools.

REFERENCES

/1/ GLOBAL POSITIONING SYSTEM, Vol. I

Papers published in NAVIGATION and reprinted by THE INSTITUTE OF NAVIGATION, Washington, D.C. 1980, ISBN: 0-936406 - 00 - 3

/2/ GLOBAL POSITIONING SYSTEM, Vol. II

Papers published in NAVIGATION and reprinted by THE INSTITUTE OF NAVIGATION, Washington, D.C. 1984, ISBN: 0-936406 - 01 - 1

/3/ Proceed. First International Symposium on Precise Positioning with the Global Positioning System, Rockville, Md.,USA, 1985

/4/ Proceed. International Federation of Surveyors - FIG - on INERTIAL, DOPPLER AND GPS MEASUREMENTS FOR NATIONAL AND ENGINEERING SURVEYS, Munich, Germany, 1985, ISSN 0173 - 1009

/5/ NUMERO SPECIAL G.P.S

Papers published in NAVIGATION by INSTITUT FRANCAIS DE NAVIGATION, Volume 33, Numéro 129, Janvier 1985.

/6/ G.L. Mader
Decimeter Level Aircraft Positioning Using GPS Carrier Phase Measurements National Oceanic and Atmospheric Administration Rockville

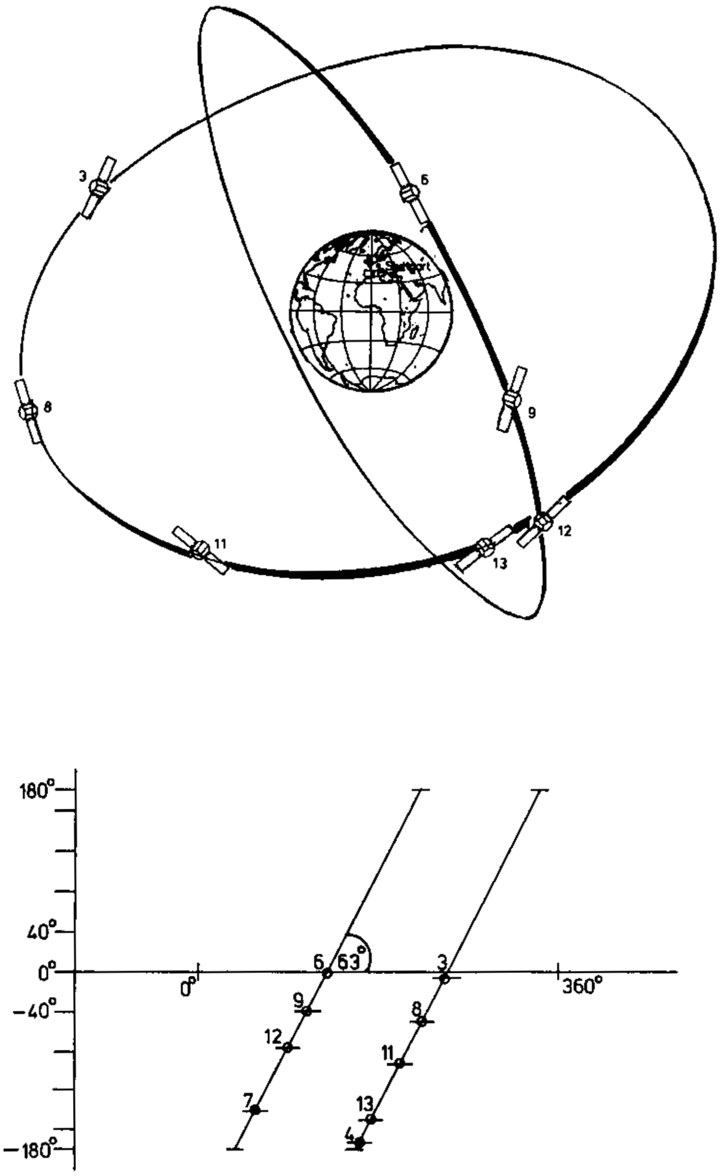


Figure 1 : Present satellite orbit configuration

```
TABLE OF VISIBILITY FOR THE DAY :  10.  6. 1986
SAT.NO.

 3      *  *  *                       *  *                             *  *  *
 6      *                       *  *  *  *  *  *                             *
 8      *  *  *  *  *                    *  *  *                             *
 9      *  *                          *  *  *  *  *  *
11         *  *  *  *  *                    *  *  *
12         *  *                          *  *  *  *  *  *  *
13                  *  *  *  *                 *  *  *  *  *


TIME    0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
```

Figure 2 : Satellite visibility for Brussels in June 10, 1986 (GMT), for July 10, 1986 the same configuration is valid if time scale is shifted by two hours to the right.

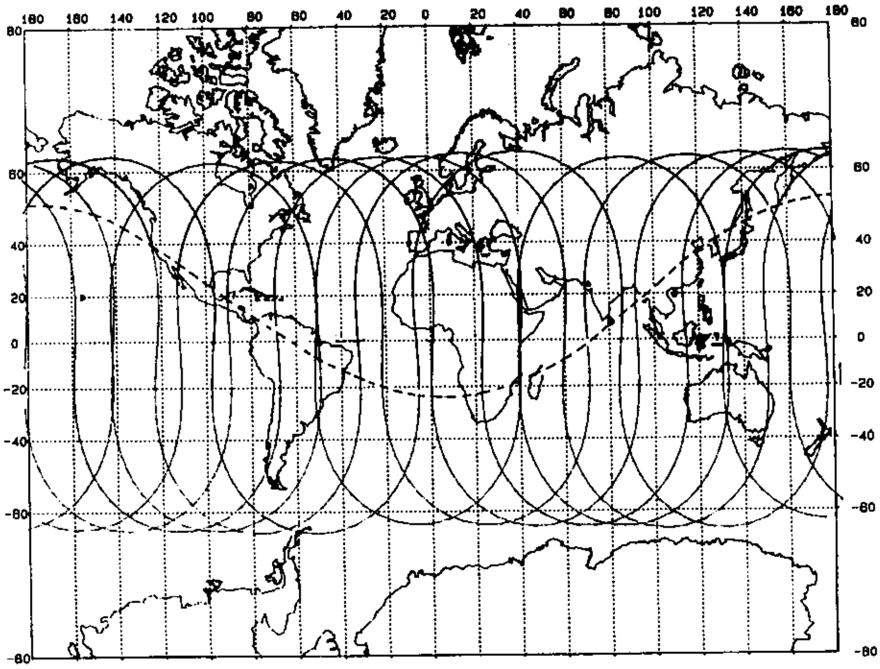


Figure 3 : SATELLITE-NO. 3,6,8,9,11,12,13 SUBSATELLITETRACK OF GPS-SATELLITES DATE : 10 6 1986

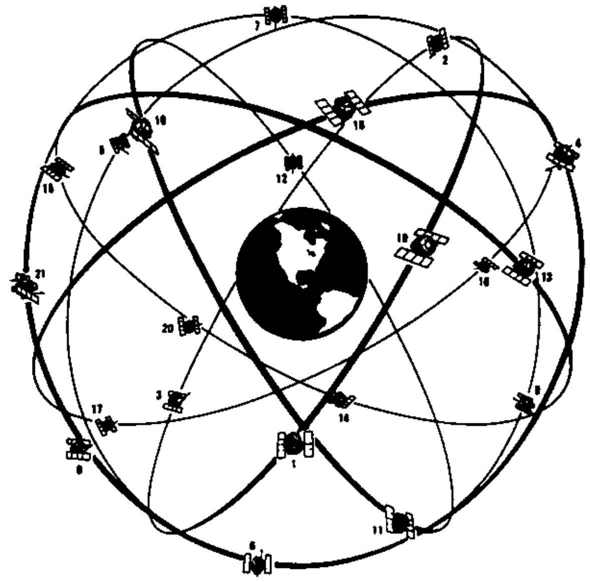


Figure 4 : Operational orbit configuration

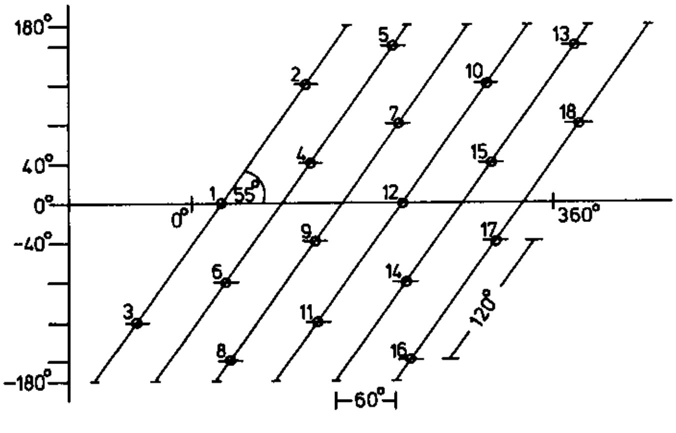


Figure 5 : Arrangement of the satellites

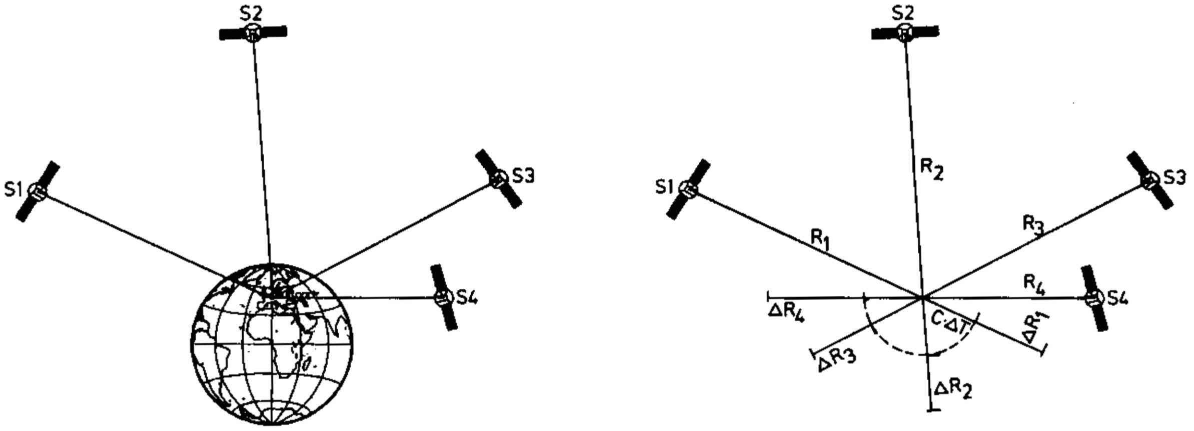


Figure 6 : Pseudo-ranging concept

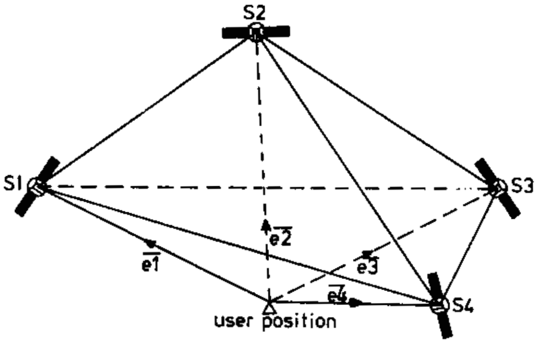


Figure 7 : The volume of the tetrahedron is proportional to 1/PDOP

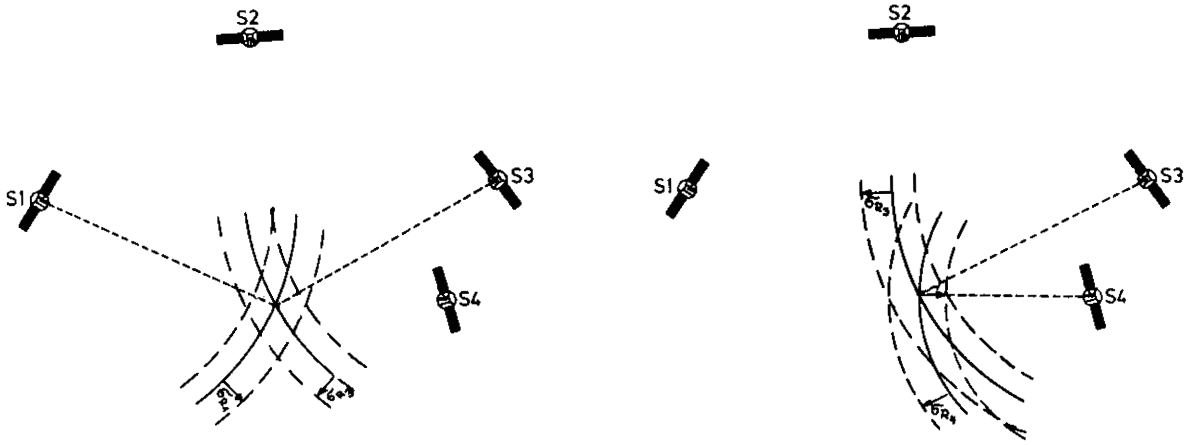


Figure 8 : Angle of intersection of the two lines of position and its influence to positioning (two examples)

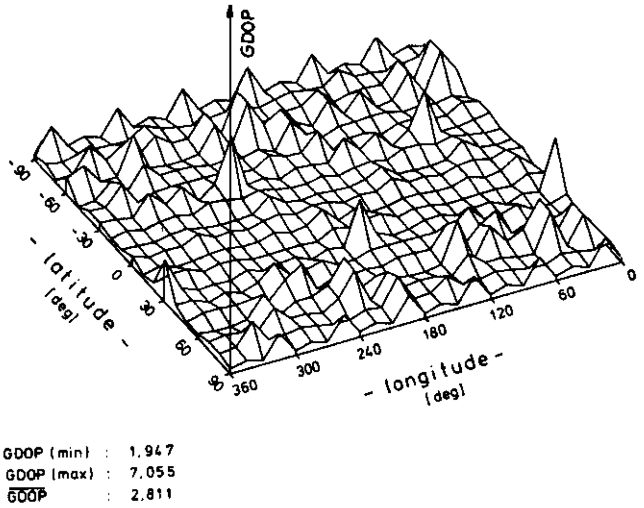


Figure 9 : Worldwide Distribution of GDOP-Values

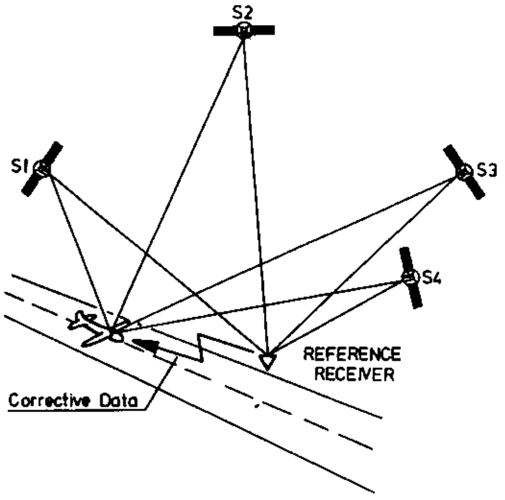


Figure 10 : Differential GPS-Measurement

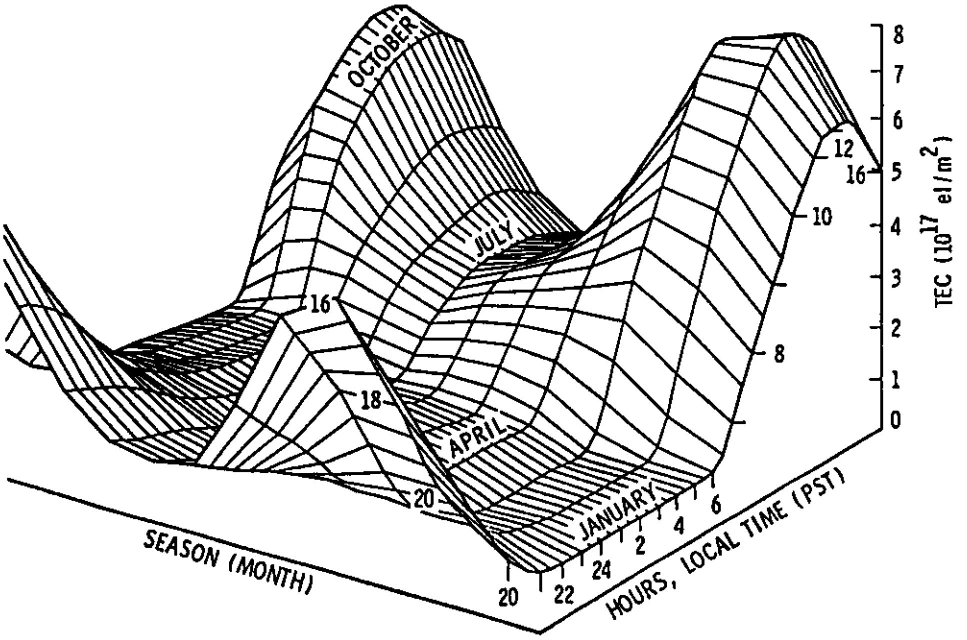
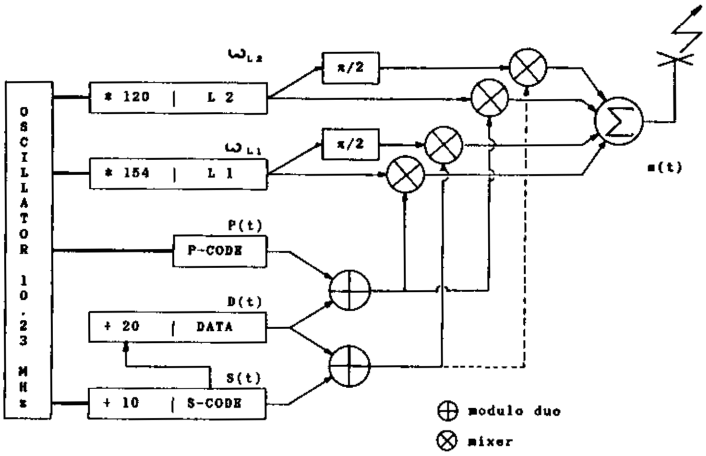


Figure 11 : 1979 Monthly Average of Total Electron Columnar Content Profile for Goldstone, Ca.



$$s(t) = A_{L1}\cdot(D(t)\cdot S(t)\cdot\sin(\omega_{L1}t + \emptyset_1) + D(t)\cdot P(t)\cdot\cos(\omega_{L1}t + \emptyset_1)) + A_{L2}\cdot D(t)\cdot P(t)\cdot\cos(\omega_{L2}t + \emptyset_2)$$

Figure 12: Satellite Signals with Block-Diagram

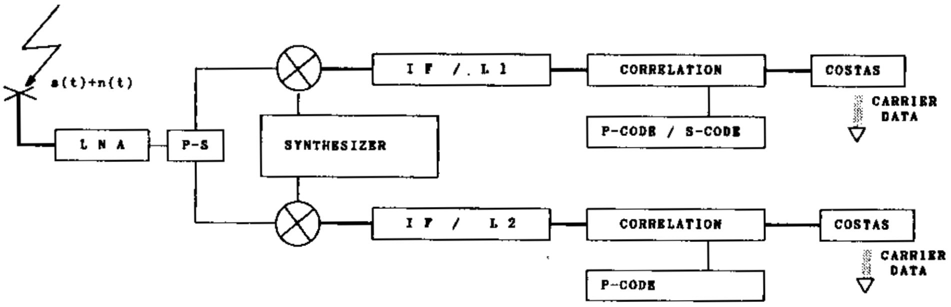


Figure 13 : Receiver Block-Diagram

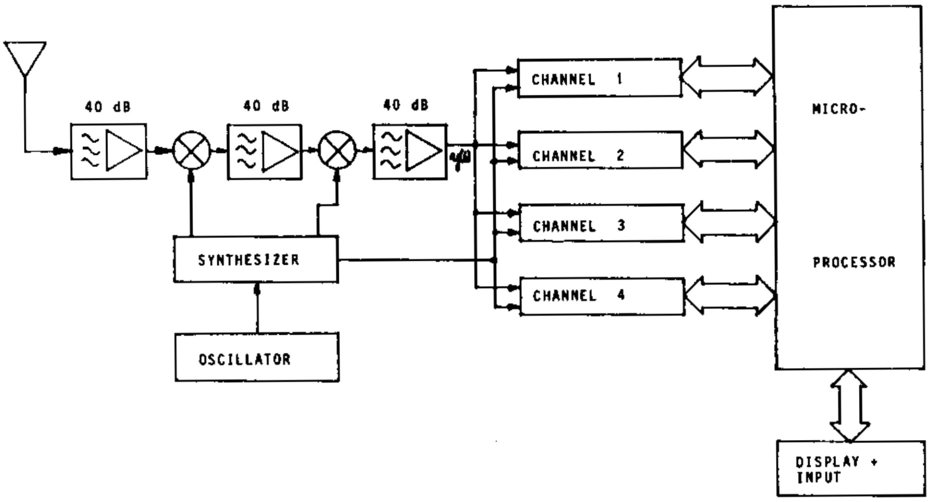


Figure 14 : SPS-Receiver Block-Diagram

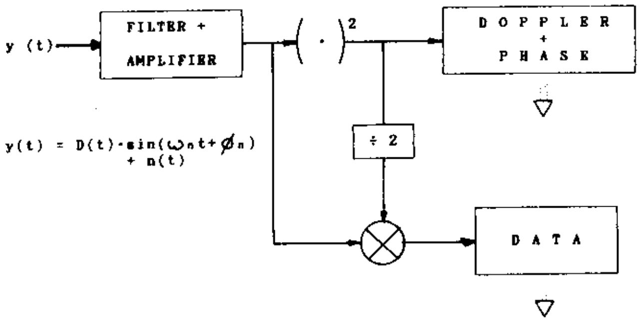


Figure 15 : Squaring Loop

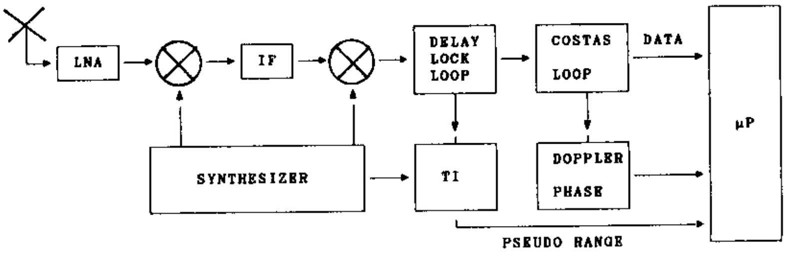


Figure 16 : Analog Receiver

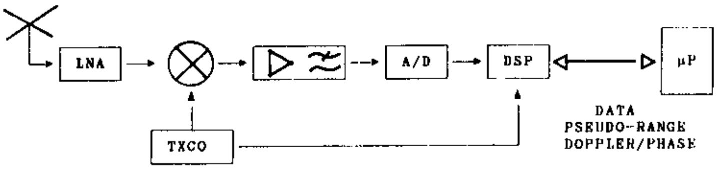


Figure 17 : Digital Receiver

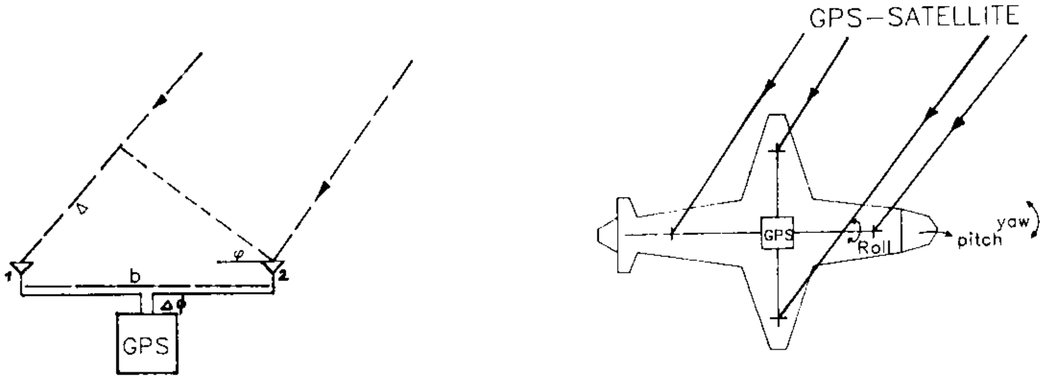


Figure 18 : Interferometric Principle for attitude control

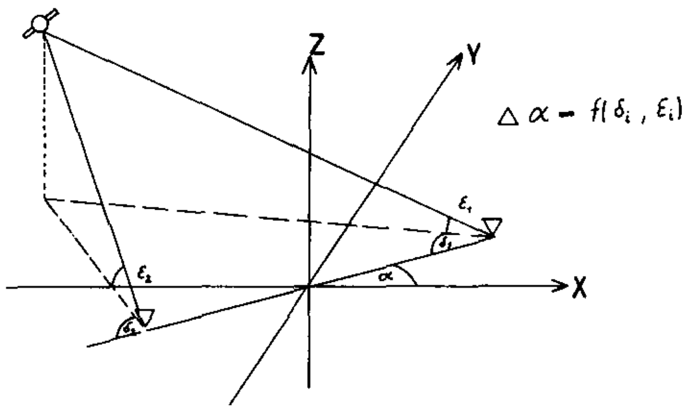


Figure 19 : Influence of Satellite Position to Orientation Measurements

SYSTEM	POSITION ACCURACY	VELOCITY ACCURACY	RANGE OF OPERATION
OMEGA	2.20 km, CEP 2-dim.	-	almost worldwide
LORAN-C	0.18 km, CEP 2-dim.	-	regional 10% of world
TACAN	0.40 km, CEP 1°	-	line of sight
ILS	5 - 10 m, 0.5°	-	line of sight
DECCA	0.20 km, CEP	-	regional less than 10%
INS	1.50 km, after 1st hour	0.8 m/s after 2 hours	near global
GPS/P	16 m, CEP 3-dim.	0.1 m/s	worldwide
GPS/CA	40 m CEP	0.5 m/s	worldwide

Table 1: Some comparisons for positioning systems

GPS PROGRAMM SCHEDULE

1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 198.

PHASE I:
CONCEPT VALIDATION PROGRAM

PHASE II: FULL
SCALE DEVELOPMENT
AND SYSTEM TEST

PHASE III: FULL
OPERATIONAL CAPABILITY

PROTOTYPE SATELLITE
DEVELOPMENT

OPERATIONAL SATELLITE
DEVELOPMENT

LAUNCH OF PROTOTYPE .... 7 OPERAT. ?? ?
SATELLITES .... SATELLITES ?? ?

TABLE 2 : TIME SCHEDULE OF GPS

RECEIVER	DESIGNATION	MEAS.	CODES	CH.	FREQU.	REMARK
JPL SERIES/SERIES X	geod./geoph.	PH , R	CR + P	6	L1,L2	hybrid
STANFORD TELEC. INC.	time/civil	PH , R	C + P	1	L1,L2	analog
COLLINS	milit.	R	C + P	4	L1,L2	an/dig
TEXAS INSTR. TI4100	civil/geod.	PH , R	C + P	4	L1,L2	dig/MX
TRIMBLE 4000A	civil	R , AR	C	1	L1	dig/MX
5000A	time/frequ.	R	C	1	L1	
MAGNAVOX X-SET	milit.	R	C + P	4	L1,12	
T-SET	civil	R	C	1	L1	
SERCEL TR5S	civil	PH , R	C	5	L1	analog
ALLEN OSBORNE TTR-5	time/pos.	R	C	1	L1	
POLYTECHNIC XR1	time/geod.	R	C	1	L1	
WILD/MAGNAVOX WM-101	geod.	R , PH	C	4	L1,L2	an/dig
JAPANES RADIO Co JLR-4000	civil	R	C	1	L1	dig/MX
SONY GPS-RECEIVER	time/nav.	R	C		L1	
LITTON AERO PROD. LGSS	civil	R , PH	C	1	L1	dig/MX
COLLINS SUNS *	milit.	R	C	1	L1	pocket sized
COLLINS NAV. TMI		R	C	1	L1	an/dig
INTERSTATE EL. ASTROLABE II	civil	R	C		L1	
CANADIAN MARCONI CMA 782	civil	R , D	C		L1	
S E L	prototype	R	C	1	L1	dig/MX
PRAKLA SEISMOS	prototype	R	C	1	L1	dig/MX

* under development for Marine Corps

L1 = 1.515426 GHz, L2 = 1.2276 GHz
MX = Multiplex

Table 3

ERROR SOURCE	ABSOL. POS.	RELAT. POS.
EPHEMERIES	3.5 M	0
SATELLITE CLOCK		
BIAS	1.5 M	0
RANDOM	0.7 M	0.7 M
IONOSPHERE	4.0 M	0
TROPOSPHERE	0.5 M	0.5 M
MULTIPATH	1.0 M	1.0 M
RECEIVER	6.0 M	6.0 M
REFERENCE POINT	0	< 2 M

Table 4: ERROR BUDGET FOR CONVENTIONAL C/A CODE RECEIVER AND DIFFERENTIAL MODE

MANUFACTURER	INSTRUMENT	MEAS.	ACC.	CODES	FREQ.	REMARK
MACROMETER INC.	MACROMETER V-1000	PH	1-5 CM		L1	260000$
JPL	SERIES-X	PH	1-2 CM		L1,L2	RESEARCH
ISTAC INC.	ISTAC-SERIES	PH	2-5 CM		L1,L2	

Table 5: CODELESS RECEIVERS applying phase measurement of various clocks and carriers

CR 410

INERTIE-GPS : UN MARIAGE DE RAISON ... A L'ESSAI

par

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INTRODUCTION

Depuis vingt ans environ (un peu plus pour les applications militaires, un peu moins pour les applications civiles), la navigation inertielle a trouvé place à bord des aéronefs de tous types: combat, transport, reconnaissance, patrouille maritime etc. Il y a donc vingt ans et plus que les sociétés spécialisées dans la navigation inertielle se trouvent confrontées au problème suivant: comment tirer le meilleur parti des aides radio-électriques à la navigation, pour "augmenter" si nécessaire les performances de la navigation inertielle pure. En d'autres termes, comment "hybrider" au mieux les centrales inertielles avec les aides radio-électriques existantes ?

Cette question connait un regain d'actualité chaque fois qu'un nouveau type d'aide radio-électrique est mis en service, c'est à dire tous les 7 à 10 ans, au cours des 20 à 25 années passées: nous nous référons aux cas de la navigation par satellites Transit, puis par émissions très basses fréquences OMEGA, enfin par satellites NAVSTAR (1). Si, à ces moyens "nouveaux", on ajoute les moyens plus classiques tels que VOR/DME, TACAN, LORAN C, voire ILS pour la phase approche, cela fait toute une panoplie d'aides radio-électriques dont il est maintenant possible de dire comment elles se marient avec la navigation inertielle. Et grâce à cette expérience passée, il est peut-être possible de mieux apprécier ce que pourra apporter le GPS.

Le GPS, en 1986, est justement à mi-parcours de sa "montée en puissance". Les données expérimentales, moyennant des extrapolations raisonnables, sont maintenant suffisantes pour qu'on puisse prédire s'il fera bon ménage avec la navigation inertielle. Le pronostic, en ce qui nous concerne, est bon. Meilleur en tout cas qu'il ne fut pour le VOR, l'OMEGA, ou même l'ILS. Ce qui n'exclut pas un certain nombre de problèmes que nous avons recensés dans cet article. En d'autres termes, l'inertie et le GPS semblent former le couple le mieux assorti que l'on ait vu depuis longtemps. Mais des différences d'humeur subsistent.

---

(1) On peut ajouter à cette liste un moyen radioélectrique très particulier de positionnement géographique: le radio-altimètre utilisé conjointement avec une carte d'altitudes numérisées de terrains et avec la navigation inertielle, dans la technique dite de "corrélation d'altitude" ("terrain contour matching"). Pour les applications militaires air/sol, ce moyen est très concurrentiel vis à vis du GPS, comme il apparait dans la suite de l'article.

1- RAPPELS SUR LES CARACTERISTIQUES DES CENTRALES INERTIELLES

Voir tableau 1, récapitulatif.

1.0- Centrales inertielles en tant que références cinématiques

Il existe un domaine où la cohabitation des centrales inertielles et du GPS ne pose aucun problème, et peut même au contraire en résoudre certains. C'est celui de l'élaboration des paramètres cinématiques du porteur: attitude, route suivie, cap, angle de dérive, vitesses angulaires et accélérations linéaires.

Il ne se pose pas de problème concernant l'élaboration des vitesses angulaires accélérations linéaires, cap, route suivie et angle de dérive dans la mesure où le GPS ne peut y apporter aucune contribution, laissant le champ libre à la centrale inertielle, que cette dernière soit très performante ou qu'il s'agisse d'une centrale "pseudo-inertielle" (2)

Il ne se pose pas de problème concernant l'élaboration des angles d'attitude, par une centrale inertielle performante, qui les fournit avec une précision de quelques minutes d'arc sans aucune aide externe. **Il y a même synergie** si, utilisant une centrale "pseudo-inertielle" (2), on essaie d'améliorer ses informations d'attitude jugées marginales. Le GPS peut alors ramener dans les "quelques minutes d'arc" une précision d'attitude qui, pour une centrale "pseudo-inertielle" livrée à elle-même, atteindrait typiquement 0,3 à 0,5 degré pour des gyroscopes de classe de dérive 0,1 à 0,3 °/h. Grâce au GPS, l'utilisateur d'angles d'attitude aura donc le sentiment de disposer d'une "véritable" centrale inertielle... pourvu que l'aide du GPS ne vienne pas à faire défaut pendant plus de 15 à 30 minutes.

Nous avons placé en tête ces considérations sur les centrales inertielles en tant que références cinématiques pour ne plus avoir à traiter ensuite que de la cohabitation de l'inertie et du GPS dans le domaine de la navigation (au sens de la connaissance de la position, et de la vitesse par rapport au sol). Pour en finir avec ces considérations préliminaires, tirons la première conclusion qui s'impose: c'est que même si la cohabitation de l'inertie et du GPS était très mauvaise pour ce qui est de la navigation, ils n'en resteraient pas moins l'un et l'autre à bord, se tournant le dos et s'occupant chacun de sa spécialité incontestée. Mais rien ne permet de prédire une pareille bouderie, bien au contraire.

---

(2) Une centrale sera dans cet article considérée comme "inertielle" de plein droit si sa dérive est de l'ordre de, ou meilleure que 1 Nm/h typiquement, en fonctionnement entièrement autonome (recherche initiale de cap comprise, au moyen d'une mécanisation en gyrocompas). Le domaine "pseudo-inertiel" commence quelque part entre 3 et 10 Nm/h obtenus dans les mêmes conditions, c'est à dire dans une gamme de précision telle que le recours à une aide radioélectrique à la navigation est pratiquement indispensable pour borner les erreurs sur un long terme de une à quelques heures. Pour les considérations performances/contraintes opérationnelles/coûts relatives à ces centrales et à leurs "hybridations", on peut se reporter aux "AGARD Conference Proceedings No 360", "Cost Effective and Affordable Guidance and Control Systems", Session 1, "Analyse combinatoire performances/coûts d'un système autonome de navigation pour aéronefs".

1.1- Centrales inertielles classiques (à axes de cardans)

Pour ce qui touche à la fonction navigation, les caractéristiques des centrales inertielles classiques sont bien connues, et la description de leurs erreurs instrumentales (erreurs des capteurs) et des conséquences de ces dernières en fonction du temps (dynamique de propagation des erreurs) se fait de façon très fiable au moyen de modèles "robustes". Autrement dit, bien que les centrales inertielles dérivent, elles n'en sont pas moins fidèles, d'humeur égale, et leurs travers peuvent être corrigés sans drames par un partenaire complémentaire, caractérisé par une grande stabilité et une bonne précision "au long cours", et auquel elles pourront pardonner quelques incartades de courte durée (c'est à dire dans la partie haute du spectre de fréquences).

D'une manière plus quantitative, on peut dire ce qui suit de la centrale inertielle classique:

- les erreurs de ses capteurs ("erreurs instrumentales") peuvent se résumer à six valeurs, dont trois représentent les dérives résiduelles de gyroscopes et trois autres les "biais" résiduels (erreurs de zéro) des accéléromètres. Ces six valeurs sont modélisées chacune comme une constante, invariable au cours du fonctionnement du système, mais ré-initialisée par "tirage au sort" à chaque nouvelle mise en route. Ce sont donc des constantes aléatoires variant "de jour à jour". Cette variation de jour à jour est supposée gaussienne, et de variance connue, ce qui permet d'initialiser la matrice de covariance du filtre de Kalman par lequel on va "hybrider" la navigation inertielle avec l'aide radio-électrique. (3) (4)

---

(3) On a ici supposé que la centrale inertielle assure la navigation horizontale et verticale ce qui, pour cette dernière, n'est possible qu'en "hybridant" avec une altitude barométrique ... ou GPS (la mécanisation en "inertie pure" est divergente à moyen terme, c'est à dire sur une durée représentant une fraction d'heure).

(4) On peut naturellement représenter les erreurs instrumentales par des modèles plus "sophistiqués", tels qu'un bruit blanc intégré (cheminement aléatoire) ou filtré par un passe-bas, ou introduire un vecteur d'état plus complexe pour englober d'autres termes d'erreurs (facteurs d'échelle etc), mais cela ne change rien de fondamental en ce qui concerne l'hybridation inertie/GPS.

- la traduction de ces erreurs instrumentales en erreurs de vitesse et position de la centrale inertielle, croissant au cours du temps, est décrite par un ensemble d'équations différentielles dont le vecteur d'état est d'ordre 9. Tous les coefficients de ces équations différentielles (termes de la matrice dynamique qui les représente) sont quasi-statiques, ne variant de façon significative que sur des durées se chiffrant en heures. Ceci est une particularité des centrales classiques à cardans, par opposition aux centrales "strap down" dont il est question plus loin, et pour lesquelles la matrice dynamique est beaucoup plus "mouvementée", car un certain nombre de ses termes dépendent des attitudes de l'aéronef, susceptibles de variations rapides.

- tout ceci aboutit, pour les centrales inertielles classiques, à des sorties de vitesse/sol extrêmement "lisses", où il n'existe pratiquement pas de "bruit" pour les fréquences "élevées" correspondant à des périodes inférieures à 30 minutes (la première "raie" perceptible se situe vers la période de Schuler, c'est à dire 84 minutes environ). Il en va de même des sorties de position, résultant de l'intégration des sorties de vitesse.

Pour fixer des ordres de grandeur, on peut donner les valeurs typiques suivantes correspondant à trois classes de précision de centrales inertielles à cardans:

	Erreur position	Erreur vitesse	Dérive gyros	Biais accéléros
* centrale "pseudo-inertielle"	6 Nm/h	8 m/s	0,06 °/h	0,0006 g
* centrale inertielle "standard"	1 Nm/h	1,3 m/s	0,01 °/h	0,0001 g
* centrale "haute précision"	0,25 Nm/h	0,4 m/s	0,003 °/h	0,00003 g

1.2- Centrales inertielles "strap down" à gyros-laser

Dans toute centrale "strap down", c'est à dire mettant en oeuvre des gyroscopes et accéléromètres liés à la structure de l'aéronef, et non pas suspendus à la cardan et stabilisés en direction, il y a des calculs numériques rapides dont les algorithmes, dits "plate-forme analytique", élaborent à partir des mesures instantanées des composants inertiels "liés", des "pseudo-mesures" d'accélérations telles qu'elles pourraient être fournies par une plate-forme à cardans qui se substituerait au bloc inertiel "strap down". En aval, les calculs sont en tous points identiques à ceux qu'effectue une centrale classique.

Ainsi, contrairement à la centrale classique dont les mesures d'accélérations sont faites selon des directions stables, et intégrées avec des cycles de l'ordre du dixième de seconde (10 Hz), la centrale "strap down" traite à une fréquence de plusieurs centaines à plusieurs milliers de Hertz des mesures accélérométriques faites dans des directions évoluant comme l'attitude de l'avion, et projetées en temps réel selon des directions stables grâce aux mesures gyrométriques. L'apparition de cette partie "haute fréquence/dynamique élevée" dans les mesures et calculs consécutifs introduit par rapport à la centrale classique les différences suivantes:

- bien qu'on puisse encore modéliser les erreurs instrumentales par 6 valeurs représentant trois dérives (gyroscopes) et trois biais (accéléromètres), comme dans une centrale à cardans, ces valeurs sont maintenant liées à des axes de mesures qui ne sont plus stables directionnellement comme dans une plate-forme, mais évoluent comme les attitudes et caps de l'aéronef. L'intégration de ces erreurs pour aboutir à des erreurs de vitesse/sol se fait donc après multiplication par des cosinus directeurs qui peuvent avoir une histoire très mouvementée. Il en résulte des erreurs de vitesse beaucoup moins "lisses" que dans une centrale à plate-forme, et de valeurs absolues plus élevées, à qualité égale de composants inertiels.

- le fait que le gyro-laser soit le capteur le plus répandu dans le domaine des centrales "strap down" (et le seul en tout cas qui entre en lice pour des précisions allant jusqu'à 1 Nm/h et même un peu mieux) ajoute une autre différence propre à ce composant: nous voulons parler de son "cheminement aléatoire" ("random walk") et des conséquences qu'il peut avoir en ce qui concerne l'hybridation inertie/radionavigation.

Sans trop entrer dans le détail du fonctionnement du gyro-laser, notamment l'existence d'un phénomène de seuil et la nécessité actuelle de le combattre par une activation angulaire mécanique ("dithering"), on peut dire l'essentiel en constatant que le gyro-laser est un générateur de bruit blanc angulaire, qui s'intègre en une dérive en forme de "cheminement aléatoire" exprimé par exemple en degrés par racine d'heure. L'originalité du gyrolaser à cet égard n'est pas le phénomène lui-même (tout, peu ou prou, est soumis à mouvement brownien, donc cheminement aléatoire...), mais son ordre de grandeur, qui est suffisant pour masquer, si on n'y prend garde, le paramètre par lequel on prétend modéliser son erreur: la dérive (ou erreur de zéro) de jour à jour.

Par exemple, un cheminement aléatoire de 0,004 degré par racine d'heure (cas d'un "*honnête*" gyro-laser), conduira à une incertitude angulaire de 0,004 degré après une heure, ou 0,002 degré après un quart d'heure. Il masquera donc l'effet d'une dérive fixe de 0,002 degré par quart d'heure, soit 0,008 degré par heure. Or, une telle dérive est déjà supérieure à ce qu'on voudrait pouvoir mesurer, pour le compenser, grâce à une hybridation inertie/radionavigation. Le cheminement aléatoire est donc un désavantage de la centrale "*strap down*", dans la mesure où il oblige à des temps d'observation plus longs si on veut identifier correctement les dérives de gyroscopes dans un filtre de Kalman inertie/radionavigation. Ceci sera particulièrement sensible pour certaines missions courtes de type militaire, telles que la défense aérienne ou l'attaque air/sol tactique.

Pour résumer les ordres de grandeur, on donne ci-après un tableau comparable à celui qui a été fourni ci-dessus pour les centrales classiques:

	Erreur position	Erreur vitesse	Dérive gyros	Biais accéléros
* centrale "pseudo-inertielle" (chemin. aléat.: 0,020 °/$\sqrt{h}$)	6 Nm/h	15 m/s	0,04 °/h	0,0004 g
* centrale inertielle "standard" (chemin. aléat.: 0,004 °/$\sqrt{h}$)	1 Nm/h	2,5 m/s	0,007 °/h	0,00007 g
* centrale "haute précision" (chemin. aléat.: 0,001 °/$\sqrt{h}$)	0,25 Nm/h	0,8 m/s	0,002 °/h	0,00002 g

On remarquera, en comparant avec le tableau correspondant relatif aux centrales classiques, que:

- la classe de précision en position est restée la même pour les trois centrales
- la *précision en vitesse* est moindre (rapport 2 environ) bien qu'on soit devenu plus exigeant pour les erreurs instrumentales (facteur 1,5 environ). Ceci résulte de la mécanisation "strap down" et du cheminement aléatoire des gyros-laser. (5)

Ce que le tableau ne dit pas, c'est que les erreurs de vitesse/sol sont non seulement plus élevées toutes choses égales par ailleurs, mais aussi plus bruitées à "haute fréquence". Alors que la première raie, pour une centrale à cardans, était vers la période de 84 minutes, on peut avec la centrale strap down trouver du bruit dans une bande *spectrale correspondant* à des *périodes* de quelques minutes, et même moins. On peut essayer de résumer ceci en considérant les dérivées des erreurs de vitesse, assimilables à des erreurs d'accélération. On arrive alors aux ordres de grandeur donnés par le tableau comparatif suivant:

	CENTRALES CLASSIQUES Classe (Nm/h):			CENTRALES "STRAP DOWN" Classe (Nm/h):		
	0,25	1	6	0,25	1	6
Erreurs de vitesse (m/s)	0,4	1,3	8	0,8	2,5	15
Erreurs apparentes d'accélérations (μg)	100	300	2000	400	1000	7000

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(5) Les cheminements aléatoires affichés dans ce tableau ont été choisis pour être homogènes avec les autres performances (dérives et biais) dans le cas de temps d'alignement relativement courts (5 à 8 minutes). Mais on peut noter en passant qu'une centrale à très bons accéléromètres et à gyros-laser très stables en dérive pourrait tomber dans la classe "pseudo-inertielle" par le simple effet d'un cheminement aléatoire capable de tout "polluer": 0,08 °/$\sqrt{h}$ par exemple (ce qui n'est déjà pas si mal...).

Dans une hybridation par filtre de Kalman, du fait des erreurs apparentes d'accélérations accrues dans les centrales strap down, la convergence du filtre sera moins rapide, et on mettra plus de temps à identifier les erreurs instrumentales de la centrale inertielle.

Notons aussi que dans ce tableau, on a fait figurer une classe "strap down haute précision", plus par symétrie avec le cas des centrales à cardans, que par référence à des équipements réellement disponibles. En effet, si la classe 0,25 Nm/h est classiquement obtenue, avec des plates-formes à gyroscopes à suspension dynamique ou électrique (on atteint même 0,1 Nm/h dans ce dernier cas), la précision de 0,25 Nm/h avec des gyros-laser reste pour l'instant un défi à relever.

2- RAPPELS SUR DES HYBRIDATIONS INERTIE/RADIONAVIGATION PRECEDEMMENT EXPERIMENTEES

L'expérience étant la mère de la sureté, on rappelle ci-après quelques précédents connus de la SAGEM en matière d'hybridation inertie/radionavigation, dont l'intérêt n'est pas négligeable pour qui s'occupe d'hybridation inertie/GPS (voir tableau 2).

2.1- Inertie/VOR-DME

C'est l'histoire d'un mariage mal assorti. La principale responsabilité en incombe au VOR. Avec une précision de l'ordre de 13 et plus, il entraine des erreurs de position supérieures à 0,4 Nm à une distance de 20 à 25 Nm. C'est déjà marginal, mais on pourrait penser que c'est suffisant pour corriger une centrale inertielle qui a dérivé typiquement de 1 Nm en une heure. Pourtant, ce n'est pas le cas. C'est que l'erreur du VOR n'est pas uniforme en fonction des radials sur lesquels on reçoit ses émissions. Ainsi, pour un avion qui parcourt 40 à 50 Nm en 5 à 10 minutes, la variation des erreurs VOR prend l'allure d'une dérive de vitesse de 0,4 Nm/(0,1 à 0,2 heure) = 2 à 4 milles nautiques par heure. C'est à dire des erreurs apparentes de vitesse nettement supérieures à celles de la centrale inertielle, bien que dans une bande de fréquence un peu plus haute (périodes de 10 à 20 minutes). Toutes les conditions sont réunies pour que le VOR "pollue" la centrale inertielle plus qu'il ne l'aide. C'est bien ce que l'on constate dans la pratique (expérience des FMS, Flight Management Systems de l'aviation commerciale).

Ainsi, VOR et inertie ne sont pas complémentaires. Le VOR peut néanmoins servir de "garde-fou" pour l'inertie. Mais ce n'est pas une réelle hybridation, au sens où le VOR aiderait à "calibrer en vol" les erreurs inertielles pour en tirer des corrections, permettant à la centrale inertielle ainsi corrigée de poursuivre avec une meilleure précision, même en l'absence de VOR. Au contraire, si on s'obstine, on appliquera à la centrale inertielle des corrections erronées qui détérioreront ses performances.

2.2- Inertie/multi-DME

C'est une combinaison gagnante. L'erreur typique du DME est inférieure à 0,2 Nm (ou 0,25 % de la distance). Surtout, elle est peu dépendante de la direction et de la distance à laquelle on se trouve par rapport à la station. Lorsque l'aéronef se déplace, cette erreur de position se traduit donc par une erreur apparente de vitesse assez faible (moins de 0,5 Nm/h). Il y a donc complémentarité par rapport à une centrale inertielle de performance moyenne (1 Nm/h). Ce serait plus marginal s'il s'agissait d'"aider" une centrale de la classe 0,25 Nm/h : on risquerait alors de se trouver dans une situation comparable à celle décrite pour le VOR.

Quelques mots sur la notion de "multi-DME", dont on trouvera les conséquences au niveau du GPS (notion de mono ou multicanal). Idéalement, on prend deux mesures instantanées de distance à deux stations DME, et on en tire un "point radioélectrique" qu'on prend comme "observation" dans le filtre de Kalman inertie/radionavigation. Mais la disponibilité de deux informations simultanées et différentes de distances DME n'est pas indispensable, du fait de la présence de la centrale inertielle.

En effet, après une première mesure de distance DME qui fournit un "lieu de position", la centrale inertielle fournit le vecteur "translation" de ce lieu, correspondant à la distance parcourue depuis par l'aéronef, jusqu'à ce qu'une nouvelle mesure DME devienne disponible (même émetteur, ou un autre) pour fournir un second lieu de position. L'intersection entre "l'ancien lieu de position translaté/inertie" et le nouveau lieu de position fournit un point "radio-inertie" utilisé comme observation dans le filtre de Kalman "inertie-radio". Cette façon de présenter les choses a surtout un objectif "didactique", car en réalité, tout ceci se trouve de façon latente et voilée dans les mécanismes d'"observation/recalage" du filtre de Kalman. Mais l'intérêt de cette présentation est de montrer un exemple très concret de synergie, dans lequel la centrale inertielle soulage le moyen radioélectrique qui lui fournit des observations de certaines contraintes "temps réel" relativement coûteuses (plus de nécessité de mesures simultanées, ou à grande cadence). La même situation se retrouve quand on transpose au cas inertie/GPS mono ou multicanal.

2.3- Inertie/Transit/Vitesse (loch ou Doppler)

La SAGEM a eu l'occasion de développer une hybridation inertie/Transit/loch électromagnétique pour servir de référence aux porte-avions de la Marine nationale française (problème de l'alignement à la mer des centrales inertielles d'avions embarqués). Ce développement s'est soldé par un succès, puisque le système, *mis en* service opérationnel en 1976, donne toujours satisfaction. Il est très instructif comme exemple de complémentarité entre navigation inertielle et radionavigation, dans la mesure où, au cours de la même période de développement, deux sources de radionavigation ont pu être comparées: *Transit et OMEGA. La conclusion qu'on a pu en* tirer est la suivante: **pour une bonne centrale inertielle, mieux vaut l'aide d'un bon point radioélectrique intermittent (Transit: un point toutes les 30 à 120 minutes) que d'un point radioélectrique permanent mais bruité "basses fréquences".**

Le Transit, système de 6 satellites mis en service par l'US Navy en 1964, puis devenu accessible aux usagers civils en 1967, est une sorte de précurseur du GPS par ses implications "technico-politiques" (accessibilité etc). On y retrouve aussi la problématique "précision/couverture/dynamique du porteur", mais avec des ordres de grandeur tels que cela constitue une sorte de "cas d'école", et presque une "caricature" du cas GPS:

- les récepteurs, comme pour le GPS, doivent être initialisés par des coordonnées géographiques approximatives

- la couverture est mondiale, comme pour le GPS, mais là encore, le lieu et l'heure de la mesure ne sont pas indifférents. Pour Transit, les "trous" temporels de 30 à 120 *minutes entre mesures sont la règle* (ils sont l'exception avec le GPS)

- lè mesure Transit, faite par effet Doppler sur l'émission d'un satellite défilant, est lente: plusieurs minutes, et même un quart d'heure, contre une seconde comme ordre de grandeur pour le GPS (mais une seconde, c'est beaucoup pour un véhicule *se déplaçant* à 500 kts)

- la précision de la mesure Transit (*200 mètres nominalement*, pour un récepteur à l'arrêt) est sensible à la vitesse de déplacement du récepteur: 200 mètres par noeud typiquement. C'est bien aussi le cas pour le GPS, ce qui amène à prévoir des variétés "basse", "moyenne" et "haute dynamique" de récepteurs. Heureusement, avec le GPS, les ordres *de grandeur sont bien moindres.*

Le cas du système hybride destiné aux porte-avions français est aussi instructif en ce qui concerne les références de vitesse utilisables pour l'hybridation. On aura noté que dans ce cas, le capteur de vitesse retenu est un loch électromagnétique, fournissant la vitesse du navire par rapport à l'eau. Les courants marins n'allaient-ils pas perturber le fonctionnement d'un filtre de Kalman dans lequel on traite des vitesses par rapport au sol ? L'expérience a montré qu'il n'en était rien, et que l'information de vitesse/mer est au contraire très profitable, du fait de la stabilité des courants marins sur d'assez grandes étendues océaniques. On ne peut pas en dire autant de certaines autres références de vitesse telles que le radar Doppler. Très valable à proximité du sol, dans l'application aux hélicoptères par exemple, le radar Doppler peut s'avérer très décevant *en* altitude (accrochages sur couches nuageuses etc). En d'autres termes,**pour une bonne centrale inertielle, mieux vaut l'aide d'une bonne source de vitesse, même intermittente, ou erronée de façon stable, que celle d'une source continue mais bruitée "basses fréquences".**

2.4- Inertie/OMEGA

Parallèlement à l'hybridation inertie/Transit mentionnée ci-dessus, et avec le même programme en vue (référence *porte-avions*), la *SAGEM* a essayé de mettre au point une hybridation inertie/OMEGA qui aurait pu être un pas de plus, soit vers la performance, soit vers la redondance. Il a fallu y renoncer compte tenu des caractéristiques fréquentielles des erreurs de l'OMEGA, car on s'est trouvé, comme pour le VOR, avec *"trop d'erreurs dans les* basses fréquences".

Cela n'enlève rien aux mérites de l'OMEGA, qui peut jouer le rôle de garde-fou par rapport à la navigation inertielle. Mais il n'y a pas entre les deux une réelle synergie. Le couple est mal assorti.

2.5- Inertie/ILS

L'ILS, on le sait, manque de redondance dans sa partie aérienne, et ses faisceaux sont par ailleurs sujets à des distorsions géométriques. D'où l'idée de lisser ces distorsions grâce aux centrales inertielles de bord, et de survivre éventuellement à la disparition des faisceaux in-extremis, par guidage inertiel (extrapolation) jusqu'au toucher et au roulage sur piste. C'est ce type d'hybridation inertie/ILS que la SAGEM a eu l'occasion de développer il y a quelques années (1976), et qui a fait l'objet d'essais instructifs, sinon couronnés de succès.

L'idée générale qui s'en dégage est la suivante: l'ILS et l'inertie sont presque complémentaires, mais pas tout à fait...si on cherche une précision de qualité métrique. Un faisceau ILS cat. III pourra par exemple avoir des distorsions, décroissant de 10 ou 20 mètres dans les cinq minutes qui précèdent le toucher des roues, à 2 ou 3 mètres dans les 20 dernières secondes. Au total, cela se traduit par des "erreurs apparentes de vitesse" de l'ordre de 10/200 = 0,05 m/s, soit 0,1 Nm/h. Et ceci dans une bande de fréquences relativement élevée (périodes de moins de 5 minutes). C'est largement suffisant pour des besoins de recalage de navigation "en route". Mais c'est marginal pour les besoins de trajectographie de qualité "métrique" tels qu'ils se manifestent en courte finale.

L'expérience s'est donc révélée instructive et pourrait avoir des résultats plus positifs avec un système radio-électrique encore amélioré, tel que le MLS.

2.6- Inertie/corrélation d'altitude

Cette technique, dite "terrain contour matching" dans les pays anglo-saxons, est exemplaire de ce que peut être une excellente synergie entre navigation inertielle et aides radio-électriques. Appliquée par la SAGEM au recalage de la navigation inertielle des avions de combat volant à basse altitude, elle a montré une bonne "robustesse", et une précision absolue comprise entre 50 et 100 mètres, qui soutient la comparaison avec le GPS en mode C/A.

L'aide radio-électrique est ici un radioaltimètre qui fournit le profil altimétrique du terrain survolé par l'avion. Il ne peut d'ailleurs le faire qu'en "s'appuyant" sur la centrale inertielle de deux façons complémentaires:

- la centrale inertielle, hybridée dans sa voie verticale par l'altitude barométrique, fournit une référence précise de niveau de vol ("flottante", en valeur absolue, mais stable à court terme), par rapport à laquelle sont "cotées" les différences de niveau du terrain défilant sous l'aéronef

- la même centrale fournit aussi les coordonnées horizontales relatives des points dont le radioaltimètre "cote" le niveau altimétrique. Les coordonnées géographiques (absolues) de ces points se déduisent de ces coordonnées relatives par une translation (erreur de navigation inertielle dans le plan horizontal)... qu'il s'agit précisément de déterminer

Cette détermination se fait par un algorithme de corrélation dans le calculateur de la centrale inertielle qui, ayant mémorisé la succession des cotes altimétriques survolées, cherche a posteriori dans une carte d'altitudes de terrain numérisées quelle est la translation de sa trajectoire horizontale supposée qui assure la meilleure corrélation avec les mesures du radioaltimètre.

On se rend compte a quel point les fonctions de la centrale inertielle et du radio-altimètre sont imbriquées, à ce stade qui consiste à obtenir une "observation" (au sens de Kalman) radioélectrique s'appuyant sur l'inertie. C'est, philosophiquement, une approche comparable à celle d'une "observation" "mono-DME/inertie", ou "GPS-monocanal/inertie" (la seule information radioélectrique ne permet pas de "faire le point", mais on y parvient par observations répétées liées entre elles par le fil d'Ariane de la trajectographie inertielle).

Naturellement, l'observation d'erreur de position inertielle une fois obtenue, on s'en sert dans le filtre de Kalman qui essaie de remonter aux erreurs de capteurs inertiels qui sont à l'origine. Typiquement, les ordres de grandeur sont les suivants:

- centrale inertielle de la classe 1 Nm/h ou mieux (l'observation serait impraticable avec une centrale "pseudo-inertielle")

- précision d'une observation d'erreur de position : 50 à 100 mètres

- espacement souhaitable des observations: variable selon la mission, mais typiquement, tous les quarts d'heure, avec dernière observation peu avant l'arrivée sur le but

Là encore, comme pour le multi-DME et le Transit, et en pensant aux contre-exemples que constituent le VOR et l'OMEGA, on peut répéter que **pour une bonne centrale inertielle, mieux vaut l'aide d'un bon point radioélectrique intermittent que celle d'un moyen de radionavigation continu, mais bruité aux basses fréquences.**

3- INERTIE/GPS : HYBRIDATIONS ET CLASSES DE PERFORMANCES

3.1- Le système GPS

Le GPS (*Global Positioning System*) est un nouveau système universel de positionnement par satellites. Etudié depuis 1973 à l'initiative de l'US Air Force, il est actuellement dans sa phase de "montée en puissance" au plan opérationnel. La constellation complète de satellites devrait être disponible vers la fin de 1989, mais les satellites déjà disponibles permettent la localisation de récepteurs variés avec la précision nominale, sous réserve de bien choisir le lieu et l'heure de fonctionnement. C'est ce qui a été fait dans les essais de couplage *inertie/GPS dont il est rendu* compte ci-après.

Le GPS permet un positionnement en 4 dimensions: latitude, longitude, altitude et temps (heure), pourvu que les émissions de quatre satellites soient captées par le récepteur, ce qui suppose la visibilité directe de ces quatre satellites. La constellation de 18 satellites (plus trois satellites de réserve, permettant de remplacer d' éventuels satellites défaillants) permet précisément cette visibilité directe en tout point du globe et à tout instant, sauf quelques "trous" spatio-temporels, notamment sur des zones méditerranéennes (une ou deux fois 30 minutes par jour, sur des zones de quelques centaines de *kilomètres*).

La position du récepteur se déduit de la mesure de distance aux quatre satellites visibles (temps de propagation des ondes) combinée à la connaissance de la position instantanée des quatre satellites (situés à 20 178 km d'altitude et décrivant leur orbite en un demi jour sidéral, soit 11 h 57 minutes, donc à *une vitesse de* l'*ordre* de 3000 m/s). La précision ultime de la position obtenue dépend principalement de la disposition géométrique relative des satellites et du récepteur. La précision pratique dépend surtout de la nature de l'émission que peut recevoir l'utilisateur, puisqu'il a été prévu deux catégories de service:

- le service "ordinaire" (SPS = standard positioning system, ou C/A = "clear acquisition" ou "coarse acquisition"), accessible à tous, et assurant une précision de 100 m à 95 % en deux dimensions (plan horizontal) et 180 m en 3 dimensions

- le service "de précision" (PPS = precision positioning system, ou "code P"), accessible avec "mot de passe" seulement, et assurant une précision de 18 m à 95 % en deux dimensions, et 33 m en trois dimensions

Le GPS est aussi en mesure de fournir, outre la position et l'heure, la vitesse du véhicule, par mesure de l' effet doppler sur les ondes reçues. Peu d'informations pratiques sont encore disponibles sur le spectre d'erreurs de cette information de vitesse, mais il est probable qu'il se situe principalement dans les hautes fréquences, donc qu'il est complémentaire de celui des centrales inertielles.

3.2- Intérêt d'un couplage inertie/GPS, *et variété des combinaisons* possibles

Voir tableau 3 (variété des combinaisons) et tableau 4 (applications envisageables).

3.2.1- L'intérêt d'un couplage inertie/GPS résulte de la bonne complémentarité des deux capteurs. En effet:

- la centrale inertielle est autonome, discrète, imbrouillable, de fonctionnement ininterrompu; les informations fournies, outre l'attitude et le cap/route extrêmement précis, sont une vitesse/sol très stable et, "en prime", la position géographique; les erreurs sur ces informations sont à variation très lente; le modèle de ces variations lentes est bien connu et robuste.

- le GPS fournit une position géographique 3D très précise; le "bruit" sur cette information est à haute fréquence; on pense qu'il en est de même pour l'information de vitesse; même si son fonctionnement peut être sujet à "éclipses", elles sont de courte durée aux yeux d'une centrale inertielle; le GPS est également discret (le véhicule porteur n'a pas à émettre) et en ce sens "autonome", bien que dépendant d'un segment spatial et terrestre conséquents; il est résistant au brouillage, quoique non entièrement "imbrouillable".

L'hybridation inertie/GPS, par les techniques de filtrage statistique (Kalman), conjugue les avantages des deux systèmes et compense leurs inconvénients. On obtient un système très précis, en position comme en vitesse, autonome au sens fort (capable de se passer au besoin du segment spatial et terrestre), fonctionnant sans interruption, et imbrouillable. Grâce à la centrale inertielle, le récepteur GPS devient moins sensible au brouillage, une fois l'"accrochage" obtenu. La présence des deux capteurs complémentaires permet non seulement de fournir des informations de meilleure qualité, mais également les indices de qualité réalistes associés (l'utilisateur sait mieux ce que vaut l'information qu'on lui fournit).

Pour obtenir le cumul des avantages de la navigation inertielle et la neutralisation de leurs inconvénients (et non l'inverse...), il faut cependant procéder à une "hybridation" avisée. Notre expérience de couplages inertiels avec une grande diversité d'aides radio-électriques, dont en dernier lieu le GPS, montre qu'une telle hybridation doit avoir les caractéristiques suivantes:

- il s'agit d'un échange **bi-directionnel** inertie-GPS

- chaque capteur préserve sa capacité de fonctionner en mode indépendant ("inertie pure", "GPS pur"), si bien qu'on peut à tout instant revenir, en "mode secours" du mode "hybride" vers l'un ou l'autre mode indépendant

- même en mode "hybride", on évite la confusion des rôles, et chaque capteur n'utilise son partenaire que pour ses bons côtés; ainsi, par exemple:

    * la navigation à l'estime, avec son caractère incrémental et ininterrompu, est assurée dans la centrale inertielle dont c'est la fonction naturelle

    * le positionnement précis est la fonction naturelle du GPS, même s'il ne peut être fourni que de façon discontinue

    * la centrale inertielle ne prend, des informations que lui envoie le GPS, que celles qui lui sont indispensables pour assurer la navigation à long terme; elle applique à ces informations des critères de validité/acceptation qui la préservent au maximum d'une possible "pollution"

    * le GPS ne prend, des informations que lui envoie la centrale inertielle, que celles qui lui sont indispensables pour mieux assurer un fonctionnement **autonome** en poursuite des satellites; il ne "ressert" pas à la centrale inertielle des informations que cette dernière a largement contribué à calculer (risque d'"autosuggestion").

Les principes définis ci-dessus, et qu'on peut résumer en parlant de "couplage lâche" entre inertie et GPS (par opposition à un "couplage serré" dans lequel on "met les oeufs dans le même panier"), sont sous-entendus dans la suite de cet article, chaque fois que l'on parle d'"hybridation inertie/GPS".

3.2.2- On a défini, dans la section 1, trois grandes classes de centrales inertielles, se subdivisant en variantes "classiques" (à cardans) et "strap down" (à gyros-laser). Concernant le GPS, deux classes de précision seront disponibles, la "courante" (code C/A, typiquement 100 mètres à 95 %) et la "haute" (code P, typiquement 20 mètres à 95 %). Concernant les récepteurs, trois variantes sont possibles: monocanal, bi-canal, cinq canaux. La différence réside dans la capacité ou non d'obtenir un point radio autonome (cas du cinq canaux, mais non des mono et bi-canal dès que la vitesse du porteur est significative), et dans la capacité à survivre à des pannes (cas du bi-canal et du cinq canaux, mais non du monocanal). En combinant tous ces cas de figure, on arriverait à un nombre de variantes respectable, dont nous n'aborderons que les plus représentatives, les autres pouvant se traiter par interpolation ou extrapolation.

3.3- Inertie hautes performances/GPS code P cinq canaux

C'est la configuration à la fois la plus performante, la plus coûteuse, et ...la plus simple à analyser et à réaliser.

Le GPS, typiquement toutes les secondes, fournit à la centrale inertielle les coordonnées géographiques et l'altitude avec une précision absolue de 20 m à 2 sigma. Notons que pour un porteur supersonique qui se déplace par exemple à 500 m/s, il faut une datation à au moins 10/500 = 0,02 seconde près si on veut tirer tout le parti de cette précision. La vitesse/sol (dans le plan horizontal et vertical) est également disponible, avec une récurrence de 1 seconde, par mesure de l'effet Doppler sur les émissions GPS reçues. C'est une situation de tout confort... pour la centrale inertielle, qui utilise comme suit les informations reçues du GPS:

- dans le plan horizontal, l'observation de position (et éventuellement de vitesse) est utilisée mais avec une récurrence nettement plus longue que ce que fournit le GPS: plusieurs secondes, typiquement (mais un pré-filtrage simple des informations GPS, avec critères d'acceptation/rejet, permet un "lissage d'entrée"). Elle entre comme observation, avec une variance de "bruit d'observation" de l'ordre de (20 m)^2, dans un filtre de Kalman très classique, où cependant les termes de covariances d'erreurs doivent être calculés avec des résolutions compatibles avec la qualité "décamétrique" recherchée (et pour les erreurs de vitesses, il s'agit de centimètres par seconde...)

- dans le plan vertical, l'observation d'altitude entre dans une boucle d'hybridation comparable à celle d'un couplage "inertie/baro-altimètre", mais là encore avec une résolution nettement accrue. Notons que l'altitude hybride inertie/GPS ne se substitue pas à l'altitude inertie/baro, et que les deux devront coexister, tant que l'inertie/baro servira au maintien des séparations verticales en aéronautique civile. Par contre, les altitudes inertie/GPS et inertie/baro pourront être éventuellement comparées... pour les besoins de la météorologie, et *l'une ou l'autre indifféremment* pourraient être utilisées si on voulait faire des observations par... corrélation d'altitudes ("terrain contour matching"), chose superfétatoire ici, sauf s'il s'agit d'éventuels relevés topographiques !

Nous n'avons pas ci-dessus précisé quelle variante de centrale inertielle hautes performances ("classique" ou "strap down") devait être couplée au GPS 5 canaux code P. La centrale "classique" est sans conteste la solution la plus rationnelle aujourd'hui. Nous avons dit plus haut que le potentiel du filtre de Kalman, dans cette configuration, était d'évaluer des erreurs de vitesse inertielle se chiffrant en centimètres par seconde, et nous avons vu dans la partie introductive consacrée aux centrales inertielles que des "bruits de vitesse" aussi faibles n'étaient aujourd'hui atteints qu'avec les meilleures centrales à plates-formes (gyroscopes à suspension dynamique, ou à suspension électrique). Mais rien n'interdit de procéder au couplage du GPS 5 canaux code P avec une centrale "strap down", qui tirera des "observations" GPS un moins bon parti que la centrale classique, sans plus. En d'autres termes, la centrale "strap down" ne sera pas tout à fait "à la hauteur" du GPS mais en tirera d'autant plus profit.

3.4- Inertie hautes performances/GPS code P mono ou bi-canal

Par rapport au cas précédent, la performance est pratiquement inchangée, mais le coût du récepteur GPS devrait se trouver réduit. Le récepteur "s'appuie" davantage sur la centrale inertielle, dans les phases de grande dynamique (virages, montées/descentes, masquage de satellites) pour procéder à son "point radionavigation". Le GPS et la centrale inertielle travaillant ici en étroite symbiose, et le récepteur GPS ne représentant par rapport à la centrale inertielle qu'un accroissement modéré d'électronique et de logiciel, la tentation est grande d'intégrer physiquement inertie et GPS dans le même boitier (voir plus loin).

3.5- Inertie moyennes performances/GPS code C/A

Il y a parallélisme presque parfait avec les configurations qui ont été considérées ci-dessus en 3.1. et 3.2. Les performances "descendent d'un cran" pour l'un et l'autre senseur (inertie et GPS), mais l'équilibre et la synergie subsistent, au niveau de précision "hectométrique" et non plus "décamétrique". Côté inertiel, la variante strap down à gyrolaser existe bel et bien, et n'est plus introduite simplement de façon académique: elle peut tirer plein parti des informations GPS, et sa qualité de vitesse/sol s'en trouvera améliorée au point de devenir comparable à celle d'une centrale classique à cardans.

Comme dit plus haut également, la tendance est manifeste d' intégrer physiquement le récepteur GPS mono ou bicanal dans la centrale inertielle, alors que le récepteur cinq canaux est précisément fait pour fonctionner de façon autonome.

C'est avec la configuration inertie moyennes performances/GPS code P et C/A bi-canal que nous avons recueilli l'essentiel de nos résultats expérimentaux, et nous renvoyons donc à la suite de l'article pour plus de détails.

3.6- "Pseudo-inertie"/GPS code C/A

C'est la configuration qui permet de maintenir en vie le concept même de "pseudo-inertie", par utilisation de l'argument périodiquement repris: "pourquoi utiliser des centrales inertielles "chères", puisque le GPS (ou, précédemment: le radar Doppler, l'OMEGA) permet de les réaliser moins performantes ?".

Ceci renvoie à un débat "performances/coûts" dont les grandes lignes ont été tracées dans un autre symposium AGARD (voir AGARD Conference Proceedings N3 360). Pour ce qui est des aspects plus spécifiquement GPS, on peut noter ce qui suit:

- une solution "pseudo-inertie/GPS" ne peut se substituer à une solution comportant une "vraie centrale inertielle" que si elle assure la continuité de performances qu'apporte cette dernière (pas de hiatus, tout au plus une dégradation lente). Cela ne semble pas totalement impossible mais la question reste ouverte pour certaines zones du globe (Méditerranée entre autres) où la couverture GPS est évanescente pendant 30 minutes à 1 heure chaque jour.

- la qualité de vitesse sol que doit pouvoir assurer l'hybridation par le GPS semble, par ailleurs, bien meilleure que ce que pouvaient apporter l'OMEGA, ou même le Doppler (cas d'anomalies provoquées par accrochage du faisceau sur couches nuageuses ou sur l'eau). Cela plaide aussi en faveur de "pseudo-inertie/GPS".

- mais si on a fait les deux pas précédents qui consistent à s'en remettre au GPS pour la continuité et la qualité de vitesse/sol, il faut alors, pour apporter un avantage net au plan économique, passer aux extrêmes, et réduire la "pseudo-centrale inertielle" à un bloc gyrométrique 3-axes, peut-être même sans accéléromètres.

On se reportera aussi au § 1.0 de cet article, pour juger de ce que le GPS peut apporter comme améliorations à une "référence cinématique" de bord. Et on constatera que si la solution "pseudo-inertie/GPS" couvre la presque totalité des besoins (en supposant une réelle continuité des "prestations" GPS), il reste encore des paramètres à obtenir (comment ?) tels que cap, route suivie et angle de dérive. C'est pourquoi il nous semble que la solution "pseudo-inertie/GPS" reste malgré tout fragile, face aux besoins système, faisant peser sur les épaules du GPS beaucoup de responsabilités (continuité, qualité de vitesse) et ne fournissant pas l'intégralité des paramètres qu'on est habitué à tirer d'une centrale inertielle au sens plein du terme.

4- COUPLAGE INERTIE/GPS : RESULTATS EXPERIMENTAUX

4.1- Historique à la SAGEM

Le premier programme aéronautique français dans lequel le GPS ait été prévu est l'avion de patrouille maritime ATL 2 (Atlantique 2ème génération), en cours de développement, et dont les premiers avions de série seront mis en service en 1989. Ces avions sont équipés basiquement de deux centrales inertielles à cardans ULISS 53, dont le format mécanique correspond sensiblement au standard "F3" (centrales inertielles pour avions d'armes), et dont les performances sont meilleures que le "1 Nm/h" classique, sans toutefois atteindre les 0,2 ou 0,3 Nm/h que la SAGEM peut proposer avec sa ligne de centrales de haute précision ULISS 60.

L'utilité d'un recours au GPS réside précisément ici dans le fait qu'on essaie de se contenter de centrales inertielles "standard", en se ménageant la possibilité de les "aider" par le GPS, **surtout dans le cas des missions de plus longue durée**. En d'autres termes, les centrales inertielles sont le moyen basique de navigation, mais le GPS leur procure un potentiel d'accroissement de performances qu'on se réserve d'utiliser ou non selon le cas (et selon la disponibilité du code P, qui n'est pas garantie à 100 % ...).

Cette approche a été définie en 1983, date à laquelle un marché d'études de sensibilité et de performances d'un filtrage inertie/GPS pour ATL 2 fut confié à la SAGEM par le STTE (Service Technique des Télécommunications et de l'Electronique de la Direction des Constructions Aéronautiques militaires). Il s'agissait dans un premier temps d'une étude de modélisation des erreurs GPS et inertielles, et de leur traitement par filtrage de Kalman. Dans un second temps, le choix d'un récepteur Magnavox, et l'enregistrement en vol de ses mesures, devait permettre de valider les hypothèses initialement retenues concernant les erreurs du GPS, et éventuellement de les ajuster. Ensuite, on passait aux essais en vol et ajustements du filtre de Kalman qui, exécuté par le calculateur de la centrale inertielle, devait permettre à cette dernière d'avoir de meilleures performances en "inertie pure" consécutive à une période de filtrage inertie/GPS de durée à déterminer (voir plus loin § 4.3). Enfin, les réglages étant optimisés, une évaluation "statistique" en vol devait intervenir sous la supervision des Services Officiels clients. Tout ce programme s'est déroulé selon l'échéancier de la figure 5, et à la date de publication de cet article, les essais finals d'évaluation en sont à leurs débuts. On notera qu'un échéancier plus serré aurait été difficile, dans la mesure où une constellation utilisable de satellites (4 satellites au moins visibles pendant des durées suffisantes) n'aurait pas été disponible de toute façon.

4.2- Propriétés des signaux GPS observés en réception

Le récepteur GPS utilisé était un bi-canal, en mode P ou C/A (les deux étant accessibles avec la performance nominale du code P, en cette période de promotion du GPS). Des observations effectuées en solo, puis en mode couplé inertie/GPS, on a pu tirer les conséquences suivantes (voir figure 6):

- le signal de vitesse/sol fourni par le récepteur GPS était trop "irrégulier" pour pouvoir être exploité au naturel. D'ailleurs, l'objet principal de notre filtrage inertie/GPS est bien d'obtenir une vitesse/sol de haute qualité, tirant parti du caractère très peu bruité de la vitesse inertielle, et de la haute précision de la position GPS. Pourtant, lorsqu'on est en vol relativement stabilisé, la précision de la vitesse/sol fournie par le GPS n'est pas sans attraits: 0,3 à 0,5 m/s typiquement. Mais les erreurs peuvent atteindre 2 à 5 m/s en cours d'évolutions, et ceci de façon prolongée, sans compter la possibilité d'"éclipses". L'utilisation de la vitesse GPS reste donc encore pour nous un sujet à explorer.

- l'information "position" fournie par le GPS se caractérise par trois modes principaux d'erreurs:

  * des erreurs en forme de "bruit blanc", tout au moins en comparaison de celles d'une centrale inertielle. C'est à dire avec un niveau suffisamment faible (valeur typique de l'ordre de 10 mètres) et un temps de corrélation suffisamment bref (moins de 60 secondes) pour que la complémentarité soit très grande avec la centrale inertielle (erreurs de valeur typique de plusieurs centaines de mètres, temps de corrélation de plusieurs dizaines de minutes)

  * des erreurs en forme d'échelons, principalement dues à une "commutation" sur les satellites sélectionnés pour faire le point. Ordre de grandeur: 10 à 50 mètres. Ce phénomène, non linéaire par nature, est extrêmement gênant pour le filtre, qu'il "induit en erreur". Il nécessite la mise en place d'un test de rejet de l'observation en entrée du filtre, si de tels "sauts" se produisent. Le filtrage est ainsi interrompu automatiquement lorsque le saut dépasse un certain seuil, le temps d'estimer la variation du biais de position GPS. Cette estimation est réalisable en exploitant la bonne complémentarité de l'inertie et du GPS.

  * des erreurs en forme de "rampes" de position, principalement dues à l'évolution de la configuration géométrique des satellites et du GDOP correspondant. Ce sont les erreurs les plus gênantes, car traduites en termes d'erreur de vitesse, elles peuvent devenir comparables aux erreurs correspondantes d'une centrale inertielle, et "dévoyer" le filtre de Kalman. Heureusement, leurs ordres de grandeur semblent tolérables (moins de 0,1 m/s habituellement) tant qu'on fonctionne avec des GDOP inférieurs à 10. Mais le danger existe pourtant, et il faut également mettre en oeuvre des tests de rejet en entrée de la centrale inertielle, suffisamment sévères pour réduire au maximum les risques de "pollution".

D'ailleurs, le récepteur GPS lui-même fournit, en même temps que l'information quantitative de position, des signaux qualitatifs de fonctionnement qu'il faut savoir utiliser à bon escient. Dans notre cas précis (voir figure 7), il s'agissait de:

- la Figure de Mérite (FOM) qui fournit non seulement un indice de qualité de la position GPS sous la forme d'un chiffre de 1 à 9 (chacun correspondant à une fourchette d'erreur de position), mais également des bits d'état de la réception GPS, et des bits de panne et de dégradation prévisible de la position (due à la constellation, à un satellite défectueux, à une trop forte corrélation inertie/GPS etc)

- l'Erreur de Position Estimée (EPE) qui est une combinaison des covariances de position du filtre GPS et de l'UERE (User Equivalent Range Error)

- les covariances d'erreurs de position brutes

- les rapports signaux/bruit des canaux de réception

La "philosophie" appliquée est qu'il vaut mieux filtrer lorsque le GPS a des performances nominales (la qualité de la vitesse/sol obtenue dans ce cas est excellente: quelques cm/s), et interrompre le filtrage dès que la précision du GPS se dégrade, ne serait-ce que de 20 m. Pour cela, compenser les sauts de biais GPS lorsque c'est possible, et reprendre le filtrage dès que possible après cette compensation, dans tous les cas où le GPS retrouve ses performances nominales.

Etant donné la cadence rapide avec laquelle les informations GPS sont fournies, les indicateurs de qualité GPS ont été utilisés de façon à effectuer une sorte de pré-filtrage inertie/GPS à haute fréquence (par rapport à l'utilisation moins fréquente qu'en fait le filtre de Kalman) pour détecter le plus tôt possible une dégradation même minime, et éviter ainsi une pollution du filtre.

Outre la vérification de l'intégrité/validité du capteur GPS, on distingue deux grandes catégories dans les tests effectués:

- ceux qui concernent le GPS: détection de sauts, rampes etc

- ceux qui sont intrinsèques au filtrage de Kalman: test de vraisemblance de l'observation en entrée du filtre, qui doit être sensiblement un bruit blanc à moyenne nulle (test à 3 sigma)

C'est la première série de tests qui a été la plus délicate à réaliser, la constellation de satellites n'étant pas encore opérationnelle et stabilisée, et les données sur le comportement du GPS (phénomènes transitoires en des endroits suffisamment variés) n'étant donc pas très abondantes. Pourtant, l'étude a montré qu'une fois bien réglés, les tests permettent un fonctionnement correct et cohérent du filtre inertie/GPS face à ces phénomènes transitoires.

4.3- Développement du filtre de Kalman inertie/GPS

Depuis la fin des années 1960, la SAGEM a développé une famille de filtres de Kalman, et en particulier des filtres "inertie/observations de position". Le filtre inertie/GPS dont il est question ici est une variante de ces derniers, caractérisée par les particularités suivantes:

- plus haute résolution des positions, vitesses, et autres paramètres du filtre, étant donné la précision demandée (décamétrique)

- problèmes de datation/synchronisation entre inertie et GPS, à soigner particulièrement pour la même raison

- algorithmes de factorisation de la matrice de covariance, assurant une meilleure stabilité et précision du filtre

La mise au point de ce filtre a commencé par une phase en centre de calcul à partir d'une simulation de navigation hybride inertie/GPS. Ce simulateur est un programme statistique de type Monte-Carlo, développé par SAGEM et comprenant:

- un générateur de trajectoire élaborant les grandeurs de référence

- un modèle de centrale inertielle aussi complet que possible du point de vue des erreurs de composants et système

- un simulateur simplifié de la constellation GPS et du récepteur (calcul du point GPS), chacun de ces segments étant entaché d'erreurs

- un modèle de navigation hybride optimale

Ce simulateur a permis d'effectuer une étude de sensibilité du filtre à certaines composantes de l'erreur de position du GPS, ainsi qu'une étude de performances (simulations statistiques du type Monte-Carlo). Dans ce dernier cas, la partie trajectoire des scenarios était identique (dynamique du porteur), et la différence apparaissait au niveau de l'enchainement des périodes de disponibilité du GPS (l'hypothèse de la discontinuité étant posée au départ). On a ainsi voulu déterminer des paramètres tels que:

- la durée minimale de filtrage pour obtenir la performance de vitesse spécifiée

- l'influence sur les performances de la répartition des périodes de filtrage au cours de la mission

- le profil de la dégradation au cours du temps des performances après disparition du GPS

A la fin de la mise au point du filtre en laboratoire, l'étude de performances a conduit aux conclusions suivantes (voir figure 8):

- avec un récepteur GPS code P, le filtrage inertie/GPS permet d'atteindre rapidement la qualité de vitesse/sol spécifiée en quelques minutes, même après une longue navigation en inertie pure; mais la "mémoire" de cette bonne qualité de vitesse est perdue aussi rapidement qu'elle est acquise, si on revient trop rapidement en inertie pure

- pour obtenir plus durablement et au bon moment la précision de vitesse/sol spécifiée, le mieux est de procéder à *un filtrage d'une durée* de l'ordre de 40 minutes juste avant la phase tactique effectuée en inertie pure

- un filtrage intervenant *en début de mission* n'apporte que peu d'amélioration en qualité de vitesse ; l'amélioration commence à devenir sensible si le filtrage intervient après une fraction significative de période de Schuler (par exemple 1 heure, la période de Schuler valant 84 minutes); le filtrage apporte l'amélioration la plus durable s'il peut s'étendre *sur plus de deux périodes* de Schuler (la centrale qui passe alors en inertie pure est presque aussi précise que si elle avait terminé depuis peu son alignement au sol)

Après cette phase de simulation, on est passé à l'écriture (en assembleur) et à la validation sur banc, du logiciel embarqué de filtrage de Kalman inertie/GPS. Le calculateur hôte, bien que de puissance relativement modeste (350 kops), n'a vu sa charge de calcul augmenter que *de 10 % environ.* Le volume additionnel de mémoire représente moins de 4 kmots de 16 bits.

4.4- Résultats d'essais en vol inertie/GPS

4.4.1- Conditions d'essais

Commencés en octobre 1985, à bord d'une Caravelle du Centre d'Essais en Vol de BRETIGNY, les essais en vol ont connu trois phases distinctes:

Première phase: Evaluation du récepteur GPS Magnavox bi-canal, mis à disposition par les services officiels fin août 1985; le récepteur est utilisé de façon autonome, pour enregistrement au sol et en vol des signaux permettant de valider et d'affiner le modèle *d'erreur* GPS *pris en compte dans* le filtre, et les réglages qui en sont la conséquence

Deuxième phase: Mise au point en vol des réglages du filtre, et surtout, des tests d'acceptation/rejet des informations GPS; vérification des performances prédites par les simulations, sur certains scenarios caractéristiques

Troisième phase: Le filtre étant réglé de façon optimale suite aux essais précédents, évaluation des performances par les Services Officiels français

L'installation d'essais en vol, conforme au schéma de la figure 9, comportait:

- un système inertiel de navigation ULISS 46 de *SAGEM, de la classe 1 Nm/h, mis en* oeuvre par son Poste de Commande et de Navigation (PCN), et relié à une centrale aérodynamique Crouzet

- un récepteur/processeur GPS bi-canal Magnavox (RPU-2) connecté à une antenne à diagramme de réception fixe, et mis en oeuvre par son Poste de Commande et de Navigation. L'assistance technique étant assurée par la société TRT.

Centrale inertielle et récepteur/processeur GPS s'échangent des informations par deux bus ARINC à 10 kbit/s. Un enregistreur et une horloge précise faisant partie de l'installation de l'avion d'essais complètent le dispositif, auquel il *faut en outre un* système de référence (en d'autres termes un "étalon" de navigation) pour évaluer la précision en temps réel. Ce système de référence est un dispositif TRIDENT III utilisant quatre balises au sol, et fournissant la position avec une erreur de l'ordre de 5 m à 1 sigma. Le même système de référence fournit, mais en temps *différé* seulement, la vitesse/sol, qui est obtenue par hybridation de la position TRIDENT et de la navigation inertielle de référence fournie par une autre centrale SAGEM, l'ULISS-45-R, qui fait partie de l'installation avion.

4.4.2- Scenarios de vols d'essais

Au 10 Juin 1986, 14 vols ont été recensés, appartenant à deux types principaux.

Type 1 : couplage inertie/GPS durant tout le vol

Il s'agit de la moitié des vols, généralement les plus courts (2 h à 3 h 30). Au retour parking, on commute la centrale inertielle sur le mode "inertie pure", et on observe l'évolution des erreurs de vitesse au point fixe.

Type 2 : couplage inertie/GPS intermittent en vol

Dans ces vols qui tentent de reproduire les scenarios d'étude, on fait intervenir le couplage à un instant donné et pour une durée donnée. Le passage en inertie pure, après filtrage inertie/GPS, se fait donc généralement en vol, et se prolonge après le retour au point fixe, comme précédemment.

4.4.3- Déroulement

Les vols dont il est rendu compte appartiennent à la phase de mise au point du filtrage, et correspondent donc à un état évolutif du logiciel qui se prête mal aux traitements statistiques : en fait, chaque vol est un cas d'espèce, nécessitant une interprétation qu'il serait trop long de développer ici.

On est donc amené à représenter les résultats de ces essais en vol obtenus en position et en vitesse sous forme de "portraits-robot", présentés sur la figure 10 et cotés de valeurs typiques déterminées d'après les derniers essais en vol et considérées comme représentatives des performances que l'on peut attendre d'un tel couplage.

4.4.4.- Résultats et commentaires

Ces résultats appellent les commentaires suivants :

- de façon générale, les essais en vol ont permis de vérifier les performances obtenues en simulation ce qui montre la qualité des simulations et la confiance que l'on peut leur accorder

- en mode survie, après 1 h 30, les performances en position (0,2Nm) et en vitesse (0,25 m/s) montrent l'efficacité du filtrage par la bonne estimation des erreurs inertielles en vol ; les performances ainsi obtenues sont au moins aussi bonnes qu'après un alignement au sol. En y ajoutant la période de navigation au sol en inertie pure, ce qui équivaut à 3 h de survie, les performances en position (0,4 Nm) et en vitesse (0,35 m/s) sont tout aussi remarquables comparées aux valeurs correspondantes en inertie pure (2,8 Nm en position ; 0,7 m/s en vitesse) ce qui représente une amélioration d'un facteur 2 en vitesse et 7 en position

- l'effet bénéfique du filtrage inertie/GPS se prolonge bien après la disparition du GPS mais on peut souligner tout particulièrement la qualité des performances dans les premières minutes de survie : moins de 100 m et 0,1 m/s après 5 mn de survie ; 180 m et 0,15 m/s après 10 mn

- enfin, les essais en vol ont montré l'excellente qualité de la position GPS à moyen et long terme mais aussi son instabilité toute relative à court terme. Sur ce point, la position hybride inertie/GPS améliore la position GPS, non pas par réduction du biais de l'erreur de position GPS mais, à court terme, par filtrage des sauts et rampes de position GPS et du bruit haute fréquence du GPS (on passe de 10-15 m à 2 m, bruit résiduel sur la position hybride)

5- INERTIE/GPS : PROGRAMMES A VENIR ET PERSPECTIVES

5.1- Programme ATL 2 (Atlantique 2ème génération)

Au-delà de la phase expérimentale dont les résultats ont été donnés ci-dessus, il est prévu pour la version opérationnelle qui entrera en service fin 1989 une configuration de système de navigation comportant:

- deux centrales inertielles ULISS 53, connectées au système d'armes par bus numérique "Digibus" à 1 Mbit/s

- un récepteur GPS bicanal, format 3/8 ATR, "dialoguant" avec les deux centrales inertielles par bus ARINC à 10 kBits/s (ARINC 575/429) fourni par la société TRT

- filtre de Kalman inertie/GPS exécuté dans les deux centrales inertielles

Il faut noter que l'ensemble d'une centrale inertielle et du récepteur GPS (même "partagé" entre les deux centrales) est considéré comme une "entité navigation" fournissant un point et une vitesse optimaux au "monde extérieur", et qu'au sein de cette entité, la ségrégation des fonctions est nette. Le GPS fournit un "point radioélectrique" lorsqu'il le peut, et on ne lui demande en aucun cas d'assurer la continuité qui est le propre d'une navigation à l'estime. La centrale inertielle, pour sa part, assure cette navigation à l'estime, et fournit en permanence une "navigation inertielle pure" non sujette à pollutions externes. En outre, elle fournit les résultats de l'hybridation inertie/GPS, et les indices de qualité de cette hybridation (1). Dans cette philosophie de fonctionnement, il est exclu par exemple que le récepteur GPS puisse fournir une pseudo-information de position qui serait le résultat de l'observation de deux satellites seulement, complétée par les informations de position inertielle: l'ensemble risquerait alors de devenir divergent par "autosuggestion".

Il est probable que cette philosophie, bien adaptée au cas des avions de patrouille, s'appliquera aussi aux futurs avions de transport ou de surveillance lointaine, quand le moment sera venu.

---

(1) L'hybridation est par ailleurs utilisée comme moyen de calibration à long terme des biais de composants inertiels, et aide à la maintenance préventive.

5.2- Inertie/GPS dans les avions d'armes futurs

Il n'est possible, à ce stade, de traiter de ce sujet que sous forme de considérations sur les architectures avioniques souhaitables en fonction des missions de ces aéronefs, et de leur accès ou non au GPS code P. En tout état de cause, une centrale inertielle au minimum, qu'elle soit de moyenne ou haute précision, équipe tous les avions d'armes modernes. Dans certains cas où la fiabilité opérationnelle est vitale (haute probabilité de réussite d'une mission, généralement air/sol), la centrale inertielle est doublée. Le mode secours, qui ne garantit pas l'exécution de la mission, mais assure le retour à la base, est assumé par l'horizon de planche de bord, et éventuellement par un couple "gyroscope de verticale/gyroscope directionnel", qu'on aurait tendance dans les solutions modernes à remplacer par une centrale "pseudo-inertielle" parfois appelée "centralette". Quels peuvent être les apports et les changements induits par l'apparition du GPS dans l'architecture ainsi décrite ?

5.2.1- Inertie moyenne précision + GPS = inertie haute précision ?

C'est la "philosophie" décrite ci-dessus pour l'ATL 2. Le problème essentiel, ici, est que "le mieux ne devienne l'ennemi du bien", au cas où l'inertie haute précision "synthétique" ainsi obtenue serait moins "robuste" que l'inertie de base. Ceci essentiellement à cause des dangers de pollution de la navigation hybride par des informations GPS marginales. Il semble donc indispensable d'organiser le logiciel de telle sorte que le mode "inertie pure" soit toujours préservé, en parallèle avec le mode inertie hybridée. Il pourra alors servir de "secours", en cas de "pollution" reconnue a posteriori. Ce type d'organisation logicielle, facile dans le cas d'une centrale inertielle à axes de cardan, demande davantage d'effort dès qu'il s'agit d'une centrale "strap down". Cela conduit en effet à dupliquer (très partiellement, cependant) l'exécution de certains logiciels rapides de la mécanisation inertielle. Mais la sécurité accrue ainsi obtenue compense largement la pénalité encourue en charge de calcul.

5.2.2- "Pseudo-inertie" + GPS = "inertie de secours" ?

Cette "équation" exprime une autre possibilité d'introduction du GPS dans l'avionique de navigation/attaque. Elle consiste à supposer que, la centrale inertielle basique étant maintenue dans sa fonction actuelle, il est souhaitable de la seconder par un "hybride pseudo-inertie/GPS" plutôt que de la doubler purement et simplement comme on aurait tendance à le faire au premier abord. La justification de cette solution doit alors provenir d'une comparaison performance/robustesse/coût par rapport à la solution basique à deux centrales (voir § 5.4. ci-après). Par "robustesse", il faut entendre principalement l'aptitude de la centrale "pseudo-inertielle" à résister, elle aussi, à une "pollution" par le moyen de radionavigation. On peut penser que le risque est ici plus faible qu'avec une centrale inertielle vraie... car il faudrait que le GPS devienne bien mauvais pour ne plus être en mesure d'apporter une aide à la centrale "pseudo-inertielle". Néanmoins, nous pensons qu'il serait intéressant, même dans ce cas, de préserver dans le logiciel de cette dernière un mode "inertie pure".

5.2.3- Combinaison des approches précédentes

Dans un avion doté d'une centrale inertielle et d'une "centralette", il est naturellement possible de réaliser l'hybridation de l'une et de l'autre, ce qui rend disponibles, par ordre de performances décroissantes:

- la performance maximale, par hybridation d'une centrale inertielle hautes performances et du GPS code P

et en secours

- la haute performance, soit en inertie pure, soit en inertie moyenne hybridée
- la moyenne performance, soit en inertie pure, soit en "centralette" hybridée
- la performance de type "pilotage", par la "centralette" non hybridée

5.3- Cas de l'aéronautique civile

C'est ici qu'est apparu le premier "standard" régissant l'intégration inertie-GPS, puisque la recommandation ARINC 738 offre la possibilité d'un équipement ADIRS (Air Data Inertial Reference System) dans lequel une centrale inertielle moyenne précision à gyros-laser est capable d'accueillir les fonctions anémo-barométrie et récepteur GPS. Rien n'est dit cependant sur la solution à adopter "pour action":

- soit il s'agit d'un récepteur GPS complet "déporté" (probablement à proximité de l'antenne), dialoguant avec le boitier ADIRS par lignes bus numériques.

- soit il s'agit simplement de l'antenne et de son électronique immédiatement associée, envoyant leurs signaux vers un jeu de cártes "récepteur GPS" implanté dans le boitier ADIRS

Tout ceci en est au stade de provisions de fonctions et d'espace, car le système GPS est encore loin d'être considéré comme autre chose qu'un "appoint" éventuel par les compagnies aériennes et par l'organisation de l'aviation civile internationale. Pourtant, c'est ce type d'équipement qui se prête le mieux aux analyses préliminaires que l'on peut faire des aspects performances/coûts d'une association inertie/GPS (voir ci-après). Concernant les redondances, trois boitiers ADIRS sont prévus dans chaque avion, donc trois récepteurs GPS incorporés sont possibles, mais le nombre d'antennes et d'électroniques associées sera probablement plus limité.

5.4- Aspects performances/coûts

Ce point a été abordé d'une manière générale et paramétrique dans un article paru dans les "AGARD Conference Proceedings No. 360", sous le titre "Analyse combinatoire performances/coûts d'un système autonome de navigation pour aéronefs". Nous donnons ci-dessous quelques valeurs numériques qui permettent d'utiliser l'article cité pour le cas particulier du couplage inertie/GPS.

Deux cas de base s'offrent à l'analyse:

5.4.1- Systèmes militaires

On peut considérer une configuration de départ comportant:

- une centrale inertielle correspondant plus ou moins au standard "F3" (3/4 ATR environ), quelles qu'en soient les performances

- une "centralette" de la classe 5 à 10 Nm/h, dans un volume identique au précédent, ou bien sensiblement moitié

- un récepteur GPS bi-canal, implanté dans un boitier 3/8 ATR

L'article des AGARD Proceedings N° 360 permet de situer la centrale inertielle et la "centralette" en rapport performances/volume/coût. Il suffit, pour compléter le tableau, de dire que le coût d'un récepteur GPS tel que spécifié ci-dessus se situe à un niveau compris entre 20 % et 50 % du coût d'une "centralette".

5.4.2- Systèmes civils

La configuration de base est celle d'un ADIRS incluant la totalité des cartes électroniques d'un récepteur GPS bi-canal code C/A (sauf cartes asociées à l'antenne). On pense dans ces conditions que l'adjonction de la fonction GPS augmente de 15 % à 30 % le coût de l'ADIRS de base, sans GPS.

Classe de performances des différentes centrales inertielles

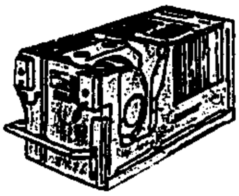
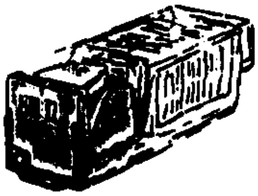
Type de centrales inertielles		Pseudo inertielles	Standards	haute précision
Centrales inertielles classiques 	position	6 Nm/h	1 Nm/h	0.25 Nm/h
	vitesse	8 m/s	1.3 m/s	0.4 m/s
Centrales strapdown à gyros-laser 	position	6 Nm/h chemin. aléat. 0.02 °/√h	1 Nm/h chemin. aléat. 0.004 °/√h	0.25 Nm/h chemin. aléat. 0.002 °/√h
	vitesse	15 m/s	2.5 m/s	0.8 m/s

TABLEAU 1

SYNERGIE DES MOYENS DE RADIONAVIGATION AVEC L'INERTIE

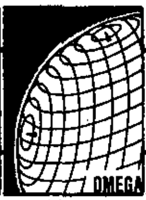
HYBRIDATION INERTIE							
SYNERGIE	MAUVAISE	TRES BONNE	BONNE	MAUVAISE	BONNE	TRES BONNE	TRES BONNE
CLASSE DE PERFORMANCES DE L'HYBRIDATION	☒	100 a 200m 0,2 a 0,4m/s	200 a 1000m	☒	2 a 10m 0,05 a 0,2m/s	50 a 100m 0,28m/s	15 a 100m 0,2m/s

TABLEAU 2

COMBINAISONS INERTIE/GPS

			1-2 CANAUX		5 CANAUX	
			C/A	P	C/A	P
	AUTONOMIE GPS		NON	NON	POSSIBLE	POSSIBLE
CARACTERISTIQUES SYSTEME INERTIEL	CLASSE 6 NM/h	PLATE-FORME	POSSIBLE (1)	MAL ASSORTI	COUTEUX ET MAL ASSORTI	
		STRAP-DOWN				
	CLASSE 1 NM/h	PLATE-FORME	OPTIMAL	OPTIMAL(2)	COUTEUX (PRIX/PERFORMANCE)	
		STRAP-DOWN	OPTIMAL(3)	SUB-OPTIM.		
	CLASSE 0.25 NM/h	PLATE-FORME	ACCEPT.	OPTIMAL(4)	COUTEUX	"RICHE"(4)
		STRAP-DOWN		HYPOTHETIQUE		

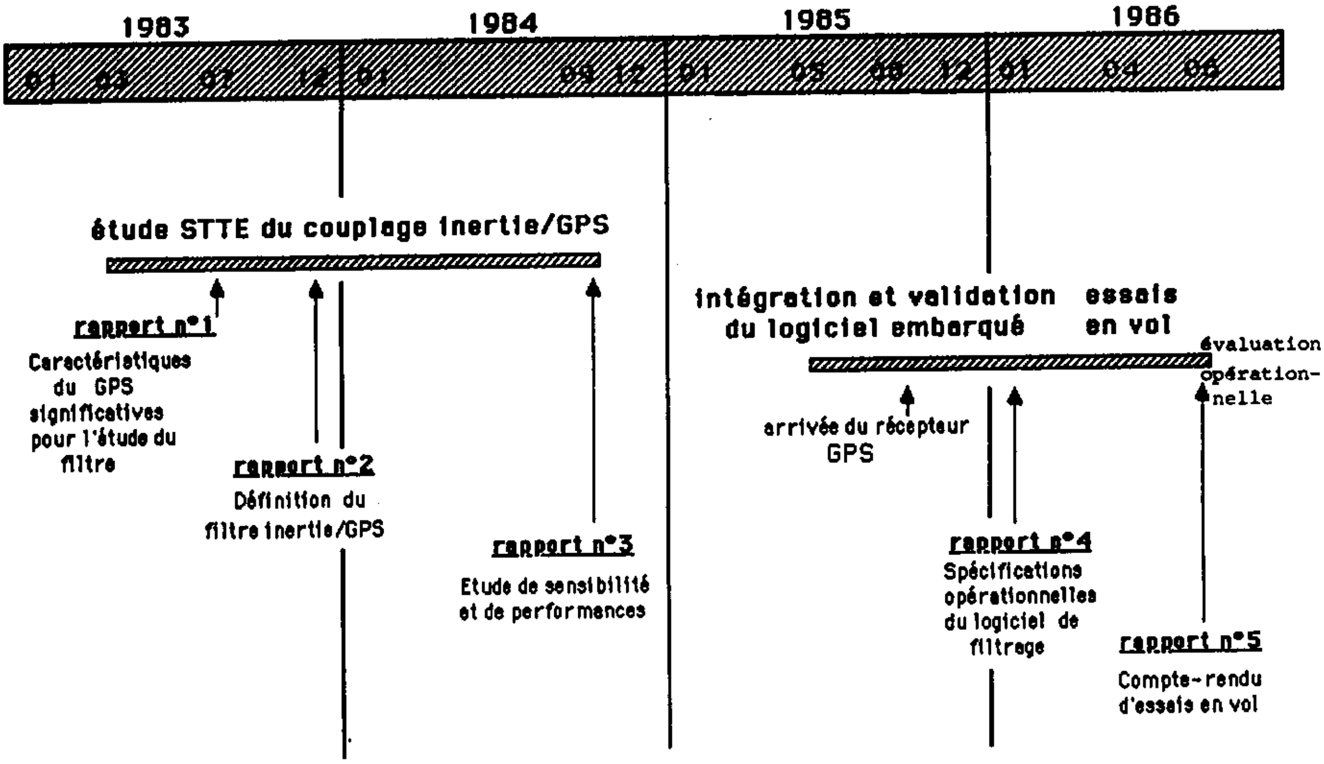
(1) PRECISION 100m, 3m/s, MAIS "ECLIPSES" POSSIBLES
(2) PRECISION 20m, 0.3m/s, MEME SI GPS INTERMITTENT
(3) PRECISION 100m, 0.6m/s, MEME SI GPS INTERMITTENT
(4) PRECISION 20m, 0.15m/s, MEME SI GPS INTERMITTENT

TABLEAU 3

Applications inertie / GPS possibles

	GPS monocanal C/A monofréquence	GPS bicanal monofréquence C/A bifréquence bicode	GPS 5 canaux bifréquence bicode
Strapdown bas de gamme (GSD) Perf: 3 à 10 Nm/h	hélicoptère	hélicoptère ou superflu	☒
Strapdown gyrolaser Perf. civile : 0.7 Nm/h	aviation civile	aviation civile	☒
Perf. militaires 0.7 à 1 Nm/h	transport/patrouille	transport / combat polyvalent	combat/applications air/sol précises
Plateforme inertielle 1 Nm/h , 1 m/s	transport/patrouille	transport / combat polyvalent	combat/applications air/sol précises
Plateforme inertielle 0.3 Nm/h 0.5 m/s	☒	transport / combat polyvalent	combat/applications air/sol précises

TABLEAU 4



Planning de developpement d'un couplage prototype inertie / gps

FIGURE 5

ERREURS TYPIQUES DU SIGNAL GPS

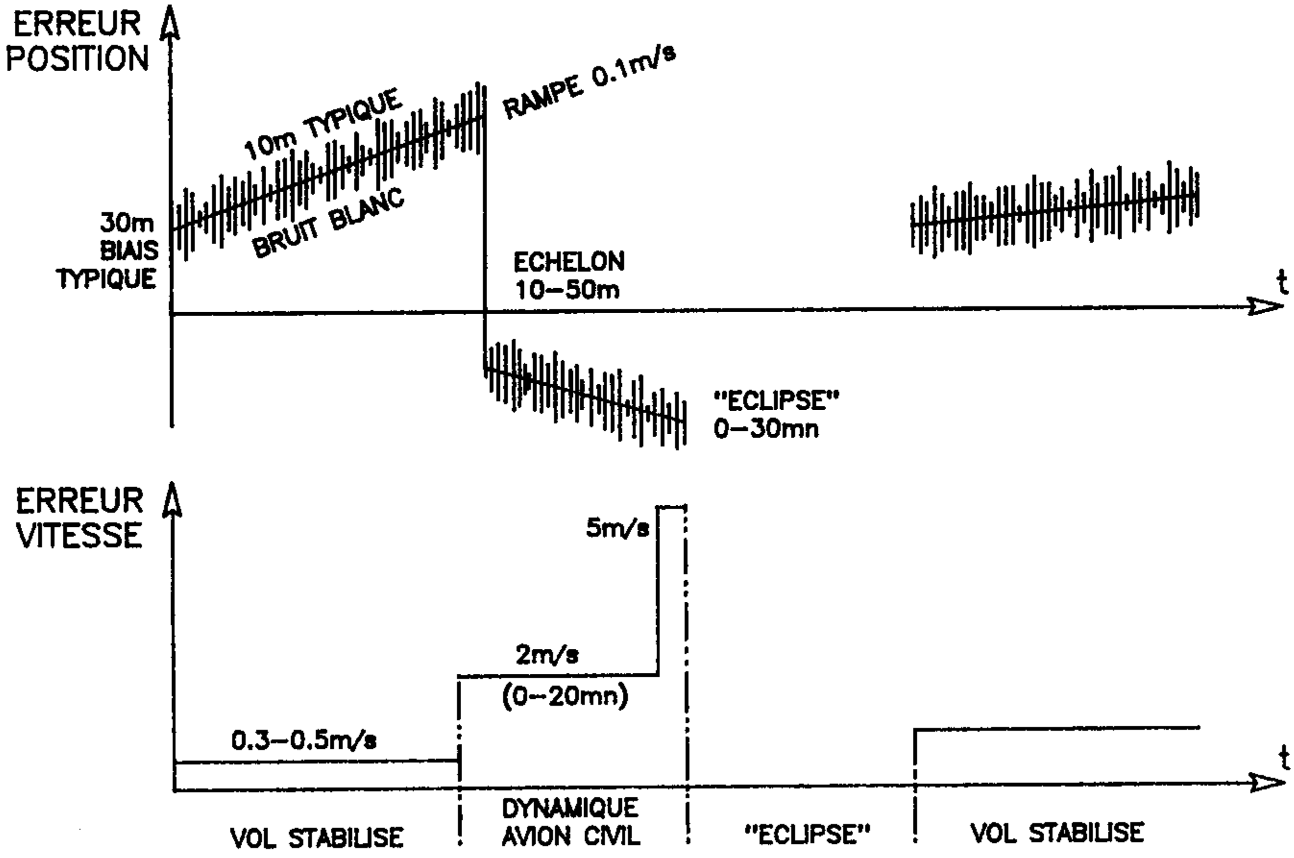


FIGURE 6

Interface Inertie / GPS

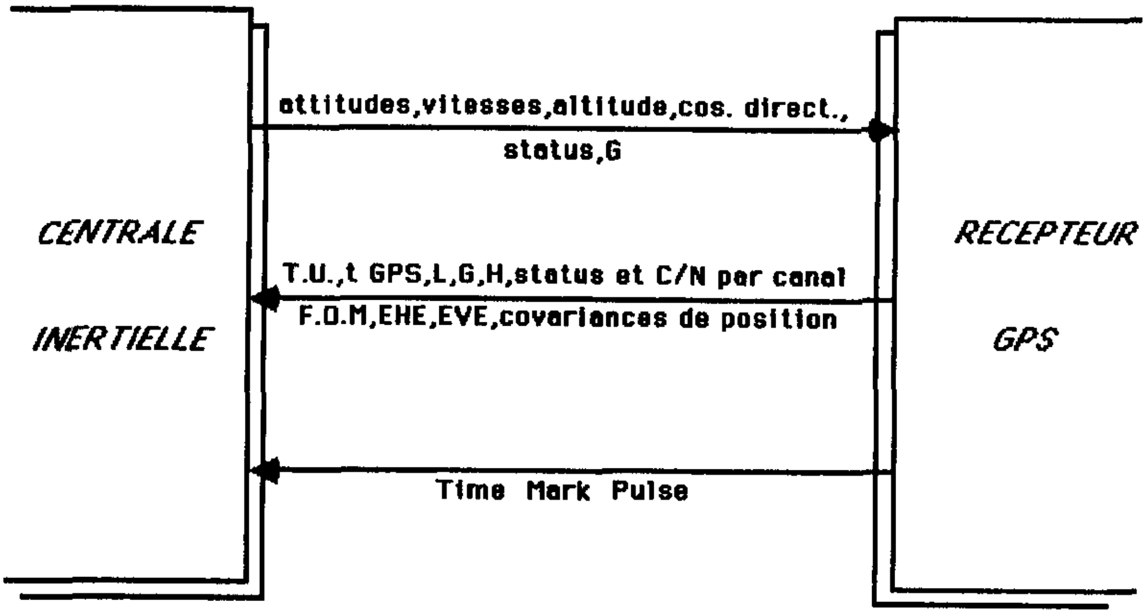


FIGURE 7

RESULTATS DE SIMULATION INERTIE/GPS

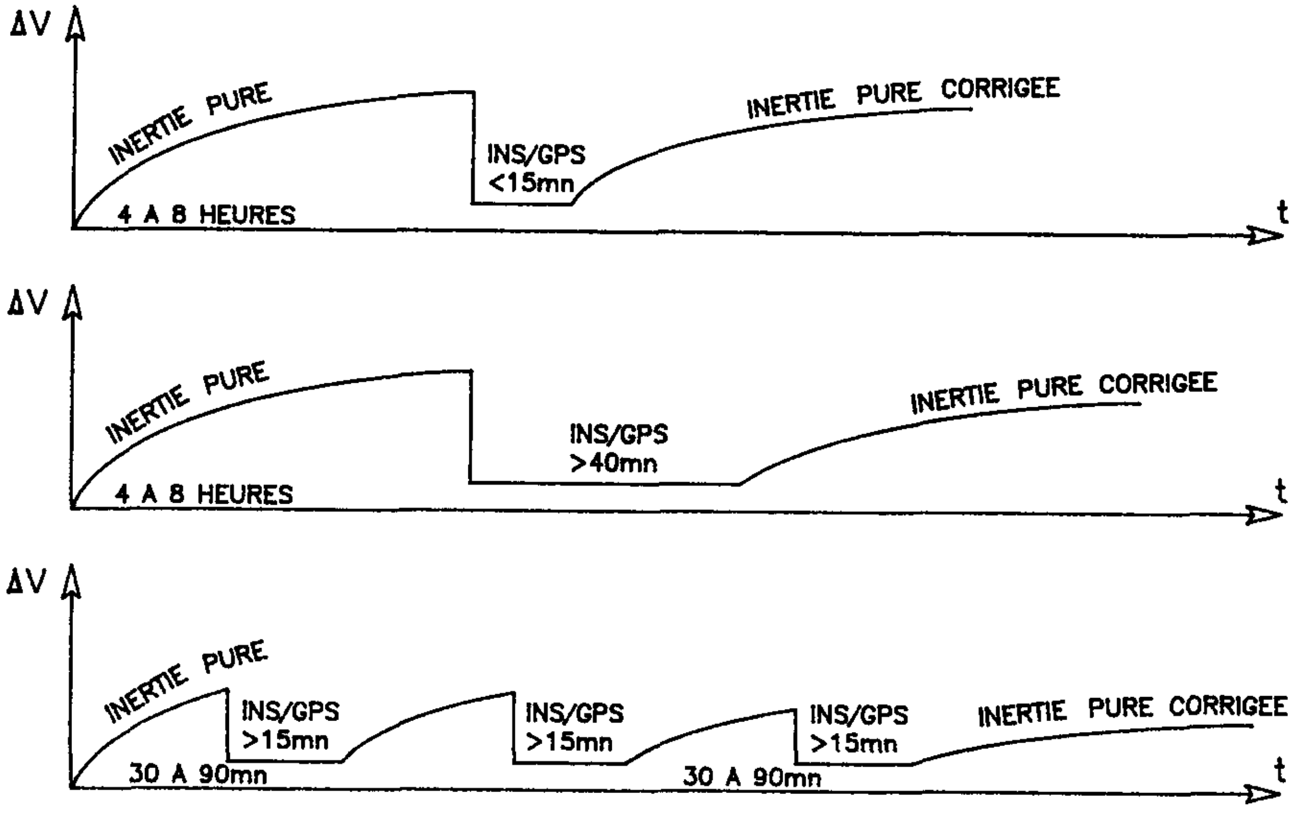
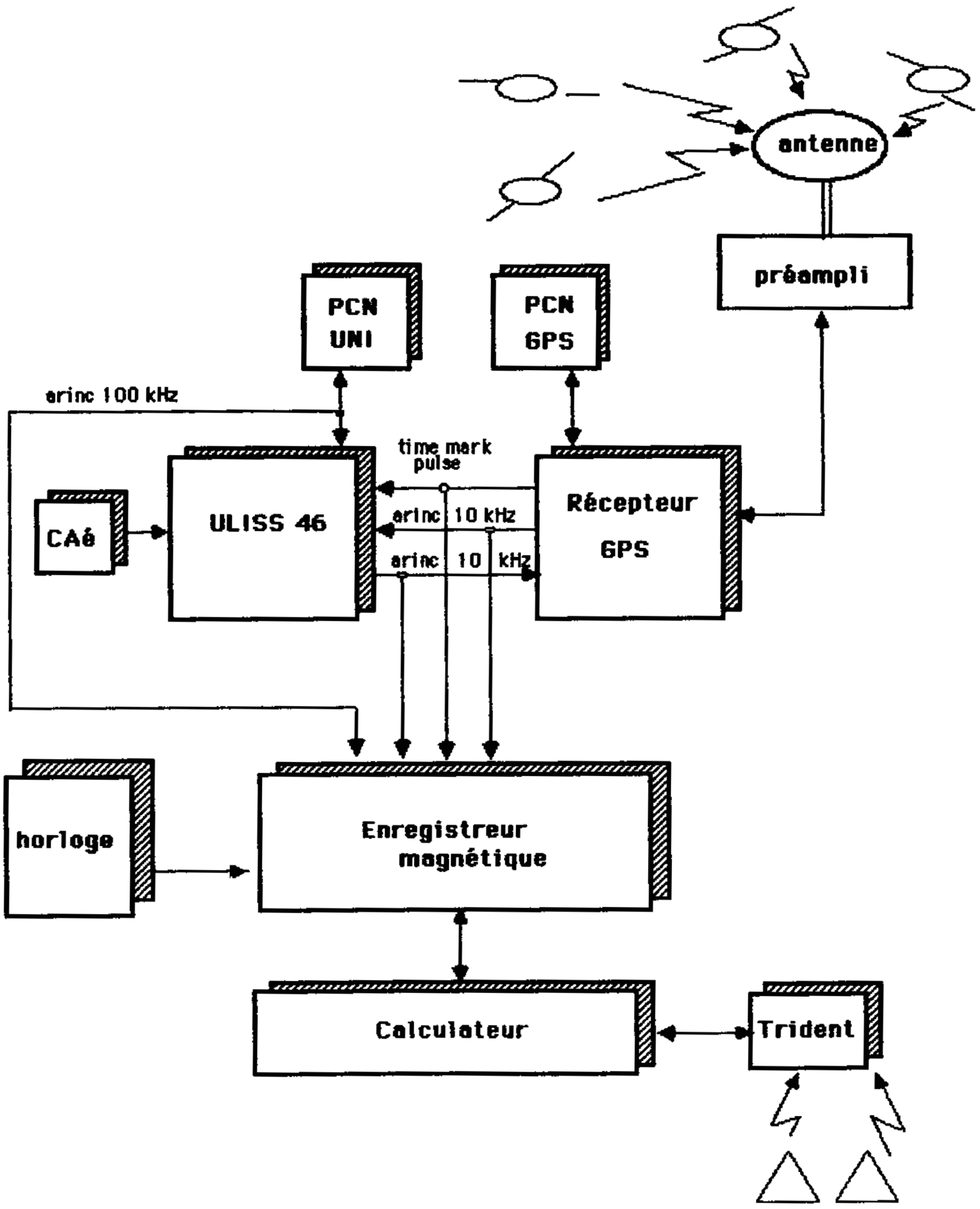


FIGURE 8



Configuration avion du couplage inertie/gps

FIGURE 9

RESULTATS TYPIQUES D'ESSAIS EN VOL

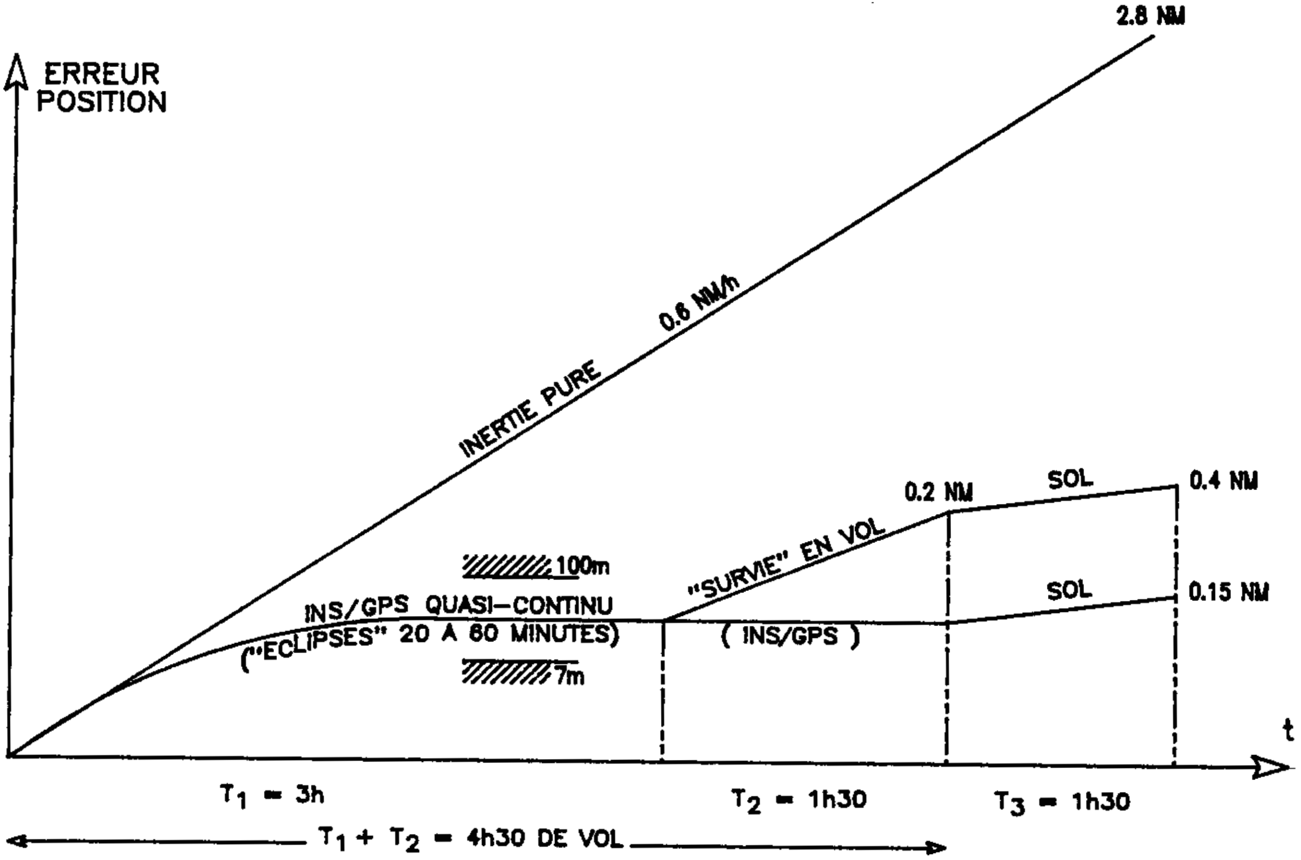


FIGURE 10 A

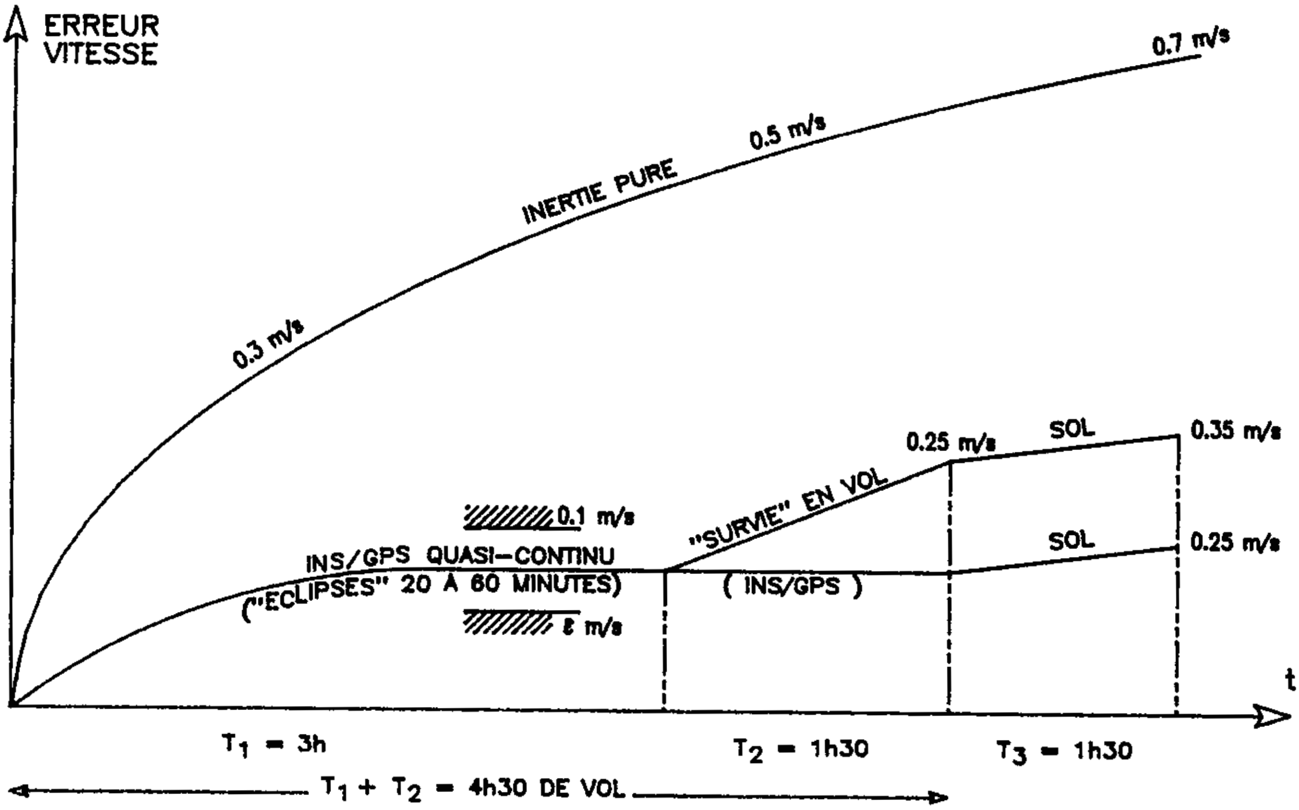


FIGURE 10 B

CP 410

COMMUNICATION, NAVIGATION, AND SURVEILLANCE SERVICES FOR THE AVIATION INDUSTRY USING SATELLITE TECHNOLOGY

by

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BACKGROUND

The operators of aircraft over oceans and land masses remote from large population centers have long had a requirement for a reliable, static free communications system capable of supporting air traffic and company operational control. Prior to the launch of Sputnik 1 in October 1957, no technology existed which was capable of fulfilling this requirement. The potential inherent in the practical realization of the ability to orbit artificial satellites was almost immediately seized upon by the aviation community. Pan American World Airways first relayed teletype and voice communications from an aircraft in flight on the VHF telemetry and command channels of the Syncom 3 satellite late in 1964. These tests were conducted using a freighter aircraft equipped with breadboard avionics and side-looking window antennas and modified nose radomes. More tests followed, once again at VHF, but this time using the NASA Application Technology Satellites Nos 1 (Pacific) and 3 (Atlantic). These tests showed such promise that the Airlines Electronics Engineering Committee (AEEC) prepared airline industry form, fit, and function standards for VHF satellite communications system avionics (ARINC Characteristic 566, published October 17, 1968) and Boeing equipped many production B747 aircraft with the necessary antenna. A public demonstration of the prototype version of this system at the AEEC general session held in Miami Beach in May 1968 convinced many people that satellite communications for commercial aircraft were here to stay.

In parallel with this practical work, the world's aviation regulatory agency's communications specialists gathered under the auspices of the International Civil Aviation Organization (ICAO) to define the system standards deemed necessary to use satellite communications in international civil aviation. This effort began in 1966 at the ICAO Comm/Ops Division meeting, following which an ICAO technical panel known as ASTRA (Application of Space Techniques Relating to Aviation) was formed. The items of reference of the ASTRA panel were:

a) To identify these space techniques which could be applied to meet established and foreseen world-wide operational requirements for International Civil Aviation.

b) To identify these applications of space technologies which offer improvements in its safety, regularity, and efficiency of international air operations more economically than can be realized by non-space techniques, and the dates by which the techniques concerned would be sufficiently developed for practical application, together with a statement of the related desired system characteristics.

The panel, which met for the first time in November 1968, at once became embroiled in controversy over system operational requirements, including navigation and surveillance capabilities for which, at that time, the airlines could identify no need. Subsequently, a greater controversy arose over the subject of its frequencies to be used for the aircraft-to-satellite and satellite-to-aircraft RF links. The airlines favored VHF, which their experiments had shown could provide reliable communications for a relatively modest investment in avionics, while the provider agencies favored L-band. In 1971, despite the objections of the airlines, the ICAO Air Navigation Commission adopted a resolution indicating that 1540-1660 MHz was the preferred band for aviation system development. While not strictly a recommendation of the ASTRA panel, being more a statement of unsubstantiated opinion of a majority of panel members, this resolution was subsequently adopted by the ICAO Council.

It should be noted that around this same time, the U.S. Office of Telecommunications Policy (OTP) declared its support for this L-band alternative and committed U.S. resources to pursuing it. A series of ministerial meetings between the U.S. and several other European and Asian states (conducted outside the framework of ICAO) resulted in a Memorandum of Understanding to implement a "preoperatonal" program known as "Aerosat." This program involved launching six satellites, providing appropriate oceanic air traffic control centers and developing and procuring avionics. The Aerosat program was conceived without the participation of the airlines, and was prosecuted despite the express concerns of these future users of the system, who would ultimately bear its costs. In the end, the airline opposition forced the U.S. to withdraw from the program, and the program was abandoned. This lesson of history should not be forgotten.

Other than some purely national activities that continued after the collapse of Aerosat, nothing further happened until recently when the international maritime communications agency INMARSAT decided that its second-generation satellites, due for launch in 1988, should provide transponders operating in the lowest 1MHz of the aeronautical mobile satellite service L-band frequencies adjacent to the maritime band and ICAO established its special committee on Future

Air Navigation Systems (FANS). This committee was charged with determining the requirements for the systems to be used for communications, navigation, and surveillance (CNS) well into the next century and almost at once determined that these systems should be satellite-based. Past controversies were forgotten as this airlines accepted L-band as the preferred frequency band and worked with the ICAO states to define CNS operational requirements. This work is continuing.

In a related field, ARINC introduced an air-ground digital data link service, known as ACARS, in 1978. Characteristics of the ACARS system were defined through the deliberations of the Airlines Electronics Engineering Committee (AEEC), which resulted in the international standards set forth in ARINC Characteristics 597 and 724. Presently, the great majority of the U.S.-based airline fleet is equipped with ACARS avionics, and installations on a world-wide basis are proceeding rapidly as corresponding ground stations are being installed by ARINC and SITA. The economic and operational benefits of a rapid, error-free and low-cost communications capability are being realized by the aviation community.

AERONAUTICAL RADIO, INC. AND AVIATION COMMUNICATION

From its earliest beginnings the air transport industry has recognized the importance of good communications to the provision of safe, efficient, and low-cost services to its customers. These include intra-airline communications to facilitate public contact with the industry as a whole and the communications needed between aircraft in the air and the ground agencies that provide the separation assurance services known as air traffic control.

In 1929, the pioneer airlines formed their own specialized aeronautical communications company, Aeronautical Radio, Inc. (ARINC), to provide these services on an industry-wide basis. The company's basic purpose has remained unchanged since that time, although, of course, the scope of its services and the technologies used to deliver them have changed dramatically. ARINC is a not-for-profit corporation whose principal stockholders, the scheduled airlines of the U.S., are also its principal customers. Its services, however, are available to all aircraft operators, large and small, U.S. and non-U.S., scheduled and supplemental, business, private, and government. Its costs are recovered from operators on the basis of use.

Of special interests in the context of this paper are ARINC's air-ground communications services. These comprise VHF voice and data transfer services between air and ground over much of North America and HF voice communications world-wide. The voice services are used for aircraft operational control and, in oceanic areas for which the FAA has separation assurance responsibility, for the communications necessary for air traffic control. The VHF data link is used for company operational control and administrative message transfer in accordance with FCC and ITU regulations governing spectrum use for such services.

Despite tremendous advances in the state-of-the-art of HF communications over the years, this service cannot provide the performance needed to support economic over-ocean air transport operations as they are evolving. The need to minimize cost demands closer aircraft separations in order to place more aircraft on optimum tracks. This, in turn, demands more effective air traffic control, the elements of which are improved communications, navigation, and surveillance. Note the addition of improved navigation and surveillance to the "operational requirements." In the 1960s and '70s the airlines' emphasis was on improved communications only.

ARINC has been in the vanguard of the air transport industry's involvement in the application of satellite technology to air-ground communications since those early experiments mentioned at above.The Corporation provided ground terminal facilities at its Annapolis, Maryland headquarters and elsewhere for the HF links with the ATS satellites and participated with the airlines in all the international discussions that preceded the abortive Aerosat program. Since then, ARINC has been involved in similar international discussions aimed at defining the technologies needed for enhanced over-ocean air traffic control, from which the ICAO FANS Committee has emerged. The result of all this is that it is now positioned to offer satellite-based services capable of meeting the needs being defined by FANS and its air transport industry. These services can be available at costs expected to be considerably lower than those of the common carrier who also are interested in providing such services.

THE AVIATION INDUSTRY SATELLITE CNS SYSTEM

In mid-1985, the air transport industry, through ARINC's Board of Directors, instructed the Corporation to design and plan for the implementation of an integrated satellite system and companion integrated avionics to provide air traffic control, company operational control, aeronautical administrative and private correspondence communications; navigation capability for enroute operations, and support for independent cooperative surveillance. "Private Correspondence" is the industry's name for an air-ground passenger telephone service.

Consideration of private correspondence at this point is important. The airlines believe that there is a public demand for a reliable, efficient and low-cost air-ground telephone service for passengers. While experimental systems introduced into service in the U.S. may not yet have reached the levels of utilization predicted, this is due to their limited availability rather than a lack of demand. Telephones are just not encountered often enough on airline aircraft for passengers to regard them as the norm and make routine use of them. The airlines are convinced that this attitude will change as aircraft equipage and service quality rise, and that a satellite-based system is economically viable. If appropriate measures are taken to ensure that passenger telephone utilization produces no compromises to safety-related services, these services can be provided at very small marginal cost. This approach is at the heart of ARINC's system design.

The airlines' needs for the full range of CNS services cannot be fulfilled until satellites having greater capacity than presently available are placed in orbit. Existing satellites can be used, however, to support a data-entry communications service. ARINC's program envisages offering such a service at an early date (mid-1987) as an interim step along the way to the full-service system. The interim system will be designed as a sub-set of the full system so that airlines will not be faced with extensive aircraft equipment changes when the full system is available. As planned, adding capability to its digital elements of the avionics will be all that is required. The aircraft antenna system and the RF avionics can remain the same.

The satellite data-only service is essentially an extension of ARINC's VHF line-of-sight data link ACARS (ARINC Communications Addressing and Reporting System) into the over-ocean and remote land environment by means of the satellite RF link. It is thus referred to as the "International ACARS" service.

On the ground, International ACARS will make use of the digital message switching system that currently supports terrestrial ACARS and several other ARINC services. This system will interface with earth stations as necessary for communications with the satellites. In the aircraft, existing ACARS avionics will be modified to interface with a satellite modem which will, in turn, be connected to a transmitter/receiver unit interfacing with its aircraft antenna system. The frequencies used will be 1535 - 1559 MHz for the satellite-to-aircraft link and 1635.5 - 1660.5MHz for the aircraft-to-satellite link. Each channel will occupy approximately 1.5kHz. This spectral occupancy results from the use of a 2400 bits/second transmitted signal and a 2 bits/hertz MSK modulation method. It includes a 0.3KHz guardband per channel.

The outbound signal to the aircraft is a continuous TDM broadcast stream. This provides a "beacon" for aircraft antenna pointing, keeps the aircraft demodulator locked for immediate message access to the modulator, prevents the possibility of outbound message blockage and eliminates message delay due to modem acquisition time.

The inbound signal from the aircraft operates in a burst mode. The access protocol used when the system is lightly loaded resembles "slotted - ALOHA." As the system becomes more heavily loaded, the protocol provides for progressive burst timing reservation to limit the probability of blockage.

International ACARS is compatible with all existing L-band satellite transponders operating in the frequency bands noted. The system design is predicated on the use of an aircraft antenna system capable of providing essentially complete coverage of the hemisphere above the aircraft with a minimum gain of 7dBiC.

The name AvSat has been given to the full-capacity aviation satellite system. AvSat will operate in the allocated Aeronautical Mobile Satellite Service (AMSS) frequency band 1545 - 1559 MHz (satellite-to-aircraft) and 1646.5 - 1660.5 (aircraft-to-satellite). Voice communications will be digitized and integrated with data communications. In order to achieve the required volume of communications in the spectrum available, the system will employ frequency re-use obtained by utilizing satellites capable of providing spot beams rather than global coverage. Nineteen beams, each of 3.5 degrees width, will provide for frequency re-use. Additionally, the spot beam technology will permit the optimal use of the satellite's RF power resource.

The system will allow direct access by multiple earth stations by means of TDM/TDMA techniques. A single aircraft may have as many as six communications channels with the ground operating at any one time using a single transceiver. An all-digital voice and data system will take advantage of the flexibility of today's electronics advances.

Using an aircraft antenna system having the coverage and minimum gain desired above for International ACARS, AvSat will provide all the voice and data communications foreseen to be needed to support aircraft operations well into the next century. The data communications capability includes that necessary for automatic dependent surveillance, in which position and other pertinent information derived and verified on board the aircraft in employed on the ground for monitoring air traffic movements and maintaining safe separation. The system design also permits data to be derived from the satellites upon which surveillance can be based, if this is eventually desired.

With an AvSat system having the capacity and other attributes required for communications and surveillance functions, concomitant navigation functions can be provided at very low marginal cost. Intrinsic to the system's design is a requirement for knowledge of each participating aircraft's location, in order to maintain continuous communication; and wideband transmission, in order to utilize efficiently both the available spectrum and costly satellite resources. Extension of these features in conjunction with altimetry will provide position-fixing accuracies sufficient for enroute navigation and surveillance requirements, about 100 to 200 meters. This accuracy will degrade in a narrow zone located within a few degrees of the equator, and of course cannot be obtained at latitudes exceeding about ± 80 degrees with geosynchronous satellites; nevertheless, the utility and low cost of this option will undoubtedly find widespread application.

CONCLUSIONS

The air transport industry is once again gearing up to embrace satellite technology. The industry has traditionally provided its own communications systems and services to support aircraft operations and is well-positioned to continue this tradition into the satellite era. International ACARS service will be available in 1987 with AvSat services following on some two years later. As before, many technical and institutional problems remain to be solved, which will prove very challenging for the industry. This time, however, there is a sound economic basis on which to proceed. This makes the likelihood of meeting and overcoming these challenges very high, indeed.

POSSIBLE CONTRIBUTIONS FROM THE SSR MODE S DATA LINK TO THE CONDUCT OF EFFICIENT AIRCAFT OPERATIONS

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1. SUMMARY

The paper entitled "Data Link - The Key to Improvements in Civil Military Air Traffic Management?", presented at the GCP Symposium, Copenhagen, in October 1979, outlined a number of potential applications of a data link, then known as ADSEL/DABS, and referred to a number of feasibility studies that were being conducted in respect of these applications. Since that date the two systems (ADSEL/DABS) have led to the emergence of SSR Mode S which is now being standardised for international use through ICAO.

This paper commences with a brief description of the Mode S data link characteristics. It then recalls a number of the applications proposed in 1979 and gives results of the studies conducted subsequently on such topics as the Controller/Pilot interfaces with the link and machine/machine data interchanges and their possible benefits to ATC. The final sections discuss present plans for more extensive data link evaluations and then propose the initial steps that could be taken in progressing from today's situation towards a system of control employing a high level of automation.

2. LIST OF SYMBOLS AND ABBREVIATIONS

A/C	Aircraft
ADSEL	Address Selective SSR (UK development of SSR)
ADS	Automatic Dependent Surveillance
AERA	Automated En-Route ATC
AIDS	Airborne Integrated Data System
ALT	Airborne Link Terminal
ARINC	Aeronautical Radio Incorporated (USA)
ARINC 429	Specification for an aircraft data bus
ATIS	Automatic Terminal Information Service
ATC	Air Traffic Control (in general)
ATS	Air Traffic Services
CAS	Calibrated Air Speed
CDU	Controller Display Unit
CRCO	Central Route Charges Office
DABS	Discrete Address Beacon System (US development of SSR)
DLAP	Data Link Applications Processor
DLPU	Data Link Processor Unit
EFIS	Electronic Flight Instrument System
FAA	Federal Aviation Administration (USA)
FMS	Flight Mangagement System
ICAO	International Civil Aviation Organisation
INS	Inertial Navigation System
ISO	International Standards Organisation
kt	Knot
r.f.	Radio Frequency
OSI	Open Systems Interconnection
SARPS	(ICAO) Standards and Recommended Practices
R/T	Radio Telephony
SICASP	(ICAO) SSR Improvements and Collision Avoidance Panel
SSR	Secondary Surveillance Radar
SSR Mode S	Selectively Addressed SSR
UKCAA	United Kingdom Civil Aviation Authority
VHF	Very High Frequency
VOLMET	Broadcast of meteorological data for aircraft (voice)

3. INTRODUCTIION

In 1979, at the time of preparing ref. 1, fuel costs were escalating rapidly and ICAO had not embarked on drawing together the developments in selectively addressed SSR, known at the time in the UK and USA as ADSEL and DABS respectively. Since then, however, two major changes have occurred : firstly, fuel costs have fallen significantly (see fig. 1) and, secondly, SSR Mode S is now being standardised for world-wide use as a surveillance system with data link communications capabilities. Additionally, in the USA, the FAA has already commenced the procurement of 137 ground stations which, by 1992, will be giving total coverage above FL 125. Furthermore, from 1987 onwards, there will be a growing requirement for airspace users to fit the Mode S airborne equipment. Doubtless because of the high ratio of general aviation aircraft to commercial aircraft in the USA, which results in a 5:1 ratio in movements, the major thrust of FAA's work on data link applications is in providing weather services, largely for the benefit of general aviation, with interest in ATC automation growing during the 1990's. In Western Europe commercial traffic movements are approximately half those in the USA, but they represent about 85% of the movements in controlled airspace and thus data link studies have been more closely related to the operation of commercial aircraft.

Although forecasts of aircraft fuel costs and the number of movements can and must be made, it will be noted from fig. 1 that there is a large discrepancy between present fuel costs and those estimated by the FAA as recently as 1983. It is thus very difficult to predict what will be the aviation community's most pressing problem in the mid 1990's - the most probable period for the initial implementation of Mode S in Europe. This could be fuel costs, excessive traffic density in certain locations, or some other issue. Accordingly, for the purposes of this paper, which is particularly related to the scene in Western Europe, any data link application will be regarded as contributing to the "conduct of efficient individual flights", provided it assists in reducing aircraft operating costs, either directly, or indirectly, e.g. by reducing the costs of ATS, as ultimately borne by the aircraft operator, either in the form of "user charges" or taxes.

4. THE BASIC MODE S DATA LINK

4.1 General

The Mode S data link can be considered as a refined extension of the conventional SSR's capability used currently to transfer from the aircraft encoded 4-digit identifiers (Mode A) and encoded altitude (Mode C) in response to ground requests (interrogations). The SSR carrier frequencies, i.e. 1030 MHz for interrogations and 1090 MHz for replies, are also used and, furthermore, until such time as electronically scanned antennas are introduced, the system will continue to use narrow beamwidth antennas rotating mechanically at speeds generally ranging from 6-15 r.p.m. - with a consequent effect on the time during which the data link can remain 'open' between a ground station and given aircraft.

4.2 Message fields

The Mode S system employs two basic format lengths: 56 and 112 bits. Data link fields are contained only in the 112-bit formats, the 56-bit formats serving for surveillance purposes only. From fig. 2 it will be noted that four basic data link message formats exist: Comm-A, Comm-B, Comm-C and Comm-D. The Comm-A (uplink) and Comm-B (downlink) messages each contain 56-bit data fields, up to four of which may be linked to form a 224-bit data message. Comm-C (uplink) and Comm-D (downlink) formats each contain 80-bit data fields, up to 16 of which may be chained to form long messages (ELM's) containing a maximum of 1280 bits. Each of these 112-bit formats carries a 24-bit address/parity (A/P) field containing the aircraft's 24-bit technical address, which gives a total of 16 million different possibilities. The address is combined with parity information derived from the remaining 88 bits. This ensures its transmission to a specific address with a very small risk of undetected error.

4.3 Communication protocols

Messages may be initiated either on the ground or in the air, but the two-way transactions required to effect the message transfer will always be under the control of the interrogator and take place in accordance with internationally agreed protocols, as outlined in refs. 2 and 3. Provision is being made in the protocols to permit interrogators in a given region to be linked in a ground network, thereby enabling the responsibility for the surveillance of specific aircraft and the data transfer transactions with them to be handled by an individual interrogator and thus avoid unnecessary loading on the r.f. channels - the most restricted element in the communications chain. Full details of the protocols will be given in ICAO SARPS material, now in preparation.

4.4 Link capacity and message coding

To the potential user of the Mode S data link, a knowledge of its maximum theoretical capacity is of little benefit because the proportion of this capacity that can be used in practice is influenced by so many factors, particularly when rotating interrogator antennas are employed. Firstly, it must be remembered that the prime task of Mode S is surveillance and thus data link functions can only be performed after this need has been met. Other factors include:

- the average duty cycle rating of the interrogator;
- the operating range of the interrogator and the distribution of the aircraft within its coverage;
- the message formats actually employed;
- the level and nature of interfering signals.

However, it might possibly be more helpful to have an indication of the amount of data that could be exchanged in the two directions during one beam sweep. Discussions with experts from the, Royal Signals and Radar Establishment (RSRE) Malvern, UK, where much of the Mode S development work in Europe has taken place, have produced the following estimate which, being readily achievable with present-day interrogators, may be regarded as conservative. With existing interrogators and assuming a 3 degree beamwidth and a rotational rate of 10r.p.m., if 20 aircraft were in the beam, 19 could each receive one Comm-A message and reply with one Comm-B and the other one could receive and then reply with one full ELM, i.e. 16 Comm-C and Comm-D segments.Studies are currently underway in Europe to prepare more precise estimates of link capacity under various operating conditions.

On the basis of the above and with the traffic densities forseeable in Europe, it appears that it should be possible to employ linked Comm-A and Comm-B messages on a number of occasions, but it will always be necessary to attempt the most efficient means of data transfer. Compact coding schemes including the use of standard word/phrase dictionaries are being developed within SICASP for international use aimed at achieving this.

4.5 Link reliability

Earlier work (see ref. 4) has shown that a single Comm-A transaction can be achieved in the first beam sweep with a probability exceeding 98%. Commercial aircraft operators will be encouraged to fit antenna diversity systems (top and bottom mounted) which should improve this figure - particularly during both climb-outs in the vicinity of the radar and manoeuvres at longer ranges. It is understood that work is currently being performed by the FAA to evaluate the link performance on the airport surface.

4.6 Data input and output

As will be discussed later, ATC's uses of the link for data transfer may be quite diverse, ranging from short compactly-coded tactical messages to long clearances, etc., with a high alphanumerical content. Aircraft performance information may also be transferred as pure binary data. Depending on the application, data generation, for transfer by the link, will be in one of three possible ways:

- automatic (machine), e.g. by computer;
- semi-automatic, i.e. where a data sequence can be released by a simple manual operation, for example, by the selection of a message from a 'menu' of stored data;
- manual, i.e. where all the information is assembled by keyboard for example, for inclusion in a data link message.

The operation of the receiving terminal in providing an output of data can be considered under three similar headings:

- automatic, for direct use in a system (machine) without the need for any manual intervention, e.g. aircraft data into a radar-tracker;
- semi-automatic, as may occur when the data is assembled for optional use as required, e.g. a message printed on a teleprinter without specific action being required at the receiving terminal;
- direct, where the recipient must participate by noting the arrival of new information and then act appropriately, e.g. an alphanumerical text which must be read prior to the acknowledgment of its contents.

It will be evident that information generated or 'input' in a given form need not be delivered or 'output' in an identical or even similar manner. It thus follows that in all except the machine/machine interchanges, there will be human factor considerations and, furthermore, a corresponding impact both on workload and reaction time and thus on the possible merit of the application, as discussed in para.7.

The principal data sources and output devices currently under consideration for Mode S link applications, together with the functional elements of the system are illustrated in fig. 3. The Data Link Applications Processor (DLAP) in the ground system serves essentially to accept data from various ground sources, which it then encodes and assembles, together with appropriate addressing, in Comm-A and Comm-C data formats, linking these as necessary for uplink transmission. It also accepts the data content of downlinked Comm-B and Comm-D messages which it then decodes and routes through to appropriate destination ports. The airborne Data Link Processor Unit (DLPU) performs similar functions, but the order of processing is of course reversed. It may additionally treat some of the aircraft data in order to get more meaningful transfers, e.g. normal acceleration data for turbulence reports.

4.7 OSI considerations

During the last year or two of Mode S data link development, as a result of the growth in the number and capabilities of other avionics systems including VHF and satellite-based data links, considerable thought has been given, particularly in the USA, to adapting the architecture of the Mode S link to the ISO Open System Interconnection form. Such an architecture would yield a number of advantages including the possibility to share the different communications channels, aircraft peripherals and parts of the DLAP and DLPU. Disadvantages may include organisational and certification difficulties plus the need for additional data bits for use in longer addresses, message security and priority definition. In themselves a few bits may sound unimportant, but they would become significant if frequently used messages required two Comm-A's, i.e. the transmission of 224 bits instead of 112, or if specific applications, e.g. the transfer of VOLMET data, could no longer be conveyed in 4 linked Comm-A messages. The whole question is currently under review within SICASP and decisions are expected shortly.

5. POSSIBLE LINK APLICATIONS

5.1 General considerations

In Europe today, most civil and military aircraft operating in controlled airspace are fitted with SSR transponders which, on receipt of interrogations from the ground, provide appropriate Mode A and Mode C replies (cf. 4.1). In addition, the transponder can be set by the aircrew to give certain emergency indications. Apart from this limited transfer of data, all other communications between the aircraft and ATC are effected by R/T, either in the form of direct controller/pilot conversation or as broadcast services. Despite the many limitations, direct voice contact between pilot and controller can be very advantageous for communications of a non-routine nature and is likely to remain so, even with the most highly automated systems. In the automated system, however, where a digital data link would be assumed, the need for R/T would be reduced considerably which would in turn minimise some of its existing limitations. Proposals for an ATC system concept employing higher levels of automation, based on the exploitation of accurate aircraft trajectory prediction techniques, have been made in refs. 5 and 6, and the use of the data link in supporting them was discussed in ref. 1. The FAA's AERA concept (ref. 7) is in many ways similar. It is believed that the link will be far more effective if it can be exploited to support systems based on similar concepts, rather than used merely to convey the information passed by R/T today. In permitting the automatic and fairly rapid two-way transfer of dynamic data (and static data too, when required) between ground-based and airborne systems, data in one system can be used to enhance the performance of the other with little direct involvement of the controller and/or pilot. The communications needs of the system, as transferred by the link, i.e. information presented visually or aurally to the controller or pilot, would then be automatically generated in accordance with a clearance covering a major portion of the flight. The problem is to arrive at this stage of development with a smooth transition from today's situation. Much experimental work is being done in Europe and elsewhere, particularly in North America, to find the solution. Some details of the European work are given below.

5.2 Communications enhancements

5.2.1 Pilot/link interface

Experimental work in EUROCONTROL has been carried out under two main headings: the pilot/link interface and the controller/link interface. Work on the former, which started in 1977 and was largely concluded in 1982, was performed to obtain aircrew reactions to a number of possible advances in ATC communications. For this, an experimental interface, known as an Airborne Link Terminal (ALT) was developed, together with a scenario thought representative of the future ATC environment. The interface, comprising a CDU and miniature hard-copy printer, was mounted on the flight deck of an A 300B Airbus flight simulator and operated in conjunction with perfect ground facilities. The display mode of the CDU could be changed automatically from 'navigation' to 'long message', the latter being shown in fig. 4. In addition, special function keys were provided for pilot responses and for access to specific ground based data banks. An evaluation lasting many "flying hours" was conducted, largely by crews from Lufthansa, the German national airline, who, during the initial stages of the work, made a recommendation that data link messages should always be replied to via the link, and R/T message likewise by R/T. They found the most attractive feature to be the hard-copy print-out of long messages, e.g. clearances, VOLMET and ATIS information. Full details of the evaluation are given in ref. 8.

Recently, further work has been done on the pilot/link interface by the Royal Aircraft Establishment (RAE) Bedford, UK, as part of a study of the link's role in civil ATC management. This work made use of the EFIS and an example of the display of a short message is shown in fig. 5. In this case RAE presented more convential navigational data rather than the slot-following information displayed on the ALT. RAE is also studying direct voice inputs for use in the aircraft environment which, in the longer term, could have data link implications.

5.2.2 Controller/link interface

Use of data link for many of the applications studied in the ALT experiments would require a very high level of automation and standardisation of ground-based systems. Because the initial implementation of Mode S in Europe is likely to be patchy and the overall level of automation inadequate, it has been necessary to consider and evaluate some less sophisticated link applications of a somewhat tactical nature thought likely to provide benefits in the short term. These include the duplication of the critical parts of R/T messages, for example, flight level clearances, the replacement of certain control messages, such as aircraft transfers, and assistance in the event of full or partial R/T failure. The evaluations have been effected by means of real-time simulations for which the planning criteria called for little or no increase in controller or pilot workloads and levels of Mode S carriage ranging from 30% to 100% of the total traffic; the simulated communications link used to date has not, however, been entirely representative of the Mode S system. The controllers and a small number of pilots participating in the simulations have been very positive in their support of the link's use both in duplicating R/T and in conditions of partial or full channel failure. The studies have also shown that in order to avoid additional controller workload, there is a need for data link message generation to be tied to the normal system inputs made by the controller to the computer.

Although further studies involving representative airborne facilities are necessary, the work to date has highlighted the need for a number of other factors to be borne in mind if the link is to be used in these limited applications. In particular:

a) R/T message duplication may be better achieved using pre-notification data link messages, i.e. sent before the R/T message, and
b) there should be a smooth transition in communications procedures whenever aircraft move from data link to non-data link areas of control or vice versa.

Point a) above arises mainly from the fact that with the variable delay in the time of delivery of Mode S messages (owing to the rotational antenna scan) it is difficult to maintain a good time relationship between R/T and data-linked messages. A report on these investigations, which were conducted at the EUROCONTROL Experimental Centre near Paris, will be available very shortly.

5.2.3 Ground data-base development

In line with the findings of the ALT experiments (cf. 5.2.1) the view is growing that aircrew access to ground-based data banks could be a very useful application of the link, particularly because it would give them data at a time of their choosing and, furthermore, facilitate the provision of hard copies of fairly detailed messages. The UKCAA is studying the problem of creating such data banks, e.g. VOLMET, using very efficient coding techniques.

5.3 Aircraft data transfers

5.3.1 Data acquisition

As mentioned in para.3, commercial aircraft make up the bulk of the traffic in controlled airspace in Europe. Many of these aircraft have advanced avionics fits and the trend towards the 'digital aircraft' is continuing. Accordingly, a number of studies have been mounted both to examine the problems of accessing aircraft data sources (see ref. 9) and to exploit data so acquired for ATC purposes. Apart from carriage of the appropriate sensor(s) by the aircraft, satisfactory data acquisition and transfer necessitates access to the relevant data source, e.g. via the ARINC 429 data bus, plus some on-board processing and a suitable data interface with the transponder, (cf. 4.6). Because data availability will thus be heavily dependent on aircraft type, it is necessary, when considering particular data applications, to make some forecasts of future aircraft population and their likely avionics installations. Two applications already studied relate to improving the performance of radar trackers and the quality of meteorological forecasts, i.e. two important factors in highly automated systems. The former would require data from the maximum possible number of aircraft, while in the latter case, data from 15-20 % of all traffic would probably suffice.

5.3.2 Experimental applications

Three experimental radar trackers have been developed (see ref. 10) and their performances assessed using data transferred via an experimental Mode S link. The trackers were known as:

- ABF (Acceleration Bias Filter, employing roll-angle data);
- HBF (heading Bias Filter, using heading data);
- VBF (Velocity Bias Filter, requiring both heading and true airspeed data).

Their performances have been assessed both statistically and subjectively (with the aid of displayed tracks) using a reference baseline first-order Kalman filter believed to represent the best available in present-day ATC systems. Full results are given in ref.11 and it appears that, whereas all the modified trackers were superior to the reference, HBF was probably the best of them in view of its performance following missing data and its simple (heading) data requirement. An example of the performance of HBF (using heading data) is compared with that of the reference tracker in fig. 6.

The need for good quality meteorological data for precise longer-term trajectory predictions and the possible use of the data link in enhancing the quality of forecast data were discussed in ref. 1. Since that time, initial feasibility studies using the Mode S link in improving the quality of forecast data have been completed (see ref.12). The later stages of the work involved the transfer of data from Tristar aircraft via an experimental Mode S link and then the World Meteorological Office network to the Regional Meteorological Office, Bracknell, UK. Examples of wind speed and other speed measurements received via the link during a typical Tristar flight are shown in fig. 7.

5.3.3 Other possible developments

The link also enables an aircraft's identification to be acquired automatically by ATC, as and when required, either in the form of a flight number inserted by the pilot, or as a tail number which could be hard-wired into the Mode S transponder installation: a unique Comm-B message has been designated for the transfer of this static data.Because of its importance for surveillance purposes, this potential link application is rated very highly by EUROCONTROL Member States.

A list of parameters thought likely to be of use for ATC purposes in the future, and generally available today from many 'digital aircraft' is given in Table 1. Against each parameter is shown the number of data bits required for an acceptable resolution and to which 3 bits for parity and a sign/status matrix will normally be added; these retain the data form in line with the ARINC 429 data bus standard. The table also gives some examples of parameters that could be grouped in a single Comm-B reply. These are described in terms of their most probable applications and whereas groups 1-7 are possibly of most interest for domestic ATC, i.e. within Mode S coverage, groups 5-10 may be combined as required to form appropriate reports in a satellite-based automatic dependent surveillance (ADS) environment .The assembling of each group could take place in the airborne DLPU (cf. 4.6) which, if designed to be OSI compatible, could also provide 'group pairs', e.g. 5 and 10, for satellite reports. Examples of ADS reports showing aircraft position (derived from the INS), altitude and ground speed are shown in fig. 8. The actual information was obtained via a Mode S link and the corresponding radar track is indicated. Other potential transfers currently commanding attention are the downlinking of FMS profile data and the uplinking of revised route information for possible introduction into the FMS. These are longer-term applications associated with very advanced ATC scenarios, but present studies should help to promote the changes that would be required in FMS's to support them.

5.4 Ground system and aircraft implications

Before any of the data link applications discussed above can be implemented, development of the ground system will be necessary and, for most applications, as many aircraft as possible will be required to carry Mode S transponders together with certain peripherals. Ground installations could range from a single Mode S interrogator capable of relaying data from one or two data bases through to a network of stations with highly automated ATC centres, supporting a strategic system of control (including communications) and also capable of very extensive machine/machine data interchange with the aircraft. Aircraft systems may range from a small display with simple input devices through to EFIS type displays, keyboard(s), a printer and powerful on-board data processing capabilities, permitting the greatest possible degree of interaction with ATC centres. One example of an application believed to have considerable potential economic benefits, which could be supported by a single ground installation and moderately equipped aircraft, is approach sequencing - a topic currently receiving considerable attention in EUROPE (see refs. 13 and 14). Fig. 9, which is derived from work described in ref. 13, shows a typical descent path and indicates the machine data transfers and communications that would take place via the link. It should be noted that the aircraft identification SN409 is purely an example and should not be compared with any flights so numbered in ref. 13.

6. FUTURE EXPERIMENTAL WORK

6.1 Background

Following on from the earlier Mode S development in the United Kingdom and the United States, EUROCONTROL has embarked on a Mode S development programme which will lead to evaluations of an experimental system comprising ground stations developed in the UK and France ,a ground-network and other ground facilities developed in the UK together with aircraft installations developed under contract for the Agency and carried in experimental aircraft and airliners of several European airlines. These evaluations will have many facets including surveillance, link performance, ground communications and data link applications. It is hoped that much of the initial data link work will involve the BAC-111 of RAE, Bedford, which will facilitate many experiments involving airborne systems. Flights should start in mid 1987. Should this time frame agree with the European Space Agency's programme of aeronautical data link experiments employing satellites, attempts will be made to study satellite/Mode S compatibility.

6.2 Topics for evaluation

Plans are currently in preparation for a number of trials and evaluations using the experimental link. The topics listed below are being considered for the overall programme.

i) Basic link operation:
  - the functioning of the DLPU with the transponder;
  - the suitability of message structures, addressing methods and operating protocols;
  - the overall availability, reliability and integrity of the entire data transfer system.

ii) Data bases:
  - the provision of ATIS and VOLMET ground data banks and their access by aircrews.

iii) Communications:
  - tactical message duplication and R/T back-up;
  - pilot interface aspects including the flexible use of display areas on multi-function displays;
  - support for approach sequencing systems;
  - support for ground-based alerting and traffic information services, e.g. GTIS.

vi) Machine/machine data transfers:
  - the acquisition and use of aircraft-derived meteorological, state-vector and profile data, e.g. for approach sequencing;
  - the delivery of initial clearances and changes of route;
  - the acquisition of FMS-computed trajectory data for ground system use.

v) Compatibility of operation with satellite-based ADS:
  - common DLPU functions;
  - the technical and operational aspects of the transition between the two systems.

7. POSSIBLE SYSTEM EVOLUTION

Understandably, because the only planned implementation programme for Mode S in Europe is for experimental purposes, no programme has yet been prepared to associate future ATC system development with the Mode S data link. Moreover, no assessment of the relative values of potential link applications has yet been completed. In an attempt to estimate how the use of the data link may be expanded to meet ATC system needs, the author has made a comparative assessment of a range of very broadly stated applications against the following criteria:

i) expected benefits to safety, crew and controller workloads and fuel economy;
ii) uplink and downlink loading;
iii) the number of installations required for beneficial operations, both ground-based and airborne;
iv) compatibility with present day operations on the ground and in the air.

The applications considered are listed below in an 'order of merit' and the principal benefits expected are indicated.

1. The downlinking of aircraft meteorological data (automation support/fuel economy).
2. Aircraft access to ground data banks (crew workload).
3. Automated approach sequencing, ground-derived alerts (fuel economy and safety respectively).
4. Tactical communications back-up (safety).
5. Strategic system support including the generation and delivery of initial clearances (workload and fuel economies).
6. The downlinking and use of aircraft state-vector and RNAV data bases (workload and safety).
7. The uplinking of route reclearances (workload and safety).
8. The downlinking and exploitation of FMS profile data (automation support/fuel economy).

Clearly, since they are based on one individual judgement made far in advance of the necessary evaluations and real cost-estimates, the results must inevitably be subjective. The above order does nevertheless suggest a possible starting sequence for data link operations: firstly, machine/machine interchanges with a small number of aircraft and secondly, crew introduction to the link via data bases followed, thirdly, by its *operational* use at a small number of busy airports to support approach sequencing, etc. Once these measures were introduced it would be easier to decide on subsequent steps towards higher levels of automation leading, ultimately, to even greater economies for the ATS community.

8. CONCLUSIONS

The international standards for SSR Mode S with a data link capability are in an advanced stage of preparation and, in the USA, the system is already being implemented. In EUROPE, where implementation is not expected before 1995, a number of studies have been initiated to assess the feasibility of using the link for applications believed to be well within its capabilities, largely in support of highly automated ATC systems. From these it emerged that:

- for controller/pilot communications, message generation should be as automatic as possible, thereby avoiding increases in controller/crew workload, and the use of compact coding will also be necessary to minimise the data transfer;
- machine/machine data interchanges appear capable of yielding considerable benefits to the operation of automated systems in a variety of areas, e.g. meteorology, radar tracking and approach sequencing.

A programme of evaluations is being prepared that will employ experimental ground-based and airborne systems developed in Europe and operating in a manner very representative of the full Mode S system. The experiments being planned will check overall system operation and also enable the benefits of various applications to be reassessed. Mode S / satellite ADS compatibility may also be investigated.

Based on very preliminary work it appears that the initial steps towards a high level of automation could be:

i) the recovery and use of aircraft-derived meteorological data (machine/machine data transfers);
ii) the provision of ground-data banks (ATIS, VOLMET);
iii) the support of approach sequencing systems.

A programme of this kind could be started at a small number of locations with only a small percentage of equipped aircraft but could readily lead towards a unified control system employing a much greater level of automation in which ground facilities would be expanded and an even greater use made of aircraft-derived data, e.g. ground computer/FMS interchanges. To facilitate this transition, avionics system designers are faced with an interesting challenge : to rationalise the provision of data sources and data communication facilities and also to make available for ATC'c use other data that are not yet accessible, on even the most modern airliner.

9. REFERENCES

1.	COX, M.E.	Data Link / The Key to Improvements in Civil/Military Air Traffic Management? (1979) AGARD Conference Proceeding 273 on Air Traffic Management, Paper 9.
2.	JENYNS, R.	SSR Mode S - An Improved Surveillance System with Data Link Capability (1985). Presented at the International Seminar on "The ATC Radar of the Future", EUROCONTROL Institute of Air Navigation, Luxembourg.
3.	--	Secondary Surveillance Radar Mode S Advisory Circular (1983) ICAO Circular 174 - AN/110.
4.	BOWES, R. NICHOLS, T.B. BONNY, J.	ADSEL - Selective Address SSR-T.B. Performance of the Evaluation 1979. AGARD-CP 273, Paper 27.
5.	MARTIN, R. BENOIT, A.	Accurate Aircraft Trajectory Predictions Applied to Future En-route Air Traffic Control (1972). Paper presented at the IATA 19th Technical Conference, Dublin, 1972. EUROCONTROL Doc. 722031, EUROCONTROL Brussels, Belgium.

6. --- "A Concept of Air Traffic Control based upon Accurate Aircraft Trajectory Predictions", Presentation to XIth General Assembly of EUROCAE, Brussels, 7th December 1973, EUROCONTROL Doc. 732041

7. GOLDMUNT, L.; KEFALIOTIS, J.T.; KLEINMAN, L.A.; SCHUCHMANN, L.; WEATHERS, D. "The AERA Concept", FAA Report: FAA-EM-81-3, 24 March, 1981

8. UCKERMANN, R.; RADKE, H. The Evaluation of an Airborne Terminal for a Digital Data Link in Aviation (Feb. 1983)/ DFVLR Report F 383-05. The DFVLR Institute for Flight-Guidance, Braunschweig, The Federal Republic of Western Germany.

9. COX, M.E. On-Line Experiments in Acquiring and Exploiting AIDS Data for ATC Purpocses (1981). Proc. 11th Symposium "Aircraft Integrated Data Systems", Sept. 1981, in Koeln-Porz, DFVLR-Mitt. 82-02.

10. THOMAS, H.W.; LEFAS, C.C. Report on the Use of Aircraft-derived Data to assist in ATC Tracking System (1981) Report No. 145 issued by EUROCONTROL Experimental Centre, Bretigny, France.

11. HULLAH, P.C.H.; DARBY-DOWNMAN, K.; MORSE, P.L.R. The Evaluation of Tracking Filters requiring Aircraft-derived Data by the Production of Filter Evaluation Tools (1984). Report No. 173, issued by EUROCONTROL, Experimental Centre. France.

12. BISIAUX, M.; COX, M.E.; FORRESTER, D.; STOREY, J.T. Possible Improvements in Meteorology for Aircraft Navigation (1982). Paper presented at the International Congress of Institutes of Navigation, Sept. 1982, Paris.

13. BENOIT, A.; SWIERSTRA, S.; DE WISPELAERE, R. Next Generation of Control Techniques in Advanced TMA's (1986). Paper 55 presented at this Symposium.

14 VOELCKERS, U. Computer Assisted Arrival Sequencing and Scheduling with the COMPAS System (1986). Paper 54 presented at this Symposium.

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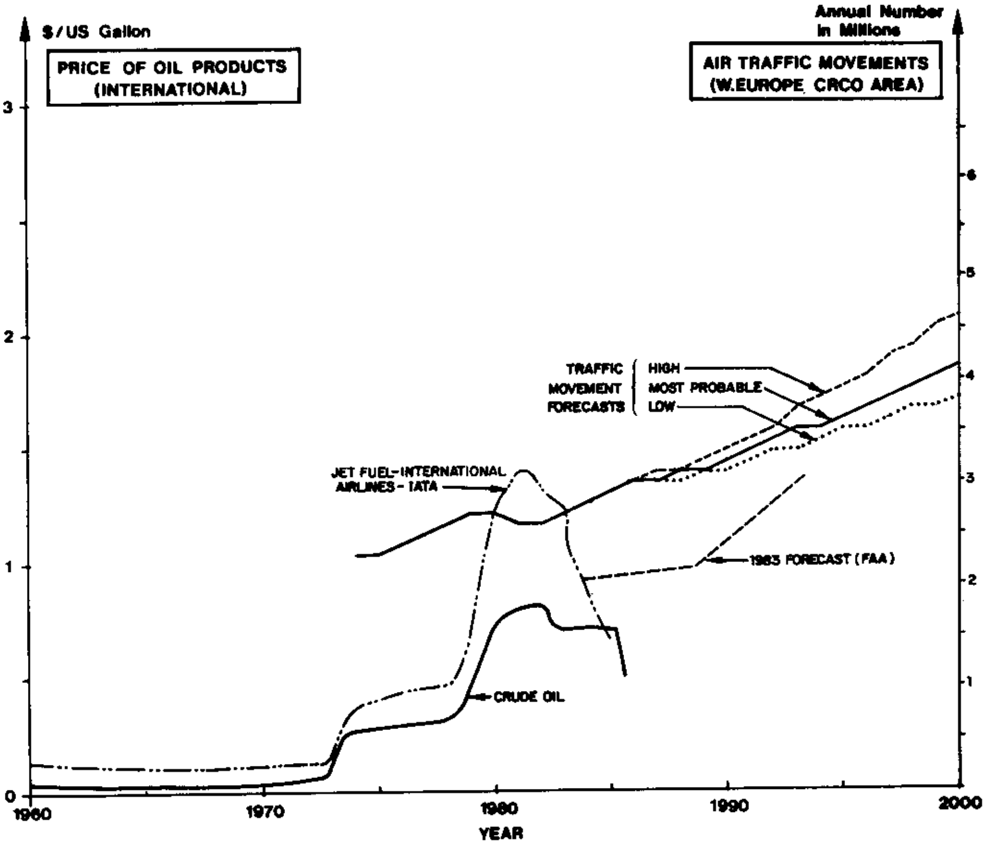

FIG. 1 - WORLD JET FUEL COSTS AND EUROPEAN AIR TRAFFIC MOVEMENTS

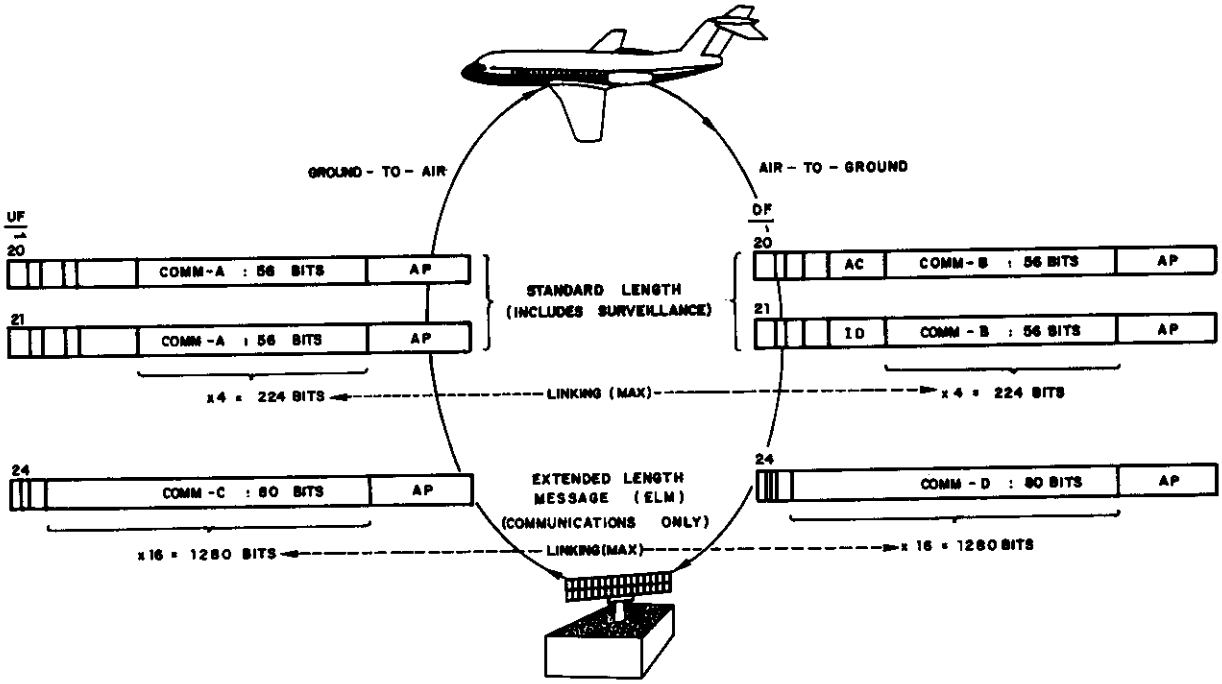

FIG. 2 - SSR MODE S - MESSAGE FORMATS AND DATA LINK FIELDS

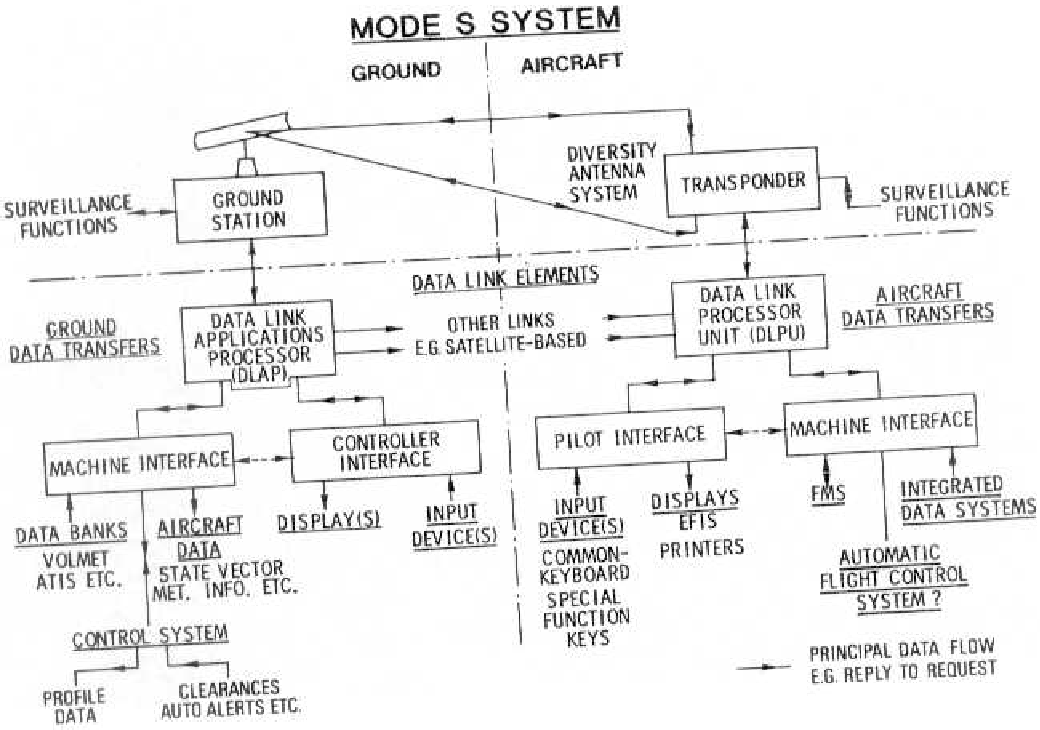

FIG. 3 - SSR MODE S - FUNCTIONAL ELEMENTS AND DATA INTERFACES

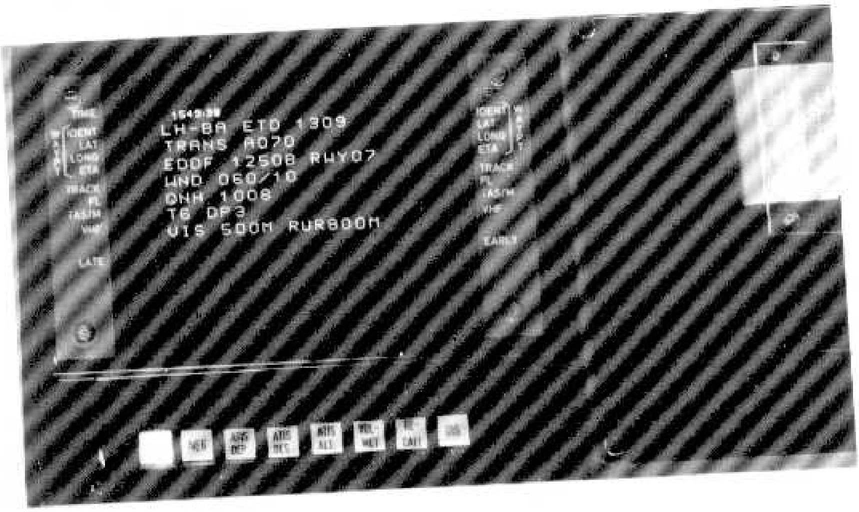
LH-BA ETD 1309
TRANS A070
EDDF 1250B RWY07
WND 060/10
QNH 1008
T6 DP3
VIS 500M RVR800M

FIG. 4 - ALT DISPLAY IN LONG-MESSAGE MODE

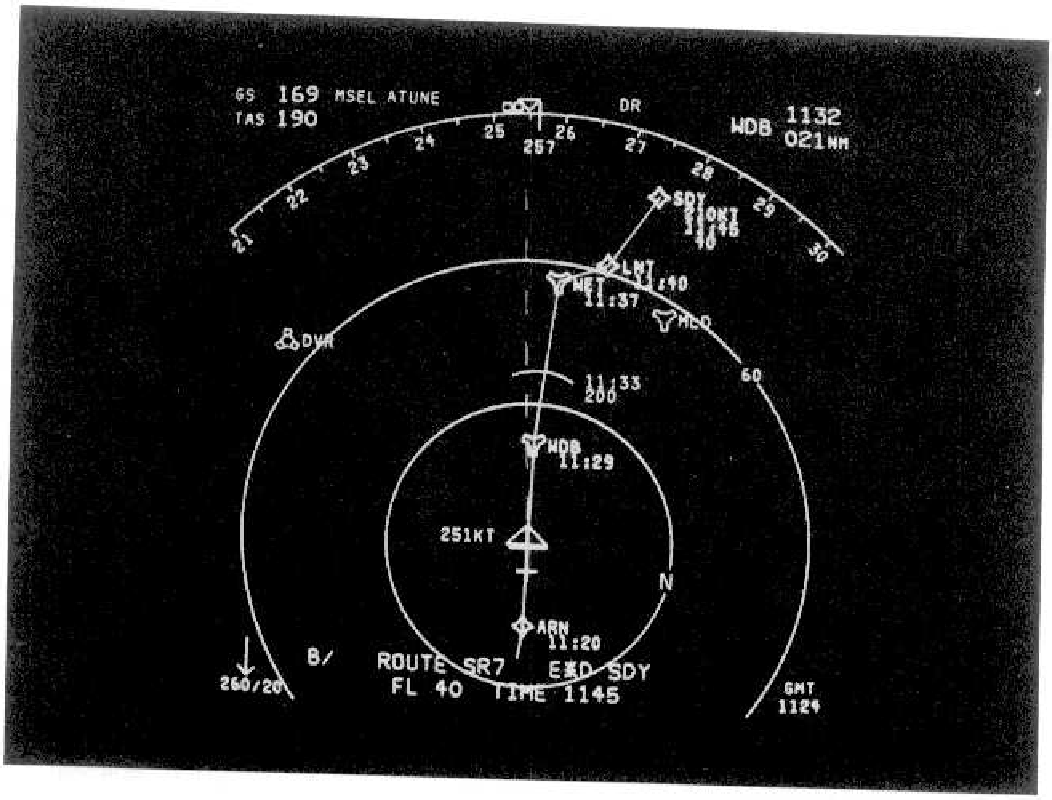

FIG. 5 - EFIS - WITH A SHORT MESSAGE DISPLAYED

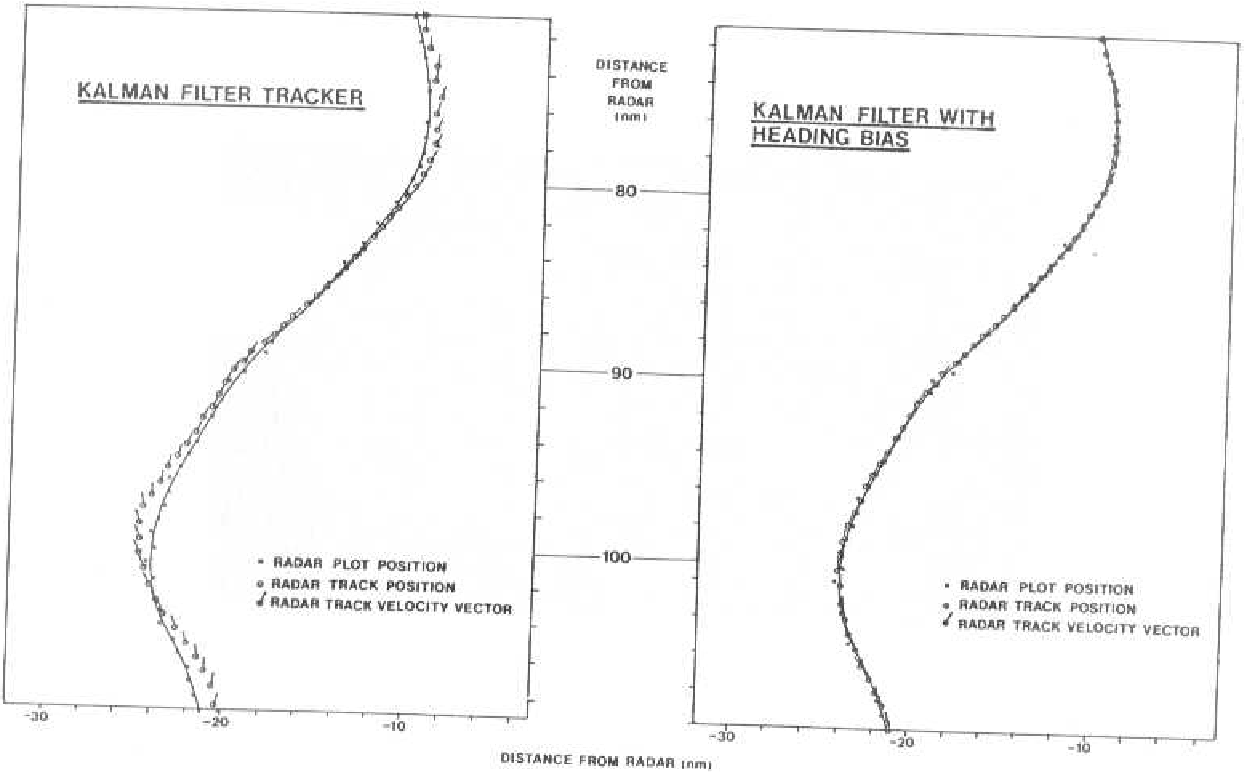

FIG. 6 - RADAR TRACKER PERFORMANCE COMPARISON - WITH AND WITHOUT AIRCRAFT HEADING DATA

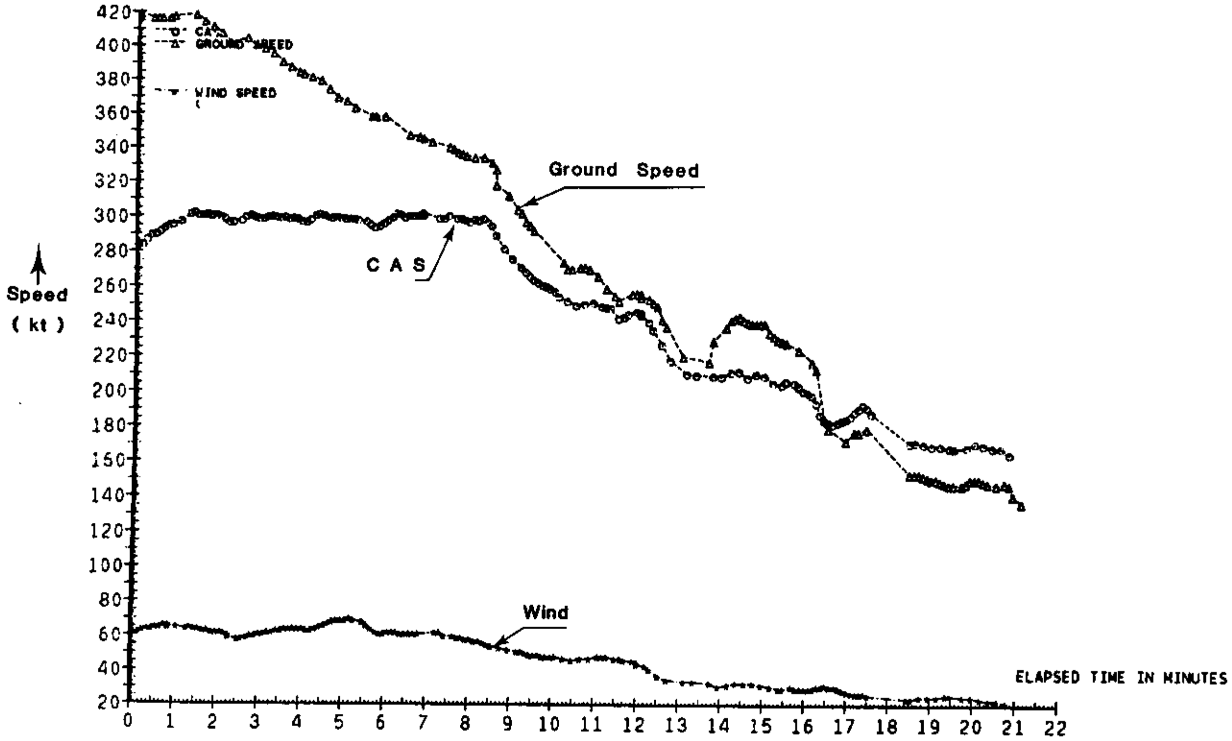

FIG. 7 - SIMULTANEOUS MEASUREMENTS OF COMPUTED AIR SPEED, GROUND SPEED AND WIND SPEED TRANSFERRED VIA THE MODE S DATA LINK

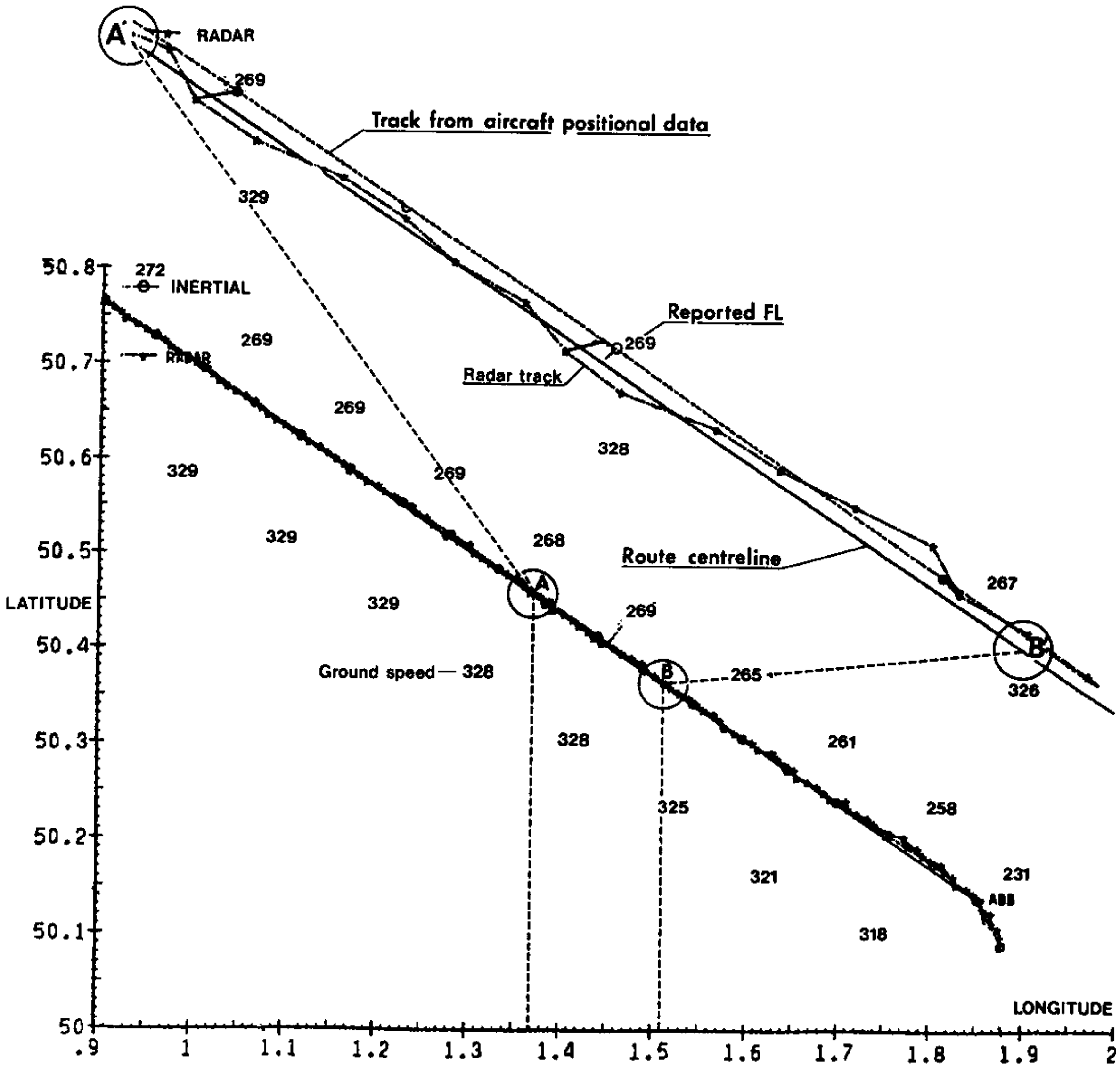

FIG. 8 - AUTOMATIC DEPENDENT SURVEILLANCE REPORT USING AIRCRAFT MEASUREMENTS OF POSITION, ALTITUDE AND GROUND SPEED

A/C POSN.	PRINCIPAL DATA LINK MESSAGES	ASSOCIATED CONTROL ACTIONS
0 - 1	Comm-B replies sent containing data groups 1, 3 and 7 (from Table 1). Group 1 data then included in all following replies.	Request to aircraft for identification, IAS and mass;then recomputation of most fuel-efficient descent point. Aircraft then requested to continue sending state-vector data in each reply.
1	Advisory message:"(SN 409) EXPECT TO START DESCENT 29NM BUN AT 250 KT IAS" Pilot acknowledgement:"(SN 409) ROGER"	Advisory message sent to aircraft.
1A	Crew requests: "ATIS FOR BUB" (BRUSSELS) Reply:" (SN 409) EBBR 0950 B RWY 25 L TRANS F050 WND 290/50, QNH 1008 T6 DP3 VIS 1.5 KM 3/050	Reply from data base.
2	Control instructs: "(SN 409) COMMENCE DESCENT AT 29NM BUN AT 250 KT IAS" Pilot acknowledgement : "(SN409) WILCO"	Control instruction sent.
2A	Advisory uplink: "(SN409) EXPECT TO TURN RT 5.5 NM BUN ON HDG 210"	Altitude rate checked from data; order in sequence modified by one slot and then advisory message sent. Continuous checking of turning point to give correct landing time.
3	Control instructs: "(SN409) AT 2.1 NM BUN TURN RT HDG 210 TO INTERCEPT ILS" Pilot acknowledgement: "(SN409) WILCO"	Instruction to start turn sent, timing within 6-12 sec. not too critical.
4	Control instructs: "(SN409) YOU ARE CLEARED TO LAND ON RWY 25L. CONTINUE DESCENT AT 160 KT IAS"	Aircraft noted more than 10 sec. ahead of planned time so minimum safe IAS requested.

NOTE : i) Only the technical address is included in each transaction - the a/c ID, SN409, would be added after the message contents and technical address have been received and verified.

ii) All of these typical messages will probably be transmitted in single or linked Comm-A and Comm-B messages. Exact requirements cannot be defined until addressing requirements are standardised.

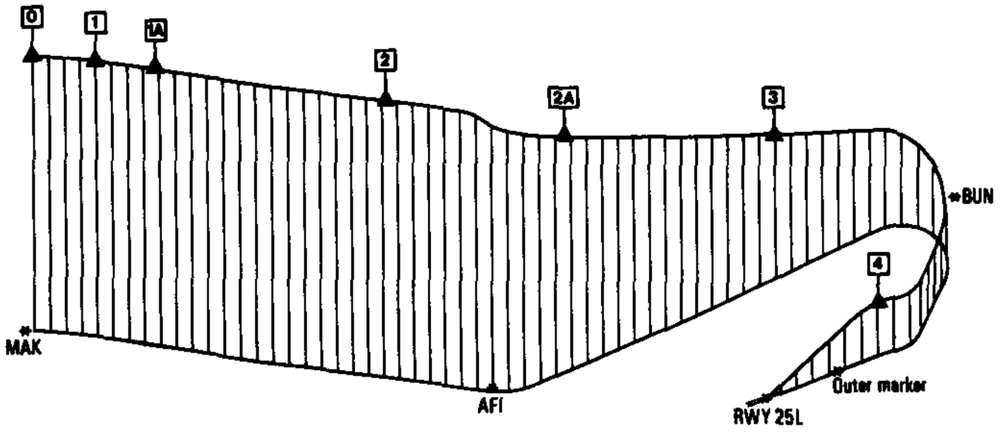

FIG. 9 - COMPUTER ASSISTED APPROACH SEQUENCING WITH DATA LINK SUPPORT

ITEM NO.	PARAMETER	BITS REQUIRED DATA ONLY	DATA + PARITY + SIGN/ STATUS MATRIX	GROUPINGS OF PARAMETERS FOR POSSIBLE APPLICATIONS											
				1	2	3	4	5	6	7	8	9	10	11	SPARES 12 - 32
				STATE-VECTOR	STATE-VECTOR(M)	LONG-TERM PREDICTION	LONG-TERM PREDICTION(M)	METEOROLOGY REPORT	METEOROLOGY REPORT (M)	FLIGHT IDENTIFICATION	CRUISE DATA	NEXT WAYPOINT REPORT	POSITION REPORT	POSITION REPORT (M)	
0	A/C IDENTIFICATION	48	-							48^0					
1	MAGNETIC HEADING	9	12	12	12	12	12								
2	ROLL ANGLE	9	12					5^1	5^1						
3	PITCH ANGLE	9	12												
4	MACH	11	14								14				
5	COMPUTED AIR SPEED	10	13			13	13								
6	TRUE AIR SPEED	11	14	14	14										
7	GROUND SPEED	12	15												
8	ALTITUDE RATE	9	12	12	12			5^2	5^2						
9	WIND SPEED	8	11					11	11						
10	WIND ANGLE	8	11					11	11						
11	DRIFT ANGLE	9	12								12				
12	TOTAL AIR TEMP.	9	12												
13	STATIC AIR TEMP.	9	12	12	12	12	12	12	12		12				
14	NORMAL ACCELERATION	8	11	6^3	6^3			6^3	6^3		6^3				
15	PRESENT POSN.-LAT.	18	21										21	21	
16	PRESENT POSN.-LONG.	18	21										21	21	
17	GROSS WEIGHT	11	14			14	14								
18	ALTITUDE(1013.25mb)	14	17										14^4	14^4	
19	ALTITUDE (BARO CORRECTED)	14	17												
20	GMT	-	-												
21	SELECTED ALTITUDE	11	14												
22	SELECTED AIR SPEED	8	11												
23	SELECTED VERT.SPEED	8	11												
24	SELECTED WAYPOINT	12	15												
25	(SELECTED LAT. (	17	20									20			
26	(WAYPOINT - LONG.	18	21									21			
27	TRACK ANGLE(TRUE)	9	12								12	12			
28/31	SPARES	TOTALS		56	56	51	51	50	50	48	56	53	56	56	

REMARKS

0) Standard Mode S format would be used.

1) Processed data showing angles exceeding approx. 5, 10 and 20°.

2) Processed data showing rates exceeding approx. 250, 500 and 1000 ft/min.

3) Processed data would show turbulence on a log.scale.

4) Reduced resolution would be adequate to show nearest FL.

M) Denotes use of metric units for speed/altitude reports.

TABLE 1 – AIRCRAFT PARAMETERS AND PROPOSED GROUPINGS FOR POSSIBLE USE IN FUTURE ATC SYSTEMS.

CP-410

SPACE-BASED MULTIFUNCTION RADAR SYSTEMS: FUTURE TOOL FOR CIVILIAN AND MILITARY SURVEILLANCE

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SUMMARY

Space-based surveillance systems, including primary radar (SBR) and secondary surveillance radar (SBSR) are of interest for both the Air Traffic Control and the Air Defence. This paper surveys the relevant state of the art, architectures considers surveillance system with special reference to the European scenario and closes with remarks pointing toward areas of future work.

1. INTRODUCTION

Satellite-borne radars became operational in 1978 with the SEASAT-A Synthetic Aperture Radar (SAR) which was the leader of the SIR (Shuttle Imaging Radar) family in the USA (1), (2); the European development in the Satellite-borne SAR includes the Active Microwave Instrument of the Earth Resource Satellite ERS-1 (1) and the X-band sensor (3) of the SIR-C SAR both to be launched at the end of this decade.

Incidentally; SEASAT and ERS-1 also include a radar altimeter (RA) to measure the distance from the underlying surface with errors of a few centimeters (1).

SAR systems are used for remote sensing and monitoring of slowly varying phenomena (tides, sea ice, crops, forestry, land use etc.) and are not suitable to survey large areas, such as a sub-continent, in a limited time (e.g. a few hours). As a matter of fact, the synthetic aperture principle itself, while allowing a relatively low average radiated power (orders of some hundreds of watts) limitates the width of the strip of surface to be imaged, i.e. of the "swath", to the order of magnitude of hundred kilometers for satellites (with height between 700 and 1000 Km) or even less for the Shuttle. Moreover, the data revewal time of a SAR is of the order of same days, depending upon the orbit.

On the other hand, from the beginning of this decade the space-based radar (SBR) concept is being considered by some authors (4-10) and by some military and civilian Authorities of the USA (5), (9) and Canadian (8), (13), (27).

The pertaining applications (4) include the defence of the fleet (5), of the Continental United States (CONUS) (5), the early warning of cruise and ballistic missiles, the Air Traffic Control (ATC) over the oceans (9) and on the CONUS (19), the monitoring of disarmament/arms control agreement and of crisis situation (7). Of course other application areas can be considered, for example in the Strategic Defence Initiative (SDI) context.

The surveillance requirements for each application are rather different, however they are all based upon the unique capability of SBR systems of detecting and tracking aircraft and missiles (even low/very low flying) without practical limitations of the line-of-sight.

For example, a satellite surveillance system compatible with today's ATC facilities (19) could extend ATC coverage in the USA and adjacent areas from the current minimum height of 2-3 Km up to ground level.

Moreover, a suitable selection of the number of platforms (e.g., six to fourteen) and of their orbit allow a coverage of the whole Earth (global coverage) (5), (7), or of extended areas where the installation of ground-based facilities is either impossible, like the Atlantic Ocean (9), or too expensive, like in desertic regions, jungle and so on.

2. MULTIFUNCTION SPACE-BASED SURVEILLANCE FOR EUROPEAN APPLICATIONS

2.1. The need for a multifunction, multi-user system

The very large cost of space-based system w.r.t. their ground-based counterpart lead to consider multifunction configurations, i.e. satisfying the requirements of many users, in order to share the cost.

For the same reason, there is a trend today to integrate Air Traffic Control and Air Defence equipment and systems, as resulted for instance by the recent joint Federal Aviation Administration (FAA) and United States Air Force (USAF) requirement for 48 L-band, three-dimensional long-range radars to upgrade surveillance around periphery of mainland USA (see: Electronics Weekly, May 29, 1985). Another example of civilian and military use of equipment and systems is the planned use of the SSR Mode S (16) in the USSR (18) including the following additional features w.r.t. the basic system under consideration by the ICAO (16):

i) Electronic beam steering of the interrogator;

ii) Ground-air transmission of computer generated vector commands for interception;

iii) Cryptography for secure air-ground-air data transmission.

As explained in the Introduction, SBR system typical coverages are as large as a subcontinent; one such system can fill the coverage gaps of the whole Europe and of a significant area (Artic, Mediterranea Sea, neighbour Atlantic Ocean). This calls for an European joint effort in research and development, with the same cooperation philosophy as the large research projects of the European Economic Community (EEC) or of the European Space Agency (ESA).

2.2. Military requirements

The military surveillance and tracking requirements for the European application can only be defined after an ad-hoc study; a baseline set of performances could be:

a) The radius of the coverage area, supposed to be circular, is about 5300 Km.

b) Surveillance is performed in a much smaller area than in item (a), including a fence and some spots where ground-based surveillance isn't effective and/or where potential threath originates (e.g. air fields and missiles installations); for convenience, the extension of this can be assumed equal to the one of an annular ring of 5300 Km radius and 200 Km thickness, i.e. 6.6×10^6 square kilometers.

c) The search data rate depend on the fence width, on the maximum speed of the targets and on the number of required detections in the fence to guarantee a cumulative probability of detection as large as 99.5%. A ~~second~~ data rate of fifty to sixty seconds insures at least four detection opportunities for a Mach 3 aircraft, more than twelve opportunities for a cruise missile or a low-elevation (terrain following) aircraft and one opportunity for a 4 Km/s ballistic missile (the latter being preferably detected, at lower speeds, just after the launch).

d) Friendly targets recognition is aided by the identification friend or foe (IFF) function, that uses the 1030-1090 MHz SSR channel and includes the same data link as the SSR Mode S (16), (17) or equivalent. The region where acquisition of friendly targets and relevant data transmission is required is generally different than the one described in item (a) and its area can be assumed such smaller (e.g. a tenth) due to the more predictable nature of this kind of traffic.

e) After identification, relevant targets are passed to the tracking function, whose most important requirements are accuracy and data rate. Both are highly dependant on the manoeuvrability (max. acceleration) and speed of the targets; for preliminary evaluation purposes, an x-y accuracy of the order of 30-50 metres and a data rate between 3 and 20 seconds (adapted to the type of target) could be assumed. The lower value of the data rate could apply to subsonic, highly manouvering low-elevation (over land) targets and the higher value to scarcely manoeuvering, high elevation targets.

f) To improve the track initialization and the resolution of crossing tracks, it is very likely that other information (than x, y location) be required. One such information is the speed, that can be extracted from the Doppler frequency when measured from two widely spaced radars. Another one, from cooperating targets, is the IFF/SSR code.
The third one is the elevation of the target, that in the case of non cooperating targets requires a 3D capability with height errors not greater than 500-1000 m.

g) The system shall be capable of detecting and tracking jammers by self-triangulation (i.e. exploiting the movement of its own platform) and/or by triangulation. It is desirable that the system include some redundancy and graceful degradation against anti-satellites (A-SAT) weaponry and against the electro-magnetic pulse (EMP) due to a nuclear blast.

2.3. Civilian requirements

There are three basic approaches to the ATC surveillance, namely:

i) the independent surveillance: it does not require any cooperation between the aircraft and the ATC systems and its sensor is the primary radar;

ii) the cooperative independent surveillance: it requires cooperation but is independent of aircraft's navigation system; its sensor is the SSR;

iii) the automatic dependent surveillance (ADS), based upon automatic read-out and presentation of aircraft navigation data; no pertaining system exist today, but satellite-based ADS systems have been proposed.

The ADS can lead to very interesting systems (from both the performance and the cost point of view), but does not comply with the general criterion of separating the main ATC function, i.e. the communication, the navigation and the surveillance, whose importance has been recognized by the International Civil Aviation Organization (22) in order to guarantee redundancy and cross-clock capabilities.

Therefore, only independent surveillance is considered in this paper. The ATC surveillance requirements can be divided in two classes pertaining to the Terminal Manoeuver Area (TMA) and to the En-Route ATC.

The dense, mixed and manoeuvring traffic of the TMA calls for greater accuracies and shorter data renewal intervals than the En-Route traffic. Today's En-Route ATC-Surveillance and tracking has data rates of 8 to 12 seconds and accuracies of 300-500 m (and even coarser near the maximum range, limited to 350-400 Km by the horizon).

The greater potential for space-based ATC surveillance is for the En-Route traffic, as the TMA surveillance can be expected to remain ground-based (i.e. utilizing the combination of the primary radar and of the SSR, generally corotating at the airport site).

Satellite systems, using the primary radar (9), the SSR (19) or both (20), (21) have been considered for ATC applications. As SSR transponders are carried on-board of most aircraft and their use is mandatory above 8.400 m (28.000 ft), the En-Route surveillance could rely, in principle on the SSR alone.
However, the SSR surveillance from the space can be affected by some significant facts, including:

a) The need for a top-mounted, circularly polarized antenna on the aircraft (for dual antenna operation with switching on the strongest interrogation).

b) The limited effective radiated power (EIRP) of the transponder (as low as 70-100 W in some cases).

c) Multipath, especially over sea, both in the interrogation and in the reply link.

d) Interference (fruit, garble), that could be significant during the transition period from the current SSR signal formats to the Mode S formats (notice that these phenomena should be very limited when the space-based surveillance does not overlay the ground-based surveillance).

In the Mode S operation the unsolicited replies (squitter) of the Mode S transponder could be used (19) in addition to, or instead of, the replies to a valid interrogation. The advantage of this technique is the saving of transmitted power (and hence the reduction of the cost of the space segment); the drawback is the loss of the "garble free" feature of the SSR Mode S and the need for special message formats to initialize the data transmission, these formats not being contained in the present Mode S draft standards.

3. SYSTEM OPTIONS AND TRADEOFFS

According to the overall requirements of the previous section, different system options can be considered.
The civilian requirements could be satisfied by a space-based secondary radar (SBSR) either including geosynchronous (at 36.000 km height) and geostationary (at 36.000 km height, on the equatorial plane) satellites or a constellation of lower-height, orbitating satellites. In both cases the power requirements on board are affordable, because they call for a peak transmitted power not greater than a few kilowatts with duty cycles below 8% - 10% (19), (20), (21). However, due to the limited radiated power of the transponder (see point (b) of the previous paragraph) the power budget in the 1090 MHz link in the geosynchronous-geostationary (GS) solution calls for a very large satellite antenna (53-55 dB gain corresponding to a diameter of over 50 m). Even with such a large antenna, the angular accuracy in the aircraft position location is very modest, i.e. corresponding to an rms error of the order of 10 Km or greater; this calls for a triangulation from two (using the height information from the transponder) or from three SBSR's thus increasing the system complexity and cost. Moreover, the large footprint (typically, 300 x 400 Km^2 wide) of the GS solution emphasizes the interference problems that have been quoted in the last part of the previous section.
A constellation of SBSR satellites eliminates most of the shortcomings of the GS solution but of course requires a greater number of satellites. By any means, the surveillance by SBSR only does not seem to be adequate for the small aircraft carrying just the belly-mounted L-band antenna, nor for some military aircraft that use time multiplexing between top and belly antennas.
To satisfy both civilian and military requirements, according to the concept of multifunction-multiuser systems, the SBSR surveillance has to be integrated with the primary radar one, i.e. with the SBR.
The SBR performance being affected by the fourth-power-of-the-range law (14), geostationary or high orbits (e.g. at 10.000 Km height) solutions cannot be considered (except for particular applications with very long dwell times) and a constellation of low-orbit satellites is the baseline solution.
The pertaining system architecture result from some fundamental choices listed hereafter.

a) Selection of height, type and inclination of the orbit.

Reducing the height for assigned dimensions of the antenna(s) means increasing the angular accuracy, reducing the footprint (and the pertinent SSR interferences) and reducing the transmitted power. On the other hand, the number of satellites, the maximum scan angle, the number of footprints to be scanned and the minimum grazing angle for a required coverage area tend to increase with the height decreasing.
Once the height of the orbit above the middle of the surveillance/tracking area (i.e. the Europe) has been fixed, the trade-off between a circular orbit and an ellyptical one should be considered, and the inclination of the orbital plane w.r.t. the equatorial one should be selected in order to maximize the weight that can be put into orbit by the selected vector (e.g. Ariane, the Shuttle or other). In this context, environmental effects should be taken into account, and basically the radiation dosage due to the Van Allen belts (5), (23) that could prevent from the use of highly-inclined orbits with height from 3000-4000 Km to 10.000 Km.

b) Selection of the operating frequency

While the SBSR frequencies are fixed by the worldwide ICAO standards for the SSR, the SBR frequencies can be selected within the radar bands. These frequency-dependent propagation phenomena should be taken into account:

i) Attenuation (in good and bad weather) (14)

ii) Faraday rotation (5), (15)

iii) Scintillation (26)

The former favours low frequencies, while Faraday rotation and scintillation increase as f^{-2} and favour high frequencies.
In most cases (5), (6), (8), (9) the trade-off lead to frequencies in the L or in the S band, i.e. in the classical bands of long-range radars where proven technology is available.

c) Selection of the number of satellites.

The number of satellites required for the assigned coverage and data rete (see the previous section) depend upon:

i) The height of the orbit.

ii) The maximum scan angle of the antenna.

iii) The use of triangulation.

The latter items requires some comments. The angular radar error from typical, low-elevation satellites (slant ranges up to 6000 Km) correspond to typical aircraft location errors, in the cross range direction, of the order of 3-6 Km for the SBR and of 1-2 Km for the SBSR. On the other band, typical range errors are one order of magnitude less (and even less, e.g. twenty or thirty times smaller, for SBSR). The use of two or three simultaneous range measurement to increase the position accuracy is attractive in these situations, the price to be paid being the increase of the number of satellites.

d) Selection of the antenna scanning law, type, polarisation and gain

Different types of antennas have been considered for SBR, including reflectors, space-fed arrays (lenses), corporate-fed planar arrays and active arrays (4), (5), (6). Possible scanning laws include slow scan (mechanical), fast scan (electronical), limited scan and full (e.g. by ± 60°) scan. Both single beam and multiple beams solution have to be considered. The number of footprints (beam positions) to be scanned during the transit time of each satellite over the coverage area, as well as the geometry of the problem, lead the selection. As far as polarisation is concerned, the requirement of lowering land/sea clutter power (for SBR) call for horizontal polarisation while the requirement of reducing reflections,especially for SBSR over sea, call for vertical polarisation (reflection coefficients over sea at 3° grazing angles and L-band are close to 0.99-0.98 for horizontal polarisation and close to 0.40 for horizontal polarisations (14)). Moreover, lowering rain clutter power call for circular polarisation.

e) Definition of the power budget and of the prime power.

A basic task of the SBR design is the minimisation of the power requirements (the ones of the SBSR being relatively negligible in an integrated system). The constant parameter of this optimisation process is the cumulative detection probability (25) for a target in the surveillance area (see item (b) of sect. 2.2), from which the single-look detection probability, and hence the transmitted power, can be evaluated after optimum number of looks.

As far as the prime power source is concerned, discarding nuclear sources for safety and acceptance reasons, the solar panels remain the only choice. Batteries should be included to guarantee 24 hr operation; their use results especially convenient for a limited (i.e. not global) coverage as they allow a significant reduction of the panels area; for the '90, batteries with 100 Wh capacity per Kg of mass are expected (10).

f) System management and data processing

This area includes:

i) Detection and confirmation strategy

ii) Primary radar/SSR (IFF) integration

iii) Acquisition and track-while-scan (TWS) management (including time sharing).
iv) On board vs. on ground data processing (for TWS)

v) SSR Mode S channel management.

g) Cost-effectiveness analysis

After the system definition, a detailed performance evaluation, possibly aided by computer simulation, and a life-cycle cost analysis should be carried out in order to verify that the considered solution is cost-effective with respect to an alternative one having the same performance, including ground-based long-range and low-altitude (gap-filler) radar stations, airborne radar systems (24) for the areas where ground stations cannot be installed and, subject to investigation, satellite-based passive sensors (in the optical, infrared or microwave frequencies) for surveillance beyond the airborne radar horizon.

4. A TYPICAL SYSTEM ARCHITECTURE

4.1. Overall system

From the requirements of section 2, the options of section 3 and some arbitrary choices, to be reevaluated in a further study (24), the following, preliminary architecture results:

a) A constellation of satellites in a circular, low (height of 750 - 1100 Km) orbit.

b) Radar operation in the L-band (1030-1090 MHz for the SBSR and between 1250 and 1350 MHz for the SBR), allowing a common antenna.

c) Number of satellites: from 8-10 (without triangulation) to 15-18 (with triangulation).

d) Antenna: phased array with full scan (angles up to ± 60°) in both planes, fast scan in one of 600 beam positions, two independent beams: one for the SBR (with horizontal polarization) and the other one for the SBSR (with vertical polarisation). Grazing angles: greater than 3° for SBSR and between 3° and 55° for SBR, limited by clutter and propagation.

Half-power beamwidth: about 0.6° in both planes, corresponding to a 700-900 square meters antenna (depending upon the aperture weighting) and to a maximum foot print dimension of 200 x 55 km^2 at the (minimum) grazing angle of 3°.

e) Prime power on board: in the tens of KW range, with batteries being charged for about 85% - 90% of the time, allowing the solar panel area to be reduced by the same amount w.r.t. a continuous operation (global coverage) case at the expense of an additional weight of some hundreds of kilograms.

f) SBR and SBSR operation thru the same antenna with two independently steerable beams and a basic period of 60 seconds.

i) SBR search: on 600 out of the about 10.000 beam positions (footprints), with 60 seconds revisit time and 50 milliseconds dwell time at the maximum range.

ii) SBR tracking (of-non-cooperating targets): on 100 beam positions, with revisit time from 3 to 20 s (average: 12.5 seconds) and dwell time from 10 to 50 ms (average: 30 milliseconds), both depending on the characteristics of the target. Sharing of 50% of the time between search and tracking.

iii) SBSR acquisition: by all-call interrogation (with a selectable interrogation beamwidth) or by hand-off of Mode S targets previously acquired by another SBSR.

iv) SBSR tracking (surveillance and data link) up to 10.000 Mode S targets with an average dwell time of 0.8 ms (actual values ranging from 1-2 ms at the smallest grazing angles to 0.1 - 0.2 ms at the greatest grazing angles) and an average revisit time of 8 seconds (revisit times anging from 2 to 16 seconds according to the target manoeuvrability and to the data transmission requirements).
(Note that electronic scan of the SBSR antenna not only does improve the data link capacity (17) but does allow an efficient time management because each beam position is scanned just when a reply is expected from that position, saving most of the round-trip time ("fast scan mode")).

4.2. Typical coverages

Let us consider for convenience the following orbital parameters.

i) Type of orbit: circular.

ii) Elevation 750 Km (i.e. the lowest compatible with a minimum grazing angle of 3° and a radius of the coverage area of 5300 Km).

iii) Inclination of the orbit: 75° with an ascending node of 0° longitude

Following a single satellite in its motion, some successive positions of the area that can be scanned by the antenna beams are shown in Figures 1, 2, 3, 4 pertaining to the satellite longitudes of 5°, 7°, 17° and 30° respectively showing the SBR/SBSR potential for very wide coverages even at relatively low orbits.

The dimensions of the footprint in a particular point of the coverage area (eastern Sicily) for an antenna beamwidth of 0.6° (25 x 25 to 30 x 30 m^2 aperture) are shown in Figures 5 and 6 for a satellite longitude of 5° and 15° respectively, showing the SBR/SBSR potential for high resolution and accuracy.

5. AREAS OF RESEARCH AND FURTHER STUDIES

The main areas of further study include system trade-offs and design, sub-systems and related technologies. The system areas have been referred to in the previous sections, and the main pertaining research should refer to:

- Optimisation of the overall system and cost-effectiveness analysis.
- Time-power management for SBR surveillance and tracking.
- Time management for SBSR surveillance, tracking and satellite-to-aircraft data link.
- On-board/on ground data processing trade-off and related data transmission requirements, including satellite-to-satellite links.
- Compensation of propagation effects.

The sub-system areas include:

- Target data (position, elevation and speed) measurement and related techniques (triangulation, superresolution, doppler frequency measurement, ambiguity solution, 3-D techniques etc.)
- SBR techniques (Moving Target Indicator and Synthetic Aperture modes, Displaced-Phase Centre Antennae, bistatic Vs. monostatic, ECCM, jammer location, waveform design and pulse compression, post-detection processing etc.).
- Phased array techniques (antenna configuration, beam steering and beam forming, adaptivity etc.).

The technological areas include:

- Prime power sources
- Very large scanning antennas
- Active array modules
- Beam forming networks
- Beam steering processors
- Fast on-board computers for radar management.
- Pulse compression/expansion networks
- Fast programmable signal processors.

6. CONCLUSION

Active microwave sensors have the unique capability of a long-range, all-weather, 24-hours operation in both a cooperating and a non-cooperating environment.

Combination of this capability with the practically unlimited field of view of satellite systems leads to very appealing satellite surveillance systems architectures, including space-based radars and space-based secondary radars for both civilian and military applications.

Relevant studies are being carried on in the USA (inter alia, at the Lincoln Laboratory of the MIT, at the Naval Research Laboratory, at the J.P.L. of the Caltech at the Federal Aviation Administration and in some big Companies) and in Canada (at the Communication Research Centre of the Canadian Government and in two Companies). Moreover, since 1985 the USSR has in operation two Radar Ocean Surveillance Satellites (RORSAT) for surveillance of ships and vessels.

A very preliminary surveillance system architecture for European applications has been described in this paper; it is felt that the multi-function and multi-users solution is the most suitable for such a large, space-based system.

An European cooperation effort would be required in order to develop this system, starting from a feasibility study and a workplan. Items to be early investigated include: (i) the potential users and the pertaining surveillance requirements, (ii) the characteristics and models of the targets and of the environment and (iii) the most critical technologies and techniques.

It is felt that now it is neither too early for a similar project to get started (as the critical technologies are developing very fastly, including MMIC and VLSI/VHPIC) nor too late, as the recent gap between Europe and USA/Canada in the area of space-based radar systems could be filled with a manageable effort and sinergistic utilisation of the conspicuous relevant know-how of the various European partners.

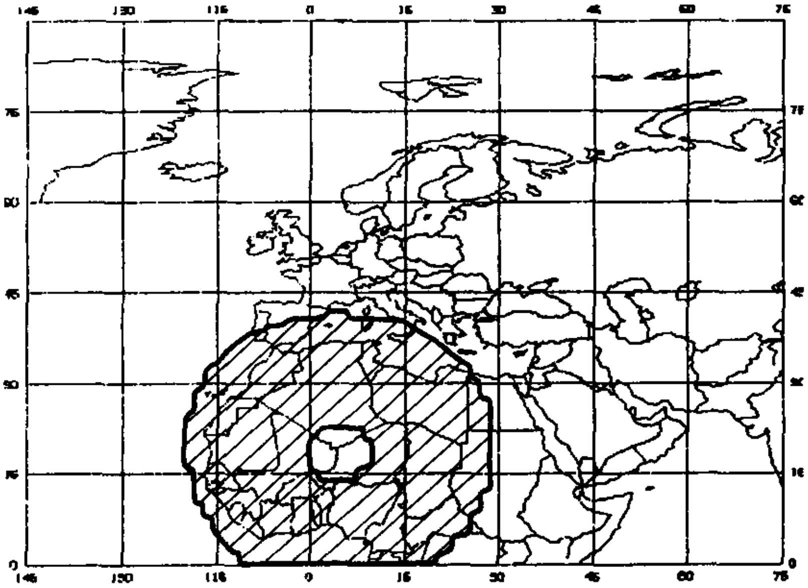

FIG. 1 - COVERAGE AT SATELLITE LONGITUDE 5°

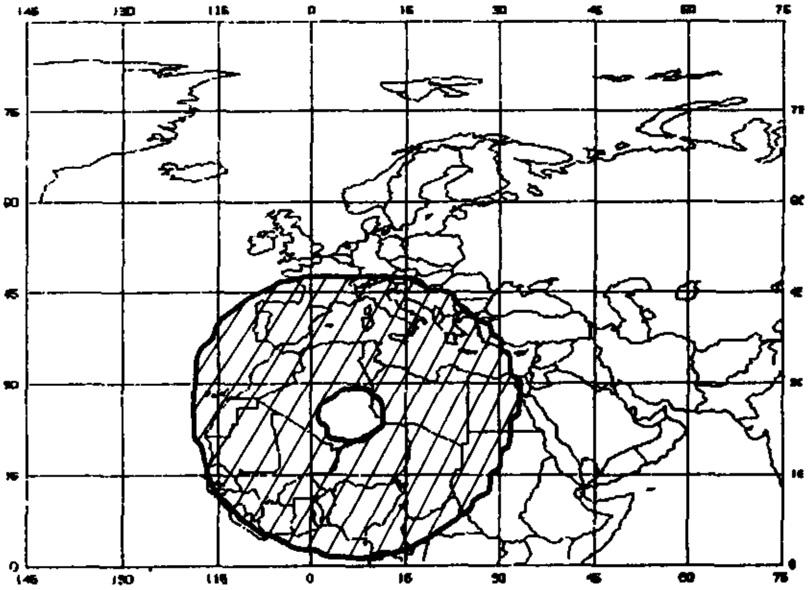

FIG. 2 - COVERAGE AT SATELLITE LONGITUDE 7°

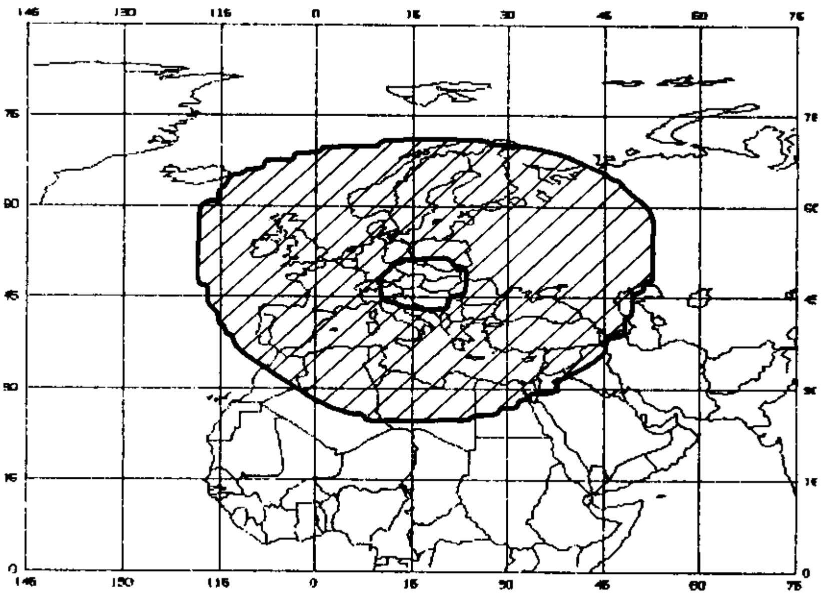

FIG. 3 - COVERAGE AT SATELLITE LONGITUDE 17°

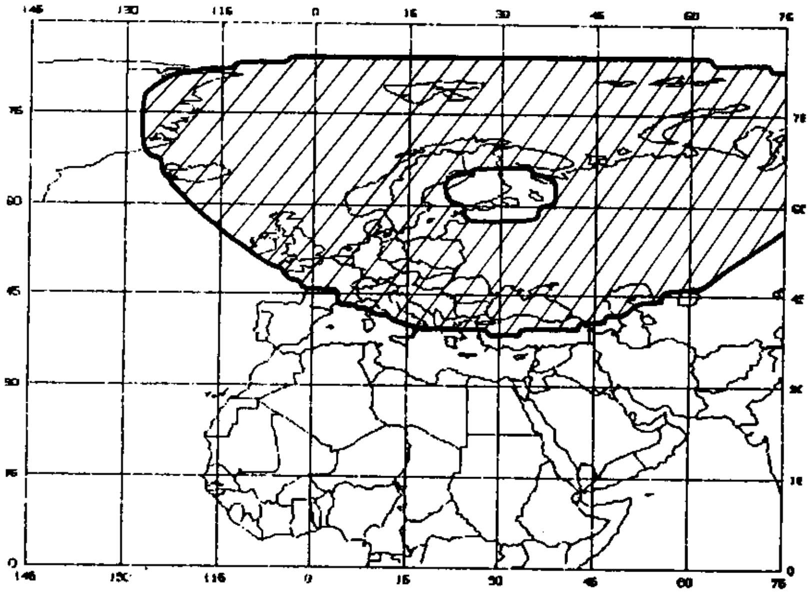

FIG. 4 - COVERAGE AT SATELLITE LONGITUDE 30°

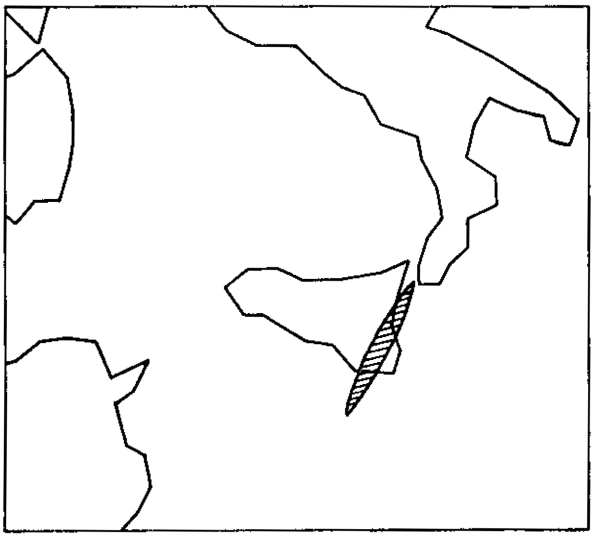

FIG. 5 - TYPICAL FOOTPRINT AT SATELLITE LONGITUDE 5°

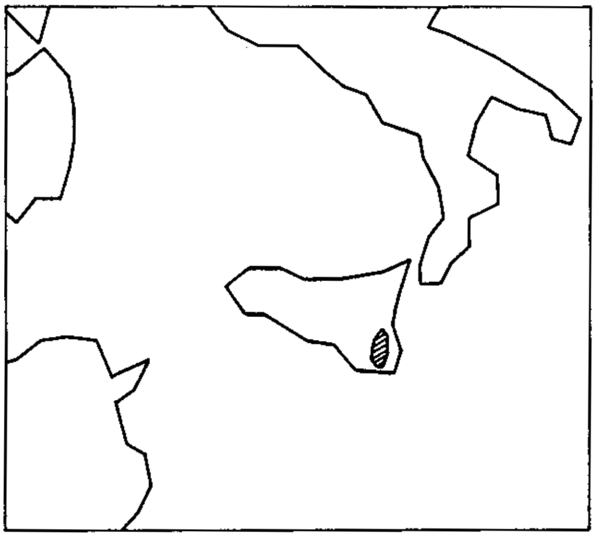

FIG. 6 - TYPICAL FOOTPRINT AT SATELLITE LONGITUDE 17°

REFERENCES

(1) T.D. Allan, ed.: "Satellite microwave remote sensing", Ellis Horwood Limited, Chicester, England, 1983.

(2) C. Elachi et. al: "Spaceborne Synthetic - Aperture Imaging Radars: Applications, Techniques and Technology", Proceedings of the IEEE, Vol. 70 No. 10, October 1982, pp 1174-1209.

(3) H. Ottl, F. Valdoni et. al. "The X-SAR Science Plan" DFVLR Mitteilung 85-17, ISSN 0176-7739, 5/12/1985.

(4) J.S. Avrin: "Space-Based Radar Prospects: An Overview", Military Electronics/Countermeasures, September 1981 and October 1981 (Part 2).

(5) E. Brookner, T.F. Mahoney: "Derivation of a satellite radar architecture for air surveillance", IEEE EASCON 1983, pp. 465-475.

(6) E. J. Kelly, G.B. Tsandoulas and V. Vitto: "A displaced phase centre antenna concept for space-based radar applications", Proc. of the Military Microwaves Conf., London, October 1984, pp. 154-164.

(7) L. Cantafio: "Space-Based Radar Concept for the Proposed United Nations International Satellite Monitoring Agency", Proc. of the Military Microwaves Conf., London, October 1984, pp. 165-174.

(8) J.S. Bird, A.W. Bridgewater: "Performance of Space-based radar in the presence of earth clutter", IEE Proc., Vol. 131, Pt.F, No. 5, August 1984, pp. 491-500.

(9) W.J. Caime: "Space-based radar applications to air traffic control", IEEE International Radar Conference, Washington, D.C., May 1985, pp. 312-321.

(10) P.K. Lee, T.F. Coffey: "Space-based bistatic radar: opportunity for future tactical air surveillance", IEEE International Radar Conference, Washington, D.C., May 1985, pp. 322-329.

(11) R.H. Martin: "A fundamental limitation on the swath coverage of pulse doppler space-based radars", paper 35-CAN-1 of the AC-243/Panel X/ RSG 3, 1985.

(12) R.H. Martin: "Advanced on-board signal processors", paper 36-CAN-2 of the AC-243/Panel X/RSG 3, 1985.

(13) B.J. Rook, J.S. Bird, A.W. Bridgewater: "Detection of near-earth target by space-based radar: development and use of computer simulations", CRC Report No. 1389, Ottawa, July 1985.

(14) L.V. Blake: "A guide to basic pulse-radar maximum-range calculation", NRL Reports No. 6930, Dec. 1969 (Part 1) and No. 7010; Dec. 1970 (Part 2).

(15) L.V. Blake: "Radar range-performance analysis", Lexington books, 1980.

(16) "SSR Mode S Beacon system: Functional Description" presented by C.A. Miller at the SICAS ICAO Panel, SICASP-WP/30, 16/5/1983 (revision of the ATC42-C report by Vincent Orlando of the MIT-Lincoln Lab.).

(17) "Application of electronic scanning antenna to SSR Mode S", COM/OPS/85 - IP/31, presented by Japan at the COM/OPS Meeting of the ICAO, Montreal, 4-28 Sept. 1985.

(18) P.J. Klass: "Soviet specialists view Mode-S radar for both ATC, Defense" Aviation Week and Space Technology, July 8, 1985, pp. 121-131.

(19) K.D. Mc Donald: "Development concerns for satellite-based Air Traffic Control surveillance systems" in Large Space Antenna Systems Technology", December 4, 1984 (available from ESA-IRS, 85 N23816).

(20) G. Galati: "Primary and secondary surveillance radars for Air Traffic Control: present and future", International Seminar on "Informatics in Air Traffic Control", Capri (Italy), 17-26 October 1985.

(21) G. Galati: "Present status and perspectives of ATC surveillance - First part: Radar Systems", presented at the national workshop of the Associazione Elettrotecnica Italiana (AEI) on "Air Navigation Aids", Milan, 27/2/1986.

(22) International Civil Aviation Organisation (ICAO): minutes of the Second Meeting of the Special Commitee on Future Air Navigation Systems (FANS), Montreal, April 1985.

(23) R.H. Martin: private communication, Rome, Jannuary 1986.

(24) A. Di Vito, G. Galati: "Performance evaluation of space-based primary and secondary surveillance radars for the European environment", in preparation.

(25) J.V. Di Franco, W.L. Rubin "Radar Detection", Chap. 13: Cumulative Detection Probability of Stationary and Moving Targets, Prentice Hall, Inc. Englewood Cliffs, New Jersey, 1968.

(26) R.A. Dana - D.L. Knepp: The impact of strong scintillation on Space Based Radar Design" IEEE Trans. on Aerospace and Electron. Syst. Vol. AES-19 No. 4, July 1983 (I part), and Vol. AES-22 No. 1, January 1986 (II part).

(27) "Canadian Firms to Study Surveillance Systems", Defense Electronic, July 1985, page 15.

CP 410

MONOPULSE SECONDARY RADAR : PRACTICAL REALIZATION AND ACHIEVEMENT

MODE S : THE RADAR OF TOMORROW

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SUMMARY

There can be no doubt that Mode S will be part of tomorrow's ATC radar. Its assets in terms of air traffic surveillance and data link are recalled. Fundamental characteristics are its comptatibility with existing SSR's, selective interrogation and monopulse reception. The monopulse SSR is a landmark in the transition towards Mode S ; it contributes several major improvements, without requiring onboard transponders to be changed. Choices made in the implementation of the system are discussed, in particular as regards the antenna, transmitter, reception and processing techniques. Through these options, full Mode S compability is maintained. Practical results have turned out to be conclusive, and so the system was taken into production and already many stations are operational round the world. The Mode S extension which has to be added to the monopulse radar is also described, and it is being operated at Orly as part of an experimental development programme.

INTRODUCTION

A review of the state-of-the-art techniques evidences that the Mode S is to be the key tool of air traffic control of the 90's. The United States have already embarked on an ambitious investment plan to provide the nation's entire upper air space with Mode S coverage by 1991. Besides, other nations among which the USSR, Japan, France, the United Kingdom, the Federal Republic of Germany and others are making advances towards Mode S implementation by conducting research and experimentation on the subject, or by setting-up monopulse secondary stations compatible with Mode S development.

The SICASP work group which was entrusted by ICAO with the drafting of regulations on Mode S, submitted the ''SARPS'' project (for standards and recommendations) for ICAO member states' approval. Guidelines, also called ''green pages'' and procedures related to Mode S are to complete the standardization plan by the year's end.

The general interest aroused by the Mode S is in great part explained by the remarkable progress which it makes possible in the control of air traffic and by the promising perspectives which it opens up in ground-to-air communications. Thanks to technological developments in radio frequencies and data processing, Mode S enables certain techniques to be applied which endow it with decisive and valuable assets.

ADVANTAGES OF THE MODE S

Safety is enhanced by Mode S utilization in traffic surveillance. The integrity and reliability of the information sent to the operational centre is greatly improved by the choice of signal formatting, message structures, protecting devices, as well as the nature of protocols and processing used. The monopulse reception and single address selective interrogation techniques greatly improve results in detection, locating and identification of aircraft. The better performance is far more evident and tangible in area of dense traffic, where the conventional secondary radar's shortcomings are clear. Thus traffic management is streamlined and optimized by the reduction of separation minima, which allows an increase in the system's total capacity and an appreciable reduction of fuel consumption.

The bi-directional data link used in Mode S offers considerable application potential. It may be a very valuable aid in the individual management of flights, and, on a par with VHF or satellite links, it may usefully convey technical and meteorological information or even information of quite a different nature, possibly strategic, too, in another context. Most probably, the first applications are likely to be as follows :

- Up-link : safeguarding of the VHF instructions, clearance, flight level allocation, information extracted from the ground data bank (meteorological by example), etc.,
- Down-link : flight plan number, temperature and airspeed measurements, aircraft key parameters, (bearing, horizontal and vertical speed, rolling). This last type of information may be useful also when it comes to refining the tracking predictions at ground station level.

Another important asset of Mode S is its compatibility with the ACAS airborne anti-collision system which radiates signals having the same formats, and which incorporates a Mode S transponder. With these different advantages, Modes S makes real headway towards the full automation of air traffic control.

RECALL OF PRINCIPLES

SSR COMPATIBILITY

The definition of Mode S techniques was to a large extent influenced by the need for total compatibility with other SSR. Thus, at all times transponders and Mode S stations may be integrated into an existing SSR environment.

Compatibility in practice means having two fundamental characteristics :

- Continuity in surveillance : SSR stations just like Mode S stations can perfectly well handle aircraft equipped with SSR transponders and aircraft having Mode S transponders. Figure 1 shows the nature of interrogations and replies exchanged.
- Coexistence of two radio-electric systems, operating on the same transmission frequency (1030 MHz) and reception frequency (1090 MHz) : the performance of each system is not perturbed by interference from the other system (this is seen from the rate of asynchronous replies, transponder inhibition time and detection probability).

SELECTIVE INTERROGATION

Selective interrogation is the very essence of Mode S. It is the outcome of techniques previously studied : the DABS in the USA, and the ADSEL technique in the United Kingdom. In the conventional SSR, interrogation is aimed at all the aircraft found in the antenna's directional lobe. This results in overlapping replies, sometimes very difficult to sort out, whenever aircraft are close together. In the new system a once-and-for-all address is aimed at each aircraft having a mode S transponder. Coding is on 24 bits, hence allowing for 16 million different combinations. This type of address makes it possible to keep track of aircraft by means of individual interrogations (called ''roll-call'') and to set up a data link with each of them. The way roll-call interrogations are sequenced is such as to avoid any overlapping of replies, thus averting altogether risks of synchronous garbling.

A mode S station transmission pattern is in fact an alternation of selective roll-call interrogations with general ''all-call'' interrogations. The latter are sent out to control those aircraft which are equipped with conventional SSR transponders, and also to establish the initial acquisition of Mode S transponders equipped aircraft as they enter into the radar's area of responsibility and whose individual address is not yet known. Once this contact is established, the ground station sends out to the Mode S transponder an order to lock out on its all-call interrogation thus the transponder no longer transmits interfering replies.

NATURE OF INTERROGATIONS AND REPLIES

Figure 2 shows the formats of the various interrogations and replies exchanged between the Mode S station and transponders ; there are 2 types of interrogations.

- Intermode interrogations (figure 2.a) : these are derived from conventional SSR interrogations, the only difference lying in the addition of another P4 pulse, which is of variable length. The coding of these interrogations is unchanged and is determined by the spacing between pulses P1 and P3. In response to these interrogations, an SSR transponder will ignore P4 and send out its reply normally. The Mode S transponder, on the other hand, will react to P4 according to its duration. It will not reply to an interrogation when meeting a short P4 pulse (0.8 µs long,SSR only all-call type interrogation). It will reply to a long P4 pulse interrogation by sending out its address (1.6 µs long, Mode S/A or C all-call type interrogation). A pulse P2 is transmitted on the control channel to inhibit transponders receiving interrogations from the side lobes (ISLS). Another pulse, P1, may also be transmitted on the same channel to reduce effects of reflected interrogations (IISLS process).

- Mode S interrogations (figure 2.b) : these are exclusively used for Mode S transponders. They are made up of three pulses : P1, P2 and P6. The first two inhibit the SSR transponders, which consequently is not triggered off at the third pulse unnecessarely. The third pulse P6 contains information coded by DPSK modulation (differential phase shift keying) ; this is well-adapted to this kind of transmission because of its immunity to interference and to multipaths effects. Data are coded on 56, or 112 bits and the last 24 bits are a combination of the aircraft target address with a sophisticated polynomial parity calculation. The error detection device causes the interrogation to be rejected by the transponder if the message received is incorrect. Mode S interrogations are of two different types :

  Like the Mode S/A or C all-call intermode interrogation, the Mode S only all-call interrogation, is unaddressed and used for initial acquisition of aircraft before their address is known by the station.

  Roll-call interrogations fall into one of the following three categories :

  - Simple surveillance type interrogations requesting altitude or Mode A code (56 bits long).
  - The same interrogations as above, to which are added 56 data bits, called comm A (112 bits long).
  - Extended length messages, 112 bits long including 80 data bits, which may be chained together in groups of 1 to 16 called comm C, to be used for data link applications requiring high capacities.

  Another pulse P5 is also radiated on the control channel so as to cancel replies to interrogations on side-lobes by masking the phase reversal synchronization signal of P6 pulse.

  Mode S transponder sends out a conventional reply (figure 2.d) to SSR stations and this reply consists of two framing pulses F1 and F2 plus 12 code pulses. As for its response to Mode S stations, (intermode or Mode S specific) it consists of a preamble of 4 pulses followed by PPM modulated coded information. (See figure 2.c). Using this modulation, as well as an error correction device based on the same polynomial and cyclical method up to transmission, leads to a very high probability of correct decoding even with interfering SSR replies. The replies are classed in the same kind of categories as the interrogations : simple surveillance reply with 56 bits, Comm B with 112 bits and Comm D messages which may be chained together in groups of 1 to 16.

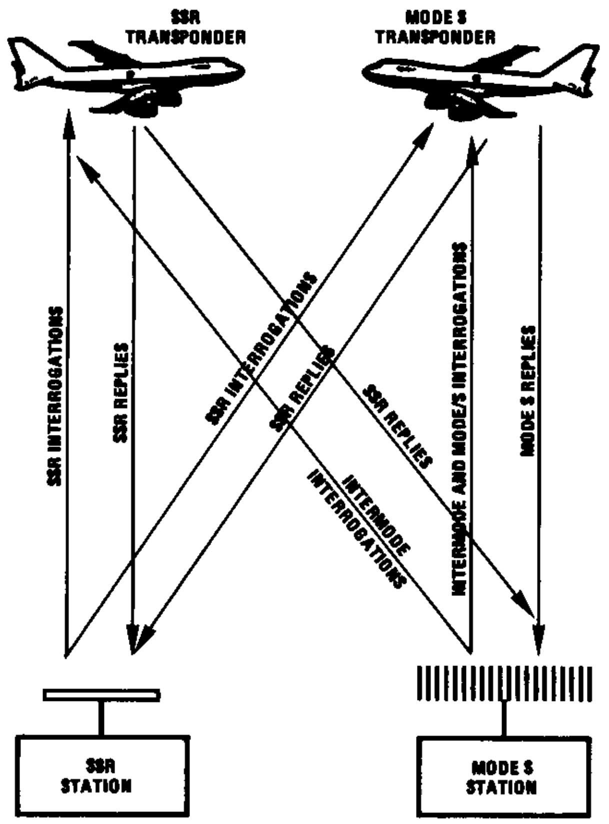


Fig 1 COMPATIBILITY BETWEEN SSR AND MODES

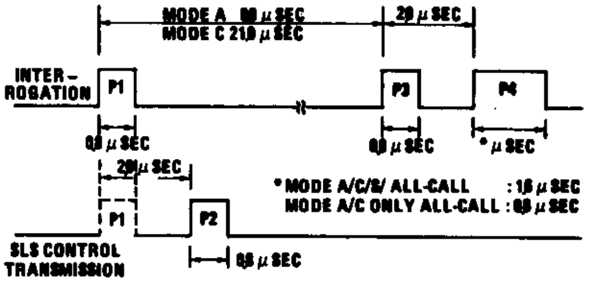


Fig 2-a INTERMODE INTERROGATION

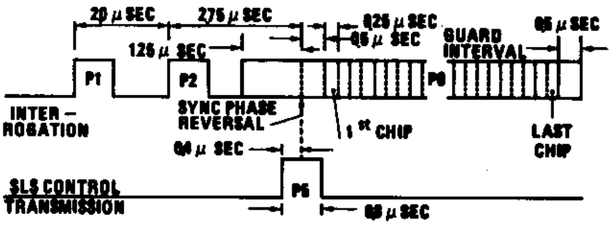


Fig 2-b MODES INTERROGATION

Fig 2.c SSR REPLY

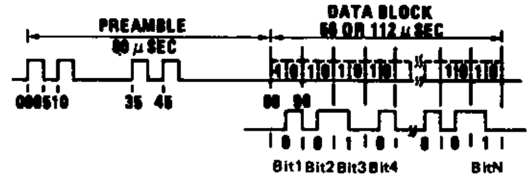
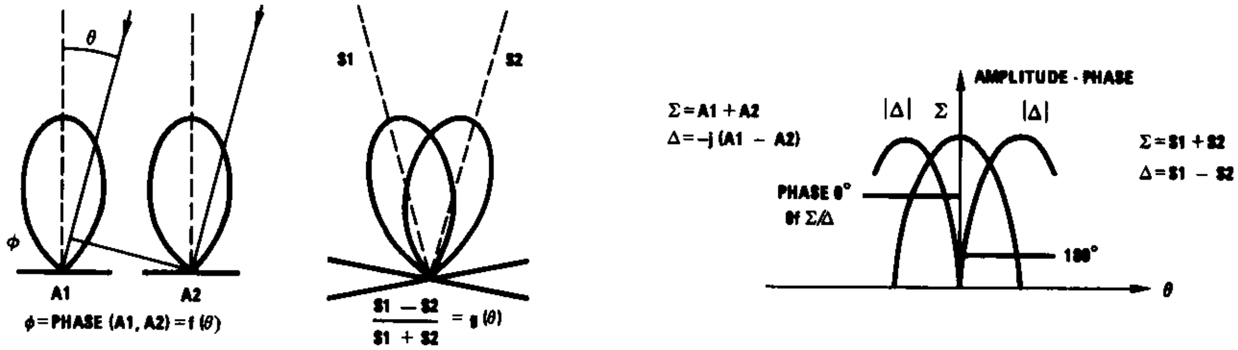


Fig 2 .d MODE S REPLY



PHASE SENSOR – 3A

AMPLITUDE SENSOR – 3B

SUM AND DIFFERENCE PATTERNS – 3C

Fig 3 MONOPULSE PRINCIPLE

MONOPULSE RECEPTION

The monopulse technique gives an off-boresight angle information on all signals received, that is to say, it gives the angle between the transponder bearing and the antenna axis. Theoretically, the monopulse technique can be classified into the phase monopulse and the amplitude monopulse. In the phase technique, similarly to what is observed in interferometry, the phase difference between two signals received on two ''antennas'' having different phase centres is measured (figure 3.a). This is due to the path difference when the source is not on the axis of the ''antennas''. In amplitude monopulse, the amplitude is measured between two signals received on two ''antennas'', which have different boresights but the same phase centre (figure 3.b). Yet, theoretically, these two monopulse techniques are considered to be related, since, by combining signals it is possible to switch from one to the other.

In practice, a monopulse antenna produces two specific patterns (sum channel Σ and difference channel Δ), which may be viewed as a combination of the amplitude and phase patterns, although, in actual fact, the creation of the patterns by the antennas is more complex (figure 3.c). The sum channel is used in the conventional way for interrogation and detection of replies in the antenna lobe. Since the amplitude of the difference channel in the main lobe varies rapidly, it is used to measure accurately and unambiguously the off-boresight angle of the received signal. This measurement must be scaled by the amplitude received on channel Σ so as to make it independent from the signal power. Monopulse receivers estimate the off-boresight angle voltage, proportional to log Δ/Σ, or $\Phi = \text{Phase}\ (\Sigma+j\Delta/\Sigma-j\Delta) = 2\ \text{tg}^{-1}\ \Delta/\Sigma$

With the monopulse technique, therefore, it is possible to locate accurately an aircraft, on receiving only one reply from its transponder and as a result :

- The fundamental requirement for Mode S is satisfied, namely, the ability to provide surveillance of Mode S transponders with a single hit per antenna scan.
- To achieve considerable progress in the surveillance of SSR transponder equipped aircraft, compared with the results given by conventional sliding window processing techniques. The decisive advantage of the monopulse SSR, which is particularly noticeable in areas of dense traffic or interference, lies in the greater azimuth accuracy and better discrimination between targets close together, by processing garbled replies. This also introduces a valuable reduction in the interrogation frequency (a ratio of 2 to 3 is typical).

PROJECTS UNDERWAY IN FRANCE

Work began in France in the seventies, on request by the French Civil Aviation Technical Department (STNA). A first stage involved integrating secondary monopulse sources onto L-band primary antennas, and evaluating a monopulse SSR reception and processing chain. Then the specifications for a Mode S station were laid down, by defining the following two complementary sub-systems :

1. The monopulse secondary radar comprising antenna, interrogator-receiver and the SSR aircraft surveillance processing.
2. The Mode S extension which, once integrated, completely manages the station's operation : sequencing of interrogation/replies, Mode S transponder surveillance, data link, etc.

With this approach, it was possible to define and implement a monopulse secondary radar genuinely compatible with transition to Mode S. Introducing the monopulse technique has entailed a complete review of the entire secondary radar chain. As a result, certain fundamental technical options were taken : the integrated primary antenna was left aside, in favour of the LVA, preference being given to phase reception over amplitude reception, and sophisticated digital decoding, fully programmed post-processing and tracking were chosen.

This radar was experimented at Orly Airport and fully approved. It was then put into production, and it was the very first operational monopulse radar, when the Linz station was inaugurated in 1984. Since, it has also been installed to equip :

- En-route stations with L-band primary radars (figure 7),
- Approach stations with S-band primary radars (figure 8),
- Autonomous secondary stations (figure 9).

The Mode S extension is incorporated into the experimental station at Orly. It is soon to be used in further experiments carried out jointly by the STNA and the CAA on the one hand, since they supply the ground stations and on the other hand EUROCONTROL who is likely to provide a number of aircraft from AIR FRANCE and BRITISH AIRWAYS with Mode S transponders.

SYSTEM DESCRIPTION

An example of Mode S station block diagram is given in figure 4.

The parts belonging to the monopulse station as it is proposed today are shown in white, while the grey parts show the items to be incorporated to make the station fully Mode S operational.

MONOPULSE SECONDARY RADAR STATION

When the system was being defined, design was influenced by the following aims :

- To optimize performance through appropriate technical and technological choices (for example, opting for a phase receiver, and for an entirely solid-state transmitter).

- To warrant complete compatibility with Mode S specifications, taking all necessary precautions to avoid restrictions that would result from certain future developments (for example : stability of the transmission frequency at ± 10 KHz, integration of DPSK modulation).

- To guarantee the greatest possible adaptability to the site, for example, automatic processing to guard against reflections.

- To seek maximum availability by duplicating all operational electronic equipment and by imposing stringent reliability constraints.

- To reduce purchase, running and complete life-cycle costs, through the modular design and through a suitable maintenance policy (for example by implementing remote control and remote monitoring).

ANTENNA

Guided by the experience already gained in monopulse radar technology and subsequently to experiments made with integrated primary antennas, a choice was soon made in favour of a Large Vertical Aperture type antenna (LVA). This antenna has two major characteristics aimed at ensuring maximum stability in the measurement of the aircraft's off-boresight angle independently of the elevation angle and which also have the effect of reducing to the minimum the effects of ground reflected signals (1) :

- A gain variation in elevation identical (parallel) in Σ and Δ patterns which are used for monopulse measurement.

- A sharp ground roll-off (gain decrease along the horizon) better than 1.8° per dB.

The antenna's efficiency in coping with multipaths has been evidenced at the mountainous site of Kiona (Cyprus), which was characterized by reflections of all kinds.

The monopulse antenna is made up of an array of vertical-polarized radiating feeds, arranged in columns. The amplitude/phase distribution on the columns has been designed to control the azimuth shape in the 3 patterns, i.e. : the sum Σ, the difference Δ and the control Ω (figure 5). The pattern in elevation is shaped by the power distribution equivalent on feeds which is identical in all columns, providing an elevation pattern optimized according to a cosecant squared law. The fact that all three patterns are generated using the same columns implies that there will be equivalent variation of patterns in elevation, while the phase centres will always be kept identical.

The antenna position data take-off is coded on 14 bits. Such accuracy is necessary in view of the coding accuracy achieved for the off-boresight angle information by the processing equipment. The rotary joint and antenna down lead cause remarkably little loss, are highly stable in phase especially in an environment of temperature changes, and do not need any periodic checking.

RECEIVER

The off-boresight angle measurement which is carried out in the receiver is in fact a true angle measurement, which is not the case in applications of the type ''tracking radar'', where the aim is simply to keep the target in the antenna axis. The receiver is well suited to both antenna types mentioned above, the integrated primary antenna and the LVA antenna. For both antennas, the off-boresight angle is calculated from the Σ and Δ RF signals. Along the antenna axis, Δ becomes null and the Σ and Δ relative phase Ω rotates by 180° on crossing the axis.

Today, two main techniques are implemented to extract the angular information : the amplitude comparison method and the phase comparison method. The first is to produce logarithmic videos log $|\Sigma|$ and log $|\Delta|$, and to compute the difference, which gives log $|\Delta|/|\Sigma|$. The log $|\Delta|/|\Sigma|$ measurement indicates at what angle the aircraft is situated with respect to the antenna axis ; however, at this stage it is not known whether this is to the right or to the left i.e. whether it is a + or - sign (figure 6.a). The right/left (+ or -) information is given by measurement of the relative phase between Σ and Δ. The second technique, consists in combining the Δ and Σ signals into phase quadrature, using a hybrid coupler, which gives the combined $\Sigma+j\Delta$ and $\Sigma-j\Delta$ signals. The off-boresight measurement involves a phase measurement on the one hand between Σ and $\Sigma+j\Delta$ and on the other hand between Σ and $\Sigma-j\Delta$; and the results are summed so as to obtain the phase angle between $\Sigma-j\Delta$ and $\Sigma+j\Delta$ (figure 6.c). These angles are measured in amplitude-phase detectors after passing through limiters. It gives a continuous, monotonic curve near or on the axis between the off-boresight output voltage and the off-boresight angle (figure 6.b).

After much experimenting with the two techniques, the choice was finally made in favour of the phase technique.

Evaluations conducted in France with calibration and normal traffic flights have evidenced the greater accuracy of the half-angle processor, because one of the amplitude receiver's characteristics is that it gives sign errors at the lobe centre. Test flights effected as part of comparative studies by the FAA have led to similar conclusions. In fact, the difference in performance is quite obvious as regards the surveillance of aircraft equipped with Mode S transponders (2).

This difference may be explained in several ways.

In theory, the monopulse receiver combines two signals, which are two complex, but usual, expressions :

$$\Sigma = \Sigma o \text{ exp. } j\ (wt + \emptyset\Sigma) \quad \text{and} \quad \Delta = \Delta o \text{ exp. } j\ (wt + \emptyset\Delta)$$

An ideal receiver would work out the complex relationship

$$\frac{\Delta}{\Sigma} = \frac{\Delta o}{\Sigma o} \exp j\ (\emptyset\Delta - \emptyset\Sigma)$$

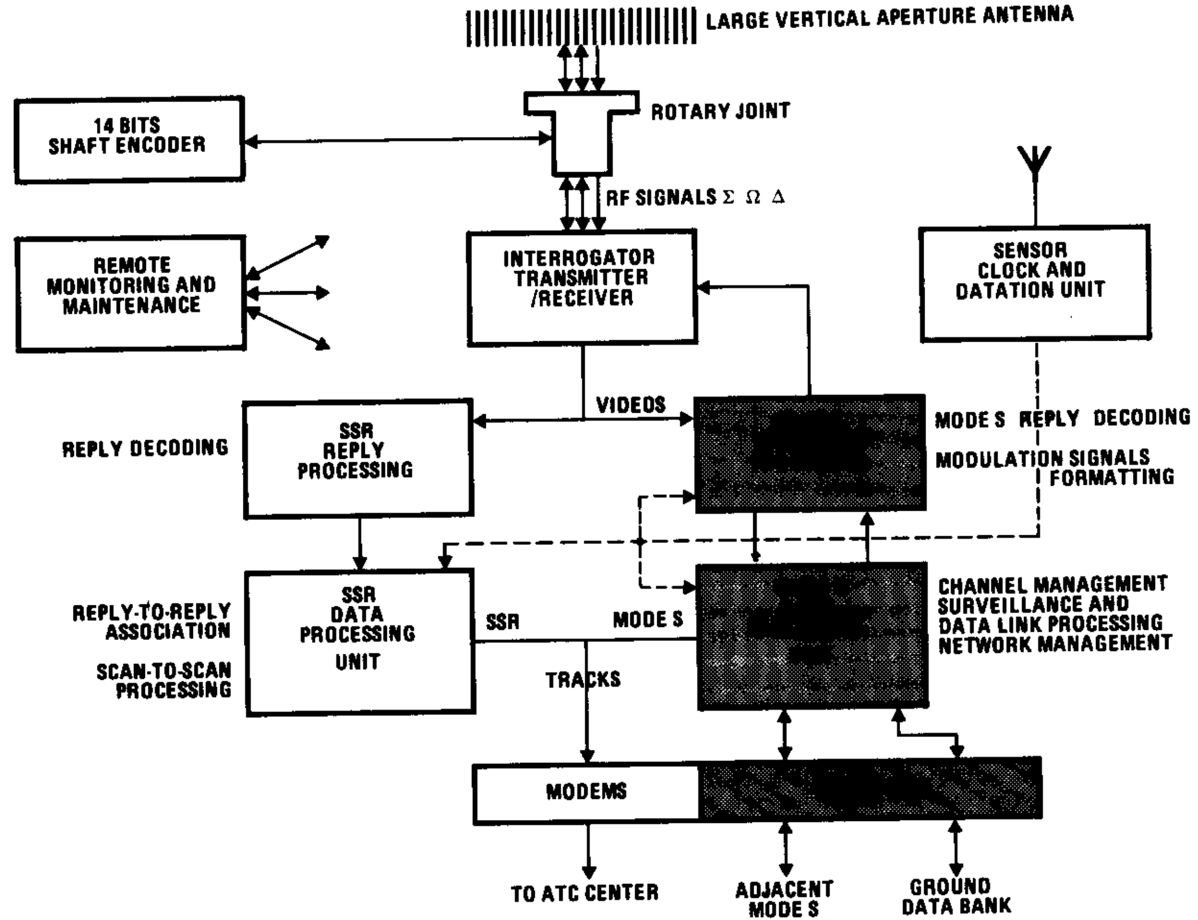


FIG 4 EXAMPLE OF MODE S STATION BLOCK DIAGRAM

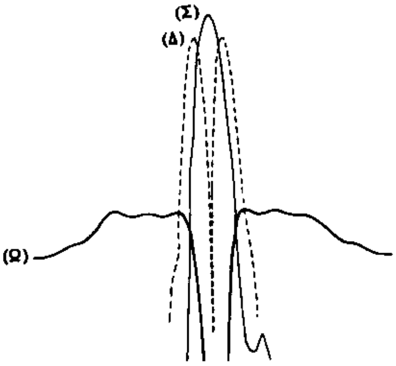


Fig 5 ANTENNA PATTERNS

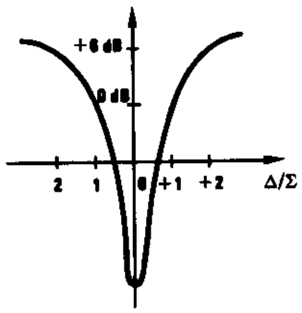


Fig 6a AMPLITUDE RECEIVER CURVE

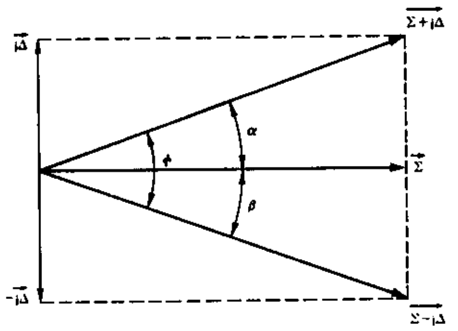


Fig 6c PHASE RECEIVER PRINCIPLE

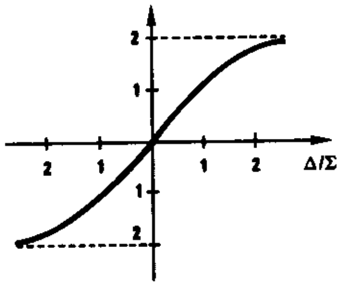


Fig 6b PHASE RECEIVER CURVE

but would only evaluate at the output the real component (3) :

$$\mathrm{Re}\left(\frac{\Delta}{\Sigma}\right) = \frac{\Delta o}{\Sigma o} \cos(\phi\Delta - \phi\Sigma)$$

which, for an ideal antenna ($\phi\Sigma = 0$, $\phi\Delta = 0$ or 180°)

would give : $\mathrm{Re}\left(\frac{\Delta}{\Sigma}\right) = \pm \frac{\Delta o}{\Sigma o}$ (Y)

The receivers described above naturally have different characteristics from an ideal receiver. Yet an analysis of the phase receiver transfer function reveals that its curve is very close to that of an ideal receiver, in particular at the lobe centre. This explains the high quality of performance achieved even when errors are present, whether they be caused by several targets, by multipath or by noise.

NB :

At a first approximation, the influence of noise, in terms of standard deviation off-axis difference is :

$$\sigma_\theta = \frac{\theta_o}{k\sqrt{2n\ S/N}} \left(1 + (k_m\ \theta/\theta o)^2\right)^{1/2}$$

where : σ_θ : standard deviation of the angle error   k : monopulse curve slope at the target angle

θ_o : beamwidth k_m : averaged monopulse slope

S/N : single pulse signal to noise ratio θ : off-boresight angle

Conversely, the amplitude receiver, which is characterized by a totally discontinuous curve at the centre, does not behave like an ideal receiver. Theoretical investigations demonstrate that measurement is degraded by up to 3 dB for signal-to-noise ratios from 10 to 20 dB (4).

In practice, two main difficulties beset the implementation of the amplitude receiver. First, circuits providing log Σ and log Δ videos, which must imperatively be matched with a difference of much less than 1 dB, do not have strictly logarithmic characteristics. This results in an accuracy error throughout the beamwidth and in particular on the beam edges. Also, measurements taken at the lobe centre are made directly on the Δ signal, which becomes cancelled, and this is technically difficult to achieve, as it involves errors in value and in sign. This drawback occurs at a point even where the energy received is at its highest and the effect of interference minimum.

A receiver of the type half-angle processor was chosen, therefore, considering its better performance and also for the following reasons :

- The stability of measurement, in time, combined with the reliability of the technique, have shown that this system needed absolutely no periodical recalibration.
- Despite its apparent complexity, the system in actual fact requires only three limited amplifiers and only one additional phase detector, it entails absolutely no extra training cost or particular maintenance means.
- The signals observed on the off-boresight video are of excellent quality and in particular, the zone where the signal is sampled by the extractor is wide and stable compared to the pulse leading edge.
- The required accuracy is obtained in the frequency range 1087 to 1093 MHz, which is the ICAO's tolerance concerning transponders. In fact, the accuracy is preserved within a ± 5 MHz margin, since the off-boresight angle curve changes but little with the frequency. Hence, it is possible to guarantee the same accuracy on transponders even transmitting outside the specified limits.
- The low-noise RF amplifiers at the input confer on the system a very wide dynamic range.

  Furthermore the receiver provides the log |Σ|, log |Δ| and log |Ω| videos and these are used in an RSLS device which compares these various signals. It is fitted with a digital STC (Sensitive Time Control), programmable in range and azimuth which allows the radar to be adapted to the site by selecting the right sensitivity.

INTERROGATOR :

The interrogator may either be driven internally, in normal SSR operation or driven externally when transmitting Mode S interrogations. The transmitter is entirely solid-state and has the following characteristics, which are indispensable to Mode S operation :

- Tolerance on the transmission frequency (1030 MHz) is less than ± 10 KHz.
- The transmitter may be fitted with two independent transmission channels : for Σ and Ω. The ISLS technique and the IISLS technique may be used respectively in mode S and in SSR. The IISLS technique is used in such a case only for small sectors finely programmable in azimuth and located in the direction of reflector planes.
- All Σ transmission channels are systematically fitted with a DPSK phase modulator to transmit P6 pulses.

Form factor is another fundamental aspect of the transmitter. It is mainly determined by the interrogation rate of the radiated Mode S, because the influence of intermode interrogations is quite weak ≈ 0.5 %. Specifications chosen are :

- 2 % mean rate over a long period of time (longer than the antenna rotation period).
- Up to 50 % on a small number of consecutive interrogations.

They make it possible to control over 400 aircraft having Mode S transponders, while also allowing the transmission during an antenna scan of chained Comm A messages (up to 4 with each of them) or the partial transmission of ELM (comm C) messages. The short term rates offer the capability of coping with heavy sectorial loads and to keep a great flexibility in the sequencing of interrogation replies and of re-interrogation in the lobe if the first transaction has failed. These assumptions are quite adequate in view of medium term applications foreseeable in data links, and they may be put into practice at a reduced cost thanks to progresses made in RF power transistors technology. The power output may be varied dynamically either in sectors in SSR operation or selectively on each interrogation when in Mode S operation.

SSR PROCESSING - OUTLINE (figure 10)

The object is to provide, for each antenna scan and for each aircraft within the radar coverage and equipped with an active transponder, a single message combining all the radar information concerning this aircraft. Basically, such information comprises the target coordinates, its heading and speed, the codes detected for each interrogation mode and possibly the time for the reception of the plot. To do this, at the entry of the processing system, the video signals sent by the receiver and the various regular data such as antenna position, interrogation mode and time if needed are collected. The plot history data established over several antenna scans are also made available.

The processing technique used is radically different from the conventional sliding window techniques. The latter are based on the range correlation of replies, applying a criterion of K detected presences out of n consecutive interrogations. In the conventional method, the plot azimuth is calculated from the median value between the azimuth of the first detected reply and the azimuth of the last detected reply, which is quite the least accurate when it comes to detection problems on the edge of the lobe. Also, with this technique, the discrimination between 2 plots at the same range is not satisfactory because it is difficult to distinguish between one aircraft's reply and another's.

The fundamentally innovative aspect of the monopulse technique is in the additional target location information within the antenna beam (off-boresight angle or OBA). With this signal, it becomes possible to calculate for each reply the target coordinates, thus correlating in azimuth the various replies from one interrogation to the next, and to process the codes far more comprehensively then is possible with conventional algorithms. Processing, although it should be conceived of globally, may be analyzed in three parts : reply processing i.e. decoding of SSR elementary replies, the association of these replies from recurrence to recurrence, or reply-to-reply processing, and scan-to-scan processing.

DECODING OF ELEMENTARY REPLIES

The aim is to detect SSR replies and to collect all the information necessary to process them into plots (range, code, OBA...). Hence the decoder simultaneously processes the sum, RSLS and OBA measurement video signals.

The sum video is used to seek out the framing pulses F_1 and F_2. Presences thus detected are kept if the RSLS video indicates that the signal has been received on the main lobe, not on the side lobe. Garbled replies, i.e. those replies which are separated from others by less than 24.65 µs are marked by special bits and a specific post processing is applied to them.

The interesting feature of the decoding process is that all the code, amplitude and OBA measurement pulses are simultaneously analyzed. The quantified sum video and the digitally coded OBA video are sent on digital delay lines (there is one per bit) especially designed as a gate array and having outputs every 1.45 µs. (spacing between code pulses). Parallel decoding enables a greater number of data to be taken into account to be used in post-processing than would be possible with serial decoding. Moreover, the data are loaded almost instantaneously, there is no danger of saturation.

For each detected presence, a message is output. It contains the following information : range, code, OBA measurement for each pulse, presence OBA reference, garbling indication bits, sum video amplitude, and antenna position at the moment of reception. The OBA reference to be used in post-processing is chosen preferably from a clear zone : it is an average between the OBA measurement of F_1 and F_2 for an isolated reply and the value of F_1 (or F_2) if there is some garbling either just behind or just before the processed reply. A doubt information is given if the values of F_1 and F_2 are not close enough. In the more complicated cases, the reference can be calculated again by taking the average between OBA values of pulses present in the plot code.

PRINCIPLES OF THE SSR SOFTWARE PROCESSING

There are two distinct steps :

- The first step is to complete extraction by a reply to reply correlation,
- The second phase is tracking, i.e. associating the plots from scan-to-scan.

Post-processing

Upon receiving a reply message, each code pulse is attributed a quality bit, by comparing its associated OBA value and the reference chosen for the reply. If there is garbling the OBA of each pulse is compared to the references of the various replies concerned.

Once this is done, the replies are then associated by range and azimuth correlation and correlation by codes and respective pulse quality. Thus plots which are at the same range but having different azimuths or codes can be discriminated. Fruits are eliminated because there is no correlation between a sufficient number of replies. The data for a plot being formed are updated by all the replies correlated with it. It is so with the plot coordinates, as with the code pulses in each mode and quality bits relating to each one of them. In certain complex cases of garbling, the extracted plot code has poor quality pulses : in tracking, quality assessment is used when there is ambiguity in the plot/track correlation.

The target azimuth is calculated for each reply, since the chosen reception technique enables an accurate locating whatever the aircraft's position in the antenna beam. However, in order to obtain the best possible result, the final plot azimuth is calculated from the mean between the two or four values closest to the lobe centre, where accuracy is greatest. The average of several samples of the same reply, then of several replies, reduces the rather weak effects of thermal noise detected on very low amplitude signals. In calculating the average, the same number of values is taken on either side of the antenna boresight so as to compensate for any difference in slope that might exist between the reference curve and the real curve. The latter is automatically corrected, and an alarm is sent when the drift exceeds a certain limit.

The monopulse post-processing described here is compatible with mode S operation and it is especially compatible with transmission scheduling where conventional SSR pulse repetition frequency is low. Thus plots can be extracted with right and validated codes, with as few as 2 hits per mode.

Local Tracking

This particular function examines the history of plots, associating them from scan to scan. The major benefit of tracking lies in the elimination of spurious plots and in the resolution of ambiguous cases of aircraft crossings. Reflections are sorted out by an automatic process based on the analysis of tracks having the same code : radar range, altitude, reception power, age and track evolution... This solves the problems of reflecting planes whether fixed or occasional. The tracking process also eliminates false plots, caused by duplication. This phenomenon is exceptional and occurs only when there is interference with the OBA over several consecutive repetitions. Selective correlation in azimuth and in code causes false plots, in such cases. These plots are very close to the real plots, in position and in code, and they are eliminated easily by tracking, especially as they tend to occur over only one antenna scan.

The tracking software differs from the simple chaining generally proposed owing to its sophisticated algorithms of correlation between plots and tracks thus, a future plot position forecast is carried out by integrating the trajectory characteristics and parameters such as the influence of thermal noise.

Data Processor

The software is available for two different types of computers. One is built around a slice microprocessor, the second, described below, has a multicell structure. The multicell computer has been designed with a view to real-time high capacity processing. The basic cell consists of a powerful 16 bit microprocessor (68 000, then to be replaced by 68 020). It is fitted with a 512 K-bytes local RAM, a vectored multi-level interrupt structure and parallel lines of communications with other cells (4 as a maximum) (figure 11). The exchanges are effected from cell to cell and not via a bus common to all the processors. The network structure has been given preference over the bus structure, owing to its greater suitability to radar processing ; thus, the processing capacity is improved. A fast real time monitor has been especially developed for this multicellular architecture. The modular design enables the number of cells to be adapted to the required load. Programming is done with a high level language : PASCAL. This set of characteristics has made this computer a common tool for several uses : MTD processing, monopulse processing, primary + secondary tracking, high capacity display ; it is also a prototype for the software part of the Mode S processing unit. In the case of SSR processing, monopulse post-processing and tracking are simultaneously stored in the same computer.

SELF TEST

All the electronics of the monopulse secondary radar station is duplicated and provided with B.I.T.E. (Built In Test Equipment). These monitor the equipment's operating, detect any fault that might have occurred and cause the switch-over to the stand-by equipment in case of failure, locating the pcb's or group of pcb's which are not functioning correctly.

Various parameters and operational procedures are constantly monitored at all levels, by the use of test sensors and by injecting fake signals : for example, antenna drive, transmission power, pulse shape, receiver sensitivity, monopulse processing decoding, reply correlation, computation of coordinates, etc. Various software parameters are also monitored, such as CPU errors, overloading, input/output errors. The rate of automatic detection of failures and automatic location thereof are globally assessed to be better than 95%.

The remote and monitoring maintenance processor (RMM) collects all the information output from each equipment and sends to the operational centres the exact configuration of each of these and the nature of any failure. Conversely, it also enables remote commands to be sent, which means that the station may be unmanned.

SSR PERFORMANCE

The system's performance have mainly been evaluated at Orly Airport, but were subsequently confirmed at other operational stations. A statistical evaluation can be made from reply messages, plots and tracks. More complex aspects are singled out for thorough investigation based on the video. The video recorder automatically tracks the designated aircraft and stores scan after scan all the videos sent to the extractor. Thus it is possible to know all the characteristics of the videos (figure 12) : amplitude, leading edge, duration, spacing, code, number of replies, and thus to validate the processing by a simultaneous analysis of presence, plots and tracks.

By far the most interesting cases occur when several aircraft's replies are garbled. Results are compared to those of conventional extractors by simultaneously recording from the two types of extractors : the improvement is most obvious (figure 13). After extraction, the detection rate (blip to scan ratio) is found to be higher than 98% and a study of degarbling reveals that decoding is correct for 95% of cases at the extractor output. Any remaining dubious case is almost certainly resolved by local tracking, and decoding can then be as high as 99.5%. Results slightly vary with the station's configuration (site, PRF, interlacing cycle, rotation speed). Local tracking is validated (tracking, decoding, bearing and speed) by means of an iterative analysis which is compared with a reference established off-line from recorded plots. Thanks to this local tracking, false plots are eliminated (reflections and others) these being deemed to account for about 1% of the extractor output plots. Illustrations given show the good quality of trajectories at the extractor output (figure 14) and at the tracking processor output (figures 15, 16 and 17).

Several methods may be used to test the system's accuracy. The first method involves a certain number of representative trajectories, and the quality of the performance is measured by the difference between the positions as they are detected and the positions as they are reconsituted. The algorithm used for reconstitution is based on the least square technique, second order model and a nine point sliding window. This monoradar experiment has inherent limits (correlated errors partly ignored, results which are not global, etc.) nevertheless it remains a convincing tool as far as calibration is concerned. The azimuth accuracy obtained is better than 0.04°σ (typical error), and generally lies between 0.015°σ and 0.03°σ (figure 18). It sometimes even approximates 0.1°σ for certain tracks partly observed by obstacles on the horizon (this is called diffraction). Another method is to consider the totality of the traffic over a longer period of time, that is, on average, more than 100.000 plots. This results in greater differences (0.06°σ) because the analysis is effected automatically and all configurations likely to occur in real traffic are taken into account. Thirdly, another method based on the TRIDENT and DME reference trajectography has confirmed positive and tangible results.

The improvement in range accuracy is obtained mainly by reducing the processing quantum. However, accuracy remains limited in range because of the transponder's reply.

MODE S EXTENSION

The Mode S extension combines all the parts to be added to a monopulse radar to confer it Mode S capability. All the data which transit through this extension are managed by the Mode S Data Processing Unit (DPU) which governs the whole of the station. Below are described the main parts of the extension. The clock and dating as well as the information remoting facilities should also be considered.

MODE S PROCESSING INTERFACE (Figure 20)

This is a real time interface between the interrogator and the Mode S processing unit to which it is connected via two high output parallel links.

On transmission, this interface provides the transmitter with the modulation signals necessary to produce intermode and Mode S modulations. Transmission takes place at the programmed instant and respecting the parameters prescribed by the software. The processing interface automatically effects the address parity coding needed for the transponder to detect errors.

On reception, the processing interface extracts Mode S replies. The first step is to detect preambles and these are accepted only if they fit into a time-prediction window provided by the Mode S data processing unit. Then the information fields are decoded via PPM demodulation and simultaneous analysis on videos issued by directional and omnidirectional patterns. Finally, it seeks out errors by examining the parity received and attempts to rectify errors.

Simultaneously, it calculates the azimuth of the target by combining the off-boresight angle values which have been sampled on those message pulses which have been decoded without ambiguity.

Experiments carried out at Orly on a transponder prototype have highlighted the efficiency of Mode S decoding in the midst of SSR interference (figure 19). The measurement accuracy confirms the quality of results obtained in SSR processing.

MODE S DATA PROCESSING UNIT (DPU)

This is like an orchestrator of the station, effecting the following tasks (figure 21) :

- Sequencing of all the activities of the RF radio-electric channel by programming the alternation of all-call and roll-call interrogations and reply windows. The DPU maintains an active list of Mode S aircraft which are within the antenna lobe, updating this list according to extracted replies and targets about to enter into the beam. This activity implies a strict real-time constraint, since the DPU should enable several messages to be exchanged with each aircraft or since it should process immediate reinterrogation when a transaction is unsuccessful.

- Surveillance of Mode S transponders by associating the reply or replies from an aircraft with the tracks created in former scans. When several stations are interconnected into a network, it can update the tracks according to messages from adjacent stations. It also computes the next-scan prediction window for the channel management processing.

- Governing all the air-ground data transactions as a function of requests made by ground centres, and of messages from transponders.

- Management of the network when, as is likely, stations have certain coverage zones in common. The DPU ensures continuity in surveillance and data exchange. A coverage map stakes out the responsibility of each station in preestablished zones.

There are two possible configurations :

- The stations are not connected to each other : in which case, certain precautions are taken so as not to degrade the detection probability of neighbouring stations (management of transponder lock out),
- The stations are connected to each other : they can exchange data files regarding bordering and common areas thus facilitating the initial target acquisition.

- Monitoring the whole Mode S station performance, by use of calibration performance monitoring equipment and internal test signals generation.

The DPU software was designed by the SADT method (structured analysis and design technique). The application of this method is top-down, modular, hierarchical and structured ; presentation is usually in graphic form. The chosen hardware architecture, built up from cells described in the paragraph ''SSR data processor'', allows computing power and memory capacity to be increased according to needs (functions realized, number of transponders, etc.).

The project is divided into steps to deal consecutively with different configurations : autonomous station, unconnected adjacent stations, and then viewing the whole network structure. Each step has its place planned as from the beginning of implementation. The overall validation is made upon simulation and testing on the sites. The implementation of protocols (either multi-site or not), between independent or netted stations, promises to be an interesting aspect of the question to be dealt with in Europe in the future.

ACKNOWLEDGEMENTS

This study has been conducted thanks to assistance from the STNA (French Civil Aviation Technical Department) which contributed to the funding of studies and tests, and thanks to the CENA (Air Navigation Studies Centre) which provided the facilities for recording and evaluating, and thanks also extend to Aeroport de Paris for making its facilities available.

REFERENCES

(1) C. GUERIN, A. PEYRAT : ''MONOPULSE SECONDARY RADAR'' INTERNATIONAL CONFERENCE ON RADAR, PARIS 22nd MAY, 1984.

(2) R.J ALIMENTI, D.P FOX, J. KENTON : ''AMPLITUDE/PHASE MONOPULSE RECEIVER COMPARISON'' FAA TECHNICAL CENTER LETTER REPORT JULY, 1982.

(3) ''MONOPULSE PRINCIPLES AND TECHNIQUES'' Samuel M. SHERMAN Artech. House.

(4) A. SINSKI, E.LEW : ''COMPARATIVE ANALYSIS OF A PHASE AND AN AMPLITUDE PROCESSOR FOR AMPLITUDE MONOPULSE SYSTEMS'' IEEE Transactions on Antennas and Propagation, May, 1983.

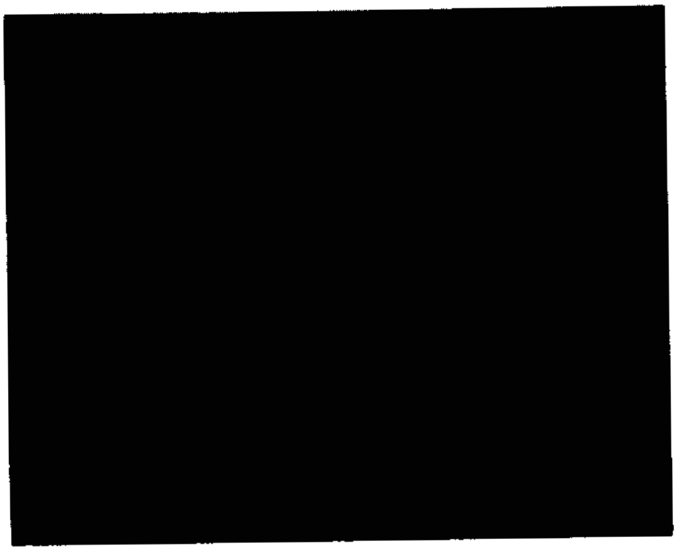


Fig 8 TERMINAL ZONE STATION

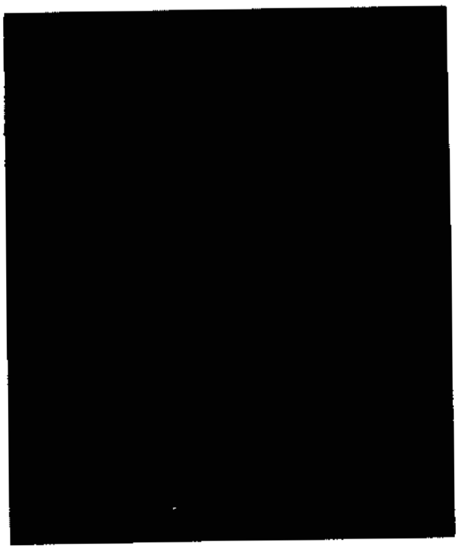


Fig 7 – EN ROUTE STATION

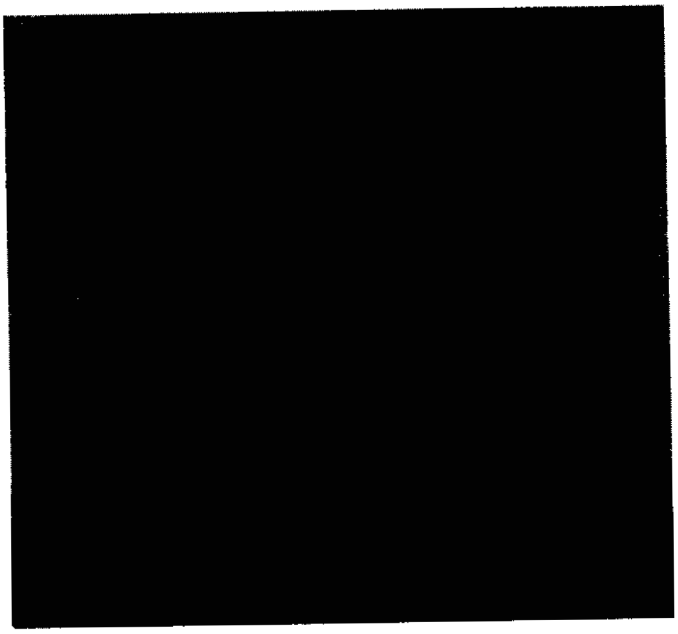


Fig 9 – AUTONOMOUS MONOPULSE STATION

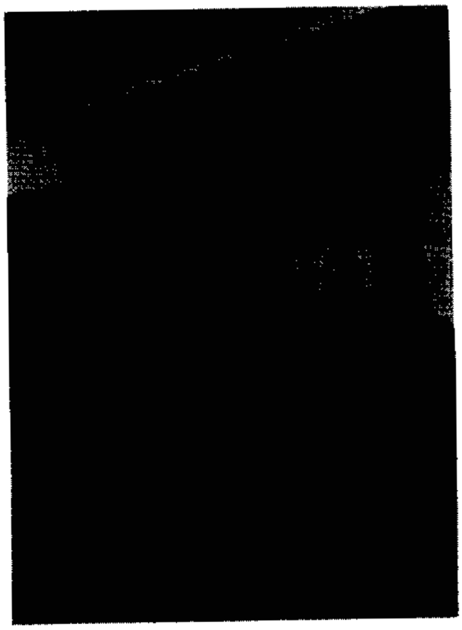


Fig 10 – INTERROGATOR AND SSR PROCESSING EQUIPMENT

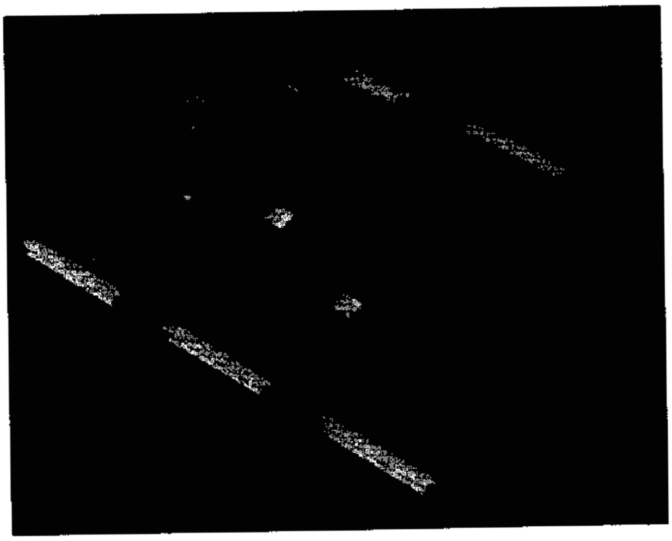


Fig 11 – CM 88 CPU CELL

Fig 12 – LOGARITHMIC SUM VIDEO (BOTTOM) AND OFF-BORESIGHT ANGLE VIDEO (TOP) OF TWO GARBLED REPLIES

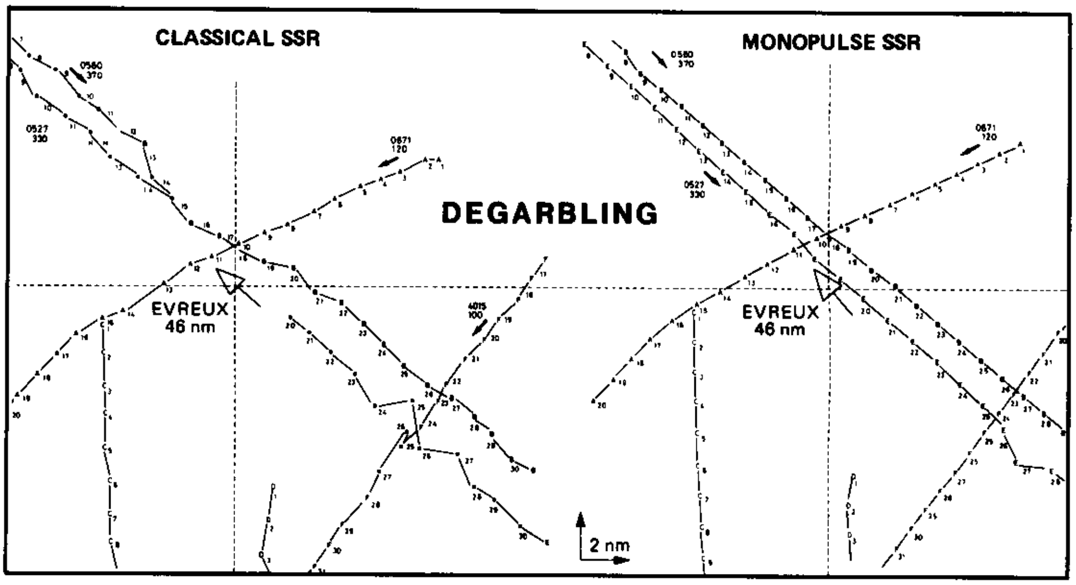


Fig 13 – COMPARISON OF RESULTS

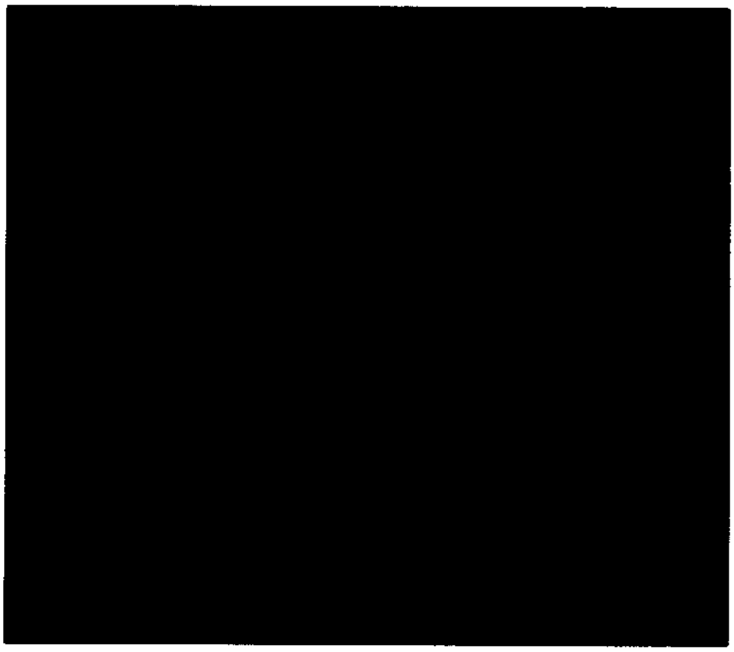


Fig 14 – DISPLAY OF MONOPULSE SSR PLOTS (BEFORE TRACKING)

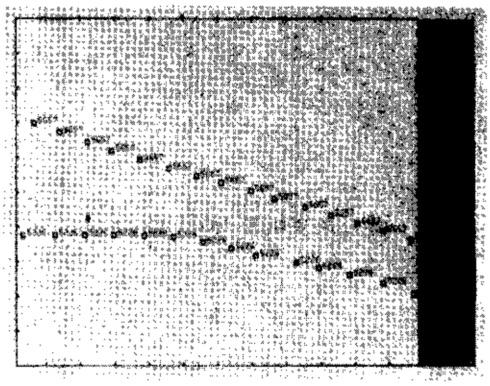


Fig 15 – AIRCRAFT OVERTAKING SITUATION (WITH MODE A INDICATION)

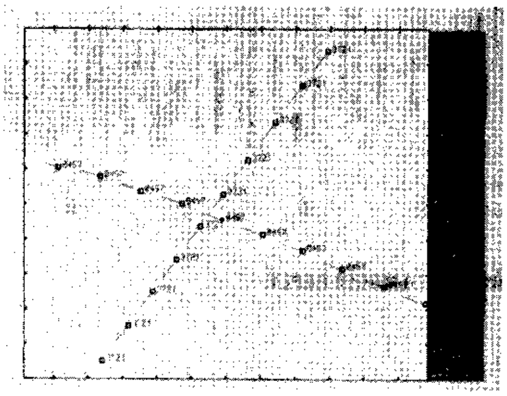


Fig 16 – TWO AIRCRAFT CROSSING SITUATION (INDICATION OF MODE A AND VELOCITY VECTOR)

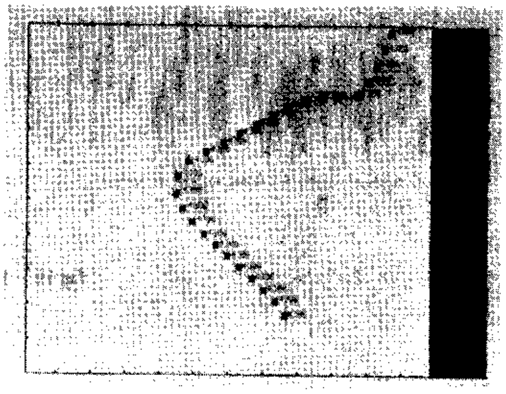
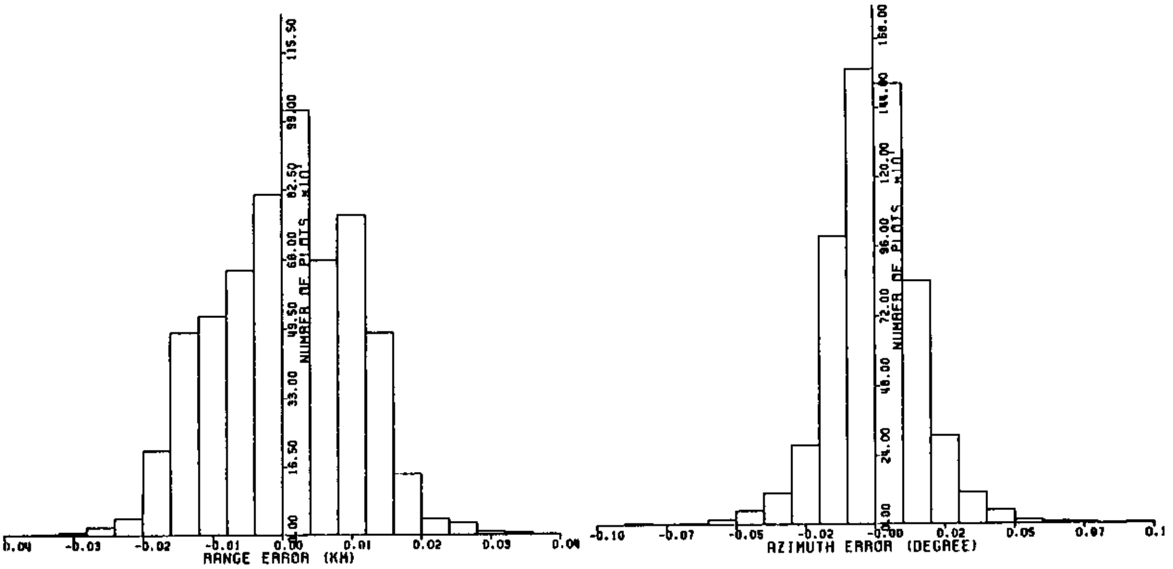


Fig 17 – RELATIVE POSITIONS OF PLOTS (X) AND TRACKS (□)



THOMSON SSR MONOPULSE LINZ 02/85 RECORD.1

NUMBER OF TRACKS : 21

NUMBER OF PLOTS : 5902

STANDARD DEVIATION OF RANGE ERROR 0.011 (KM)

THOMSON SSR MONOPULSE LINZ 02/85 RECORD.1

NUMBER OF TRACKS : 21

NUMBER OF PLOTS : 5902

STANDARD DEVIATION OF AZIMUTH ERROR : 0.017 (DEGREE)

Fig 18 – HISTOGRAM OF RANGE ERROR AND AZIMUTH ERROR

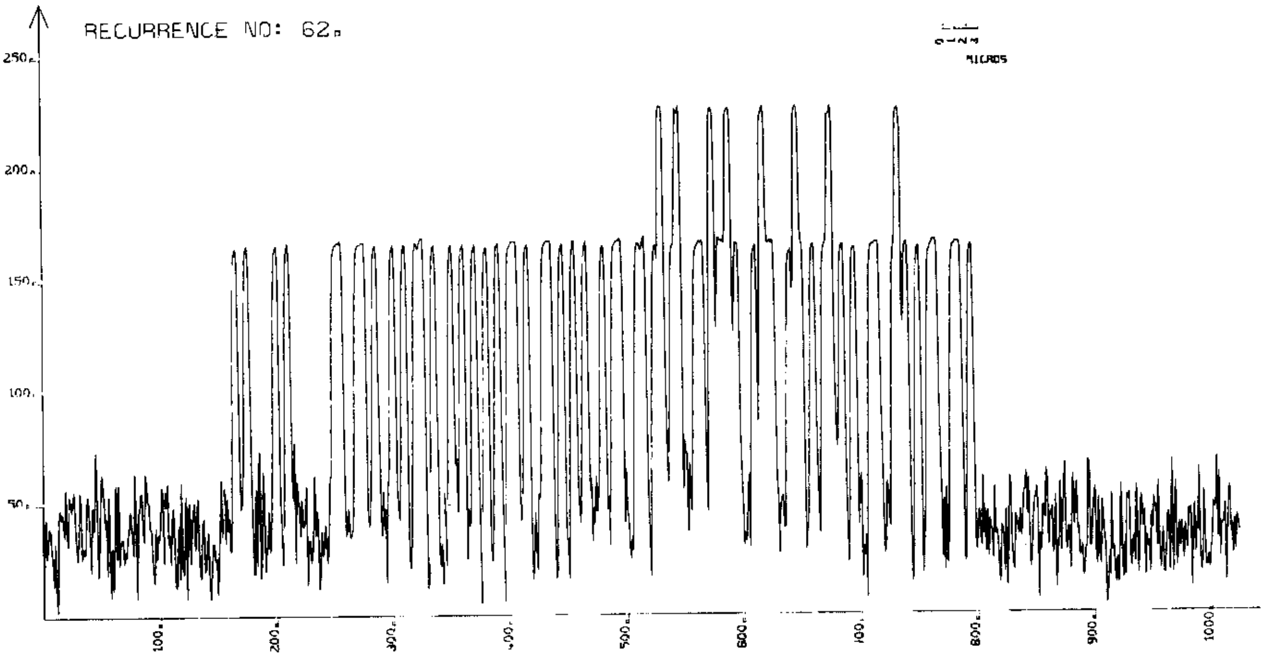


Fig 19 – SSR REPLY INTERFERING WITH MODES REPLY

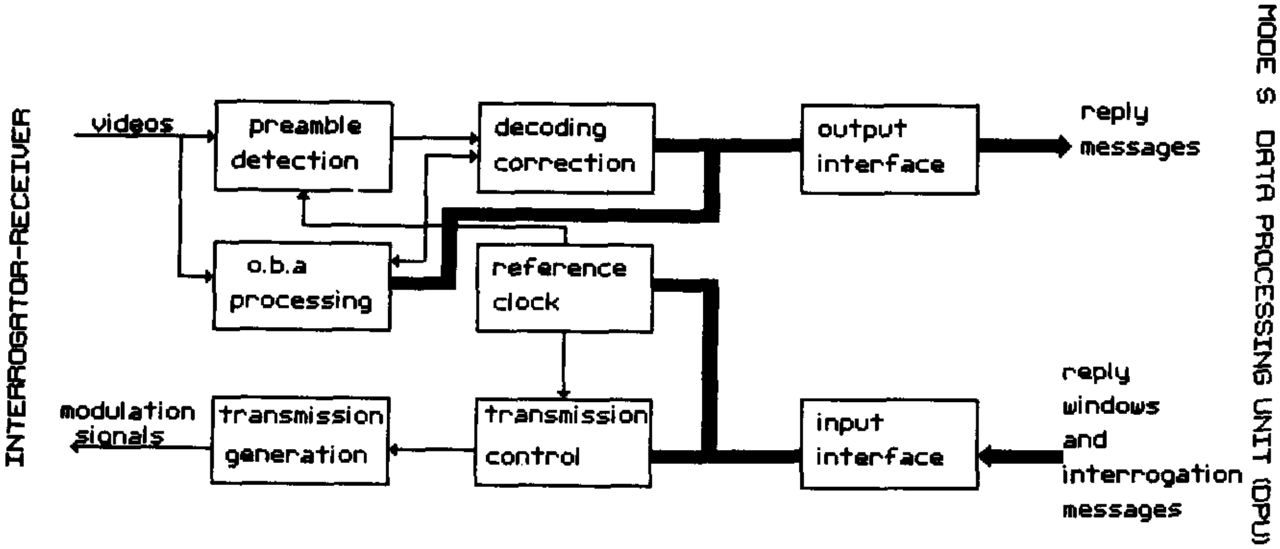


FIG.20 MODE S PROCESSING INTERFACE

- CHANNEL MANAGEMENT
- SURVEILLANCE PROCESSING
- DATA LINK PROCESSING
- NETWORK MANAGEMENT
- PERFORMANCE MONITORING

FUNCTIONS IMPLEMENTED IN THE MODE S DATA PROCESSING UNIT

FIG .21

CP 410

A PRACTICAL EXAMPLE OF MOVING TARGET DETECTION (MTD) PROCESSING FOR AN AIR TRAFFIC CONTROL RADAR WITH WEATHER CHANNEL

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SUMMARY

An ATC radar processing system of the Moving Target Detector (MTD) type, comprising a separate processing channel, called weather channel, is presented. The MTD processing is implemented in a high performance coherent radar system. It is designed to improve target detection in various forms of clutter, while providing low output false alarm rate. The chosen signal processing algorithms are based on the use of an 8-doppler filter bank, on CFAR thresholding and on an adaptive clutter map. The weather channel indicates to the user the areas of radar coverage where dangerous precipitation occur. Programmable modular processors are used for the digital signal processing and data processing. Their processing power enables to carry out complex adaptive algorithms. This equipment is incorporated in a radar station which can be unmanned, thanks to the equipment automatic built-in tests and the Remote Maintenance and Monitoring system. Results of experiments with the described processing system clearly show that the MTD processing improves the final picture quality. In particular, the detection probability is higher both in clear zones and in clutter, while the false alarm rate remains low, thanks to adaptive processing and algorithms using the estimated radial velocity.

1. INTRODUCTION

This article describes an ATC radar processing of the Moving Target Detector (MTD) type ; it comprises an independent processing channel called weather channel, which supplies meteorological data. The MTD processing technique is aimed at improving the detection of useful targets in the midst of clutter (reference 1-2-3-4-5). The algorithms employed are detailed, as well as the performance to be expected, in particular the improvement in the radar picture presented to the operator. The processing system is made up of programmable processors, of which the architecture and other main features are described, as is the radar station remote monitoring and maintenance system. Finally, results obtained in experiments are given.

2. HOW THE PROCESSING SYSTEM IS ORGANIZED

The processing system described here is designed for integration in a 2D radar and comprises an ATC channel and a weather channel, both duplicated. Figure 2.1. shows a block diagram with receiver and processing channels for ATC and meteorological data (non-duplicated). The processing in the ATC channel is of the Moving Target Detector (MTD) type. The weather channel is independent of the ATC channel. The conventional ATC detection data, used for control and the weather information, are displayed simultaneously.

The MTD processing has been designed for a highly stable transmitter-receiver channel, enhancing the detection of targets in the midst of clutter. The transmitter is a highly stable klystron transmitter. The radar transmits bursts of pulses, in a burst-staggered mode.

The receiver chain has a high dynamic range and is perfectly linear. The received RF is attenuated, in response to the attenuation command generated by the MTD processor : the attenuation control is adaptive and computed at each antenna scan, so that the signals to be processed may perfectly fit into the receiver dynamic range. This method is most efficient in avoiding saturation of the receiver chain, even in the presence of very heavy ground clutter or weather clutter. This function is most important for MTD processing since any non-linearity would distort the spectrum of the received echoes. The attenuated signal is then transposed to an intermediate frequency and is processed by a linear receiver of 60 dB dynamic range, providing in-phase and quadrature video signals. These signals are sampled by an analog digital converter and are encoded on 12 bits.

The digital data of an 8-pulse Coherent Processing Interval (CPI) are stored in the data memory of the Signal Processor. The processor performs doppler filtering and detection on the stored samples, so as to determine the coordinates of cells containing useful echoes called "primitive target reports".

Messages are sent to the Post-Processor, containing the doppler and amplitude characteristics of each primitive target. This Post-Processor associates together those primitive targets which are related to the same target, evaluating the position and characteristics of the plot thus formed : this is the Correlation and Interpolation function. False alarms are here checked and, if need be, the detection threshold of the signal processor is modified accordingly.

Then the plots are processed in the tracking function, which works by scan-to-scan correlation so as to eliminate the residual false alarm. When the radar operates in the diversity mode, the plots, output by the Correlation and Interpolation function from the two ATC processing channels, are associated together. The tracking function also performs primary and secondary radar plot association.

The role of the weather signals receiver and processor channel is to show up the zones in which weather phenomena involving some danger for aircraft are found. An analysis of signals from the orthogonal circular polarization channel and in particular an analysis of the intensity of echoes gives a clear idea of the intensity of precipitations within the radar coverage (ref. 6-7).

The architecture which has been chosen is a weather channel completely independent from the ATC reception and processing. The received RF signals are attenuated according to the attenuation commands generated by the weather processor. Thus, the attenuation law which is applied may be different from that applied in the ATC channel and adapted to the weather signals. Signals are then transposed to the intermediate frequency and processed by a linear receiver which produces video signals in phase and in quadrature.

These signals are sampled and coded on 12 bits by the weather processor, which, after having eliminated the unwanted echoes (i.e., ground clutter, aircraft, interference), evaluates the intensity of the weather echoes. Each time this level exceeds a predetermined threshold, a "weather primitive target" is created. The role of the post-processor is then to establish the contours of zones in which the weather echoes exceed the threshold. From the six predefined levels, two may be simultaneously displayed.

3. ALGORITHMS AND PROCESSING PERFORMANCE

3.1. ATC CHANNEL SIGNAL PROCESSING

Figure 3.1. shows a block diagram of the signal processing in the ATC channel. The MTD signal processing, compared with an ordinary MTI processing, is designed to improve useful target detection despite ground and weather clutter. Improvement of detection and false alarm rate result in a better quality picture for the operator. The processing discussed here uses a set of 8 doppler filters, by means of which useful targets and clutter can be separated, provided that they have different radial velocities. A detection threshold is applied at the output of each filter : its role is both to eliminate clutter echoes in the filters which are clutter contaminated and to optimize useful detection of targets in the filter corresponding to their radial velocity. The filter for very low or null velocities is called the Zero Velocity Filter (ZVF). The ZVF output is used in the scan-to-scan estimation of an adaptive clutter map. The threshold applied at the ZVF output is calculated from the clutter map information. The other doppler channels are subjected to a cell averaging type threshold. When the detection threshold is exceeded in more than one doppler channel, a primitive target is deemed to be present and a message containing the primitive target's characteristics (amplitude and doppler) is sent to the Post-Processor.

Figure 3.2. shows the response curve of one of the filters versus normalized frequency. Side lobes are lower than 40 dB : this results in a good rejection of ground clutter, rain clutter and chaff. The contrast is shown in figure 3.3., as a function of the useful target's doppler velocity. The contrast is defined as the gain in the signal-to-clutter power ratio brought about by the set of filters. Characteristics used in the gaussian clutter model are given. The antenna lobe modulation is taken into account, as well as the stability of the transmitter-receiver chain (3 mrd). Coefficients used for filtering and detection are encoded on 16 bits : this makes it possible to implement the processing algorithms most efficiently, while reducing the truncating. The fact that there is no front-end canceller ahead of the filter set means that the coherent integration gain is preserved for each filter. Thus, the losses in the gain of signal-to-noise ratio caused by an MTI filter are avoided, as is the need for extra pulses to initialize the filter.

The ZVF output is used in the computation of the average value of clutter in each cell of the coverage being processed. The map has 768 000 cells. The algorithm used is a first order integrator, its time constant being adjusted to about 15 antenna scans. The ZVF output is subjected to a threshold calculated from the information which has been stored in the clutter map. This is a CFAR threshold : it can eliminate clutter echoes; it also makes it possible to detect targets having a tangential trajectory as long as these exceed the clutter level. The target visibility curve is optimized by the ZVF and by automatic selection of filters 1 and 7 on either side of the ZVF, as a function of the level of ground clutter.

Non-Zero doppler channel outputs are compared to separate CFAR thresholds : the cell being examined is compared to the highest of the averages of the 8 cells preceeding and of the 8 cells following the examined cell and the 2 adjacent ones. The noise false alarm rate is adjusted by means of a multiplying factor. This factor may be modified (either increased or decreased) automatically, on an instruction from the Post-Processor, depending on whether or not there is a risk of overloading the latter, for example if there are angels. If there is clutter at the ZVF output, thresholds implemented in the Non-Zero doppler channels are corrected by a fraction of the amplitude of the echo in the ZVF. For each filter, this correction value is different and it is applied only when the echo in the ZVF is above a programmed level. With this adaptive processing, residues above the rejection level of doppler filters can be eliminated.

3.2. PRIMITIVE TARGET REPORTS PROCESSING

Given the width of the antenna lobe and of the transmitted pulse, a single target can give rise to several primitive target reports. The Correlation and Interpolation function builds the radar plots ; it calculates their position, doppler velocity, and quality degree and then transfers these data to the tracking function. An algorithm is also applied to eliminate angels.

Each incoming primitive target is compared to a threshold device ; the threshold applied is determined by the density of primitive targets existing in the geographical sector and the doppler filter of the incoming primitive target. Therefore, primitive targets of low amplitude are eliminated if found in large numbers within the same geographical and doppler sector, as often occurs with angels. Also, the incident load is checked : if there is a danger of overloading, the signal processing detection threshold may be modified so as to reduce false alarms.

If several primitive target reports are close together in range and in azimuth, they are associated to create a plot. An algorithm of the barycentre type, weighted by the primitive target amplitude, is used for the estimation of the range and azimuth of each plot which has been formed. The radial velocity of each plot, which is not characterized by a blind CPI, is calculated. The ambiguous speeds are interpolated in each burst on the basis of the known maximum amplitudes of the primitive targets. The ambiguity is resolved at least in part by reference to the ambiguous speeds of 2 consecutive bursts. The ambiguity of estimation is then equal to 5 or 6 times the speed corresponding to the lowest of the two pulse repetition frequencies.

To each plot, a quality degree is attributed as a function of the azimuth extension. Several flags may be positioned : presence of a "blind burst", echo possibly reflected by a ground vehicle, assumed crossing of tracks, etc.. Information concerning the origin of the plot are thus supplied to the tracking function, which can then confirm or invalidate this data, by an analysis of the plot's behaviour over several antenna scans.

Plots, once formed and interpolated are subjected to a device reducing the residual false alarm and regulating the tracking function load. This adaptive device eliminates first and foremost plots with low amplitude and low doppler velocity and which are concentrated in the same geographical sectors. If overload is detected in the tracking processor, dubious plots are automatically rejected.

3.3. PLOT TRACKING ALGORITHMS

The tracking function performs plot correlation from scan-to-scan, in order to eliminate residual false alarm. The main functions are :

- Correlation between incident plots and stored tracks, and resolution of ambiguous cases,
- Initiation of new tracks,
- Updating of established tracks.

Correlation between an incident plot and stored tracks in the same area is attempted. This correlation is effective only if the plot is found in the window surrounding the track's predicted position. This window is optimized so as to take into account radar noise and the target's evolutionary characteristics (turning, acceleration, deceleration). There are four possibilities :

- The plot correlates with only one track,
- Several plots can be correlated with the same track (if the zone has a high traffic density),
- The plot can be correlated with several tracks,
- Several plots and several tracks can be inter-correlated.

Such ambiguous cases are isolated and handled so as to give the most coherent tracks : by optimizing globally the distance between incident plots and forecast positions. Consistency between incident radial velocity and forecast radial velocity is sought.

Incident plots which have not been successfully correlated give rise to a new track, except if the plots are dubious. If, after a new initiation, several plots can be correlated with the new track, various directions are possible, one of which will be validated at the next antenna scan while the others will be abandoned.

At each antenna rotation, the established tracks are updated. When this is done, the track information is recalculated in the light of information introduced by the newly correlated plot :

- The new position, as well as the predicted position at the next scan (in X, Y coordinates) are calculated through a α, β filtering algorithm. Coefficients α and β are chosen as a function of the track's history.
  - The filtering criteria become more stringent as the plots line up and follow one another in a straight line.
  - Filtering criteria are less stringent when some evolution begins to take place.
- Target speed.
- Area of expected detection for the next antenna scan, called correlation window.
- Track quality, reflecting its history and calculated as a function of :
  - Possible detection gaps,
  - Quality of received plots,
  - Coherence in the trajectory,
  - Consistency in the radial velocity,
  - Any correlation ambiguity which may have occurred.
- Track status :
  - Status confirmed, if the mobility criterion is satisfied and similarly with the quality. The track is then displayed,
  - Status not confirmed, if the quality is not high enough and mobility not satisfactory.

When it is created, a track is unconfirmed. It becomes confirmed if it is constant in presence during N consecutive antenna scans (for example, N = 3), if its mobility is satisfactory and its trajectory consistent. A track is cancelled if its quality falls below a certain set threshold, and it is then no longer displayed. This happens for example after M consecutive detection gaps (for example : M = 3).

3.4. WEATHER CHANNEL SIGNAL PROCESSING

The signal processing in the weather channel is shown in the block diagram of Figure 3.4. The processing cell corresponds to 16 range gates on one burst of 8 pulses.

Clutter is eliminated through doppler filtering using digital, non-recursive filters. Depending on the level of ground clutter, a filter is chosen which attenuates to a lesser or greater degree around the zero frequency.

Four filters are possible :

- Filter 0 : all-pass filter (no clutter)
- Filter 1 : high-pass filter (medium clutter)
- Filter 2 : high-pass filter (heavy clutter)
- Filter 3 : high-pass filter (very heavy clutter).

An example of a filter response curve is shown in Figure 3.5. Filter selection is determined by means of a fixed map, initialized under clear weather conditions.

Interference is detected in the following manner : the power output by the doppler filter of the first four pulses is compared to the power obtained at the last four pulses. If the difference between these two values is too high, this is interpreted as interference.

An aircraft is detected by comparing the power in each range gate with the mean power for a weather cell (16 range quanta). If an aircraft is detected, the mean power is recalculated after elimination of the range gate under examination.

Weather reflectivity is evaluated in each weather cell by examining the power of weather echoes in each range gate, after undesirable echoes have been eliminated. The mean reflectivity is then again averaged over several antenna scans.

Weather reflectivity once evaluated in each weather cell is compared to a fixed detection threshold. If reflectivity exceeds this threshold, a weather primitive target is declared. The threshold value is the lowest displayable level.

3.5. WEATHER CHANNEL POST-PROCESSING ALGORITHMS

The purpose of the weather post-processing is to build up, from the weather primitive targets, zone contours containing weather phenomenon exceeding a predetermined level. Two levels from the six pre-established may be simultaneously displayed. The weather picture is updated every 6 scans. A smoothing matrix is applied to the reflectivity information contained in the video map. To each cell in X, Y coordinates in the weather map to be displayed, is attributed the reflectivity of the cell in polar coordinates (ρ,Θ) which contains the (X,Y) cell centre. The weather map is scanned line by line ; a vector is started as soon as the first display threshold is exceeded and this vector is deemed to end as soon as the signal falls below this threshold. The load is regulated by counting the number of vectors to be displayed and hardening the smoothing criteria or the selected display thresholds so as to reduce the number of vectors if there is overloading.

4. IMPLEMENTATION OF THE PROCESSING SYSTEM

4.1. GENERAL REMARKS

Programmed processing was opted for in the implementation of the ATC and weather channel processing systems described above. This approach offers the advantage of flexibility in adaptation. The processing algorithms are implemented in two types of processors : a modular programmable processor which is adapted to the signal processing and a modular computer adapted to the data processing. The MTD signal processing algorithms are incorporated into a signal processor. So is the weather channel signal processor. Correlation and Interpolation functions, tracking and weather post-processing take place, on the other hand, in the modular computer designed for data processing (Cf Figure 2.1). The architecture which has been chosen for these two processors offers an advantage in that the number of different printed circuit types is limited. This reduces the life-cycle cost of the equipment. Remote maintenance and monitoring is built into the radar station which houses the above described processors. The radar station can therefore be unmanned.

4.2. SIGNAL PROCESSOR

The architecture which was adopted in the Signal Processor for the MTD processing and weather processing algorithms is of the type "Multiple Instructions, Multiple Data Paths" (MIMD). The basic module of this system is the Signal Processing Programmable Module (MPTS in French). In the MTD application described here, the processor can have up to 8 MPTS modules each working on a radar coverage segment (Figure 4.1.). All modules execute the same programme. There is a deliberate degree of overlapping between the radar coverage segments allocated to each module, so that the range-cell averaging threshold may be calculated correctly. In the weather processing application, the number of modules in the structure is different, since the processing load to be carried out is also different.

An MPTS module is available, in addition to modules required for the processing : with this extra module, it is possible to test the Signal Processor in real time, and to reconfigure it automatically in case of a failure. This module can take over each of the operational modules in turn while the test programme is being run. When the result of the test is negative, the module then takes over from the failed down unit (until it is repaired). Thus the signal processor continues to run smoothly even if a failure occurs in a module.

The Signal Processing Programmable Module is made up of 3 elements : a processor element, data storage and a sequencer. The first has two 16-bit computing units, one of which is a fast multiplier. The data storage (12 Kwords of 16 bits) works in a ping-pong fashion, while the sequencer has a programme memory of 4 K instructions, 128 bits each. These are organized around 2 buses : the computing units and the scratch-pad memories communicate with each other via an internal bus ; the processor communicates with the outside world (acquisition of signals to be processed, data from the clutter map, interface with the post-processor, test data) via the external bus. The MPTS module's processing power is of the order of 25 MOPS. The MPTS module is contained within a single printed circuit. Figure 4.2. is a photograph of this module.

4.3. DATA PROCESSOR

The Correlation, Interpolation and tracking algorithms as well as the weather channel post-processing algorithms are performed in a computer having a multi-processor architecture. The basic cell consists of a powerful microprocessor (68000 family), fitted with a 512 Kbytes local memory, a vectored multi-level interrupt structure and parallel lines of communications with other cells. Thus each cell may be connected to 4 other cells, forming a network of processors. The modular design of the processor is such as to allow for the possibility of adjusting the configuration to the processing load and for the memory to be sized for a given application. A real-time, high-speed monitor adapted to the multi- processor structure was developed for the computer. The PASCAL language is used for application programming. A monitoring function is also incorporated. If anything goes wrong, it is capable of initiating self-test programmes in each of the processors which make up the computing unit, so as to isolate the failed printed circuit.

4.4. REMOTE MAINTENANCE AND MONITORING (RMM)

Each equipment of the radar chain is connected by a bus (IEEE 488) to a central computer in charge of system surveillance. Automatic built-in tests have been designed in each unit of the radar chain, to detect and notify the faulty printed circuit. If a failure occurs in one of these elements, this information is immediately remote-signalled through the station's RMM system. Thus maintenance involves merely replacing the faulty cards and repairing them in a maintenance workshop. This possibility of remote maintenance and monitoring means the station may be unmanned.

5. EXPERIMENTAL RESULTS

5.1. OVERVIEW

The prototype for the MTD processing chain described hereabove was experimented in 1984 and 1985, in close partnership with Technical Teams from the French Air Navigation Department, at the radar station of Lyon Satolas. The radar is an L-band magnetron radar with conventional MTI type processing. The main characteristics of the radar are : range : 120 NM, peak transmitted power : 2 MW, frequencies : 1346 MHz and 1304 MHz, rotation speed : 7.5 rpm, phase stability : 12 mrd. The site of Lyon Satolas is difficult on account of the quantity and amplitude of ground echoes within the radar's coverage as is shown in Figure 5.1.

Experimentation was aimed at :

a) demonstrating the reliability of an entirely programmed processing,

b) showing the improvement in quality of the synthetic picture displayed to the operator with the MTD processing chain, compared with that produced with a conventional MTI channel : detection improvement both in clear and clutter zones, detection of tangential targets, better accuracy in the target's position, improvement also in the false alarm rate at the channel output, in part at least thanks to the adaptive nature of the algorithms implemented.

5.2. IMPROVEMENT IN DETECTION

Figures 5.2 and 5.3 show pictures taken simultaneously at the MTI and MTD processing outputs. It is clear that the detection quality is higher at the output of the MTD processing chain. The fact that the Lyon Satolas site was difficult has highlighted the improvement in target detection, introduced by an 8-filter MTD type processing, especially when there is clutter.

Figures 5.4 and 5.5 show on the one hand a photograph of the display output by the MTI processing and on the other hand, a recorded plot graphic at the output of the MTD processing, both representing the same situation. On this graphic, plots which are obtained by the zero velocity filter are marked with the symbol 0 ; situations shown are cases where targets are detected at null radial speed and with ground clutter. It is quite clear that the detection by MTD processing of aircraft on tangential trajectories is more efficient than with MTI processing. This illustrates the advantage of having a ZVF in the MTD system.

5.3. EVALUATION OF THE PLOT POSITION ACCURACY

A statistical evaluation of the accuracy of the position (range and azimuth) of plots reconstructed with the MTD post-processing Correlation and Interpolation function has been carried out from recordings of plots. For each target, the actual trajectory has been reconstructed by applying the method of least squares. The difference between actual measured position and the reconstructed theoretical position has thus been calculated.

Figures 5.6 and 5.7 show histograms of errors which have occurred in range and in azimuth. The mean error in range and in azimuth is null. The range error standard deviation has been calculated to be 0.017 NM, or 14% of the pulse width, out of more than 10 000 measurements taken, for plots of signal-to-noise ratio superior to 20 dB. The azimuth error standard deviation has been evaluated at 0.13° or 5.5% of the antenna lobe for plots of signal to noise ratio superior to 20 dB. This is less than the standard deviation of the azimuth quantization introduced by the 8 recurrence burst processing mode (0.20°).

5.4. QUALITY OF THE EVALUATION OF THE TARGETS RADIAL VELOCITY

The radial velocity calculated by the MTD processing *has been compared with the actual radial velocity*, calculated from reconstructed trajectories. Figure 5.8 shows an example of the radial velocity values calculated and reconstructed for each antenna scan, for a target having a mean signal-to-noise ratio of 21 dB. The two velocities will be seen to match perfectly. The standard deviation of radial velocity error has been evaluated at about 5 m/s (or 7% of the mean PRF). *The quality of the radial velocity* estimation make it viable in algorithms for the elimination of false plots or for tracking. These sophisticated algorithms contribute to the low false alarm rate.

6. CONCLUSION

Results of experiments with the above-described processing system clearly show that the MTD processing improves the final picture quality. In particular, the detection probability is higher both in clear zones and in clutter, while the false alarm rate remains low. In this respect, *adaptive processing and* algorithms using the estimated radial velocity play an important role. Another positive point is the accuracy in estimation of the aircraft positions. The system produces a synthetic picture where areas of dangerous meteorological occurrences are shown up, which is another valuable feature. The fact that powerful programmable processors are used to implement the entirety of the processing provides great flexibility and enables to carry out complex adaptive algorithms. Since the processors used are modular, the equipment may be sized to the amount of computation necessary for a particular application. The number of different printed circuit types making up the equipment is limited, which contributes to lessen maintenance costs of the radar station. The latter can be unmanned, thanks to the remote maintenance and monitoring system.

REFERENCES :

1. C.E. Muehe - "Digital Signal Processor for Air Traffic Control Radars", NE Elec. and Mtg (NEREM), Boston, Mass., U.S.
2. C.E. Muehe, L. Cartledge, W.H. Drury, E.M. Hofstetter, M. Labitt, P.B. Mc Corison, V.J. Sferripo - "New Techniques Applied to Air Traffic Control Radars", Proc. of IEEE, Vol. 62, N°6, June 1974, p. 716-723.
3. L. Carrledge, R.M. O'Donnell - "Description and Performance Evaluation of the Moving Target Detector", Lincoln Laboratory Report ATC-69 - Boston, Mass., U.S., 1977.
4. J. *Anderson and David Karp* - "Evaluation of the MTD in a High Clutter Environment", IEEE International Radar Conference, 1980.
5. G. Lepere, C. Bruno - "Programmed Processing for Air Traffic Control Radars : Implementation of an *MTD Type System*", *International Conference on radar*, Paris, May 1984.
6. V. Schwarz - "Which Meteorological Data are Needed in Aeronautics ?" ICAO Bulletin, May 1983.
7. D. Karp - "*En-route Weather Data Extraction from ATC Radar Systems*", DOT - FAA - RD - 82 - 5 - March, 1982.

ACKNOWLEDGEMENTS

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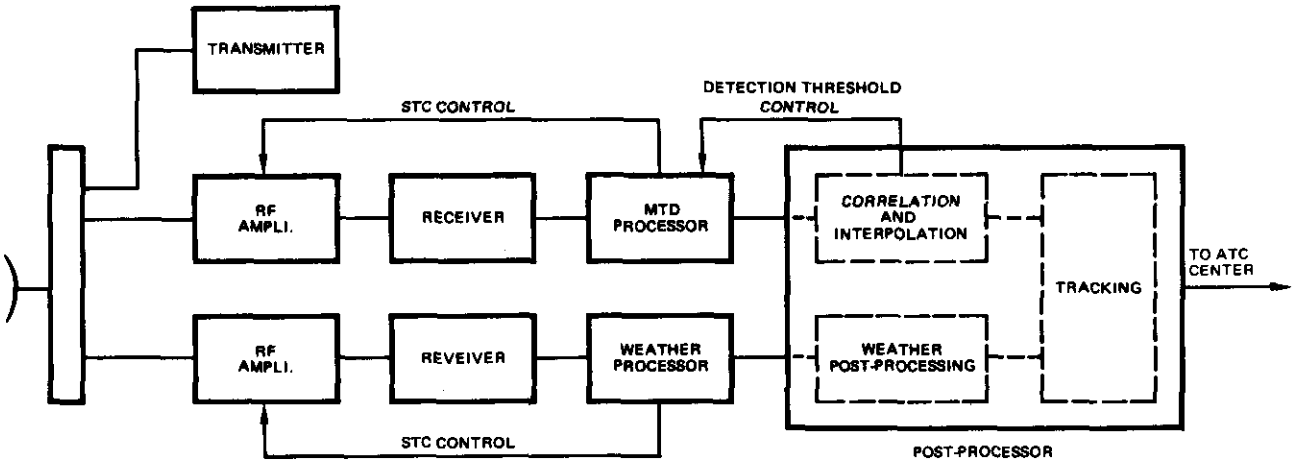

Fig 2.1 – BLOCK DIAGRAM OF ATC AND WEATHER CHANNELS

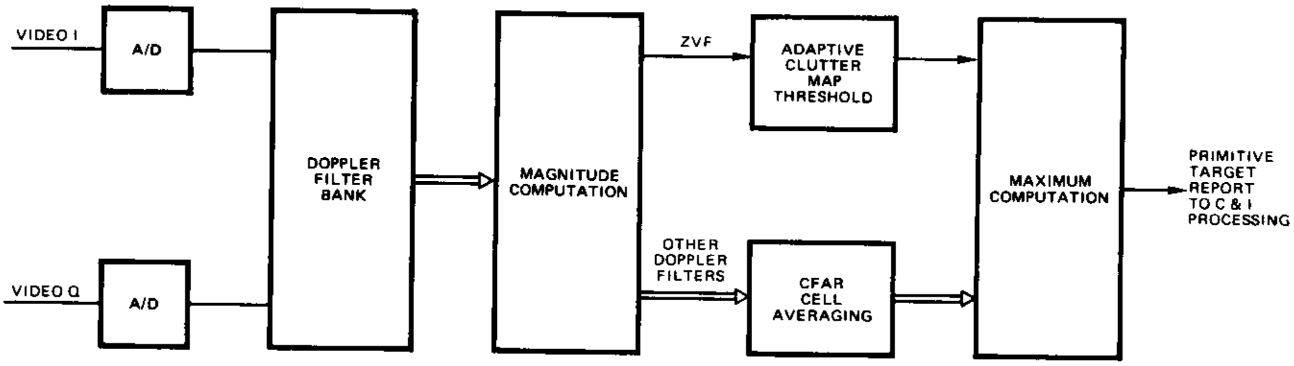

Fig 3.1 – BLOCK DIAGRAM OF AN MTD TYPE DIGITAL SIGNAL PROCESSING

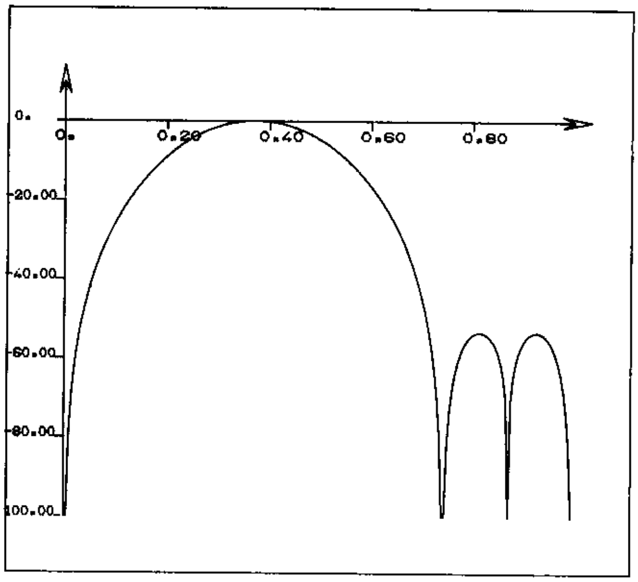

Fig 3.2 – EXAMPLE OF MTD DOPPLER FILTER

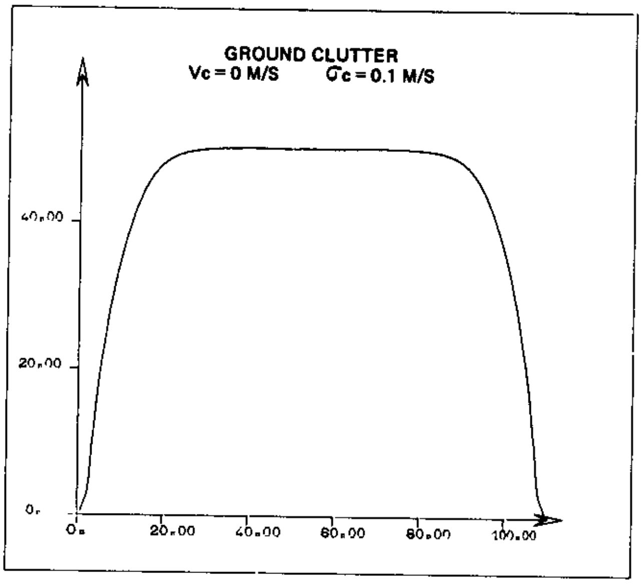

Fig 3.3 – CONTRAST GAIN VERSUS TARGET RADIAL VELOCITY

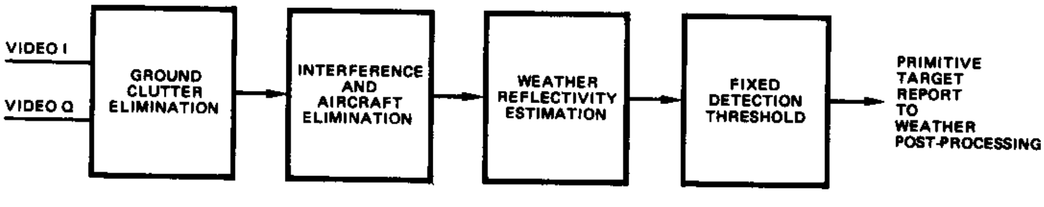

Fig 3.4 – BLOCK DIAGRAM OF WEATHER SIGNAL PROCESSING

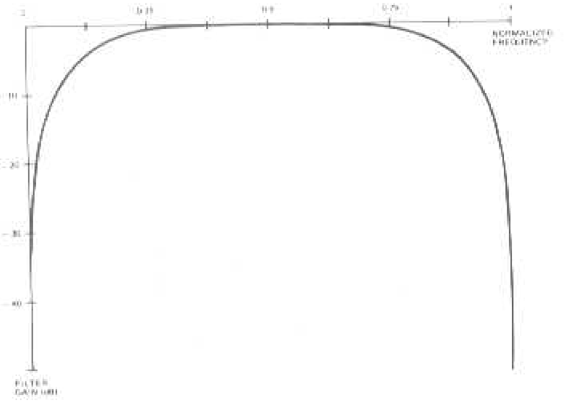

Fig 3.5 – EXAMPLE OF GROUND CLUTTER FILTER

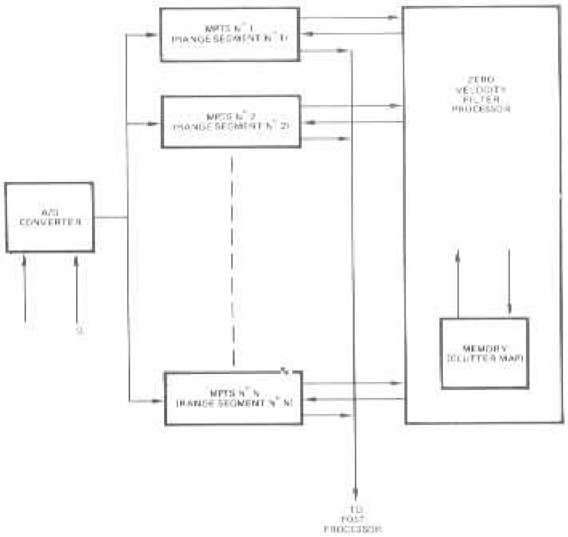

Fig 4.1 – MTD PROCESSOR ARCHITECTURE

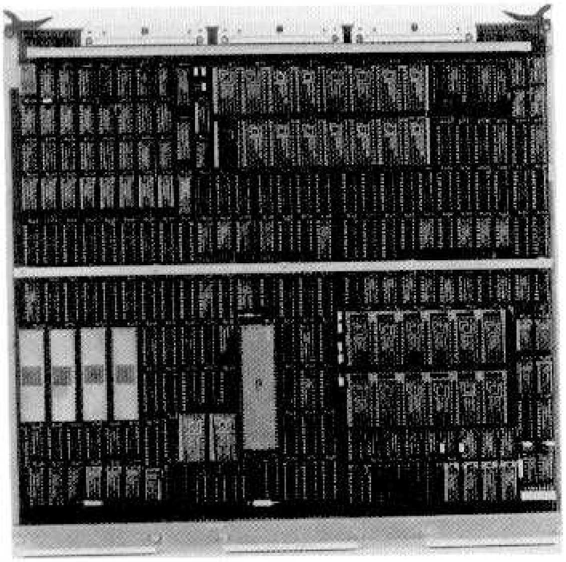

Fig 4.2 – MPTS MODULE

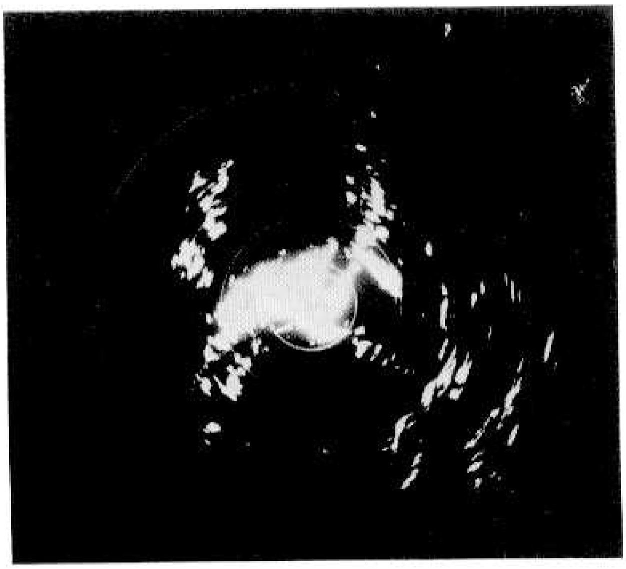

Fig 5.1 – RAW VIDEO AT LYON-SATOLAS (0 dB ATTENUATION)

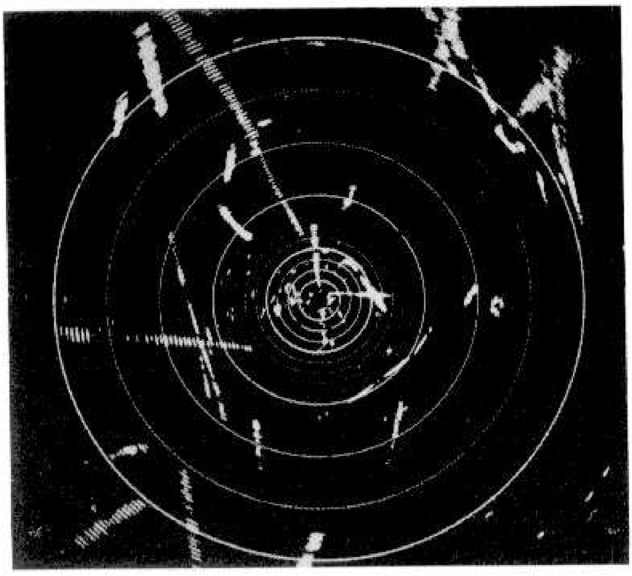

Fig 5.2 – MTI PROCESSING OUTPUT (RANGE MARKS = 10 NM)

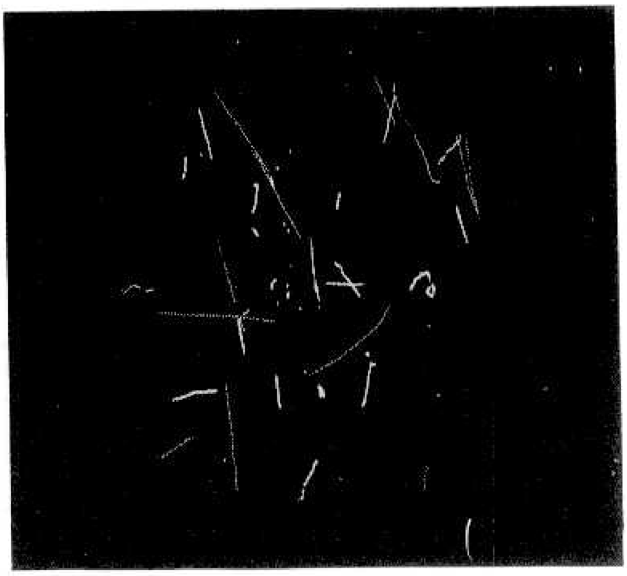

Fig 5.3 – MTD PROCESSING OUTPUT

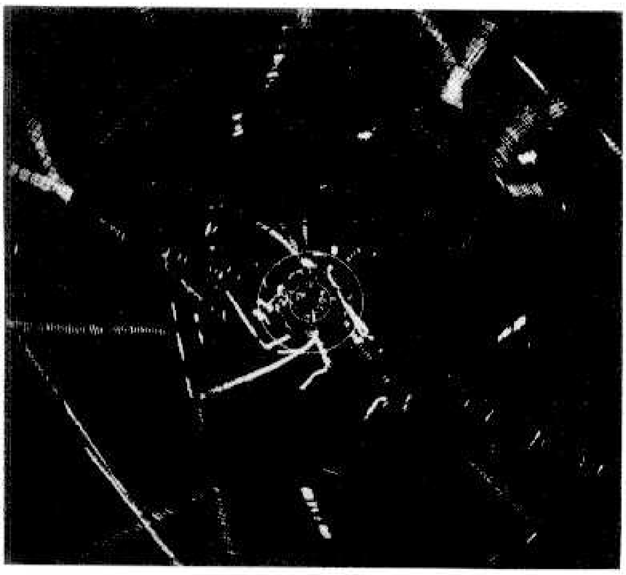

Fig 5-4 – MTI PROCESSING OUTPUT (RANGE MARKS = 10 NM)

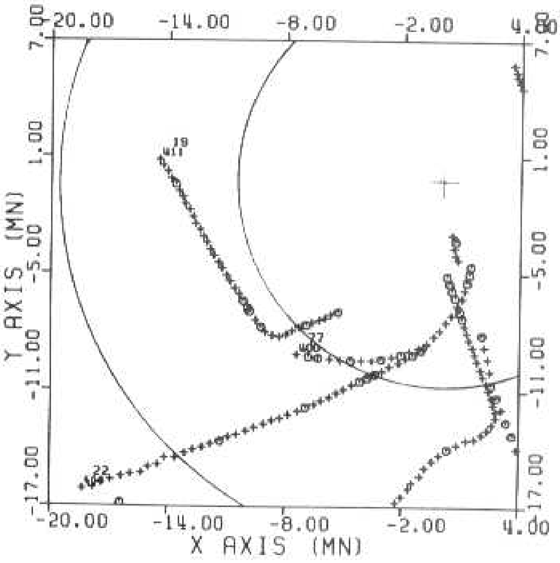

Fig 5.5 – DETAIL OF MTD OUTPUT
(O CORRESPONDS TO ZERO VELOCITY FILTER OUTPUT)

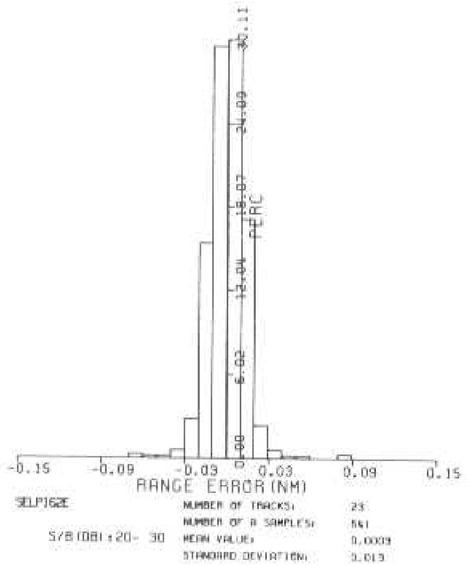

Fig 5.6 – RANGE ERROR HISTOGRAM

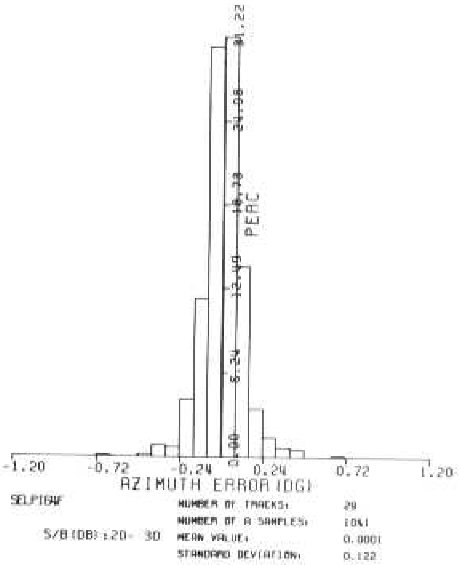

Fig 5.7 – AZIMUTH ERROR HISTOGRAM

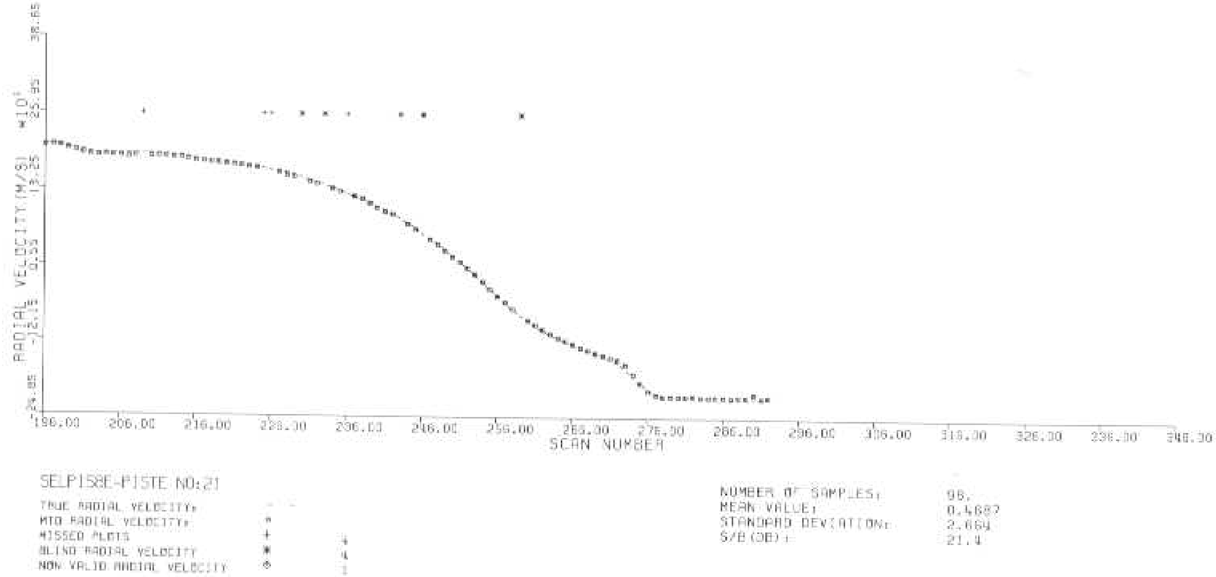

Fig 5.8 – MTD RADIAL VELOCITY (□) AND TRUE RADIAL VELOCITY (–) VERSUS SCAN NUMBER

CP 410

MICROWAVE LANDING SYSTEM (MLS) AREA NAVIGATION: COMPUTED CENTERLINE EXPERIMENTS AND SYSTEM ACCURACY ANALYSES IN AN RF ENVIRONMENT

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SUMMARY

By definition of the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPS) the Time Reference Scanning Beam (TRSB) Microwave Landing System (MLS) will supplant the existing Instrument Landing System (ILS) as the recognized international standard as early as 1995. Among numerous other advantages, the MLS provides the ability to determine the aircraft's position in three dimensional space over a large coverage volume in the airport terminal area. The use of this capability to navigate and execute approaches throughout this volume of coverage results with the application of a technique known as Microwave Landing Sytem Area Navigation (MLS RNAV). Applications of MLS RNAV can be as simple as executing approaches offset from but parallel to the MLS 0° azimuth or as complex as multi-segment and curved path approaches. MLS RNAV is particularly adaptable to helicopter operations. It allows approaches to heliports located away from the main instrumented runway. In order to assess and further develop the potential capabilities of MLS RNAV, the FAA Technical Center has undertaken the task of performing analytical studies, as well as the development of a prototype MLS RNAV system. Application of this system to helicopter operations are particularly being emphasized.

The unique feature of this work is that besides the onboard data acquisition systems, an independent source of position information was, at times, available for comparison. The source was independent position tracking in the form of laser or radar data. The work reviewed in this paper should have immediate application in the development of MLS RNAV Terminal Area Instrument Approach Procedures (TERPS). It is also hoped that data gained in flying the system will be of use to standards setting organizations such as the Radio Technical Commission for Aeronautics in the United States and EUROCAE Working Group 27 in Europe.

LIST OF SYMBOLS

Symbol	Definition
θ	Received MLS Azimuth Angle
ϕ	Received MLS Elevation Angle
ρ	DME/P Slant Range
θ_i	Approach Course
ϕ_i	Glide Path Angle
θ_r	Magnetic Bearing of 0° Azimuth
θ_G	Grid Angle
C_{WH}	Azimuth Course Width at Terminal Waypoint
C_{WC}	Azimuth Course Width at Initial Waypoint
DTG	Distance to Go
HTE	Vertical (Height) Error
CTE	Cross Track Error
(X_a, Y_a, Z_a)	MLS Azimuth Unit Coordinates
(X_e, Y_e, Z_e)	MLS Elevation Unit Coordinates
(X_d, Y_d, Z_d)	MLS DME/P Unit Coordinate
(θ, ϕ, ρ)	MLS Coordinate Triple
(x, y, z)	Cartesian Triple Produced by MLS Reconstruction Algorithms

INTRODUCTION

BACKGROUND

The Microwave Landing System (MLS) is currently being implemented in the United States. The ground equipment consists of three navigation signal source elements. Lateral guidance is provided by the azimuth (AZ) transmitter, vertical guidance by the elevation angle transmitter (EL), and distance information by precision distance measuring equipment (DME/P). Airborne receivers have the built-in flexibility of having the pilot select the approach azimuth and elevation angle within certain limits. Basic MLS signal coverage provides azimuth guidance through an arc of 120°, and elevation coverage from 0.9° to 20° above the horizon. Ranging information in coverage is provided out to at least 20 miles (32 km). MLS ground equipment transmits auxiliary information in the form of data words. These data words can be interpreted by airborne receivers. The words include information about the layout of the MLS ground equipment in relation to the primary instrument runway.

The accuracy of the MLS is a significant improvement over ILS component accuracies. This fact coupled with the large coverage volume of the MLS will permit increased utility of the MLS to provide terminal area navigation and precision approach guidance. With the addition of an airborne navigation computer, an area navigation methodology based on MLS guidance is achievable. In larger aircraft existing navigation computers and automatic flight control systems (AFCS) could be coupled with the MLS airborne receiver to provide the MLS RNAV capability. One unique feature of MLS RNAV is its ability to provide precision RNAV guidance in at least a portion of the MLS coverage volume. In order to standardize the development of MLS RNAV and identify minimum equipment performance standards the Radio Technical Commmission for Aeronautics (RTCA) has formed a special committee. This committee is preparing a draft document outlining the minimum operating performance standards for MLS RNAV equipment (reference 1).

Draft minimum performance standards have been developed for three different levels of equipment. The most distinguishing feature between the three levels of equipment is the route construction capability. The least capable level only has a single segment route construction capability. The next level has a multiple segment capability. The most advanced system can compute curved flight path routes in both the horizontal and vertical dimensions. Even with the least capable level of equipment single segment MLS RNAV offers many useful extensions of MLS guidance for many general aviation and helicopter operators. These users, more than likely, do not have onboard navigation computers and are not equipped with an AFCS. Parallel offset approaches provides one of the most useful extensions of MLS guidance to users equipped with MLS RNAV. Offset parallel precision approaches would permit the servicing of parallel runways with one MLS system. At several locations terrain restrictions will not permit the azimuth transmitter to be sited on the extended runway centerline 1000 feet beyond the stop end of the runway. Figure 1 depicts an example of an offset approach.

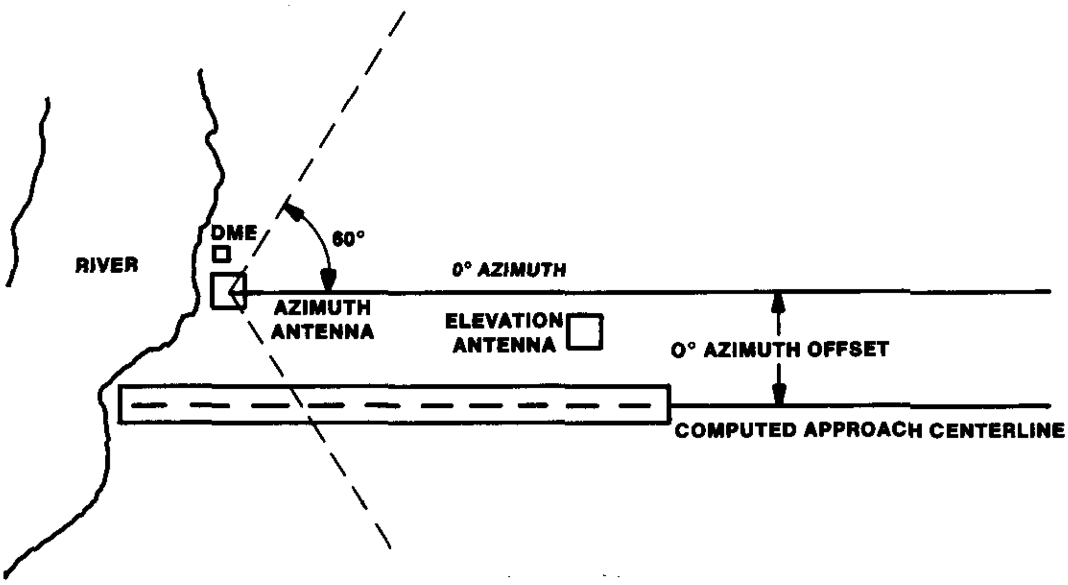

FIGURE 1. EXAMPLE OF MLS RNAV OFFSET AZIMUTH COMPUTED CENTERLINE APPORACH.

Helicopter operators could benefit from MLS RNAV in several ways. A simple single segment RNAV system could be used to provide guidance for a parasite approach to a heliport located within the coverage volume of an exiting MLS. This same methodology could be used to permit precision instrument approaches by helicopters to points that are separated from the primary instrument runway. This would reduce traffic congestion by removing the generally slower helicopter from the flow of traffic to the primary instrument runway. An example is presented in figure 2. Production MLS is scheduled to be implemented at several heliports. Terrain restrictions and obstacles around the heliports could reduce the effectiveness of the system. In urban areas heliports are often sited adjacent to bodies of water or flood plains. With a single segment MLS RNAV it would be possible to construct a point in space precision approach to a point over the open area. This could result in reduced approach minimums and increase the utility of the MLS. Figure 3 presents an example of a point in space precision approach.

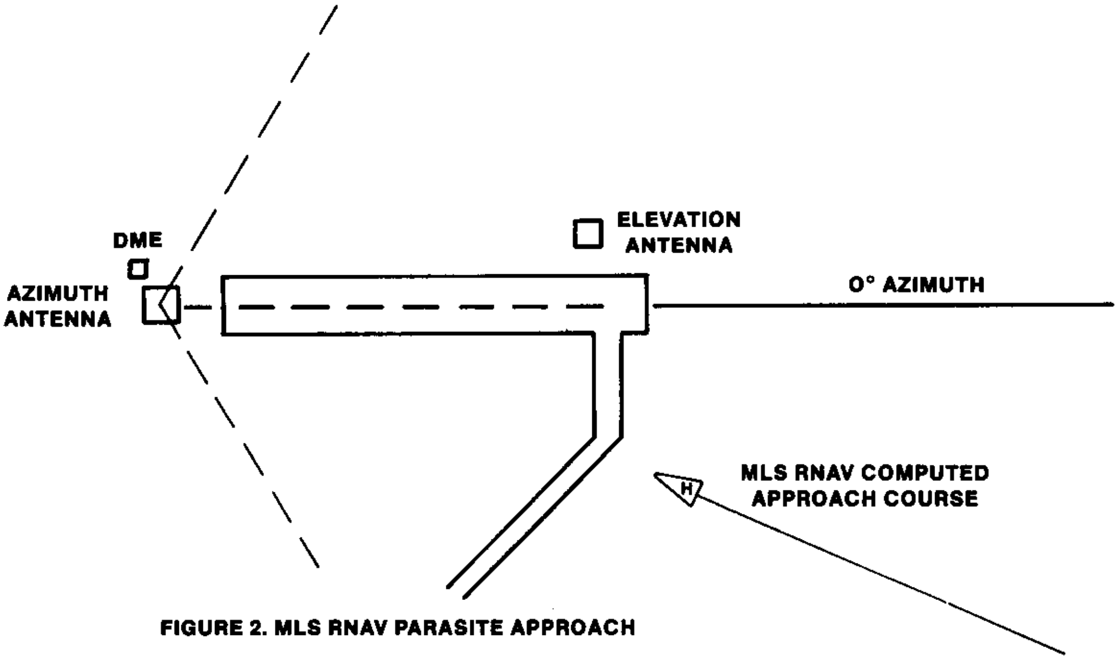

FIGURE 2. MLS RNAV PARASITE APPROACH

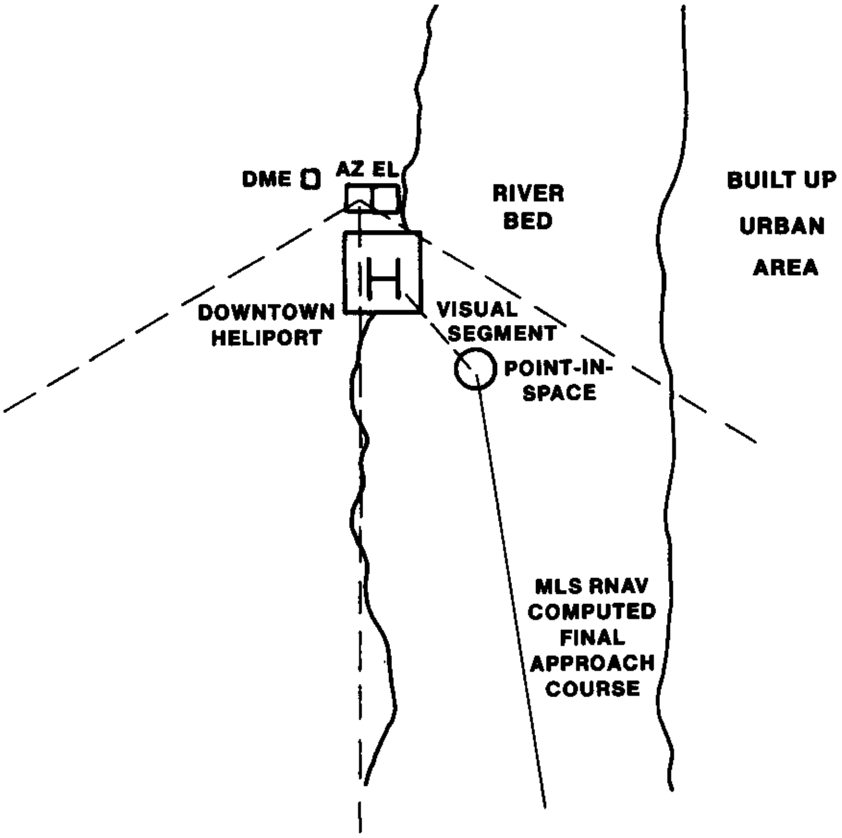

FIGURE 3. MLS RNAV POINT-IN - SPACE APPROACH

The RTCA Special Committee is currently investigating several issues. These issues include MLS RNAV accuracy and navigation function and cockpit display update rates. Other issues address MLS RNAV position determination methodology and definition of the MLS RNAV coordinate reference system. Analyses of some of these issues have been conducted at the FAA Technical Center in Atlantic City, New Jersey. A simple single segment prototype MLS RNAV system was built at the FAA Technical Center. This system was used to demonstrate the feasibility of applying MLS RNAV techniques to sythetically compute an extended runway centerline.

MLS RNAV EQUIPMENT DESCRIPTION

The principal constituents of our prototype level 1 (RTCA defined least capable) capability equipment are the MLS angle receiver, DME/P interrogator and a Motorola 68000 microprocessor *VMEbus*^{TM} *based computer.* Interfaces and digital to analog converters are needed to route navigation guidance information output from the computer to existing cockpit displays. The MLS angle receiver and DME interrogator provide digital output of received azimuth (θ) and elevation (ϕ) angles, along with DME/P digital range (ρ). These words are transmitted to the digital input interfaces in the system card cage. The computer utilizes this input along with cockpit display and control unit input provided by the pilot. The computer then outputs the necessary navigational guidance and awareness information in digital form to the system output interfaces. These interfaces supply the data to appropriate digital to analog converters in the system card cage. This information is converted to provide a -150 to +150 microamp full scale analog signal to drive standard course deviation (CDI) and vertical deviation indicators (VDI) in the cockpit. Awareness information such as bearing and distance to the azimuth unit can also be presented using existing cockpit displays. Watch dog timers are employed to drop failure/fault flags if guidance information is absent for two or more seconds. The display update rate of the prototype unit is currently set to 5 Hertz (Hz). A detailed hardware block diagram is shown in figure 4.

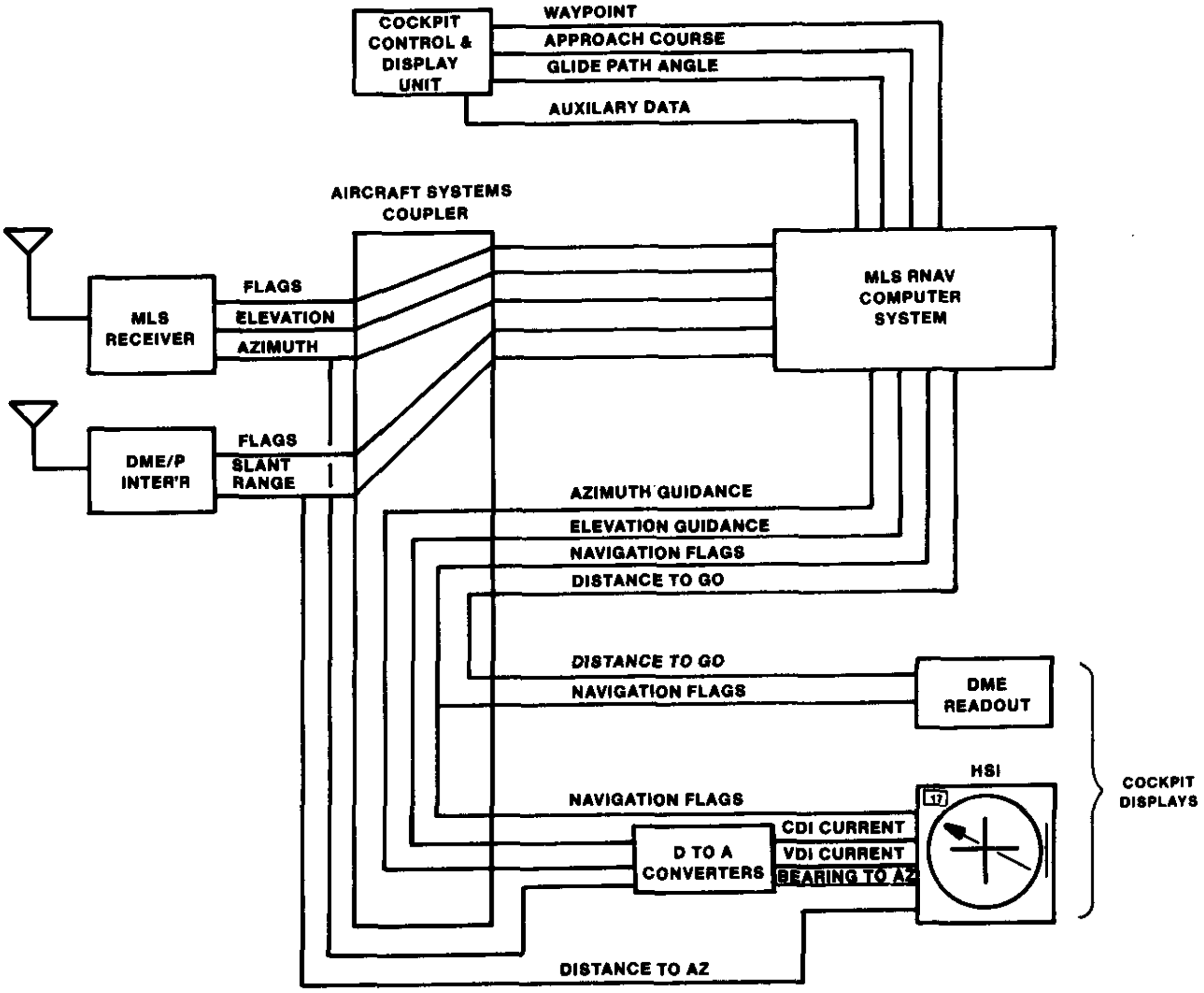

FIGURE 4. MLS RNAV SYSTEM BLOCK DIAGRAM

The algorithms used for position determination and guidance are programmed in the FORTRAN language. An overview of the prototype system software design is shown in figure 5. Algorithm input comes from three sources. The MLS coordinate triple (θ,ϕ,ρ) is provided by the MLS angle receiver and DME/P interrogator. The MLS ground equipment provides information to support airborne resolution of the equipment siting geometry. Currently, studies are being conducted to determine if siting differences in the z-plane must be identified. Other information provided by the ground equipment includes the magnetic bearing of the 0° azimuth (θ_r) and lateral course width sensitivity information. The final source of input to the algorithms is the cockpit entered data. This includes the terminal waypoint cartesian triple (X_h,Y_h,Z_h), the final approach course (θ_i), and the glide path angle (ϕ_i) to be flown to the terminal waypoint. The final approach segment length may also be identified to support course width tailoring requirements. Auxiliary algorithm features support fault/failure detection and coasting of display presentation for short time periods.

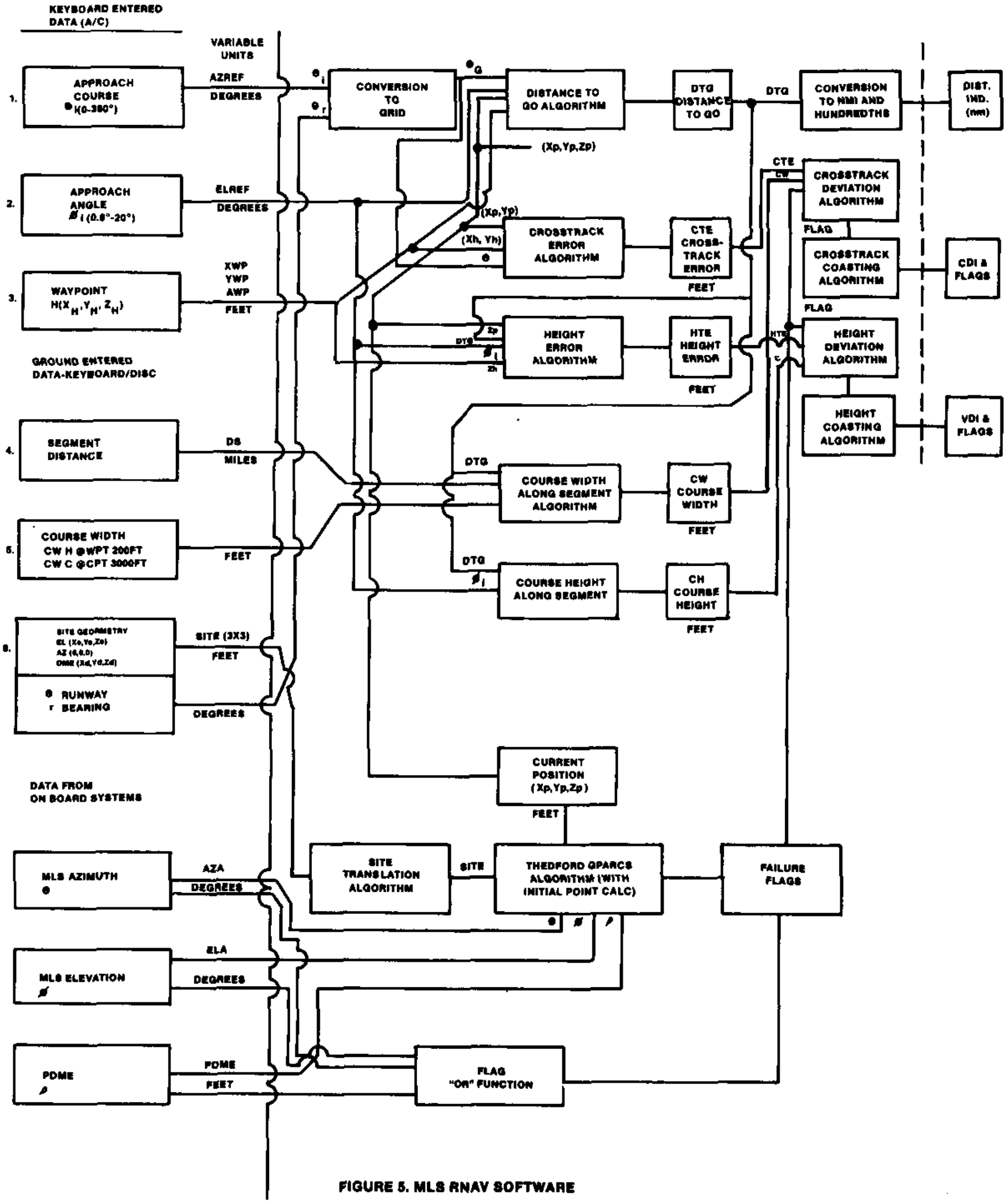

FIGURE 5. MLS RNAV SOFTWARE

ANALYTICAL STUDIES

Prior to implementation of the FAA prototype level 1 MLS RNAV system in flyable hardware form, extensive analytical studies were conducted. These studies encompassed a number of functional areas including:

1. The derivation, progamming and testing of a comprehensive set of algorithms for transformation of the MLS coordinate triple (θ,ϕ,ρ) to Cartesian triple (X,Y,Z). These algorithms are called MLS reconstruction algorithms.

2. Assessment of the accuracy of the MLS reconstruction algorithms through simulation and the use of live flight data.

3. The development, programming and testing of the complete MLS RNAV software package.

Additionally, accuracy studies were conducted in order to quantify:

1. The effects inducted by signal source errors in MLS RNAV position determination.

2. The error in glide path angle resulting from offset approaches when elevation guidance is conic and not planar.

MLS RECONSTRUCTION ALGORITHMS

The three ground based transmitting units, azimuth, elevation and precision distance measuring equipment define a generalized MLS coordinte system with the triple (θ,ϕ,ρ). Knowing the triple and the relative positions of the ground units, it is possible to locate the position of the aircraft in space.

With a three dimensional MLS RNAV it is possible to determine position independently of the conventional MLS raw data approach course. Practicality and simplicity dictate that a cartesian coordinate (X,Y,Z) reference sytem be employed. In our development the origin of this coordinate system is placed at the phase center of the azimuth antenna. The y axis is aligned parallel to the 0° azimuth. In order to obtain aircraft position in this coordinate system it was necessary to develop a set of equations to convert the coordinate triple (θ,ϕ,ρ) into the new cartesian coordinate triple. For obvious reasons this transformation must be unique in the region of application. These equations when implemented on a digital computer, are known as the MLS reconstruction algorithms. These algorithms run the gamut from a simple exact solution for (X,Y,Z) to a complex fully general iterative solution. The degree of sophistication is dependent on the ground unit geometry, with most sophistication required when the ground units are sited in different z-planes. Work is in progress to determine the effect on position determination when the siting location z coordinates are unknown. Underlying the development of the reconstruction algorithms is the concept of the intersection of loci defined by the MLS ground units. As shown in figure 6, the loci of constant DME/P distance (ρ) defines a sphere with center located at the ground unit site (X_d,Y_d,Z_d). The elevation unit defines a cone of exterior angle (ϕ) centered at its location (X_e,Y_e,Z_e). The azimuth unit defines a plane or cone of angle (θ) relative to the X-Z plane depending on whether a planar or conic azimuth signal pattern is used. The intersection of these three surfaces defines the possible locations of the aircraft in space. Four points result from the intersection of the surfaces, but the correct solution can be chosen based on apriori knowledge of the geometry. A total of twelve different reconstruction algorithms have been developed at the FAA Technical Center. A description of the siting geometry, the signal propagation pattern and the method of solution of these algorithms are contained in table 1.

ALGORITHM TESTING

The algorithms have been validated through a variety of methods. The first was a grid test procedure. This entails iterating through the points in (X,Y,Z) space and synthesizing the triple (θ,ϕ,ρ) for a given ground unit geometry. The synthesized triple is then input to the algorithms and the resulting (X',Y',Z') compared with the original point in cartesian three space. Besides grid tests certain algorithms, notably cases 11 and 12 were tested via simulation of single segment MLS RNAV route flights. Figures 7, 8, and 9 depict the results of this testing. In the example presented, case 12 algorithms were used to reconstruct aircraft position along a route which biases the 0° azimuth at a 10° angle. The terminal waypoint was located 3600 feet (1097m) in front of the elevation antenna on the extended runway centerline. In the figures the along, cross track and height error along the RNAV segment are depicted as functions of the true slant range from the DME/P ground unit. In all dimensions the resulting errors were quite small. The saw tooth pattern on figure 7 reflects the granularity in the test procedure. Position determination was tested every 100 feet (30 m) on the segment from 2.6 nautical miles (4.2 km) into the terminal waypoint.

Other issues such as flight dynamic effects on algorithm performance and algorithm cycle timing were also investigated. The most complex forms of the algorithms (cases

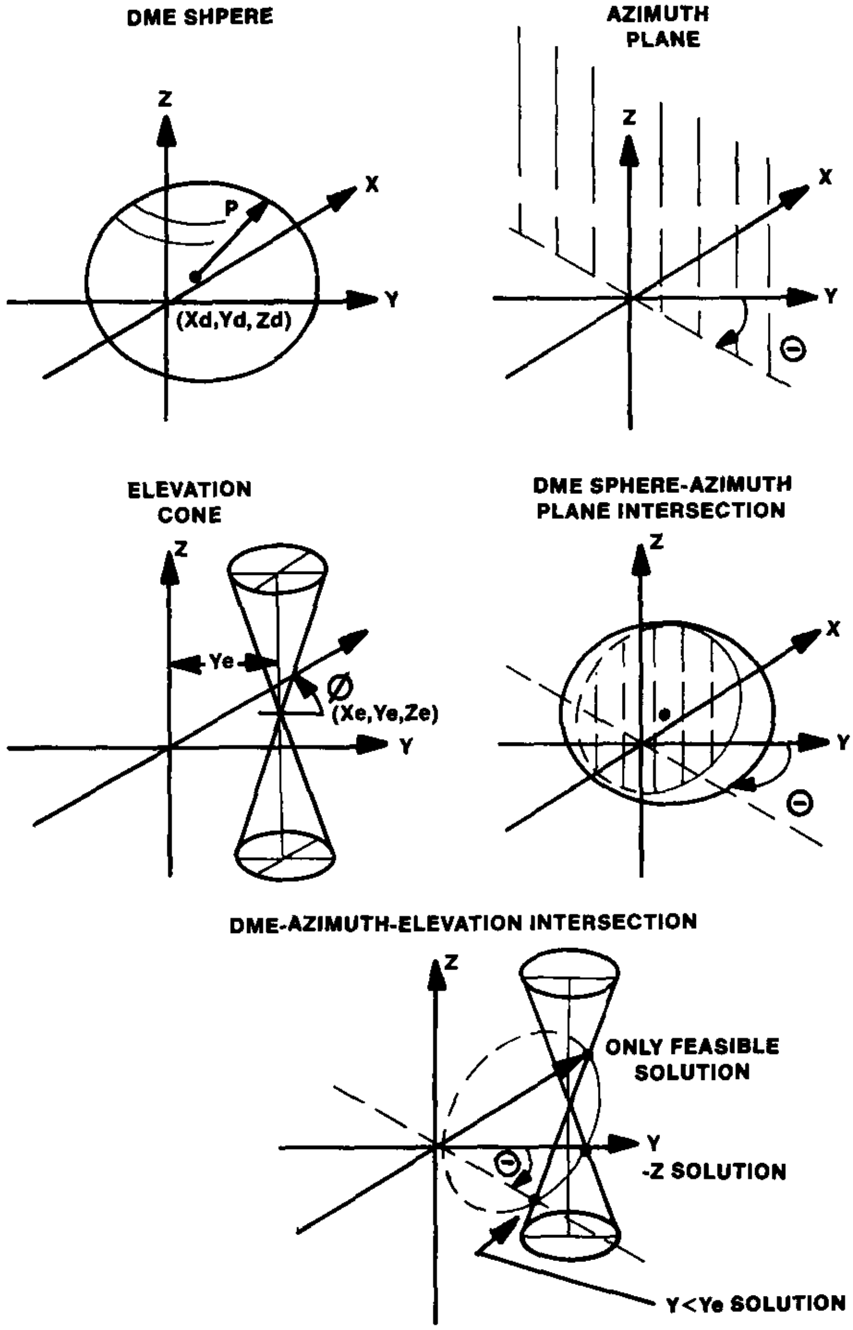

FIGURE 6 GRAPHICAL SOLUTION

11 and 12 were selected for testing) with live flight data. This data consisted of time oriented triples (θ, ϕ, ρ) recorded on tape in the course of executing conventional MLS approaches and departures with the S-76 helicopter. Independent tracking of the helicopter while executing these profiles was provided by the Extended Area Instrumented Radar (EAIR) and/or laser tracking. The flight derived triples were input to the MLS reconstruction algorithm which generated the (x,y,z) output. These triples were then compared with the independently obtained tracking data using a time oriented data merge procedure. It should be noted that differences obtained in this comparison reflect more than algorithm error. Other errors include signal source error, receiver performance, and site alignment errors. Despite this, excellent results were obtained. Table 2 presents the means and twice the standard deviations of the differences between MLS RNAV position and the indepedently tracked position for each approach or departure profile flown by the helicopter. Approaches were flown from approximately 4 miles (6.5 km) into a specified decision height (DH), on a specified glide path angle and the 0° azimuth. Departures were flown out to approximately 4 miles and a specified altitude without a vertical guidance reference. Departures were flown on the 20° left and the 20° right azimuth as well as the 0° azimuth. The excellent results in table 2 actually represent the equivalent of navigation system error.

TABLE 1. MLS RECONSTRUCTION ALGORITHMS

CASE	DESCRIPTION	SOLUTION
1	DME & AZ COLOCATED, PLANAR AZ AZ & EL COLINEAR, SAME Z PLANE	EXACT
2	DME & AZ COLOCATED, PLANAR AZ AZ & EL OFFSET, SAME Z PLANE	EXACT
3	DME & AZ COLOCATED, CONICAL AZ AZ & EL COLINEAR, SAME Z PLANE	EXACT
4	DME & AZ COLOCATED, CONICAL AZ AZ & EL OFFSET, SAME Z PLANE	EXACT
5	DME & AZ COLOCATED, PLANAR AZ AZ & EL COLINEAR, DIFFERENT Z PLANES	ITERATIVE
6	DME & AZ COLOCATED, CONICAL AZ AZ & EL COLINEAR, DIFFERENT Z PLANES	ITERATIVE
7	"THEDFORD ALGORITHM" EXTENSION CONICAL AZ, DME REFERENCE FRAME AZ & EL POSITIONS COMPLETELY GENERAL	ITERATIVE
8	"THEDFORD ALGORITHM" EXTENSION CONICAL AZ, DME & AZ COLOCATED	ITERATIVE
9	COMPLETELY GENERAL SOLUTION CONICAL AZ NONLINEAR SEIDEL INTERATION	ITERATIVE
10	COMPLETELY GENERAL SOLUTION PLANAR AZ NONLINAR SEIDEL ITERATION	ITERATIVE
11	"THEDFORD ALGORITHM" PLANAR AZ, DME REFERENCE FRAME AZ & EL POSITIONS COMPLETELY GENERAL	ITERATIVE
12	"SHREEVES ALGORITHM" CONIC AZ & EL COMPLETELY GENERAL AZ, EL & DME POSITIONS	NEWTON/RAPSON JACOBIAN ITERATION

DME = Precision DME Antenna
AZ = Azimuth Antenna
EL = Elevation Antenna

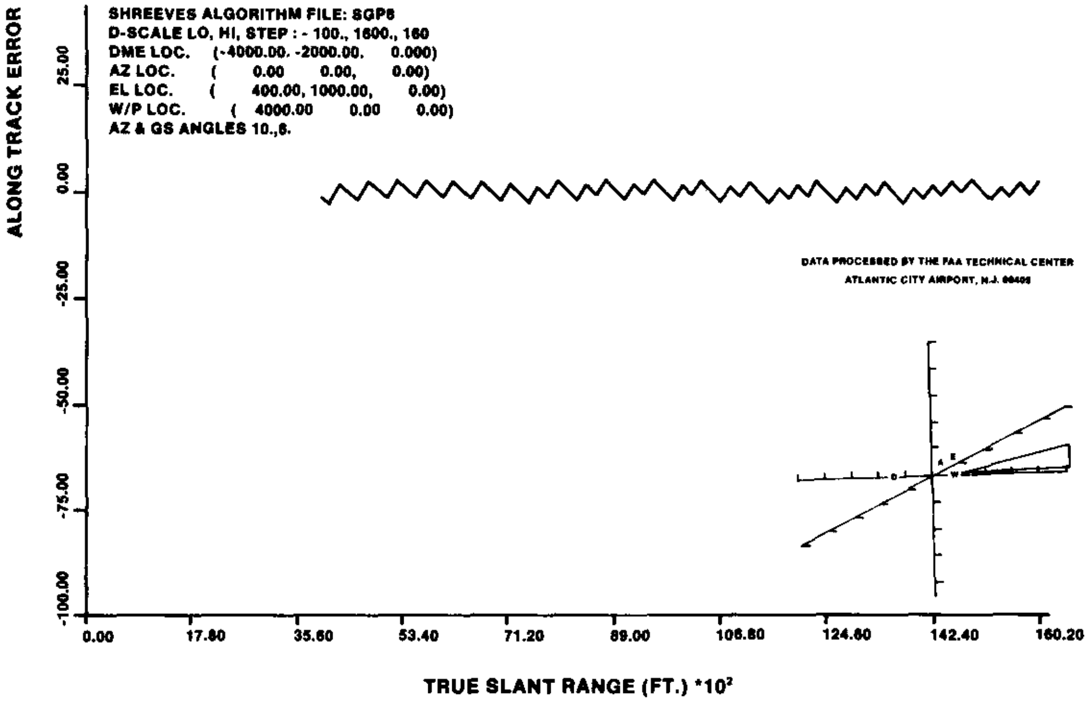

FIGURE 7 ALGORITHM ALONG TRACK ERROR

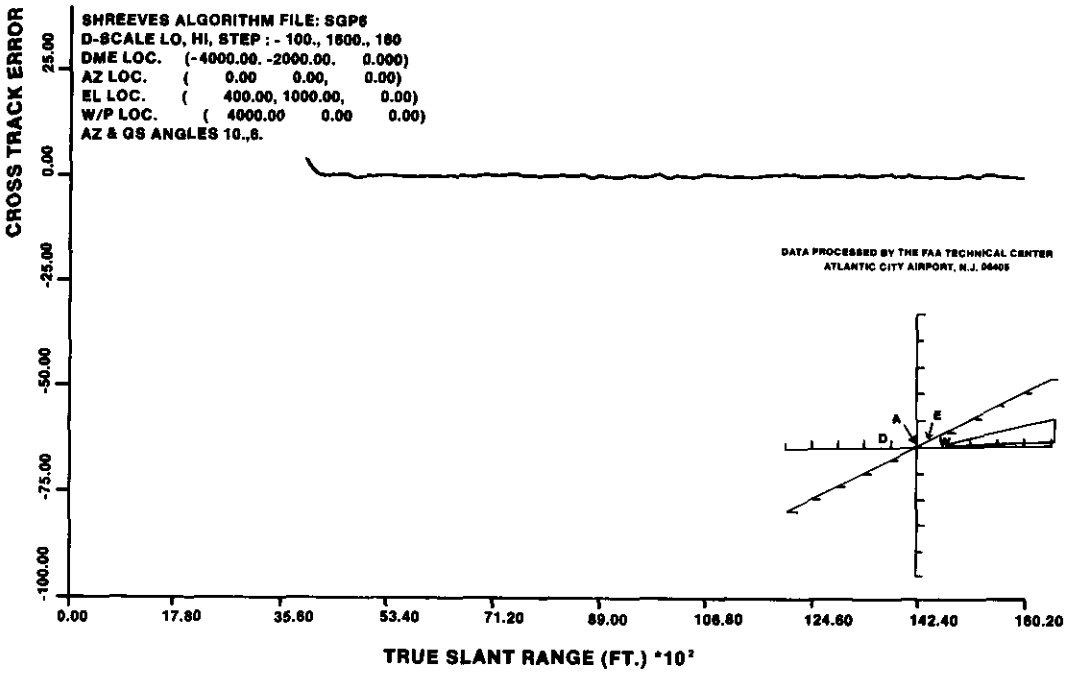

FIGURE 8. ALGORITHM CROSS TRACK ERROR

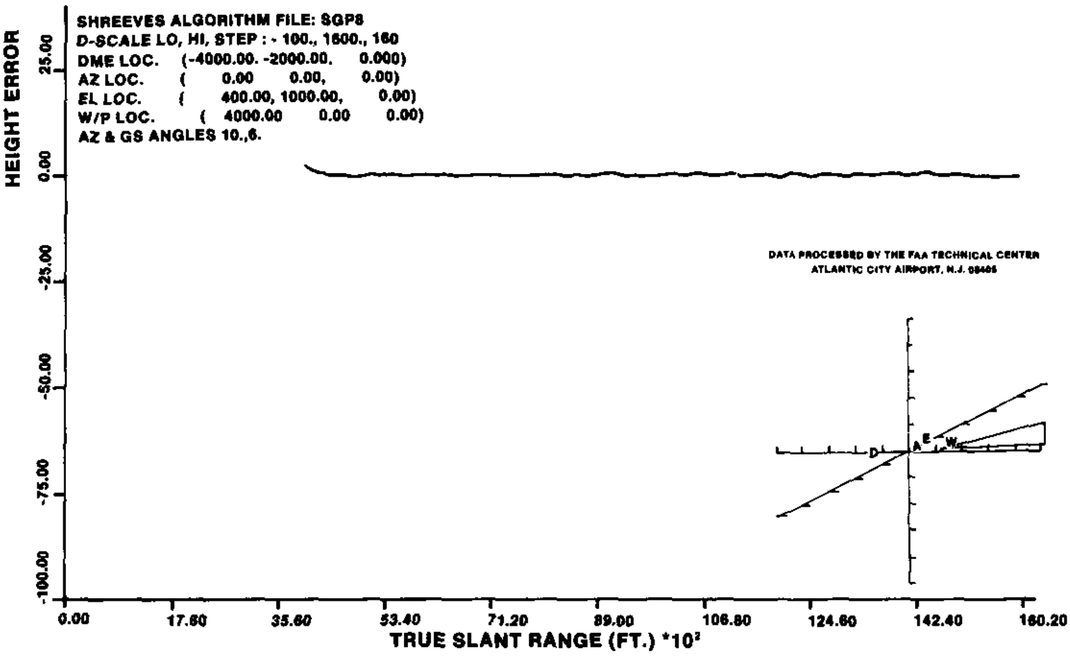

FIGURE 9. ALGORITHM VERTICAL ERROR

An additional level of system simulation was performed by playing the MLS and DME/P data through the MLS RNAV system software depicted in figure 5. The Thedford algorithm, case 11, was used for the transformation. The entire software suite was found to consume less then .02 seconds per update cycle. Iterative solution convergence were always satisfied. The timing analysis was accomplished on a PDP 11/23 minicomputer which is slower than the prototype system's Motorola 68000 VMEbus™ based computer.

MLS RNAV CONCEPT ACCURACY ANALYSIS

Simulation and accuracy tasks were initiated at the FAA Technical Center to determine the theoretical limits of performance of an MLS RNAV system. Regardless of how accurate MLS reconstruction algorithms are, other system limitations such as signal source error may limit the application of MLS RNAV techniques within the total volume of signal coverage. These limitations will influence the establishment of MLS RNAV TERPS procedures and approach minima. Analysis has focused on the most useful application of MLS RNAV, the parallel offset approach.

Since the (θ, ϕ, ρ) to (X,Y,Z) transformations are nonlinear transformations, no direct computational procedure existed for determination of signal source error impact on MLS RNAV position determination. Hence, analysis of signal source error effects on position determination was accomplished through the use of Monte Carlo simulation methods. Case 1 reconstruction algorithms were used since they represent the most common ground unit siting. The exact MLS coordinate triple $(\theta_t, \phi_t, \rho_t)$ was obtained for a particular DH, elevation angle and offset magnitude combination. Using Monte Carlo methodology the triple $(\theta_t, \phi_t, \rho_t)$ was obtained for a particular DH, elevation angle and offset magnitude combination. The perturbed triple $(\theta_p, \phi_p, \rho_p)$ was input to the reconstruction algorithm. This procedure was replicated 1000 times and the variation in the resulting cartesian triple was noted. Table 3 presents cross track error results when a 6° glide path angle is used to arrive at a 300' DH. The errors are presented as a function of the magnitude of offset of the approach being simulated and the along track distance between the azimuth and elevation units. Cross track error increases with increasing offset values. However, the cross track error decreases as the azimuth to elevation unit distance increases.

TABLE 2. TOTAL SYSTEM ERROR IN POSITION DETERMINATION

Run No.	Approach Angle (Deg.)	DH or Final Alt. (ft)	Along Track Error (ft)		Cross Track Error (ft)		Height Error (ft)	
			$\bar{X}$	2σ	$\bar{X}$	2σ	$\bar{X}$	2σ
1	Departure	800	-46.86	47.30	-8.92	25.26	-7.26	31.70
2	3.0	150	11.90	50.46	-4.60	18.64	-8.07	21.12
3	6.0	200	30.66	50.46	-1.02	11.84	-7.87	16.21
4	Departure	2000	-18.82	31.22	27.67	26.47	2.97	19.62
5	9.0	350	16.09	28.98	-0.22	14.28	-11.60	26.96
6	6.0	150	21.96	58.11	-2.34	27.62	-2.20	21.48
7	3.0	100	40.59	86.02	-15.81	48.30	-1.27	28.98
8	3.0	200	10.07	65.16	-6.09	15.82	4.36	31.16
9	3.0	200	0.56	50.32	16.17	25.88	6.70	29.98
10	Departure 20°L	1400	7.90	48.12	-7.01	21.66	-7.52	19.64
11	6.0	200	4.67	33.02	-10.72	22.08	-4.13	24.34
12	6.0	300	16.54	43.28	-5.69	24.62	-3.67	20.30
13	Departure	2000	-39.23	51.32	-5.05	25.00	10.73	18.16
14	9.0	350	26.47	65.84	-2.84	30.14	2.14	34.88
15	3.0	100	30.82	67.48	8.71	26.18	0.64	32.30
16	3.0	150	26.33	63.30	-8.92	22.44	-1.49	26.64
17	Departure	2000	-25.41	44.54	-8.08	34.36	2.77	27.10
18	9.0	350	21.30	72.14	-1.77	25.54	-2.85	24.14
19	Departure 20°R	1400	11.11	35.08	-5.30	42.06	1.82	44.54
20	6.0	300	23.92	62.34	-8.42	39.44	-1.21	18.47
21	6.0	200	26.70	69.18	-30.88	37.86	0.49	38.90
22	3.0	200	9.64	30.06	1.59	12.68	-5.52	21.42
23	3.0	150	23.41	58.72	-1.27	9.38	-3.73	20.24
24	3.0	100	25.57	50.42	-0.93	11.92	-6.06	19.54

Another limitation which must be considered is the error in vertical position which results when the elevation angle signal pattern is conical. Table 4 presents this error as a function of elevation angle DH and magnitude of offset. Note that the vertical position error increases with increases in the elevation angle or magnitude of offset in the approach being simulated. Information in table 4 can be used to identify the amount of offset which can be tolerated without causing an increase in Catagory 1 approach minima when using raw elevation guidance. Theoretically, Catagory 1 approach minima could be applied across larger offset magnitudes if the vertical position error was eliminated with computed glide path guidance.

COMPUTED CENTERLINE EXPERIMENTS

BACKGROUND

Parallel offset approaches as alluded to previously, are among the most useful applications of MLS RNAV. In many cases, geometry and obstructions will prevent the azimuth antenna from being sited conventionally on the extended runway centerline 1000 feet beyond the stop end of the runway. The purpose of these experiments was to demonstrate the feasibility of conducting precision MLS RNAV approaches to Catagory 1 approach minima when the azimuth was offset. This capability of MLS is a significant enhancement over a conventional ILS which has an offset localizer. When the conventional ILS has the localizer offset the operator must pay a penalty in increased approach minima. Using a simple prototype MLS RNAV system installed in a Sikorsky S-76 helicopter the FAA Technical Center conducted computed centerline experimentation at both the Atlantic City Airport and Washington National Airport.

TABLE 3. CROSSTRACK APPROACH FIX DISPLACEMENT ERROR 2 SIGMA, AT DH=300 FT DUE TO AZIMUTH OFFSET

Offset (ft)	6° GLIDE PATH ANGLE AZIMUTH TO ELEVATION DISTANCE (FT)														
	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	10000
100	3	3	3	3	3	2	2	2	2	2	2	2	2	2	1
200	7	6	6	5	5	5	5	4	4	4	4	3	3	3	3
300	10	9	9	8	8	7	7	6	6	6	6	5	5	5	5
400	14	13	12	11	10	10	9	8	8	8	8	7	7	6	6
500	17	16	14	13	13	12	11	10	10	9	9	9	9	8	7
600	20	19	17	16	15	14	13	13	12	11	11	11	10	9	9
700	23	23	20	19	17	17	15	15	14	13	13	12	12	11	11
800	28	25	23	21	20	19	18	17	16	15	15	14	13	12	12
900	30	26	25	24	21	21	20	19	18	17	16	15	15	14	14
1000	32	30	29	26	25	23	22	21	20	19	18	18	16	16	16
1100	37	33	31	29	28	25	24	33	22	20	20	18	18	18	16
1200	39	38	35	31	29	27	26	26	24	23	21	21	20	19	18
1300	42	37	37	34	32	30	29	28	26	24	23	22	22	21	18
1400	46	41	39	36	35	31	29	28	27	25	25	23	23	22	21
1500	49	46	41	40	37	33	31	31	29	29	27	26	24	23	22
1600	52	47	44	42	39	35	34	33	31	29	27	27	26	26	24
1700	53	50	46	43	42	38	34	34	32	31	30	30	27	27	26
1800	55	53	49	46	43	41	40	36	35	35	32	30	29	28	27
1900	59	56	53	48	45	43	41	38	36	36	34	32	30	30	29
2000	61	58	53	50	47	45	43	41	37	36	35	36	33	30	30
2100	65	63	54	53	50	46	43	42	37	37	37	35	34	31	30
2200	68	62	58	54	51	49	45	43	42	39	37	36	35	34	32
2300	70	65	59	56	52	51	48	45	45	41	40	40	36	35	33
2400	73	67	63	61	56	53	51	47	45	42	41	42	38	36	35
2500	73	70	65	61	57	55	51	50	47	46	42	41	40	38	37

TABLE 4. VERT. POSITION ERROR (FEET) DUE TO OFFSET OF CONIC ELEVATION

Glidepath Approach	3.°	4.5°	6.°	9.°
DH	200. ft	250. ft	300. ft	350. ft
0	0	0	0	0
100	0	0	0	0
200	0	0	1	1
300	1	1	2	3
400	1	2	3	6
500	2	3	5	9
600	2	4	7	13
700	3	6	9	17
800	4	8	12	22
900	5	10	15	28
1000	7	12	18	34
1100	8	15	22	41
1200	10	17	25.	48
1300	11	20	30	56
1400	13	23	34	64
1500	15	26	39	73
1600	17	30	44	82
1700	19	34	49	92
1800	21	37	55	101
1900	23	41	60	112
2000	26	45	66	122
2100	28	50	72	133
2200	31	54	79	144
2300	34	59	85	155
2400	36	63	92	167
2500	39	68	99	178

GROUND EQUIPMENT

As described in reference 3, the Bendix MLS system employed at Washington National airport consists of an azimuth unit which is offset laterally 275 feet (84m) from runway 33 centerline. It provides proportional guidance within ±10° about the phase center of the antenna. Full fly right or fly left guidance is provided from 10° to 40° on either side of the proportional coverage segment. A modified Cardion Corporation DME/P unit is collocated with the azimuth antenna. The elevation antenna is located 258 feet (79m) inside the runway 33 threshold and 250 feet (76m) laterally from the runway centerline. Proportional vertical guidance is provided between 1° and 15° above the horizon. The siting configuration for Washington National Airport is illustrated in figure 10. The currently charted procedure requires the pilot to fly the final approach on the 2° left azimuth until intercepting the extended runway centerline 2663 feet (812m) from the runway theshold. At that point, either visual contact with the runway is made and the approach completed by turning left to align the aircraft with the runway centerline or a missed approach is executed. The large distance between the intercept and the runway threshold results in high approach minima, well above catagory 1 minima.

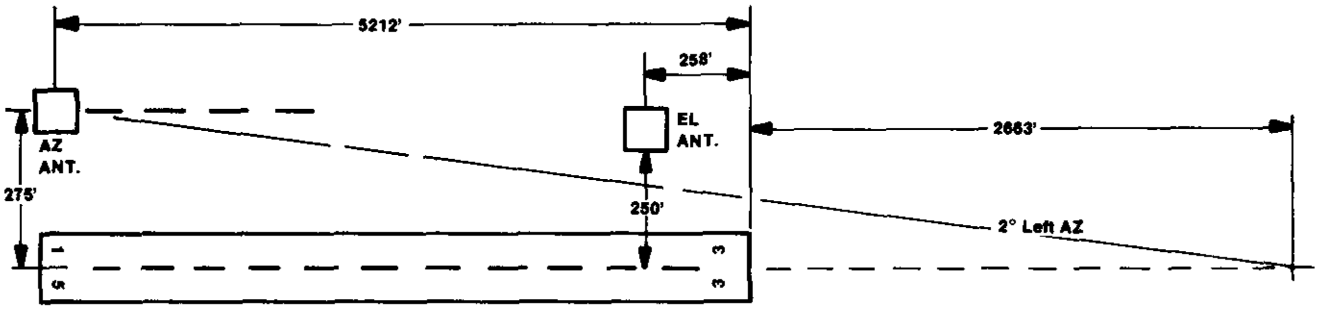

FIGURE 10. WASHINGTON NATIONAL OFFSET AZIMUTH SITING

AIRBORNE EQUIPMENT

Using simple prototype MLS RNAV equipment to process raw MLS receiver and DME/P data, a synthetic extended runway centerline was constructed and data guidance presented relative to that constructed path. Although elevation information is required to construct the extended runway centerline and derive lateral guidance information, only raw elevation information was used to provide vertical guidance during the approaches. The airborne equipment performed the digital to analog conversions and output of analog guidance including course deviation and vertical deviation information on the pilot's horizontal situation indicator. With the prototype system the following specific functions were performed with software:

1. Coordinate transformation using case 1 algorithms.
2. Azimuth course width tailoring to control displayed guidance sensitivity.
3. Coasting of guidance output for up to two seconds in absence of MLS data input.
4. Output of guidance signals and failure/fault flags to cockpit displays.

The entire system was clocked to run at a 4 Hz rate.

COMPUTED CENTERLINE RESULTS

In addition to developmental flights at the Atlantic City Airport, nine offset computed centerline approaches were flown at Washington National Airport. Test run conditions for each approach are shown in table 5. The glide path used for all approaches was 4.6°. This is the minimum charted glide path angle for runway 33 approaches. Final approach segment airspeeds were indicative of approach catagory A through C aircraft speeds. The final approach airspeeds ranged from 80 to 120 knots. All approaches were flown down to DH's of at least 200 feet with two approaches continuing to touchdown. For the approaches flown to touchdown, lateral and vertical guidance were followed to touchdown. Both approaches flown to touchdown resulted in termination within 4 feet of the runway centerline.

TABLE 5. COMPUTED CENTERLINE APPROACH CONDITIONS AT WASHINGTON NATIONAL AIRPORT

Run #	A/C	Date 1985	Indicated Airspeed (kts)	DH (feet)	Elev. (deg)	Wind (kts/deg)	Baro (In. Hg.)
1	N-38	July 23	80	200	4.6	310/08	30.07
2	N-38	July 23	80	200	4.6	310/08	30.07
3	N-38	July 23	100	200	4.6	310/08	30.07
4	N-38	July 23	90	200	4.6	340/06	30.07
5	N-38	July 23	90	200	4.6	340/06	30.07
6	N-38	July 23	120	200	4.6	340/06	30.07
7	N-38	July 23	90	200	4.6	310/13	30.07
8*	N-38	July 23	90	TD	4.6	310/13	30.07
9*	N-38	July 23	90	TD	4.6	310/08	30.07

*Flown to Touchdown

The course flyability, high accuracy and low dispersion afforded by this simple system are evidenced by the low means and standard deviations in the displayed CDI needle position in table 6. Composite plots of the cross track and vertical track deviations for all nine approaches are shown in figures 11 and 12.

TABLE 6. FLIGHT TEST DATA STATISTICS

Run #	Samples	Velocity (kts	Azimuth Mean (1)	Azimuth Standard Deviation (1)	Equivalent Crosstrack Displacement (ft) At DH	At 3 mi.
1	259	80	-0.0242	0.0635	44	101
2	227	80	-0.0562	0.0739	52	118
3	283	100	-0.0140	0.0747	52	118
4	239	90	-0.0654	0.2293	160	314
5	221	90	-0.0173	0.1126	79	180
6	127	120	+0.0437	0.0810	57	130
7	245	90	-0.0276	0.0927	65	148
8	301	90	-0.0361	0.1096	77	175
9	311	90	-0.0258	0.0925	65	147

(1) Expressed as a percentage of ± 150 microamps full scale current.

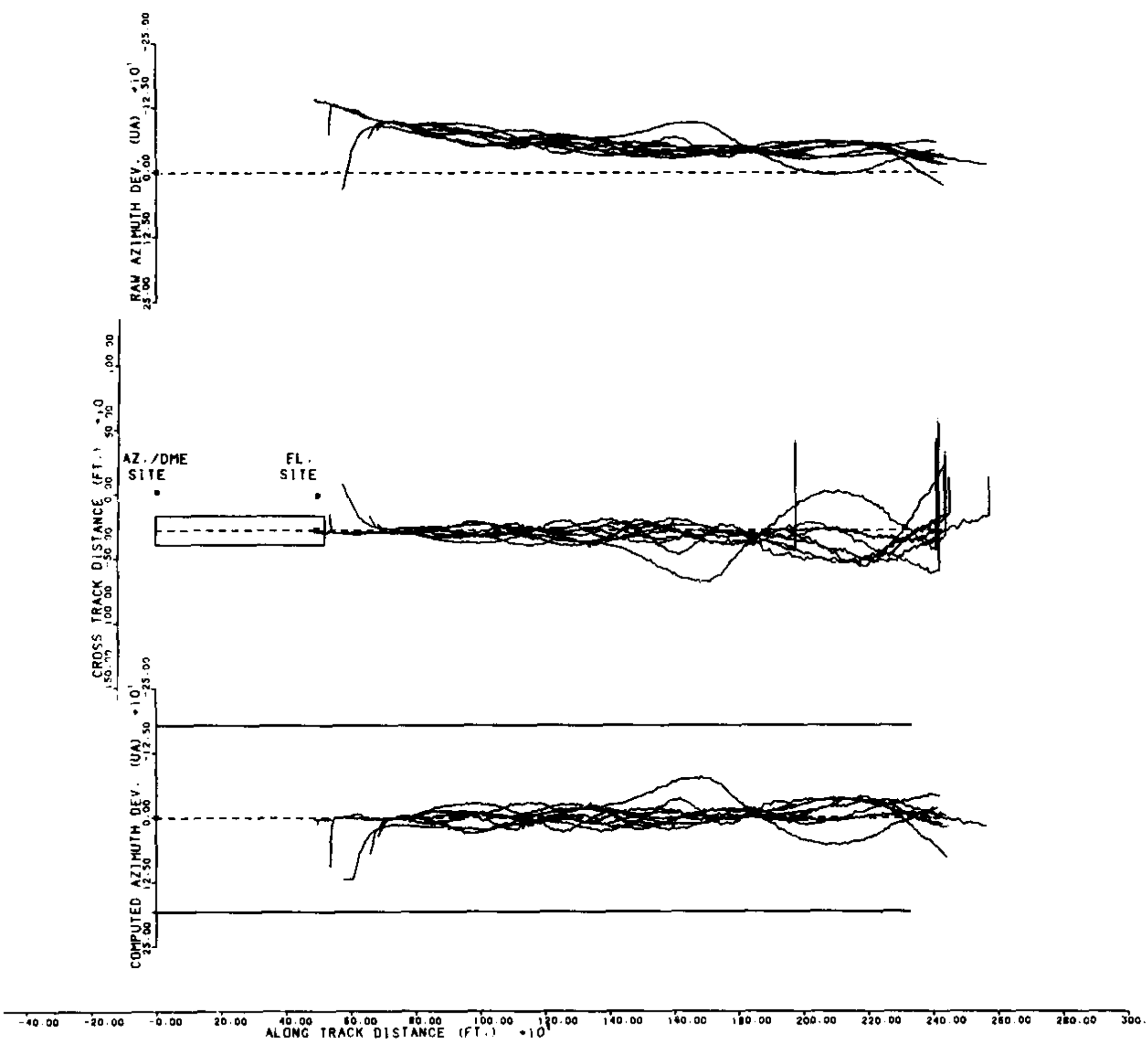

FIGURE11. RAW AZIMUTH, COMPUTED AZIMUTH AND CROSSTRACK DEVIATIONS

Particularly noteworthy is the difference between the raw received azimuth and the CDI position maintained by the pilot. This identifies the performance of the pilot in maintaining the track along the computed centerline.

Initial experimentation at Atlantic City identified problems with course width sensitivity. Sensitivity in the displayed offset parallel approach course is influenced by the amount of offset, the along track azimuth to elevation unit distance and the display update rate. Demonstration subject pilots had no difficulty in flying computed centerline approaches when the course width was tailored to provide ±350 feet (107 m) full scale cross track deviation sensitivity at the runway threshold and then splaying at 1.96° to 3 nautical miles (4.8 km) distance from the azimuth unit. Beyond this point course width splayed at 2.5°. Position determination and display update rates certainly influence system performance. Based on the Washington demonstration results, the 4 Hz rate was deemed the absolute minimum required for precision approaches.

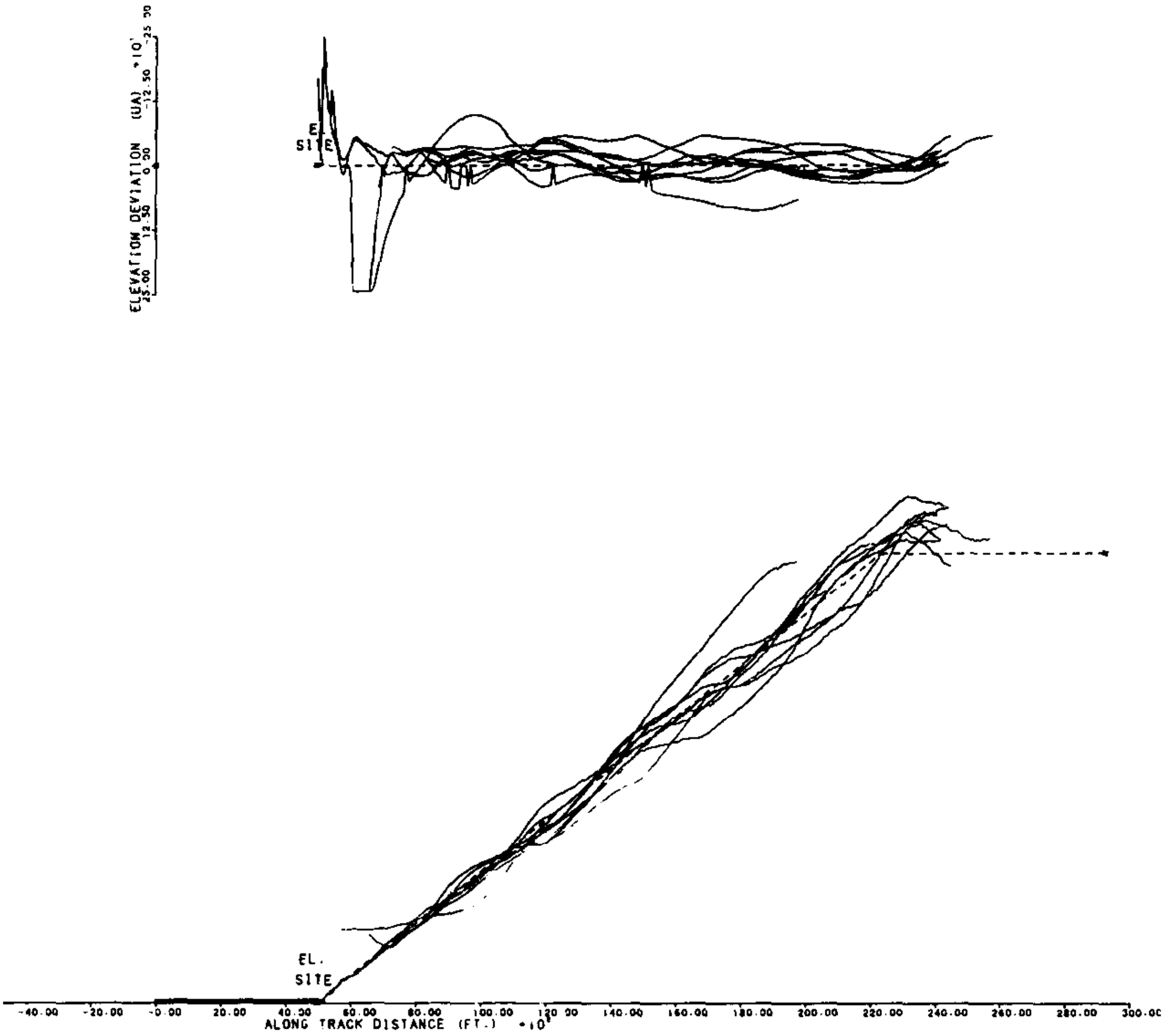

FIGURE 12. VERTICAL POSITION AND ELEVATION DEVIATIONS

CONCLUSIONS

Several relevant conclusions can be drawn from the analytical studies and computed centerline experimentation conducted by the FAA Technical Center.

1. The feasibility of performing computed centerline approaches when a parallel offset precision approach course is synthesized has been demonstrated. With minimum capability MLS RNAV equipment, parallel offset approaches were easily and accurately flown. The range of offset magnitudes to which this technique can be applied and resulting approach minima which can be supported must be investigated.

2. Course width sensitivity and tailoring required for precision MLS RNAV approaches are a function of several variables including system cycle rate, along track distance between the azimuth and elevation units, and approach path orientation. Course width sensitivity and tailoring must both permit adquate pilot performance (approach course flyability) and prevent excessive consumption of airspace when applying MLS RNAV techniques.

3. The degree of sophistication of MLS reconstruction algorithms must be studied in more detail. Of particular importance is the impact which siting ground units in different z-planes may have on position determination.

4. The influence of signal source error on reconstructed position requires additional analysis. The results of this analysis will scope the extent of application of MLS RNAV techniques in establishing approach procedures and minima.

5. The interaction of factors such as system cycle rate, course width sensitivity, and ground equipment geometry must be studied in more detail prior to establishing MLS RNAV approach procedures and minima.

REFERENCES

1. Minimum Operational Performance Standards for Microwave Landing System Area Navigation Systems, Sixth Draft, April 1986 Radio Technical Commission for Aeronautics - Special Committee 151 Washington, D.C., USA.

2. Henry W. Redlien and Robert J. Kelly, Microwave Landing Ssytem: The New International Standard, Advances in Electronics and Electron Physics, Vol. 57, 1981, Academic Press Inc., New York, New York.

3. J.E. Townsend, Engineering Flights on the Bendix Small Community MLS, Runway 33, Washington National Airport, FAA Technical Center Letter Report, CT-82-100-102LR, September 1982.

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CP 410

MLS: Its technical features and operational capabilities

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Summary:

The ILS/MLS transition plan was developed by the COM/OPS Divisional Meeting of ICAO. It highlights the technical and operational problems to be solved with the implementation of MLS. Taking into account present developments in guidance and control automation in the airplane cockpit as well as in ATC systems, the following aspects are analyzed and presented here:

(1) Complexity of MLS approach procedures and function allocation to ATC and aircraft

(2) Cockpit automation and presentation of MLS approach information

(3) Aspects of all weather approach and landing with military aircraft.

1. Introduction

The MLS represents an all weather landing system with great advantages against the ILS. However, the MLS itself does not solve all the problems related to the goal of improved terminal operation under Categories II and III weather conditions.

The MLS generates and transmits azimuth, elevation and ranging guidance data which provide accurate, continuous three-dimensional position information within the coverage envelope of the system as installed at the respective airport/airfield. The ranging element is generated within the PDME element installed with the MLS.

Note that the MLS and DME ground equipment does provide the signals only. The processing and the computing of the three-dimensional position relative to the runway is done in the airborne receiving and processing equipment.

We are not going to reiterate the disadvantages of the ILS and the advantages of the MLS. This has been dealt with in many papers on various occasions. What we think being necessary is to demonstrate the operational restrictions still prevailing with MLS, and to discuss the problems to be solved to overcome these restrictions.

As an introduction Fig. 1 shows the summary of curved and close-in approaches made with the MLS equipped "Terminal Controlled Vehicle" (TCV) B-737 airplane during the demonstration of the US Time Reference Scanning Beam (TRSB) MLS to the ICAO All Weather Operations Panel (AWOP) in the years 1976 and 77 /1/.

Today the final centerline segment (FCLS) envisaged for MLS approaches is still 3 NM or more, depending on weather conditions and on type of approach flown.

From this restriction we can conclude that the problems to be solved are quite complex. And they need concerted consideration of airport, ATC and airplane or user aspects and needs, before the technical benefits given with the MLS lead to the operational benefits expected by the aviation community.

2. ILS/MLS Transition Plan and its operational aspects

The ILS/MLS transition plan was developed by the Communications/Operations (COM/OPS) Divisional Meeting of ICAO in Spetember 1985 /2/. Fig. 2 shows the operational aspects of this transition plan.

From Fig. 2 it can be seen, that the time schedule of the implementation of MLS as primary system meanwhile has slipped by 3 years from 1995 to 1998.

The meeting realised and stated a number of operational problems existing related to the implementation of MLS. Priority 1 was given to those problems and procedure design considerations, which need an urgent solution for an early implementation during transition phase I. The list of items (after /3/) considered by the COM/OPS Divisional Meeting is presented in /3/. In the following a few areas shall be discussed which - in our opinion - have to be tackled taking into account present developments in guidance and control automation in the airplane cockpit as well as in ATC systems. The problem areas dealt with in this paper are:

(1) Complexity of MLS approach procedures and function allocation to ATC and Aircraft

(2) Cockpit automation and presentation of MLS approach information

(3) Aspects of all weather approach and landing with military aircraft

3. Complex MLS Approach Procedures

The federal Aviation Agency (FAA) has recently launched a study aimed at developing the MLS operational application /4/.

Fig. 3 shows a plan view illustrating a typical "curved" and "segmented" approach procedure for category C transport aircraft. This looks very promising.However, it leaves the reader to interpret the difference between curved and segmented approach; and it leaves to answer some questions, and to solve some problems.

Questions:

- Why do we need 3.6 NM straight and level flight, when entering the MLS coverage area? - Possibly to allow time for ATC to compute the optimum conflict free approach paths for each aircraft entering.
- Why do we need a 3.0 NM common FCLS? - Possibly to provide buffer time/zone, reducing the load on ATC in case a missed approach clearance is required because of slowed down ground operations or other incidental conditions.

An individual approach procedure can easily be established using the on-board computing capacity of modern flight control and navigation systems. This has been done during the TRSB-MLS demonstration flights with the TCV B-737, summarized in Fig. 1.

The problem is becoming highly complex, if the NASA goal is required to be achieved, which states 40 sec. ± 5 separation of landing operations /5/.

In Fig. 4 and 5 the traffic flow over a period of 10 minutes is demonstrated under (less demanding) 60 sec landing separation conditions. The underlying assumptions for this traffic flow are:

- Provide the shortest approach path from entering the MLS coverage to a point 3 NM from the threshold; turn radius of 1.5 NM applied.
- Final approach speed (or landing configuration) should be set as late as feasible before reaching the FCLS.
- In case of conflict the methods speed control or/and approach path control apply.

Within this sampling period the first aircraft reaches the FCLS at 12:04 minutes. We have therefore to look at the time period from 12:04 to 12:10 for assessment of the control load for the ATC approach control sector.

During this period the approach controller has to control 6 aircraft on a variety of curved approach paths, and 3 conflicts have to be dealt with. Every additional aircraft entering the MLS area, exceeding the 6 aircraft under control, would create another conflict. This control load can not be handled manually. The control task shows a great degree of difficulty because of the complexity of the traffic situation. Under these conditions the time budget of the approach controller would have been hopelessly overloaded. Every clearance being established must take into account a number of other aircraft flying on different radials or turning onto a new radial.

Consequently more automation is required, if the goal of increasing flexibiity and approach traffic flow shall be realised. More automation is required in ATC, in the aircraft, and in the information exchange between the two.

In reality there will be a number of initial approach fixes and a number of standard curved or segmented approach procedures layed down for each airport.

Every incoming airplane is assigned an approach procedure depending on its arrival route. The approach procedures can not be assigned arbitrarily.

The basic separation for arriving aircraft has to be established before there entry into the MLS coverage area.

Even under these conditions the control task of establishing conflict free approach paths for a greater number of aircraft, and the task of guiding them on their paths can no longer be performed manually.

In the following the automation requirements for ATC, aircraft systems, and the communication link are stated:

(1) Automation required in the ATC system

- A data base of standard curved/segmented approach paths for defined entry points into the MLS coverage area

- o Algorithms to establish the clearances required to separate an airport demand dependent number of arrivals before their entry into the MLS coverage area
- o Algorithms to compute optimum conflict free approach paths and assigning a respective time/position slot for the incoming aircraft
- o Algorithms for the missed approach case

The data needed from every aircraft include such as position, heading, track, speed, height, vertical speed, and possibly energy data as well. The latter could be used to monitor the accuracy of time/position slot keeping of the aircraft.

In case more than one runway being served by one MLS, the number of approach paths increase. In case aircraft of different speed and glide slope capabilities are included, the complexity of the algorithms for computing the time/position slots increases considerably.

(2) Automation required in the aircraft systems

- o A data base containing the standard curved/segmented approach paths including missed approach procedures of the arrival airport and the alternates (in military operation)
- o Algorithms to compute curved/segmented approach paths based on azimuth, elevation and distance to threshold transmitted from MLS
- o Algorithms to include time into the approach path computation to allow operation within a time/position slot assigned by ATC.
- o A flight management system, which allow different auto approach modes to be applied:
  - standard approach paths, based on stored data, MLS data, and aircraft derived dynamic flight data
  - non-standard approach paths, based on stored runway data, MLS and flight data
  - time/position slot guided path, based on ATC derived slot data, MLS and flight data together with stored airport (runway) data

In case the "ATC guided auto approach" mode (based on time/position slot) is selected, the flight management or flight control computer is engaged to accept auto approach commands from the ATC computer. The flight safety and collision avoidance monitoring tasks need further consideration and definition. There is no question that the related problems can be solved. However, it will take some time, until all aircraft are equipped with the respective flight management systems enabling to fly the "ATC guided auto approach mode". Without this mode, the MLS possibilities can hardly be turned into realities.

(3) Data Link requirement

The concept for automation of the ATC - and the flight managment system illustrates that the conventional method of data and information exchange does no longer serve the purpose.

At present the ATC receives limited aircraft and flight data via the transponder message. The guidance is still based on verbal communication. With MLS a data link is required that allows ATC to receive the flight data required from the aircraft and to transmit the control guidance data to the aircraft.

4. Cockpit automation and MLS approach information

The flight management system of the aircraft must provide the display computations for appropriate display of horizontal and vertical situation, and of director information required to monitor on auto approach or even to fly it manually as applicable.

Two displays are required, a horizontal display and an attitude/director display.

(1) Horizontal display for approach path planning and for navigation during the initial and intermediate approach phase. Display parameters:

- o MLS coverage area
- o Terrain reference, runway and other airport relevant data
- o Standard approach paths or (if applicable) approach path assigned
- o Present position, time and other navigation information (to be defined)

Approach mode:

- MLS coverage and guidance information
- Terrain reference information (from data base if available)
- Assigned approach path
- Time/position slot assigned
- Present position with trend vector
- Other flight and navigation data to be defined

Symbology envisaged has been published by NASA /5/, Fig. 6.

(2) Attitude/director display

A number of investigations have been performed resulting in a set of parameters to be displayed on the vertical situation or attitude and director display or on the head-up display (HUD).

Fig. 7 presents a survey of three sources:

- NASA used the EADI (electronic attitude director indicator) display format shown in Fig. 8 and the integrated situation display format (Fig. 9) in conjunction with the development and the demonstration flights for ICAO MLS evaluation.
- The Royal Aircraft Establishment has performed fixed wing low visibility approaches/landings using the HS 748 aircraft without and equipped with a Mono-HUD /6/.
- Avions Marcel Dassault has performed a similar study, named "Research and Development Program of Electronic Systems for the Display of Synthetized Informations" (PERSEPOLIS) in 1979, Fig. 10 /7/.

Besides the display parameters proposed in Fig. 7 information is required to signal to the pilot safety critical conditions:

- slow airspeed/AOA too high
- excessive deviation
- go around command
- system failure conditions as required

These considerations illustrate that a certain degree of automation at the man-machine interface is required to enable the pilot to monitor an MLS auto approach under optimum situation awareness conditions. Only then can we expect the pilot to establish confidence into the system and to take over to manual control in case of failure.

5. Aspects on all weather terminal operations with military aircraft

The military all weather terminal operation scenario requires considerations, which are not based only on the civil approach comprising MLS, approach lighting and autoland technology and system improvements.

These considerations for the 90ies should include the technology development of the airborne equipment, and the use of limited ground equipment only. Position, track, and glide slope finding and keeping could be based on:

- Sensor technology development (Radar, FLIR, INS)
- C^3 system development (GPS, ITIDS)
- Integrated navigation, flight and thrust control technology development.
- Terrain reference navigation

If this is done, minimum ground installations are required only:

- MLS, or Laser Beam (for ground guided operation)
- Precision signal (radar) reflectors equipment for runway position and configuration (for aircraft guided operation)
- Final approach path lighting (limited)
- Runway lighting

(1) Airborne radar guided CAT II approach

The concept for the performance of airborne radar aided CAT II approach (ARCA) has been studied in more detail by the Radar-Division of the AEG Company /8/. It shows that the ARCA can be considered as supplementary method to MLS/PDME. With minimum ground equipment, not requiring fixed installations, great flexibility of operational applications can be achieved, such as use for minimum operating strip operation; use on motorway stretches and others.

(2) Approach using GPS/INS/TRN information

A Global Positioning System (GPS) is currently reported of having an update rate of 10 Hz with a 3 to 5 second restoration delay in the event of signal loss (compared with 1 second for the DME/P). At an approach speed of 200 kts. an unaided IN, with drift rate of 1 NM/hr, updated at 3 NM from the runway threshold will result in a 28 m path offset at touchdown. For an update at 1 NM the path offset will be 9.23 m. Studies carried out have shown that a GPS aided IN with Kalman filters can significantly improve the overall positional accuracy of the resultant data displays.

A proposed operation of approach and landing is the useage of GPS position and velocity updates compared to a stored digital representation of the desired approach path. This path will have been computed from the desired approach profile and data specifying the exact location and orientation of the runway. The deviation from this desired path is computed for each update of actual position, and the resultant information is used as flight command data. The study assesses the accuracy of this system, with an update rate of one in 3 seconds and an approach speed of 100 kts, to be sufficient for Cat. II operation.

Glossary

AWOP	All Weather Operations Panel
COM/OPS	Communications/Operations
EADI	Electronic Attitude Director Information
FAA	Federal Aviation Agency
FCLS	Final Centerline Segment
HUD	Head up Display
TCV	Terminal configured vehicle
TRSB	Time reference scanning beam

References

/1/ John P. Reeder, Robert A. Schmitz
Operational Benefits from the Terminal
Configured Vehicle NASA Langley Res.
Center, May 1978

/2/ ICAO
COM/OPS/85-WP/105
Appendix B to the Report on Agenda
Item 1
ICAO ILS/MLS Transition Plan
COM/OPS Divisional Meeting, Sept. 1985

/3/ ICAO
COM/OPS/85-WP/102, 13/9/85
Report on Agenda
Item 3
MLS operational aspects
COM/OPS Divisional Meeting, Sept. 1985

/4/ FAA Order, Directive No. 7110 (9-85)
Air Traffic Control Facility Program
for the Microwave Landing System

/5/ Samuel A. Morello, Lee H. Person Jr.
Terminal-Area Flight Experience with
the NASA Terminal Configured Vehicle
NASA Langley Res. Center, April 1978

/6/ R.B. Lumsden, T. Brown
Military Fixed Wing Low Visibility
Approach and Landing (U)
Techn. Memorandum FS(B) 488,
RAE, 5. August 1982

/7/ Avions Marcel Dassault-Breguet Aviation
Head up Display System - PERSEPOLIS
Symbology, Sept. 1979

/8/ G. Och, F. Jehle, R. Drescher
Concept for Airborne-Radar
CAT II Approach
AEG-Aktiengesellschaft, Radar Division
A14E27-1/86-TNR/ST, 31.01.86

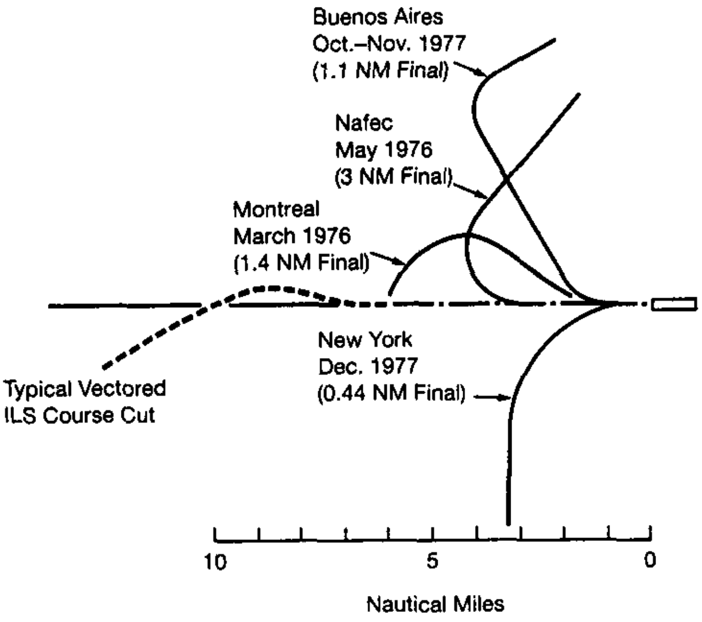


Fig. 1 Summary of the curved and close in approaches demonstrated to AWOP /1/

Phase	I till 1989	II 1990–1997	III 1998–1999	IV 2000 onward
Status	ILS primary MLS optional	ILS primary MLS recommended	MLS primary ILS optional	MLS only
Operational use of MLS	• ILS-type MLS apprs. • Higher glidepath for STOL, VTOL • Improved intercept procedures • Introduction of segmented apprs.	• Increased use of improved applications • Introduction of more complex appr. procedures	General introduction of complex applications	Complex applications implemented
Problems of implementation	• Definition of guidance on curved/ segmented and steeper appr. paths • Specification of ATC and aircraft hard- and software rquts.	• Developm. of algorithms for automation rqud. in ATC and aircraft • Spec. and Developm. of Data Link rquts. • Define RNAV based on MLS area navigation rquts.	• Joint operation of aircraft with differing level of automation	

Fig. 2 ILS/MLS transition plan, operational aspects

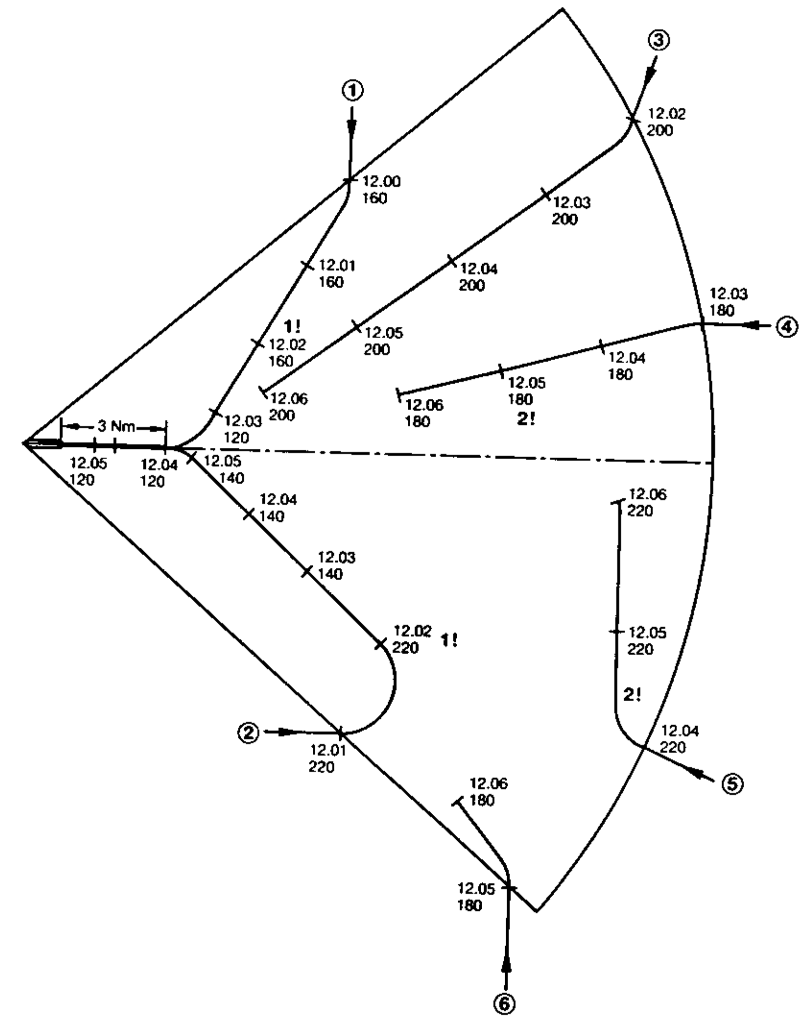


Fig. 4 Plan view illustrating the traffic flow over a 10 minute period - 1

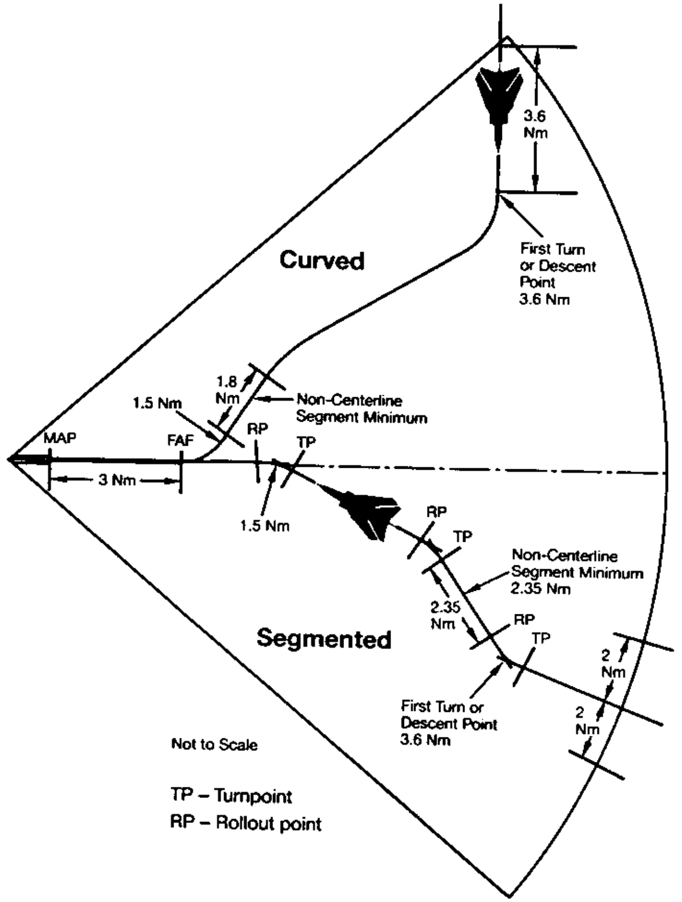


Fig. 3 Plan view illustrating a typical curved and segmented approach /4/

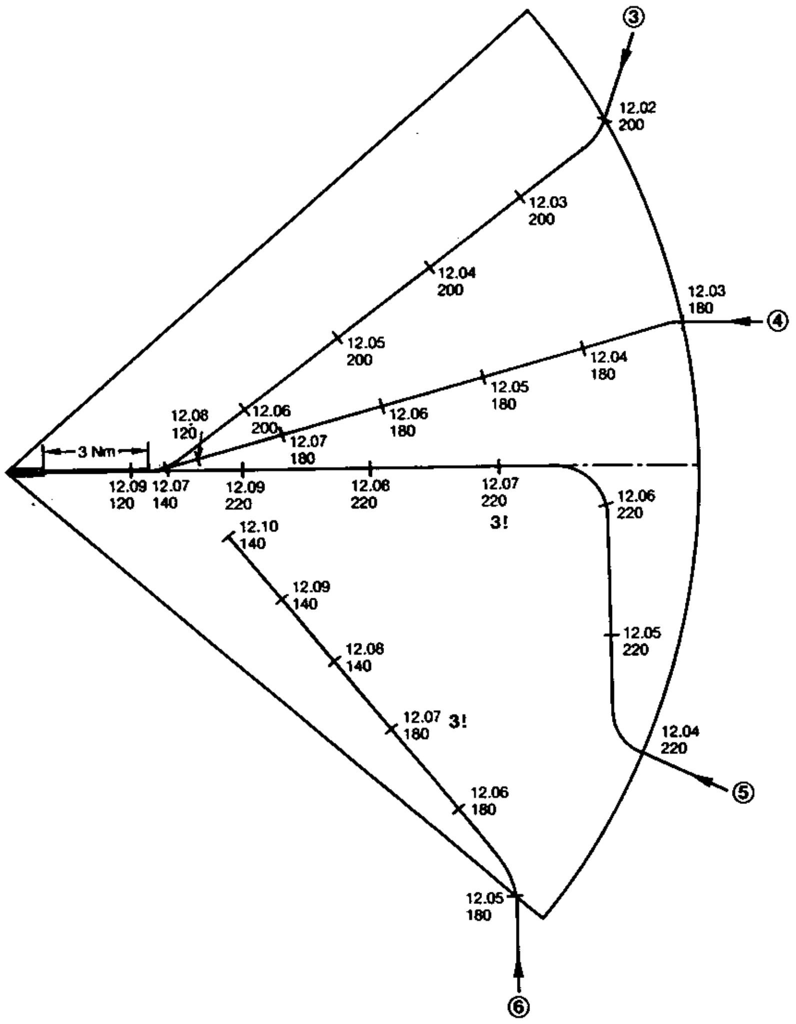
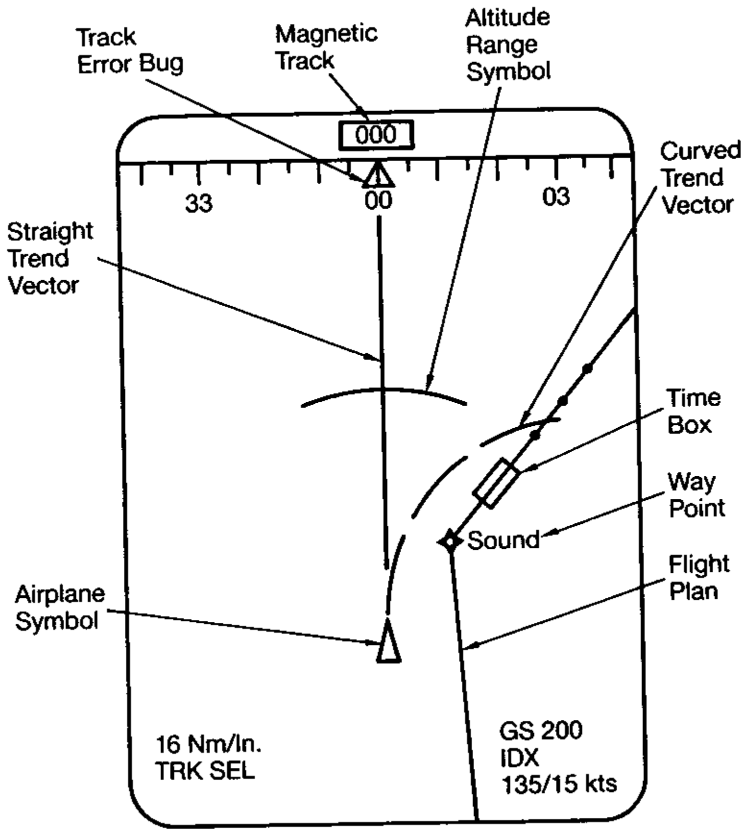


Fig. 5 Plan view illustrating the traffic flow over a 10 minute period - 2



x Fig. 6 Horizontal situation display /5/

	NASA /1/ EADI – Display	RAE /6/ Mono – HUD	Marc. Dassault /7/ HUD	Proposed ADI format
1	Aircraft symbol	same	same (fixed)	Aircraft symbol
2	Flight path angle	same	same	Flight path angle
3	Flt. path acceleration	same	Total energy (potential flt.p.)	Flt. path acceleration
4	Glidepath scale/dev.	Required glidepath	Preselected flt. path (numeric value)	Preselected glidepath (numeric value)
5	Pitch scale	same	same	Pitch scale
6	Radio height	same	same	Radio height
7	(Flt. path acceleration)	IAS, speed error	AOA, thrust guidance	Speed error
8	Localizer scale/dev. Glidepath (see above)	ILS cross	ILS/MLS window	MLS window
9	Track scale, track angle pointer	Heading scale, set heading bug	Heading scale, cmd. track Track error relat. 2 to 9	MLS command track Track error
10	Horizon	–	same	Horizon
11	Bank angle scale/point.	–	relation of 2 to 8/10	Bank angle scale
12	Perspective rwy.		same	Perspective rwy.

Fig. 7 ILS/MLS approach display parameters of the sources analyzed

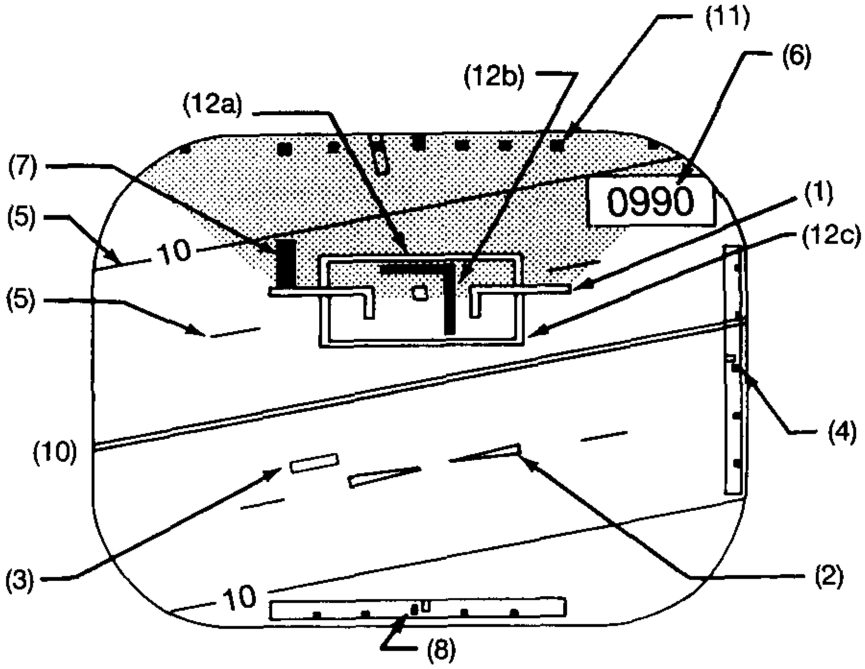


Fig. 8 EADI landing symbology

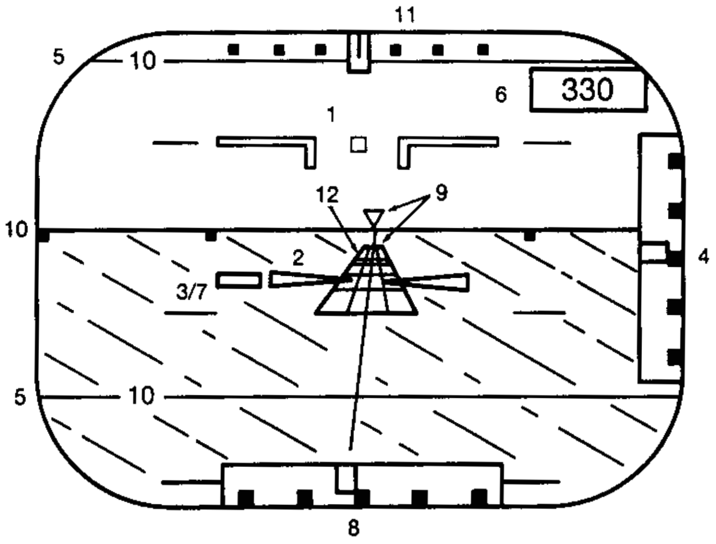


Fig. 9 Integrated situation display format with calculated perspective runway /5/

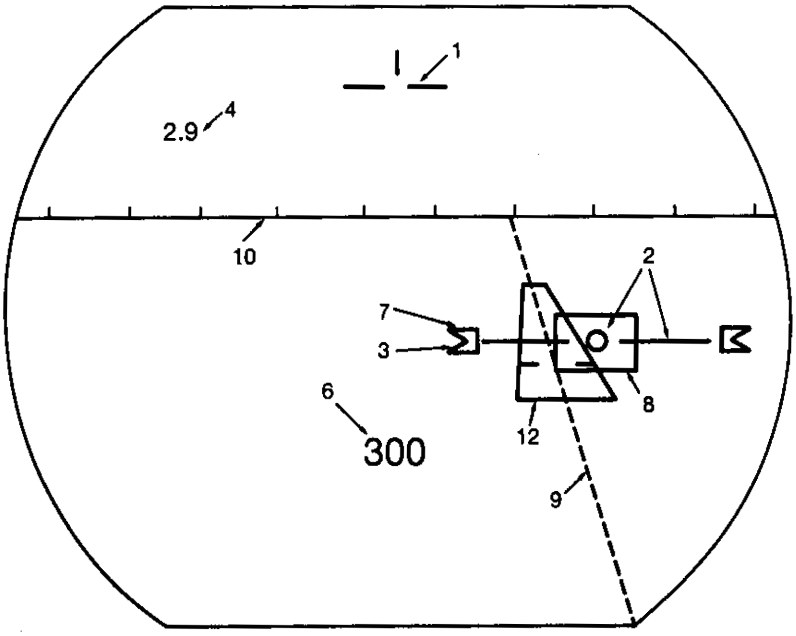


Fig. 10 PERSEPOLIS MLS symbology on HUD /7/

CP-410

ADVANCED ATC: AN AIRCRAFT PERSPECTIVE

by
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SUMMARY

The principal operational improvements desired by commercial aircraft operators in the United States are efficient aircraft operations and delay reductions at the major terminals. This paper describes efforts underway within the Advanced Transport Operating Systems Program at the Langley Research Center to provide a technology basis for reducing delay while improving aircraft efficiency. The principal thrust is the development of time-based traffic control concepts which could be used within the framework of the upgraded National Airspace System and which would allow conventionally equipped aircraft to operate in a manner compatible with advanced aircraft.

1. INTRODUCTION

The principal operational improvements desired by commercial aircraft operators in the United States are more efficient aircraft operations and delay reductions at the major terminals. Some improvements in aircraft operational efficiency through the use of airborne flight management systems have been realized. Those improvements, however have been limited to departure operations and to arrivals during off-peak hours. Because the present Air Traffic Control (ATC) is a tactical system that handles delays through a series of local separation actions, the opportunity to realize arrival efficiency is severely restricted during periods of heavy traffic. The objectives of separation and efficiency are not mutually exclusive but require a sophisticated ground/airborne interactive process which is strategic in nature to manage the en route/terminal flow control and scheduling region. Earlier activities oriented toward that approach are documented in references 1 and 2.

In the broad sense efficient aircraft operations include not only taking delays efficiently but also reducing those delays. Unless capacity is increased, the already existing delay/capacity problem will only worsen as projected traffic increases occur. What is needed is an approach that is broad enough to simultaneously address several issues. How can aircraft operations during peak demand periods be improved? How can ATC not only accommodate aircraft with advanced avionics but go further and take advantage of this capability while still handling conventionally equipped traffic? What can be done to improve delivery precision and reduce interarrival separation so as to increase capacity? The answers to these issues lie in the areas of ATC/aircraft interaction, flexible fuel-efficient 4-D flight management systems, and automated controller aids. An integrated approach to resolve those issues will be postulated and some supporting research will be presented.

1.1 APPROACH

Fundamental factors which affect delay and operational efficiency were reviewed in a recent NASA planning exercise to identify methods to improve the ATC/aircraft system performance. It was concluded that capacity limitations of the United States National Airspace Sysem (NAS) was a major obstacle to improved operational efficiency. This is a longstanding problem which has been obscured by events such as the controllers strike and deregulation but which is again coming to the fore (reference 3). Furthermore, delay and its associated cost, are magnified by capacity limitations as indicated in figure 1 (reference 4). In addition even modest growth predictions estimate a 60 percent increase in commercial traffic in the United States by the year 2000 (references 3 and 5). Such a growth cannot be accommodated without major improvements. In what is presently an informal working relationship, the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) are evaluating a time-based traffic management process which is aimed at resolving the issues raised in the Introduction. Since air traffic control will remain a centralized, ground-based process, a portion of the advanced capability would be imbedded in the instructions generated on the ground so that all aircraft operate in a similar fashion. Such an approach requires considerable sophistication on the ground in the form of automatically generated advisories for the air traffic controllers and an attendant degree of confidence in the advisories by the controllers. The ground automation improvements will be feasible as a result of the computer upgrade embodied in the FAA's National Airspace System Plan which is covered in separate papers at this conference. It is important that there also be an integrated man/machine development effort to insure controller/automation system performance improvements.

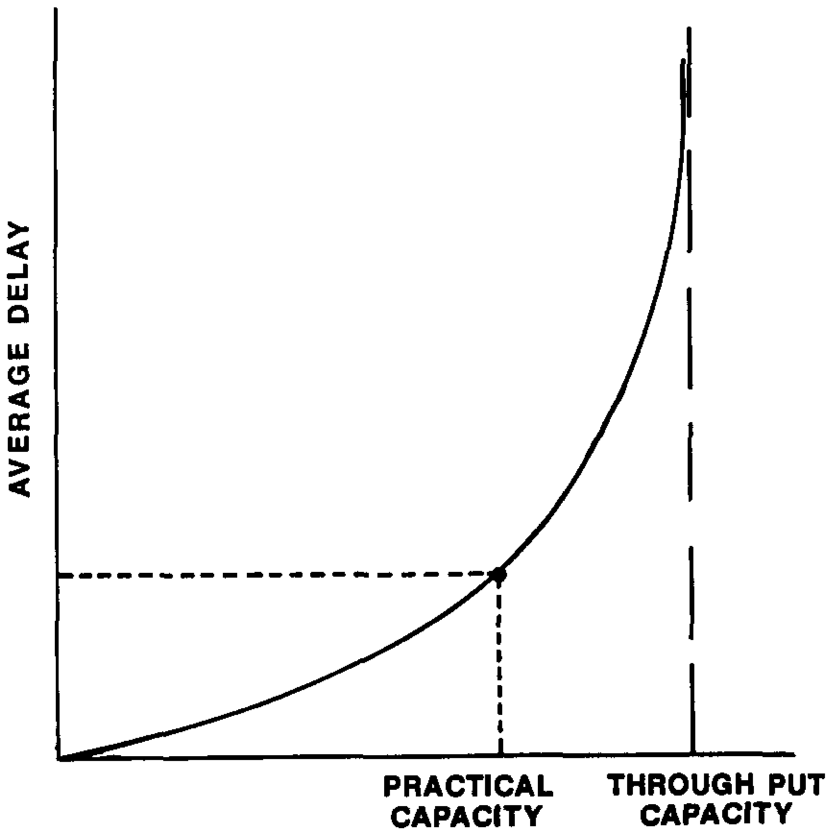


Figure 1. - Relationship between Capacity and Delay.

In recognition of the issues discussed above, the NASA Langley Research Center Advanced Transport Operating Systems (ATOPS) Program Office has prepared a long range plan to guide our research in the next decade as we explore technological solutions to safely and efficiently increase airport capacity. The plan we have developed has as its goal to increase the National Airspace System (NAS) Instrument Meteorological Conditons (IMC) throughput while reducing aircraft Direct Operating Cost (DOC). This paper will focus on the first phase of the plan shown in the table and review two areas of work at NASA Langley that are the cornerstones to improving delivery precision and increasing aircraft operating efficiency.

DELIVERY PRECISION WITH IMPROVED EFFICIENCY

- JOINT EFFORT WITH FAA & INDUSTRY
- ADAPTIVE TIME-CONTROL ATC CONCEPT
- AIRCRAFT EFFICIENCY EMBEDDED
- CONVENTIONAL & 4-D EQUIPPED A/C CONSIDERED

PAYOFF: POTENTIAL FOR CAPACITY IMPROVEMENTS, REDUCTIONS IN DELAYS, FUEL USAGE, AND CONTROLLER WORKLOAD

2. TIME-BASED AIR TRAFFIC CONTROL

2.1 A Concept for the Evolution of Time-Based Flow Control

One of the principal thrusts of the ATOPS research program is to define and evaluate an evolutionary ATC concept which would improve the capacity, reliability, and economy of extended terminal flow operations (en route approach, transition, and terminal flight to the runway) when used with projected ground and avionic hardware. The concept would assist the air traffic controller with traffic management in the extended terminal area and is a step in the direction of using computers for control assistance, not just data formatting and transfer. It is evolutionary, accommodating today's aircraft as well as 4-D equipped advanced technology aircraft. The algorithm, employing simplified aircraft performance models, is designed for integration into the manual, voice-linked ATC system and will accommodate further automation.

The proposed time-based flow control system was designed to bridge the gap between today's en route terminal process for handling arrival traffic at major terminals and the future situation where most of the aircraft will have advanced 4-D flight management systems capable of data exchange with automated ground equipment. The current En Route Metering (ERM) is characterized by coarse planning and lack of coupling between terminal and en route control. ERM uses interarrival time spacings based only an an average arrival rate without performance modeling or controller aids to deliver aircraft at the desired times. The terminal control facility operates on the output of the ERM process without knowing its intended landing sequence or target times. The terminal control process is characterized by several controllers solving successive localized merge and separation problems (tactical rather than strategic control).

In essence the proposed time-based flow control system integrates en route metering, fuel-efficient profile descents and terminal sequencing and spacing with computer-generated controller aids to fully use runway capacity and improve fleet fuel efficiency. The principal features of the concept are shown in figure 2. The major steps in the proposed system's operation are as follows:

1. Derandomize the aircraft arrival stream into the extended terminal area by establishing a proposed aircraft landing sequence and building a list of aircraft target landing times based on safe separation. The desired meter fix time as a result of the assigned landing is also determined.

2. Nominal estimated time of arrivals used in step 1 are based on fairly simple yet representative aircraft performance models. Using these models, a fuel efficient ground expected trajectory is computed to meet the aircraft's assigned target landing time.

3. Computer-generated assistance to help meet aircraft target times based on the trajectory calculations is given to the controller.

4. Adjustments to the target landing times and perhaps even changes in the landing sequence will be necessary to accommodate errors and uncertainties.

5. The aircraft trajectory will be fine-tuned in the final approach region to meet the final target landing time with limited uncertainty.

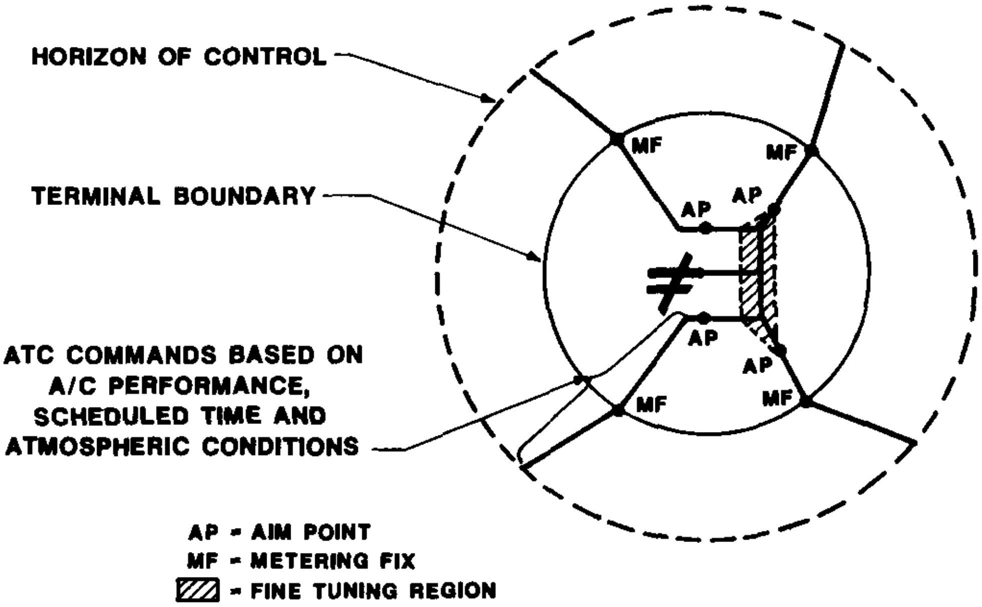


Figure 2. - Terminal/EnRoute Flow Control System.

The proposed extended terminal time-based concept briefly described earlier has several potential benefits. The metering, sequencing, and scheduling of aircraft to the terminal takes place early enough in the en route airspace so most of the required delay can be taken in a more fuel-efficient manner. The en route and terminal control are integrated and coupled so that the strategic fuel-efficient descent is continued into the terminal down to the aim point near the final approach region; thus, 4-D equipped aircraft will be allowed to use and benefit from their capability. The concept serves both current and 4-D equipped aircraft by using ground-aided profile descent instructions for unequipped aircraft and target time objectives for equipped traffic. The Mach/CAS flight idle thrust descent type of profiles calculated for the unequipped aircraft can be flown with today's conventionally instrumented cockpit.

The time-based concept could be integrated into the manual voice-linked ATC system in an evolutionary manner and later accommodate National Airspace System (NAS) features such as data link and further ground automation. Time-based flow control will ultimately be used to its fullest potential when the two time-based phenomena that currently limit longitudinal separation, runway occupancy and wake vortex decay time, can be satisfactorily manipulated and modeled. Research and development in the areas of runway guidance, high-speed turnoffs, accurate weather prediction and wake vortex modeling will eventually permit the use of variable reduced time separation as a function of weather conditions. That is the ultimate goal toward which the proposed concept is intended.

2.2 Dynamic Control of Arrival Traffic

Starting at the horizon of control boundary, there is a range of minimum and maximum landing times considered by the current algorithm that the aircraft can achieve by varying its speed between nominal approach values and slower speeds limited by performance considerations. If the landing time assigned exceeds the maximum speed control time then the additional delay must be absorbed by path stretching or holding. For the sake of discussion, let us assume that the scheduling process has assigned a landing time within the range attainable by speed control. The time and distance associated with all descent and deceleration segments are calculated from point-mass equations of motion for a clean-configuration with flight idle thrust and using predicted winds. The details of the trajectory calculation are presented in reference 6. As shown in figure 3 the vertical flight path is divided into a cruise segment and several descent and level deceleration segments. An iterative process is used to determine the required metering-fix altitude and time once given the end or aim point, the wind and the nominal speeds for the segments inside the terminal area from the meter fix. Another iterative process calculates the cruise Mach, the Mach/CAS descent to the metering fix and time to begin the descent so that the aircraft arrives at the metering fix at the prescribed time, altitude and speed.

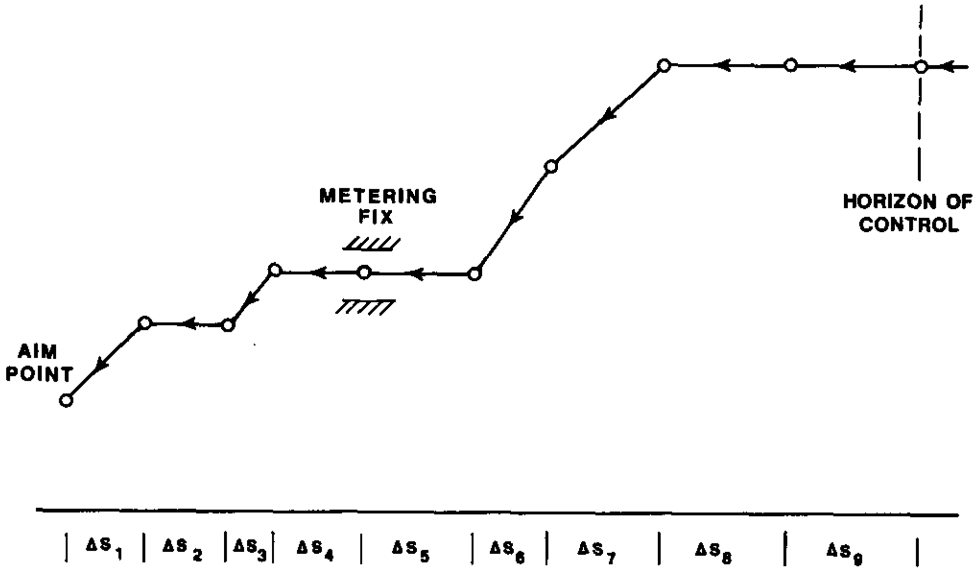


Figure 3. - Mach/CAS Level and Flight Idle Descent Vertical Flight Path Segments.

Let us follow the sequence of events, depicted in figure 4 as an aircraft flies from the horizon of control to the runway in the proposed time-based flow control system. At the horizon of control boundary, the ground system begins the process of determining the landing sequence. The nominal arrival speeds and route distances to the runway are used to determine aircraft un-delayed ETA's. Initially the sequencing criteria used is a projected first-to-reach runway ordering. More advanced versions could employ sequencing algorithms which take advantage of the variable spacing between classes of aircraft to slightly increase the runway throughput rate.

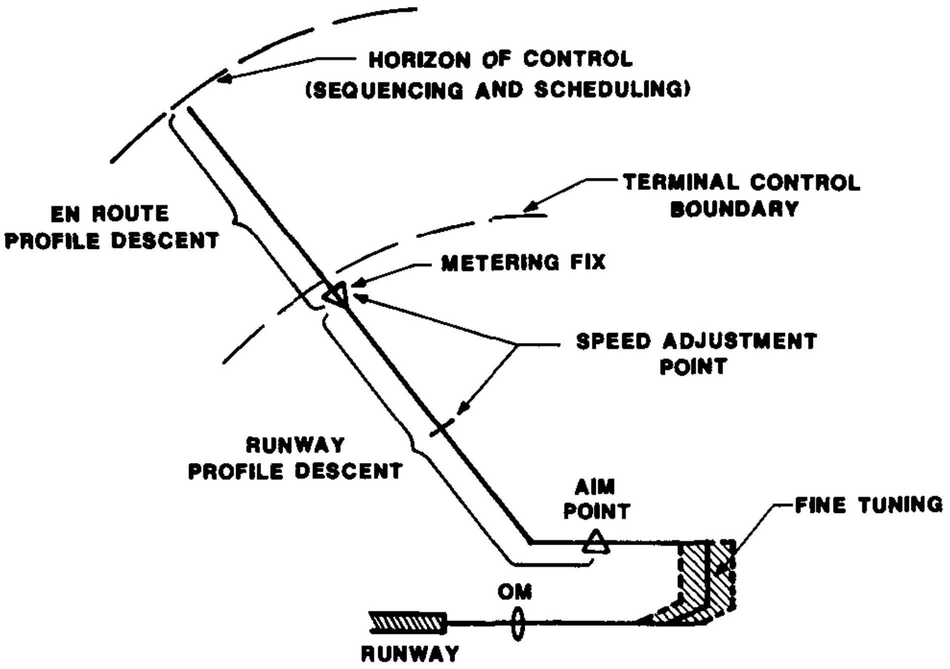
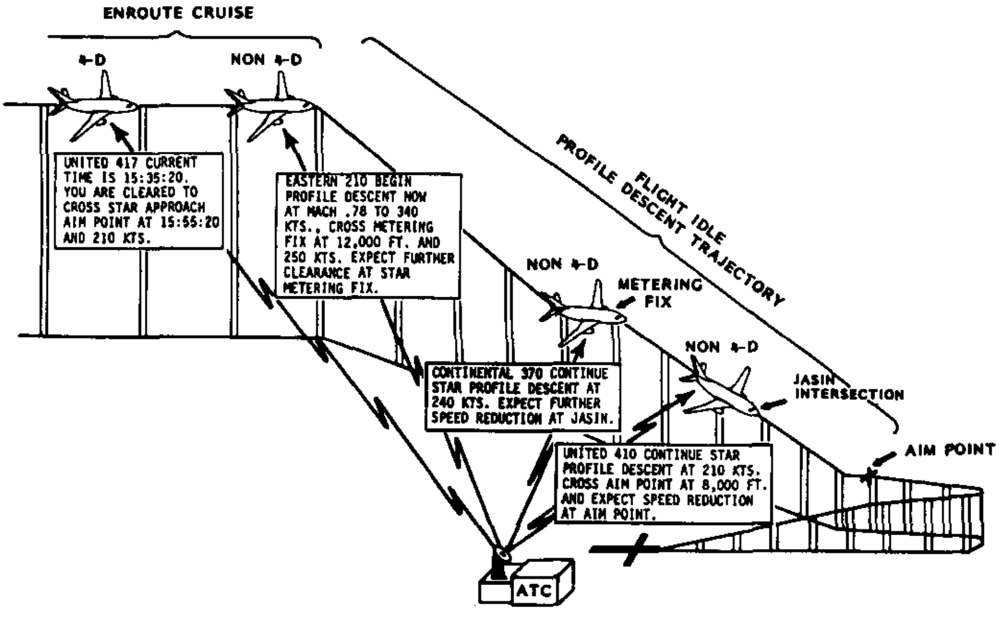


Figure 4. - Sequence of Events.

The target landing time for our example aircraft is determined by taking the larger of the following: (the aircraft's un-delayed estimated landing time) or (the landing time of the previously scheduled aircraft + separation criteria + buffer time to account for system delivery uncertainty). From the trajectory calculations briefly described earlier, a non 4-D aircraft's desired meter fix time, the Mach cruise and the time to begin as well as the Mach/CAS speed to perform the descent are displayed to the controller. Using this information the controller can assist the non 4-D aircraft to meet its schedule in a fuel-efficient manner. The 4-D equipped aircraft could be given either its meter fix or aim point time. The question of how often the 4-D aircraft's time should be updated is an issue that will be studied. Figure 5 gives examples of the type of controller messages envisioned for both 4-D and non 4-D traffic. Coordination and interfacing between ground system designers and airborne flight management builders will be necessary to insure compatability between the paths flown by 4-D and non 4-D aircraft. This issue is addressed in section 3. Ideally the only difference would be the greater precision expected from the 4-D aircraft.



UNITED 417 CURRENT TIME IS 15:35:20. YOU ARE CLEARED TO CROSS STAR APPROACH AIM POINT AT 15:55:20 AND 210 KTS.

EASTERN 210 BEGIN PROFILE DESCENT NOW AT MACH .78 TO 340 KTS., CROSS METERING FIX AT 12,000 FT. AND 250 KTS. EXPECT FURTHER CLEARANCE AT STAR METERING FIX.

CONTINENTAL 370 CONTINUE STAR PROFILE DESCENT AT 240 KTS. EXPECT FURTHER SPEED REDUCTION AT JASIN.

UNITED 410 CONTINUE STAR PROFILE DESCENT AT 210 KTS. CROSS AIM POINT AT 8,000 FT. AND EXPECT SPEED REDUCTION AT AIM POINT.

Figure 5. - Example Time-Based Flow Control Instructions for 4-D and Non 4-D Equipped Aircraft.

The aircraft's scheduled landing may be changed when it arrives at the meter fix either because of the action of preceding traffic or because of the aircraft's own meter fix time error. The time-based system must be flexible enough to accommodate variable aircraft time errors particularly in the initial implementation when a large percentage of unequipped aircraft will be present. Depending on circumstances the aircraft's schedule may be slipped forward or backward, and its sequence may even be altered if the schedule slippage warrants such action. Using the aircraft's updated landing time based on its actual meter fix arrival, the trajectory calculations determine the profile descent speeds needed to meet the target landing time. Those speeds are given to the unequipped aircraft whereas the aim point (bottom of runway profile descent) time is given to the 4-D aircraft. Example controller messages inside the meter fix are also shown in figure 5.

In the final approach region there are two computer-aided fine-tuning maneuvers which attempt to reduce the delivery error. In keeping with the evolutionary approach, the initial design was configured to be similar to the conventional approach peformed today. Future real-time experiments with both 4-D equipped and unequipped cockpits will explore the advantages of other vectoring and geometry schemes. The process currently under study is based on a continually updated ETA calculation which displays how early the aircraft would be if its turn instructions were issued now. With expected response times factored in, the display indicates when and to what heading the controller should vector the aircraft for the base and centerline intercept segments. The fine-tuning region must accommodate minor schedule changes due to other aircraft errors, wind estimate errors or own aircraft flight errors which have accumulated since the last speed control point.

2.3 *Horizon of Control Effect*

The extended terminal, time-based flow control concept has been developed and incorporated into the TAATM (Terminal Area Air-Traffic Model) simulation. A fast-time parametric sensitivity evaluation of the basic extended terminal area flow controls concept is underway using TAATM in a four corner-post, Denver runway 26L configuration with IFR arrival commercial traffic. One of the variables considered is the horizon of control.

A major goal of the proposed system is to meter, sequence and initially schedule arrival aircraft early enough in the approach so that the required delays needed to derandomize the traffic can be taken in a fuel efficient manner. The question is how early? Figure 6 was plotted to shed some light on the question. The expected en route delay and its standard deviation for the two separation standards are shown for various horizons of control (flight time between scheduling and meter fix). The data were obtained from a simulation with a saturation (35 aircraft per hour) sample of large and heavy aircraft using IFR 3/4/5 and 2/3/4 nautical miles separations and a meter fix delivery error standard deviation of 30 seconds. Also shown on the plot are contours of delay possible by speed reduction to Mach 0.67 for a range of initial cruise speeds. Using the Mach 0.78 initial cruise speed and the 3/4/5 nautical mile separation as an example we see that a horizon of control of 27.5 minutes from the meter fix is enough so that speed control will handle all the en route delays that are less than the expected delay plus 1 σ.

Figure 6 showed the slight en route delay effect which results from changing the horizon of control. There is also a terminal effect which must be considered. From the moment an aircraft is scheduled at the horizon of control point and begins its flight toward the meter fix, there are schedule changes that occur as a result of preceding traffic meter fix time errors and flight error inside the terminal. Consequently, when an aircraft arrives at the meter fix its target time may have shifted from that originally assigned. The longer the flight time the more the schedule landing time is likely to change. Figure 7 shows this effect. The expected terminal time delay plus 1σ is shown as a function of horizon of control for the 3/4/5 traffic separation standards and error conditions as existed in figure 6. Also shown is an example nominal terminal speed delay control capability boundary. A system goal is to use fuel-efficient speed control inside the terminal as well as en route without resorting to path stretching. What we seek is a horizon of control that is large enough to handle most of the expected en route delays and yet does not impose terminal delays that exceed the terminal profile descent speed control capability. For the simulation conditions given (.78 cruise Mach, 3/4/5 separation) the horizon of control window should be between 27.5 and 40.5 minutes from the meter fix. It should be noted that slower cruise Mach will narrow the control window or may require path stretching.

2.4 Close-In Delivery Precision Performance

Like any ATC system that must keep violation of specified separations to a low probability level, the proposed time-based system capacity is sensitive to final system delivery precision. This comes about because a delivery error (σ) dependent interarrival time buffer must be added to the separation time to prevent a separation violation. Figure 8 shows an example of runway arrival rate for transport aircraft as a function of separation standard and the system interarrival error standard deviation which maintains the same low probability of violations. A key issue as related to system capacity becomes the delivery precision of any proposed evolutionary time-based system.

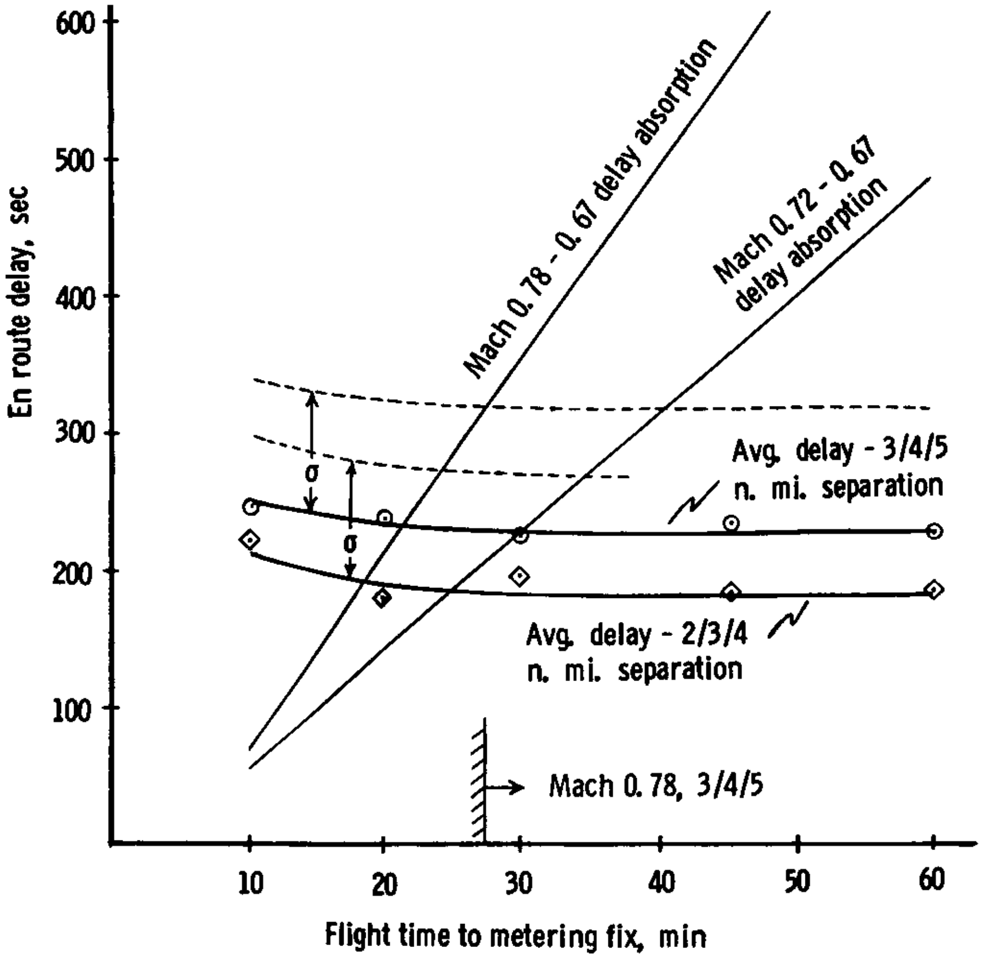


Figure 6. - Horizon of Control to Efficiently Absorb Delay for Range of Cruise Speeds.

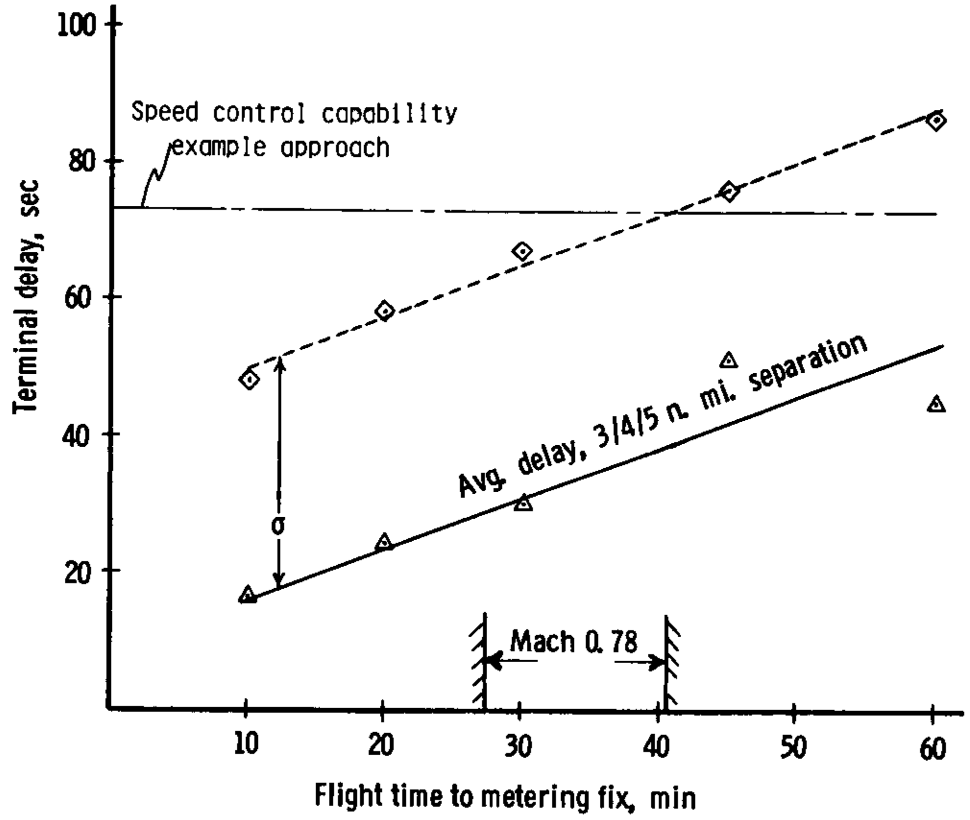


Figure 7. - Horizon of Control Limits to Stay Within the Terminal Delay Capability.

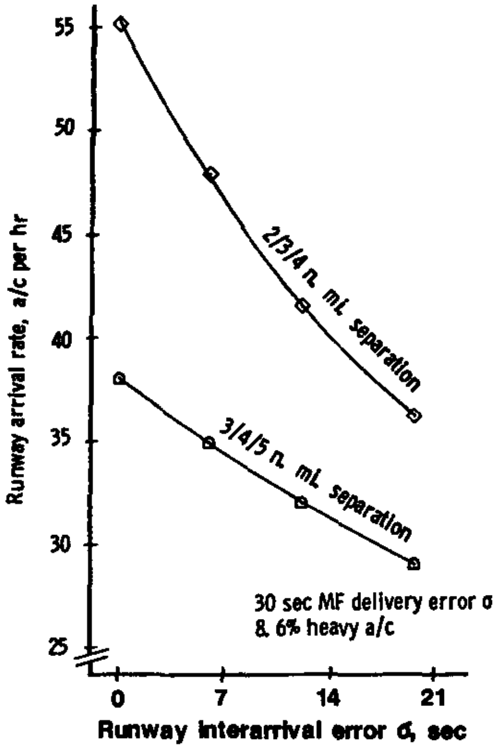


Figure 8. - Impact of Runway Interarrival Error on Arrival Rate.

There is reason to believe that aircraft equipped with advanced flight management systems with 4-D control can achieve less than 5 seconds standard deviation (references 7 to 10). The principal constraint on the system will be the accuracy with which non-4-D-equipped aircraft are handled. There are simulated results which indicate what the actual system performance will be. The fast-time simulation used to obtain the data of figures 6, 7, and 8 yielded an interarrival error standard deviation of 6.5 seconds. Real-time piloted cockpit/controller interaction studies are planned to verify that finding. An earlier study to assess navigation effects, reference 11, used the same fast-time model. In that study the fast-time simulation predicted interarrival error standard deviation of 7.9 and 9.2 seconds for two navigation systems. Piloted simulation studies yielding parallel findings of 5.3 and 10 seconds. The results of a different speed and vectoring scheme in the terminal (reference 12) indicated a single aircraft delivery σ of 9.4 seconds which translates to about 13.3 seconds interarrival σ. There is reason to believe that with controller aiding, the interarrival error standard deviation for unequipped traffic can be reduced to the region of 8 to 12 seconds as compared to the 18 to 20 seconds (reference 13) typical for current manual control system. This would theoretically yield an arrival rate increase in the range of 8 to 18 percent when operating under U.S. IFR wake vortex separation rules.

3. SOME 4D-EQUIPPED AIRCRAFT AND SYSTEM REQUIREMENTS

A primary requirement for the evolving time-based ATC system is to minimize costs for aircraft operators. In order to satisfy this requirement, careful consideration must be given to accommodating 4D-equipped aircraft preferred flight trajectories. Further, flight time and speed profile selection for aircraft during heavy demand situations must attempt to minimize operating costs for each airplane while reducing overall system delays. In order to accomplish these goals, knowledge of airplane operating cost sensitivity to flight time for a given range must be integrated into the design of the ground ATC scheduling system. Requirements for airplane performance models and atmospheric variation effects must also be determined.

3.1 Flight Time and Speed Selection

For a given range, every airplane has a spectrum of minimum fuel required for flight times spanning the speed capabilities of the airplane. An example of fuel versus time performance spectrum for a typical twin-jet transport airplane is shown in figure 9. The maximum and minimum times on the plot correspond to the minimum and maximum operational speeds for this airplane. Some additional speed capability remains at these extremes; however, it is not desirable to schedule an airplane to fly at the absolute airframe limits. The values of fuel for times between the two extremes represent the minimum fuel the airplane would require by flying an optimal speed schedule for the given time and range. A time window of 29 minutes to 36 minutes is therefore available for this airplane to fly the 200 nautical mile range without path changes or holding operations.

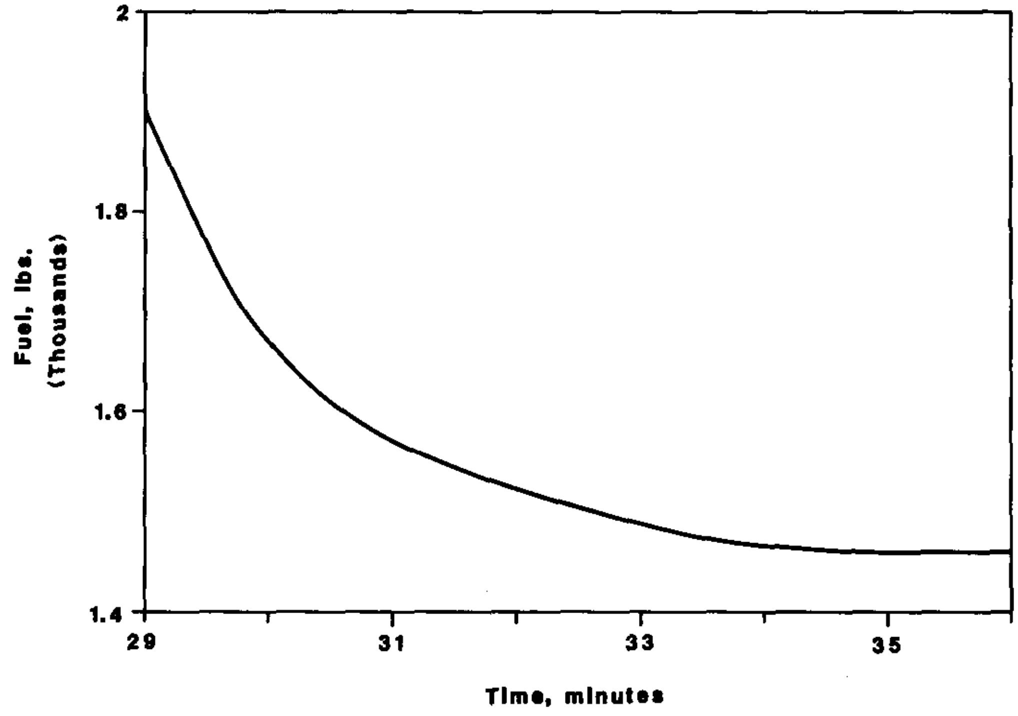


Figure 9. - Fuel-Time Performance Spectrum for a Twin Jet Transport (200 n.mi. range, descending from FL350 to 5000 ft. for a flight time of 31.5 min.).

3.1.1 Minimum cost time selection

Choice of desired flight time for a given range is a function of operator cost of time and fuel. A useful parameter defining a cost ratio between time and fuel costs is given below:

cost ratio = Ct/(Ct+Cf)

where,

Ct = time cost, $/sec

Cf = fuel cost, $/lb of fuel

When time costs are the overriding concern, the cost ratio will approach 1, corresponding to the minimum time point on figure 9. For minimum fuel operations the cost ratio will be near 0, corresponding to the time for minimum fuel (approximately 35 minutes on figure 9). Typical values of cost ratios for operators of the twin-jet transport in the United States ranged between 0.4 and 0.6 during 1985.

The fuel versus time performance spectrum can now be used to determine the desired flight time for a particular cost ratio. In addition, cost penalties for times other than the desired time can be calculated. Figure 10 illustrates the cost penalties as a function of flight time for the performance spectrum of figure 9 with a 0.5 cost ratio. The desired time for this particular situation is 31.2 minutes. The line labeled "optimal profile" presents the cost penalty (relative to the cost for 31.2 minutes) for times achieved by flying the minimum fuel profiles defined in figure 9. This represents the minimum cost penalty for any given flight time for a 0.5 cost ratio. Also shown on the figure are cost penalties incurred if flight times greater than the desired time of 31.2 minutes are absorbed by holding at cruise altitude rather than adjusting the speed profile. This corresponds to the current ATC practice where time guidance is not available to controllers and holding patterns are standard methods for absorbing delay. Substantial additional cost penalties result from this practice.

Considering the optimal profile data presented in figure 10, a user-preferred time window of controllability can be established. The full 7 minute time window (29 to 36 minutes) can result in cost penalties of 6 percent at the extremes. In order to keep penalties to 1 percent or less, the time window must be reduced to approximately 3 minutes (30 to 33 minutes flight time). In other words, a six-fold improvement in cost savings can be achieved by roughly halving the time window. Airplanes with different cost ratios will have different preferred time windows, as shown in figure 11. If actual cost ratio is known for a particular airplane, flight times could be established accordingly. An alternate approach would be to establish a narrow time window defined by an overlapping range of cost penalties for a given airplane type. For example, using the data in figure 11, a time window of 1.5 minutes (30.5 to 32 minutes) would provide all operators of this twin-jet airplane with cost penalties of no more than 1 percent.

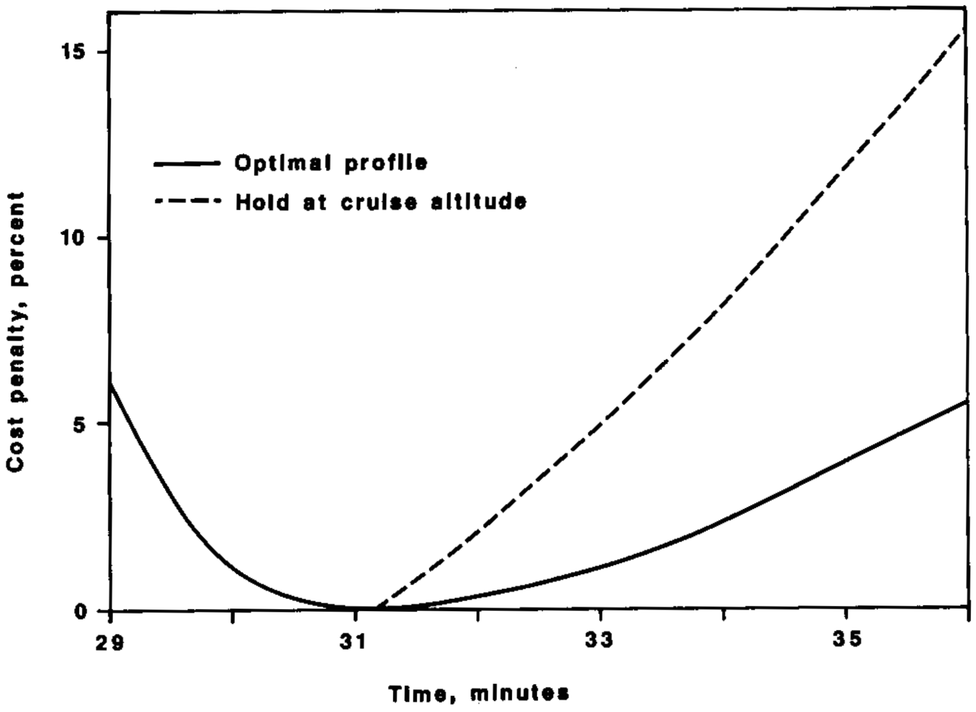


Figure 10. - Fixed Time Cost Penalty for a Twin Jet Transport (Cost Ratio = 0.5, 200 n.mi. range, descending from FL350 to 5000 ft.).

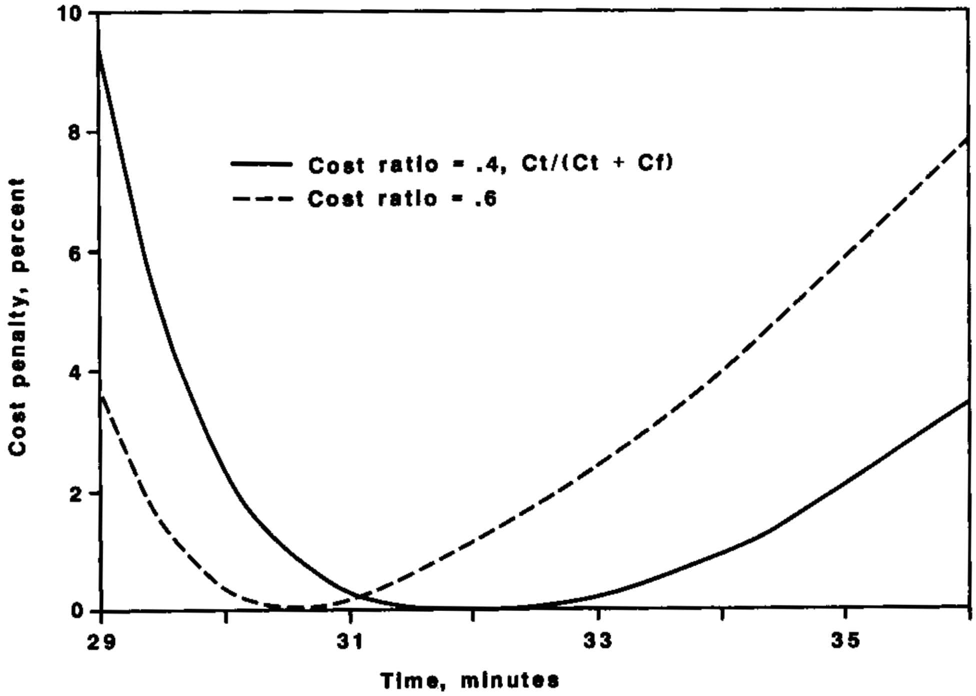


Figure 11. - Fixed Time Cost Penalties for Two Cost Ratios for a Twin Jet Transport (200 n.mi. range, descending from FL350 to 5000 ft.).

Knowledge of airplane performance characteristics, and possibly cost ratio, can provide valuable guidelines to ATC assignment of flight times during moderate traffic conditions. The ability to assign early as well as late times within a reasonable cost envelop can enhance the handling of mixed and dense traffic with random arrival gaps. Landing slot tradeoffs between aircraft, based on cost penalty time windows, may provide additional gains in capacity. Under saturated traffic conditions, however, minimization of time delays will be the primary function of time-based ATC.

3.1.2 Profile Compatibility

The preceding discussion has assumed a single optimum speed profile exists for each point on the fuel versus time performance spectrum. In reality, there is a wide range of speed profiles which will produce comparable fuel usage for a given range and flight time. This provides flexibility in choosing speeds which both minimize fuel and provide tactical airplane separation while achieving desired arrival time. This same speed flexibility can also lead to incompatibilities between ground and airborne systems.

The determination of a speed profile for a given time and range can be accomplished using a variety of techniques. Depending on the strategy employed by a particular algorithm, a significant variation in speeds at a given distance from the airport is possible. For example, a common operational strategy is to fly a constant Mach number in cruise, initiate descent at the same Mach number and transition to a constant calibrated airspeed for the remainder of the descent. A wide range of cruise Mach and final descent airspeed combinations are capable of producing the same flight time. Figure 12 illustrates the speed combinations for a 31.5 minute flight of the twin-jet transport covering a 200 nautical mile range. The speed combination yielding the minimum fuel for this flight segment is approximately a .72 Mach cruise and 290 knot descent calibrated airspeed. As shown on the figure, there is a wide band of speed combinations which achieve the same end conditions with no more than 1 percent increase in fuel over the minimum fuel speeds.

The relative insensitivity of fuel usage as a function of speed profile can be used to advantage in the ATC process. Cruise speeds of airplanes can be adjusted to avoid local traffic separation problems while maintaining arrival time sequencing and capacity at the airport. This is particularly important when handling a mix of traffic with different inbound cruise speeds. The flexibility of selecting alternate speed profiles to achieve fixed flight time may be required in order to provide desired capacity levels at some airports. This flexibility will also alleviate compatibility problems between profiles calculated by ground algorithms and those computed by airborne flight management systems.

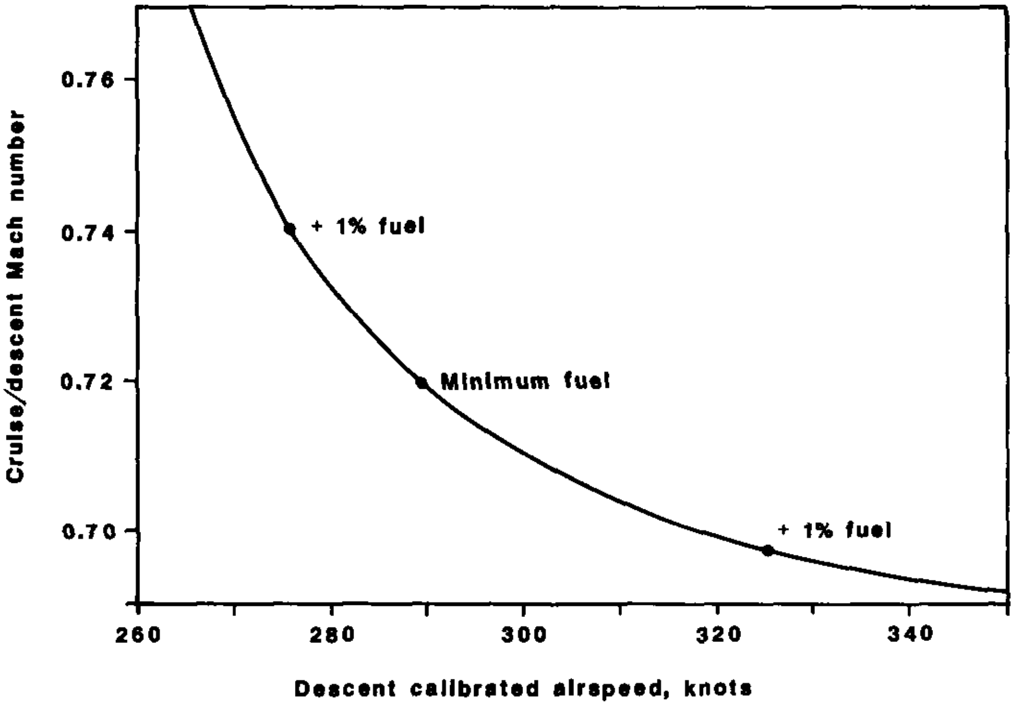


Figure 12. - Fixed Time Speed Flexibility for Twin Jet Transport (200 n.mi. range, descending from FL350 to 5000 ft. for a flight time of 31.5 minutes).

3.2 Modeling Requirements

Both ground-based and airborne trajectory generation algorithms require analytical models of the atmosphere (wind, temperature, and pressure) and airplane performance. The structure and accuracy of these models can be critical to the results of the algorithm. Choice of model structure is largely dictated by the flight strategy employed by the algorithm. Model accuracy requirements are dependent on the level of performance penalties associated with errors in the model. Parametric sensitivity studies are being conducted to characterize and quantify the penalties due to mismodeled atmospheric conditions and airplane performance for both time-constrained and unconstrained operations. Of particular interest to time-based ATC development is the required accuracy of wind and atmospheric temperature modeling for cost effective operation.

3.2.1 Atmospheric Effects

Airplane performance must incorporate atmospheric variations in pressure, temperature and wind to generate satisfactory flight trajectories. Highly volatile atmospheric variations can produce significant differences in predicted and observed conditions. Variations in wind speed and direction will directly affect the time required to fly a fixed range. Changes in temperature will affect true airspeed and geometric altitude rate during climb and descent.

Initial sensitivity studies have documented the cost penalties resulting from wind errors during a cruise/descent flight segment for a typical twin-jet airplane. Figure 13 shows the cost penalty for flying a 200 nautical mile cruise/descent flight segment in both known and unknown winds with the same arrival time required for all conditions. The cost penalties are relative to the minimum cost which could be obtained for the given wind condition if time were not fixed. The results for known winds therefore reflect the penalty incurred by not adjusting flight time based on actual winds. The penalties for unknown winds include the effect of not computing the flight trajectory based on actual winds. For this particular flight segment, winds on the order of 22 to 25 knots (headwind to tailwind) can be tolerated for no more than a one percent cost penalty if they are known to the airplane's trajectory generator. Unknown winds must be no more than 10 to 15 knots for the same one percent penalty, with tailwinds being more restrictive. These data are useful both for the design of airborne wind models as well as for determining recomputation criteria and data update requirements for advanced flight management systems and ground scheduling algorithms.

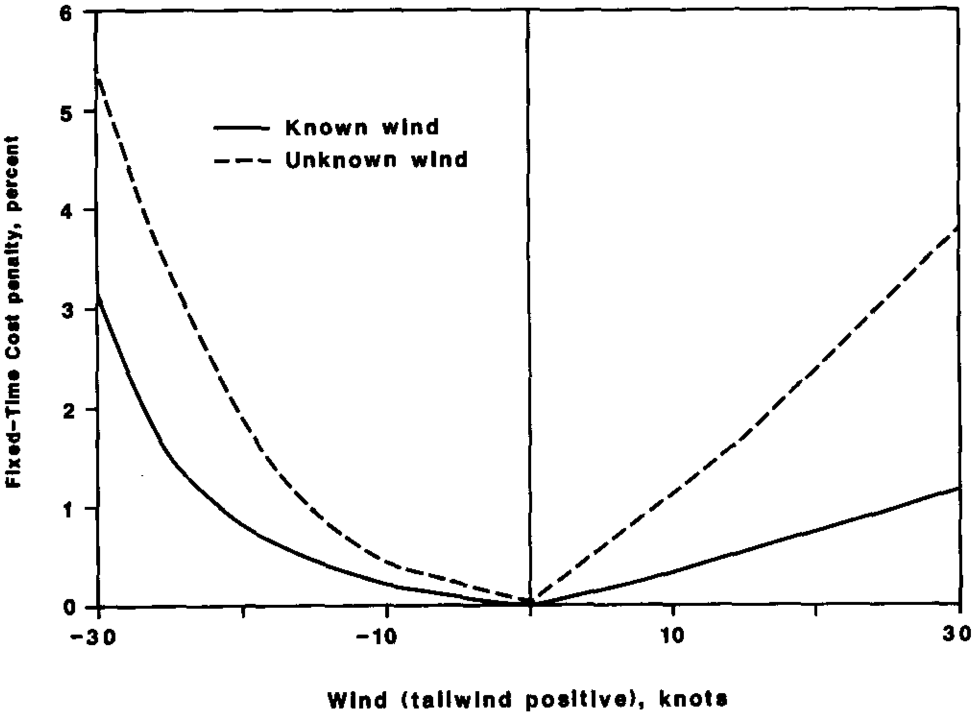


Figure 13. - Wind Effect on Fixed Time Cost Penalty for Twin Jet Transport (Cost ratio = 0.5, 200 n.mi. range, FL330 to 10000 ft.).

4. CONCLUDING REMARKS

The previous two sections of this paper have described two of the cornerstones of our research to develop a technology foundation for reducing the aircraft interarrival time error at the outer marker while increasing aircraft efficiency. Figure 14 shows how this research fits together with other current and prior research focused on delivery precision. The ATOPS program with its Transport Systems Research Vehicle (TSRV) aircraft is uniquely capable of integrating these pieces into coherent, coordinated experiments that address every facet of the issue. An example set of experiments to provide definition of some of the options and issues in delivery precision is shown in figure 15. The TSRV aircraft will be flown while embedded in a ground-based simulation with computer-generated aircraft. This effort will evaluate the controller/pilot issues, capabilities of equipped and unequipped aircraft, and define the delivery precision attainable.

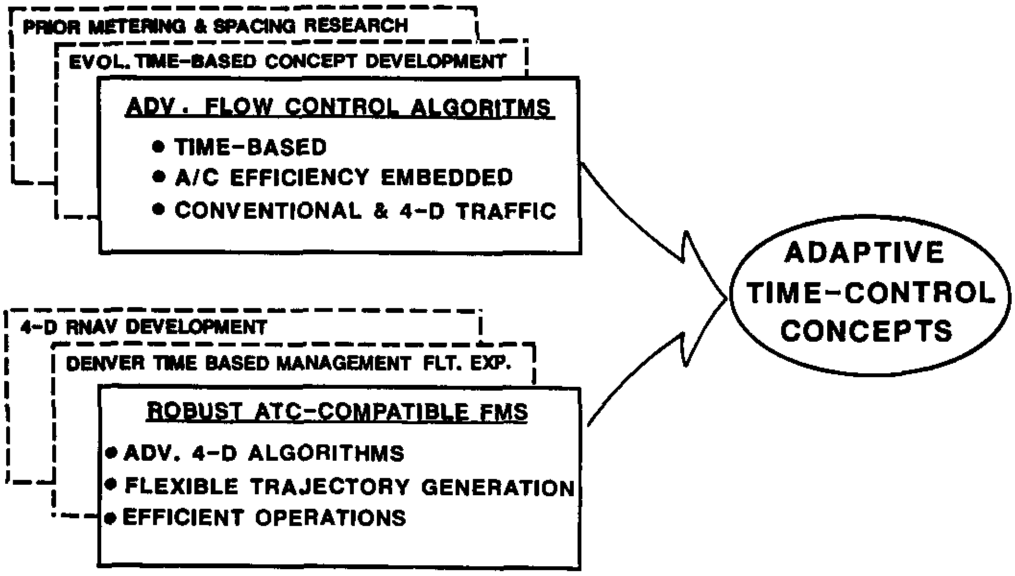


Figure 14. - Technology Integration for Improved Delivery Precision.

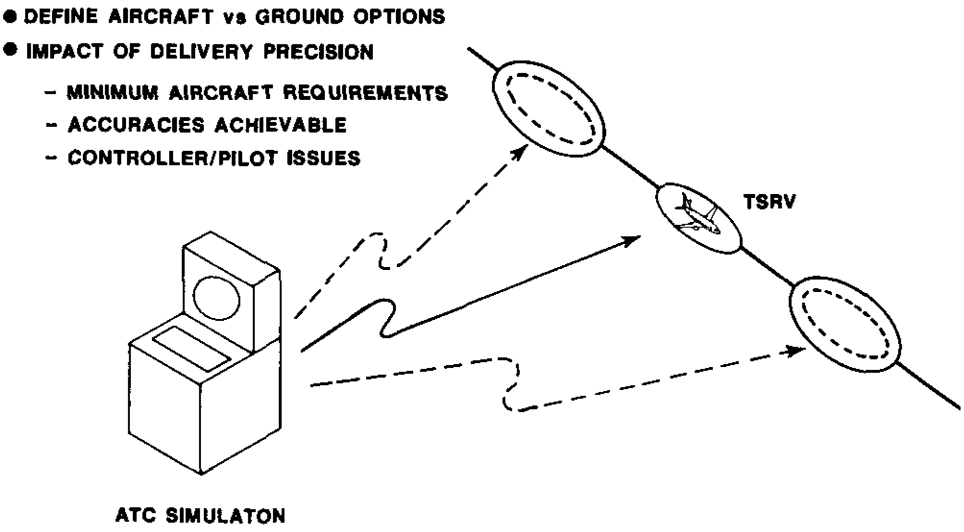


Figure 15. - Experimental Evaluation of Delivery Precision Capability.

Today there is a major airport capacity problem in the United States, and it promises to get substantially worse by the turn of the century. This lack of capacity reduces the viability of air transportation by causing delays and inefficient operation of aircraft. A number of technological developments have been identified that offer the potential for increasing airport capacity and thereby reducing delays while increasing aircraft operating efficiency. Research described in this paper is underway as a part of the ATOPS long range plan mentioned in Section 1.

REFERENCES

1. Benoit, Andre; and Swiessta, Sip: *Dynamic Control of Inbound* Flights for Minimum Cost Operation AGARD Conference Proceeding No. 340, October 1982.

2. Erwin, R. L. Jr.: Strategic Control of Terminal Area Traffic. AGARD-CP-188, February 1976.

3. Aviation Week & Space Technology; January 21, 1985, pp. 36-37.

4. Rogers, John; Pearrall, Lawrence; Hoffer, Stefan; Pfeifer, Mark; DeCarma, David: Airfield and Airspace Capacity/Delay Policy Analysis. FAA-APO-81-14, December 1981.

5. Anon: .Civil 1985-1997 FAA Aviation Forecasts for FY 1985-1997, FAA-APO-86-1

6. DeJernett, F. R.: Effects of Aircraft and Flight Parameters on *Energy-Efficient* Profile Descents In Time-Based Metered Traffic. NASA CR-17023, February 1984, Addendum November 1984.

7. Bruckner, J. M. H.; *et al.*: *3D/4D Area Navigation System* Design, Development, and Implementation. FAA-RD-77-79, July 1977.

8. Heimbold, R. L.; Lee, H. P.; and Leffler, M. F.: Development of Advanced Avionics *System Applicable* to *Terminal*-Configured Vehicles. NASA CR-3280, September 1980.

9. Moor, D. A.: Time Flies, An In-Service Evaluation of a 4-D Flight Management System. Proceedings of 6th Digital Avionics System Conference, AIAA, December 3-6, 1984.

10. Adam, V.; and Lechner, W.: Investigations on Four Dimensional Guidance in the TMA. AGARD Conference Proceedings No. 340, October 1982.

11. Credeur, L.; Davis, D.; and Capron, W. R.: Evaluation of *Microwave Landing System* (MLS) Effect on the Delivery Performance of a Fixed-Path Metering and Spacing System. NASA TP-1844, August 1981.

12. Pelegrin, M.; *and Imbert*, N.: *Accurate Timing* In Landings Through Air Traffic Control. AGARD Conference Proceedings No. 240, Guidance and Control Design Considerations for Low-Altitude and Terminal-Area Flight. April 1978.

13. Haines, A. L.: Parameters of Future ATC Systems Relating to Airport Capacity/Delay. FAA-EM-78-8, April 1978.

CP 410

STRATEGIC CONTROL TO IMPROVE EFFICIENCY OF AIR TRAFFIC MANAGEMENT

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SUMMARY

This paper deals with the strategic control concept, intended as a new management philosophy that can improve efficiency of Air Traffic Control (ATC) systems. After having introduced a classification of the different ATC functions, based on a multilevel scheme, strategic control is decomposed in a hierarchy of sub-functions. Subsequently, the "on-line strategic control of flights" is considered and the mathematical aspects of this problem are illustrated.

Then the structure of a real time solution algorithm, proposed in a previous work, and a possible scheme of route-time profile generation are reported. Finally, computational efficiency of the proposed approach is discussed.

1. INTRODUCTION

The current ATC systems are mainly conceived to ensure, with short period interventions, safety of flights. In fact, today the air traffic controller uses radar to assess the traffic situation and speed, altitude and heading instructions to separate and space aircraft. This is a "tactical" system using relative-position separation in which the planning horizon is very short and the situation is allowed to develop before solutions are offered.

The pilot does his own navigation only when there are no nearby aircraft. As the flight encounters traffic of increasing density, ATC intervenes more and more until in a busy terminal area the controller is vectoring the airplane continuously in all three dimensions and in airspeed. This control system is manpower intensive, uses relatively inefficient flight paths to solve traffic situations and is at or near its capacity in handling traffic and supporting increased runway operations.

This management phylosophy, probably, will not be suitable in the future, when congestion phenomena will occur more often in the most important terminal areas. Therefore, it seems necessary to introduce in the future ATC systems not only more automated procedures to keep proper safety levels, but also planning functions to increase system capacity and reduce total cost. In this manner it is possible to improve system efficiency. Now, an effective planning action depends on the availability of long term accurate forecasts and adequate control techniques.

In recent years, several scientists have carried out studies in these two directions; consequently, they have introduced a new control concept defined as "strategic control".

For example, the North Atlantic ATC operation can be considered as a strategic system in that, because of a lack of radar, separation is planned for the total over ocean flight before an aircraft is put into the system.

Nevertheless, different and, sometimes, contrasting meanings are assigned in literature to the above term.

In [1] a classification of different control functions is proposed; in particular "strategic control" is seen as a long term off-line planning of traffic flows and/or of single routes. On the contrary, "tactical control" is a short term on-line action. This distinction is also taken up in [2] and, from a certain point of wiev, in [3]. Instead, in [4], [5] and [6] "strategic control" is not necessarily an off-line planning, but may also imply an on-line planning action, based on the knowledge of the current state of the system. A special concept of "strategic control" is proposed in [7, 8], where this function is considered as the ability of defining, for each plane, an optimal four-dimensional path. This route must be followed with such a precision to ensure the preservation of time and distance standard separations.

From another point of view, the strategic approach only prevents conflicts [9], while in [5] it could also improve system performance in terms of global economy.

To overcome the difficulties caused by these different interpretations, the author and others, on the basis of a concept reported in [10], have proposed a representation of the ATC based on a multilevel scheme, where a well defined function is associated to each level [11], [12]. Moreover, a mathematical formulation of the "strategic control of flights" is provided [11] and a solution algorithm in the case of control on pre-assigned optimal routes is designed [13].

The following works [14, 15] deal also with the on-line control of flights, but without the hypothesis of space routes fixed as nominal ones.

At present, we feel that there is a general agreement on the soundness of introducing in ATC systems a somewhat planning function with effectiveness depends on developments of navigation techniques, air ground communication devices, new opportunities of data processing offered by modern computers and new perspectives open by expert systems and decision support systems.

Therefore, in this paper, on the basis of the mentioned researches, "strategic control" is viewed as a hierarchy of different planning sub-functions, each one referring to a different time horizon. Then, particular attention is devoted to the on-line strategic control of flights because this function appears to be more critical to implement. For this reason, the possibility of real time solution of the mathematical problem and the design of route time profile generation system are also analized and discussed.

2. A MULTILEVEL MODEL OF AIR TRAFFIC CONTROL

The ATC problem is a typically large scale problem characterized by:
high number of variables and constraints;
numerous sub-systems and strong interactions;

- numerous control objectives also conflicting;
- limitations and complexity of models used to forecast the movement of airplanes and traffic evolution;
- *fast dynamics and real-time interventions;*
- presence of several human operators in the system (pilots, controllers, etc.), each having a certain independence on decision taking.

To approach this problem it seems fit to utilize appropriate decomposition criteria based on a hierarchy of control functions, each related to a different time horizon. Fig. 1 represents a possible scheme where both the available resources and a long term air traffic demand are supposed to be known.

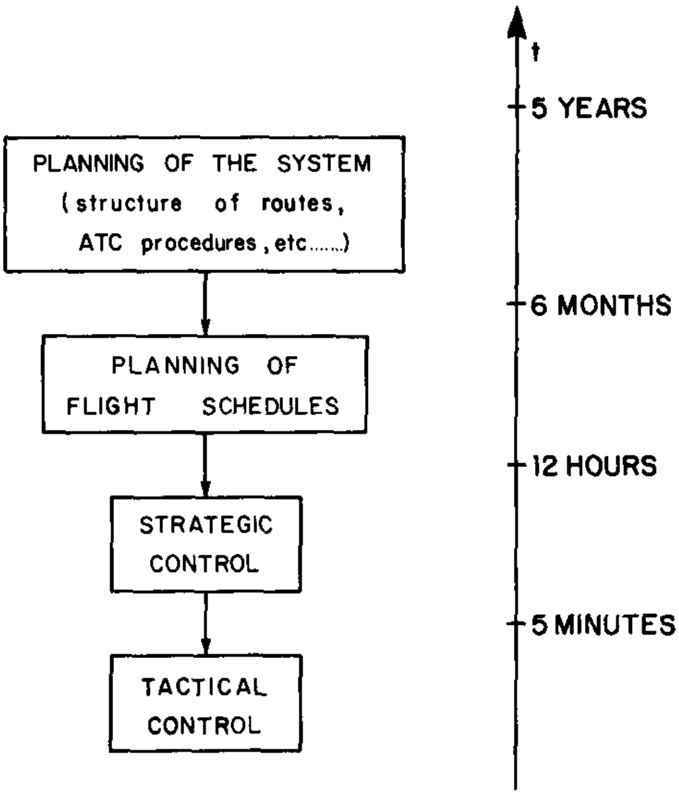

Fig. 1 – MULTILEVEL MODEL OF AIR TRAFFIC CONTROL

The higher level is associated with the planning of the air space structure, routes and ATC procedures and, generally, with the evolution of the overall control systems.

The second level represents the planning activity of flights carried out, within a time horizon of a few months, in connection with the estimated traffic demand.

The level called "strategic control" represents a planning activity of *medium-long term interventions to organize traffic flows* and/or define amendements to single flight plans. Finally, tactical control is a real-time control action to satisfy short-term requirements and/or to *solve emergency situations.*

At present, the actions relative to the first two levels are not being carried out on the basis of optimization criteria. For example, in general, there is no coordination in the decision of the airlines; consequently, it is not possible to prevent the congestion situations.

Available studies refer especially to the two lowest levels of the mentioned hierarchy or, more precisely, to sub-functions of these levels. In particular, strategic control, up to now, has only been utilized in a partial and limited manner; in fact, the current ATC systems are still mainly based on tactical control actions. On the contrary, *we feel that a systematic introduction* of a strategic function could constitute the most relevant and revolutionary innovations in air traffic control. In fact, this approach seems to be, in theory, *the only one able to minimize the operational* cost and, at the same time, improve safety standards in ATC (see also Ref. 7,8).

In practice, the implementation of a control function that optimizes planning of flights, implies considerable difficulties depending on the necessity of long-term right forecasts and inadequacy of the available methodologies to solve problems of such complexity.

3. STRATEGIC CONTROL

To simplify the previous problem it seems convenient to decompose, in its turn, the strategic control function on the basis of a multilevel model of distinct sub-functions.

A first decomposition criterion could be a distinction between "off-line" and "on-line" control. For off-line control we mean a planning activity carried out before interested planes enter the system (generally, before departure) and based exclusively on traffic forecasts. Instead, for on-line control we mean a control activity based mainly on observations of the current state of the system and worked out in a rather short period (in comparison with dynamics of flights) to allow subsequent interventions on the controlled traffic.

A second criterion could be based on a distinction between control on aggregate variables (traffic flows) and control on variables relative to single planes (flight plans). Fig. 2 represents a multilevel decomposition of strategic control corresponding to the above criteria.

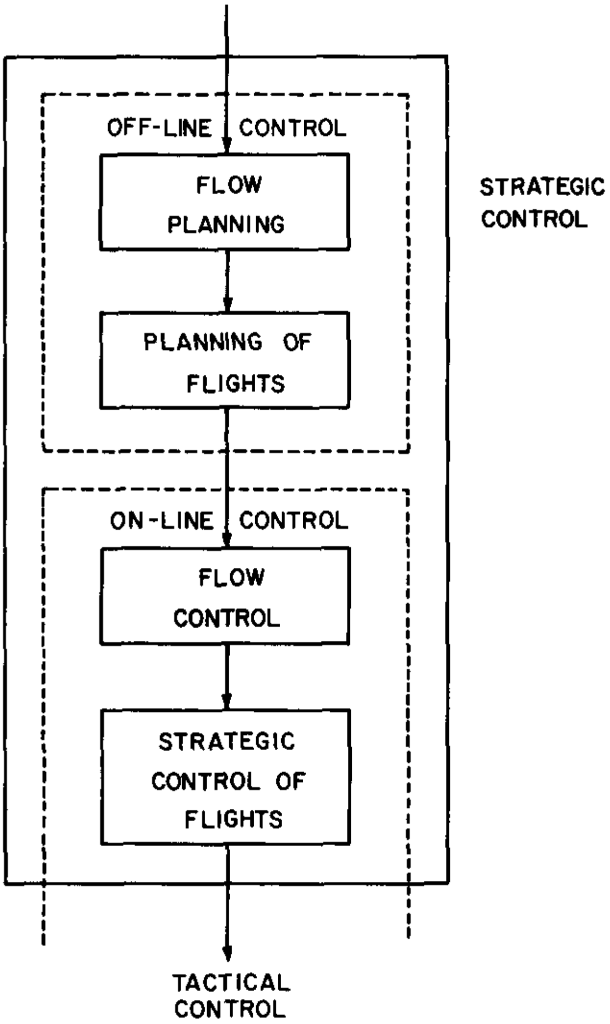

Fig. 2 - MULTILEVEL MODEL OF STRATEGIC CONTROL

To completely understand the meaning of this model, one must point out that the hierarchical order of the various levels refers mainly to the different time horizon and,generally, doesn't express a decisional hierarchy in the control actions. More precisely, we can say that higher levels basically ought to simplify decisional problem relative to the lower levels.

In the following functions associated to each level and relative operations are illustrated.

3.1. Flow Planning

The flow planning functiòn should be carried out within a few hours, comparing the expected traffic demand with an estimate of the system capacity (airways, terminal areas). Then, a distribution of traffic flows in the airspace should be determined to relate the demand to the capacity.

3.2. Planning of Flights

On the basis of flow planning and of the same time horizon, this off-line activity should determine amendments for the requested flight plans. These amendments should have the aim both of reducing the a priori conflict probability and satisfying a somewhat optimal criterion.

We must also specify that many random factors affect the above process; so we represent the flights by utilizing a simplified model made up, for example, of passing times and altitudes at the way-points of the planned route.

3.3. *Flow Control*

The on-line flow control refers to a time horizon of about 15-30 minutes and, in particular, it should forecast local and short-period traffic peaks and reduce possible effects on the system. This can occur both by imposing delays on the flows upstream of the traffic congestion and planning a different distribution of the traffic in adjacent sectors.

3.4. Strategic Control of Flights (SCF)

This function has the same time horizon as the on-line flow control. It should plan free conflict trajectories on the basis of observation of the current state of the system in order to satisfy the constraints on the airplane performances, space structures and possible flow limitations.

In the following sections we consider,in detail, the on-line strategic control of flights.

4. STRATEGIC CONTROL OF FLIGHTS

As previously mentioned, the task of on-line SCF is to optimize flight plans of single airplanes in a prefixed region with a time horizon of about 15-30 minutes.

The sub-system associated with the SCF function can be outlined as in fig. 3, where both inputs and outputs are indicated. The inputs are the flight plans of the airlines, the information relative to the state of the system and the limitations imposed by flow control. The outputs are the amendments to the flight plans that represent control interventions on the planes of the system and can be useful information for tactical control.

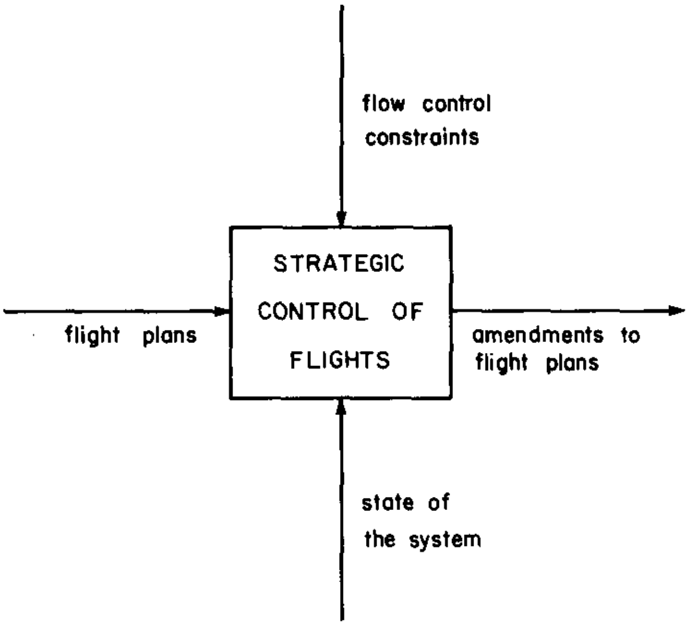

Fig. 3 - REPRESENTATION OF THE SCF FUNCTION

More in detail, the requested flight plans should be optimal from the point of view of fuel and/or time consumption if each plane were alone in the system. Instead, information on the state of the system concerns radar data on the flights evolution, short and medium term meteorological forecasts and state of the ATC infrastructures. As for restrictions imposed by flow control, these limit the control action on the single plane according to the flow planning in the control region. In particular, such limitations can refer to the maintaining of appropriate separations when planes fly over prefixed points of the controlled airspace.

Finally, for amendments to flight plans we mean:

- variations of altitude levels in comparison with the nominal flight plans;
- imposing route delays through the speed control;
- imposing reroutings and/or holding patterns;
- imposing departure delays.

Now, to build a mathematical model of the SCF, we must first establish a control region, a time horizon and a representation of the airways network and the trajectories of planes; then we must define control variables, constraints and the objective function to optimize.

4.1. Control region

The possibility to carry out a strategic action on the single plane depends greatly on the extent of the region where a coordinating intervention is possible. In fact, SCF,generally, aims to follow an efficient profile during all phases of the flight (take-off, cruise, landing). Therefore, the more flight plans (compared with global traffic) refer to the prefixed control region, the more significant SCF is. Nevertheless, even not considering political, normative and organizational difficulties, an upper bound to the extent of the control region is derived because of the limited performances both of mathematical methodologies and real time computation systems.

In fact, the problem complexity increases when the dimensions of the control region increase.

4.2. Time horizon

The time horizon is mainly determined by the maximum time interval in which it is possible to accurately predict future traffic situation in the control region.

At present, the available models seem to be able to provide adequate forecasts for look-ahead times of about 15-30 minutes. This limit could also bring to a spatial decomposition of the control action in the fixed region.

4.3. Airspace and planes trajectories representation

Given a control region R, the representation of the space and planned trajectories must be accurate enough to make a meaningful control action and, at the same time, simple enough to permit real-time data processing.

To this end, in the following, airspace is described through a network representing both the airways and the terminal areas.

More in detail, the network nodes represent:

- the intersection of the airways with the R boundary;
- the intersection of the airways with the terminal areas boundary;
- the intersection of two or more airways;
- the waypoints fixed on each airway.

Obviously, the arcs represent all possible connections of the nodes.

A set of discrete altitude levels is also associated with each node so that constraints on vertical separation, imposed by safety requirements, are respected.

As for the representation of flights, we utilize a discrete model whose trajectories are defined by the set of nodes subsequently crossed, by the corresponding altitude levels and by the passing times on each node.

In this model we don't consider the dynamics of flights between two following nodes and within the terminal area; nevertheless, the problem solutions are forced to be consistent with the performances of airplanes.

5. MATHEMATICAL MODEL

In this section, we summarize a possible mathematical formulation of SCF. The interested reader can find complete details in [14, 15].

In particular, the problem can be stated as an optimization problem with the hypothesis that the nodes subsequently crossed are fixed on the basis of the nominal flight plan. In this framework one must determine altitude levels and passing times on the trajectories nodes, so that an appropriate constraints set is satisfied and a cost function is minimized.

5.1. Altitude Constraints

First of all, we must specify the set H_k^i of altitude levels allowable for plane i in each node k of the trajectory. Then, we must consider that a speed range, consistent with the performances of plane i, corresponds to each allowable level.

In such a way, knowing the distance between two subsequent nodes k and $\tilde{k}$, we can determine, for each speed and for each level h of k, the altitude levels reachable in $\tilde{k}$. Among these levels, we will only consider levels satisfying eventual control needs in $\tilde{k}$ and/or limitations on the maximum shifting of the actual altitude level from the nominal one. Therefore, if we introduce binary variables, it is easy to express in a mathematical form the two following constraints:

plane i can occupy only one of the allowable levels of node k; (1)

if plane i starts from a level h of k, it can occupy only one level of the set allowed in node $\tilde{k}$. (2)

5.2. Transit time constraints

As regards to transit time of plane i on node k, denoted with t_k^i, we must distinguish between constraints depending on planes performances and constraints related to safety standards and possible restrinctions of traffic flows on the airways network.

Constraints on planes performances imply that

the time interval of plane i to transit from node k to node $\tilde{k}$ has a maximum and minimum value; (3)

as regards to safety constraints and possible further restrictions caused by flow control, we can state that

if two planes i, r cross,subsequently,node k at the same level, they must have a minimum separation time $\Delta T_k^{i,r}$. (4)

An exact definition of transit times in each node can be meaningless, especially for those nodes far from the initial one. To improve this model it can be convenient to associate a time window, consistent with plane performances and assigned standard separations, with each plane and each node instead of a transit time.

In this case constraints (3) and (4) must be formally modified.

5.3. Objective function

We may consider several objective functions. The first possibility is to minimize total delay of planes in the control region. In this case the objective function can be expressed as

$$J_1 = \sum_{i \in I} \alpha^i_{k^i_f} t^i_{k^i_f} \tag{5}$$

where $\alpha^i_{k^i_f}$ are weight coefficients depending on the class of plane i and the terminal node k_f.

In particular, J_1 seems meaningful in the terminal area where, because of operational reasons, the main objective is to minimize the final delay.

When we consider larger airspace regions, we must also take into account the cost connected with deviations from the nominal flight profile. In this case, the objective function could be expressed as

$$J_2 = \sum_{i \in I} \sum_{k \in K^i} \left\{ \sum_{h \in H^i_k} \sum_{j \in H^i_k} \alpha^i_{khj} q^i_{kh} q^i_{\tilde{k}j} \, | t^i_k - t^i_k - \tau^i_{khj} | + \beta^i_k \, | \sum_{h \in H^i_r} (q^i_{kh} - \bar{q}^i_{kh}) z_h | \right\} \tag{6}$$

where

I	*represents the set of indexes of flights in the region considered in the time interval* [to, to + T];
K^i	is the set of nominal path nodes crossed in R by plane i in the time interval [to, to + T];
q^i_{kh} , $\bar{q}^i_{kh}$	are bynary variables indicating *if the plane i occupies or not the level h of node k, respectively,* in the actual path and in the nominal path;
$\bar{\tau}^i_{khj}$	represents, for plane *i*, the *transit time from level h of node k to level j of the* subsequent node following fuel minimum consumption profile;
α^i_{khj}, β^i_k	*are appropriate weight coefficients.*

The first term of (6) represents the total shifting of transit times between couples of adjacent nodes from the corresponding times in the fuel minimum consumption profile; the second *term represents* the total deviation of altitude levels from the nominal ones. Therefore, J_2 could be utilized as a cost index related to the total fuel consumption.

In this model one must also notice that, if delay costs and deviation costs from the nominal flight profile were evaluable in homogeneous quantitative terms, we could take as an objective function $J_3 = J_1 + J_2$, where arrival times and fuel consumptions are simultaneously considered.

On the basis of this model the minimization of whichever objective function, with the previous constraints, is a mixed variables non linear optimization problem.

6. REAL TIME SOLUTION ALGORITHM

The use of the general model above illustrated, *involves several computational and operational* difficulties. In fact, mathematical complexity increases with the number of planes to be controlled; moreover, the provided control methodology may conflict with current ATC procedures. With regard to these problems, we must consider that the suggested control philosophy may require, for every new plane entering the control region, an intervention on all planes previously planned. Consequently, this *could involve* heavy operational difficulties.

To partially overcome these difficulties, in the following, we shall consider a simplified model of SCF based on the hypothesis that flights planning is carried out according to the FIFO (first in, first out) discipline.

More in detail, we decide that planning action, for each new plane entering the control region is carried out assuming, as constraints, the *flight* plans of airplanes *still in the system. This hypothesis,obviously, reduces solution* optimality, but it reduces also mathematical complexity (variables relative to only-one plane must be taken into account). Moreover, the suggested control method becomes consistent with the current ATC procedures.

On this basis the mathematical model can be simplified by considering planning only one plane at a time.

Since minimization of $J_3 = J_1 + J_2$ remains a problem which difficulty increases with the number of nodes of the trajectory, *in* the following, a decomposition algorithmic procedure of the control problem is illustrated.

In such a way, in general, a sub-optimal solution of global problem can be obtained. More in detail the solution method consists in two sequential steps:

1) determine a solution satisfying constraints (1) ÷ (4) and minimizing only deviations of *altitude levels from the nominal ones;*
2) for the levels fixed in the first step, determine a solution satisfying constraints (3) and (4) and minimizing transit times deviations *from the those relative to the nominal flight path* (or delay on terminal node).

Thus, we obtain two different sub-problems that can be denoted, respectively, as "altitude control" and "speed control". For both these problems, details on mathematical models and solution algorithms can be found in [14, 15]. In the following we recall only the mathematical aspects of each problem and the techniques utilized to solve them.

6.1. *Altitude Control*

The "altitude control", corresponding to step 1), is an optimization problem with mixed variables, levels h_k and transit times t_k, where t_k are not present in the objective function, but only in the constraints. This problem can be suitably formulated and effectively solved by a branch and bound technique. In this step, corresponding to each feasible solution found, a sequence of consistent time windows (one for each level) is also determined. Thus, a sequence of transit times on fixed nodes, satisfying all con*straints, can be easily defined.*

6.2. Speed Control

This problem corresponds to the problem defined in step 2). In fact, since we suppose that the altitude levels are the nominal ones or those computed in step 1), the control action carried out in step 2) is equivalent to the control of the plane speed. The problem, thus stated, is a linear programming one with mixed variables. To solve it we have suggested a hybrid algorithm that utilizes dynamic programming and a branch and bound technique. Dynamic programming is used to transform a problem with mixed variables into a problem with only discrete variables. The latter is then solved by an enumerative procedure.

An important aspect of this method is that, since no discretization of the continuous variables t_k is necessary, the optimal solution can be reached.

Fig. 4 represents the basic structure of the algorithm here illustrated, while in fig. 5 a complete scheme of route-time profile generation system is showed.

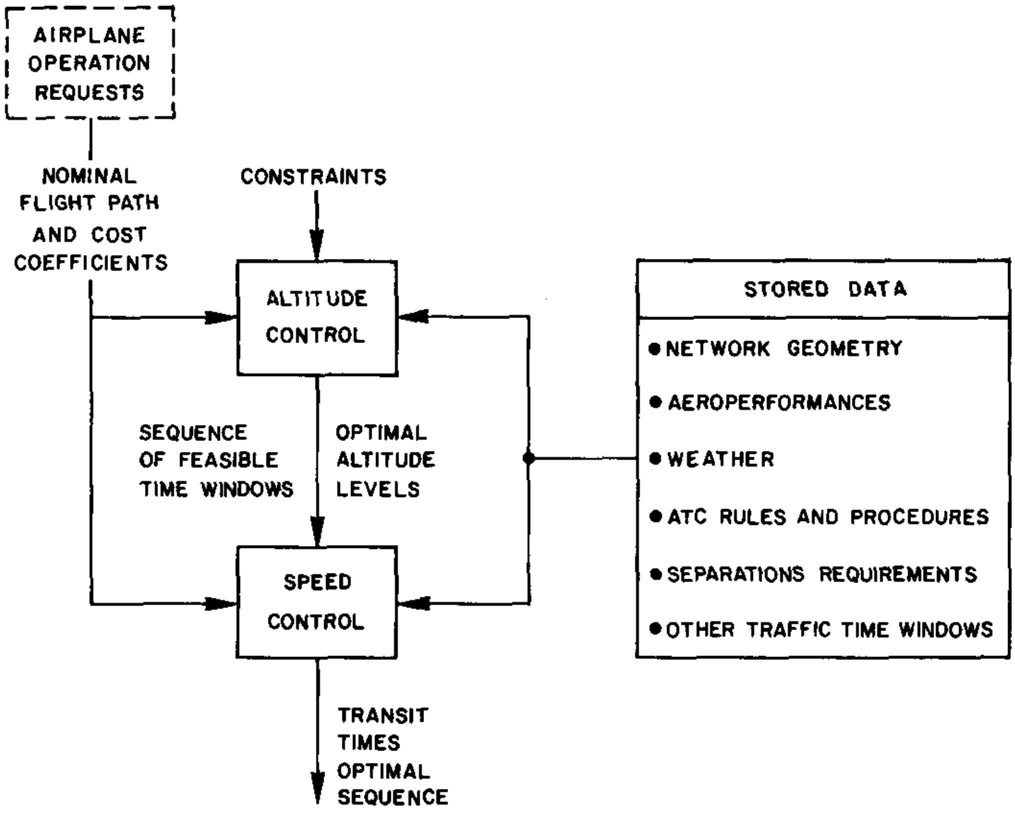

Fig. 4-STRATEGIC CONTROL ALGORITHM STRUCTURE

7. COMPUTATIONAL TESTS

The algorithm previously described, has been implemented on a UNIVAC 1100/82 computer and different series of tests have been performed. More in detail, in a first step, the altitude levels have been determined; subsequently, transit time on the prefixed nodes have been computed.

With this approach the altitude levels and the consistent time windows, determined in the first step, are utilized as input data for the second.

Numerical tests were carried out by considering an increasing number of nodes N = 5, 10, 15, 17, 20 for a total of 400 tests.

For each test the values of all parameters have been chosen uniformly distributed over fixed intervals, by imposing appropriate limits to ensure reciprocal consistency and operational meaningfulness. The results are fully reported in Table 1 where, for each value of N, the most significant computation times are indicated. In particular, t_a is the time required to determine altitudes and it coincides with the time necessary to find the first global feasible solution; t_0 is the time relative to the optimal solution and t_g is the global computation time.

Number of nodes	5	10	15	17	20
Number of tests	150	110	100	40	10
t_a (sec)	.014	.27	6.2	17	102
t_0 (sec)	.014	.27	7.2	17	102
t_g (sec)	.014	.37	7.4	19	112

TABLE 1

The results show that the suggested approach can be used to solve real-time problems until the number of nodes of trajectory is less than 20. For N = 20 the algorithm behaviour begins to look unsatisfactory.

However, one must notice that computation times strongly depend both on the number of nodes N and on the number of feasible windows corresponding to the various levels. This indicates that the tests mostly increasing the mean computation times, are those that simulate traffic congestion situations which happen only in special operational conditions.

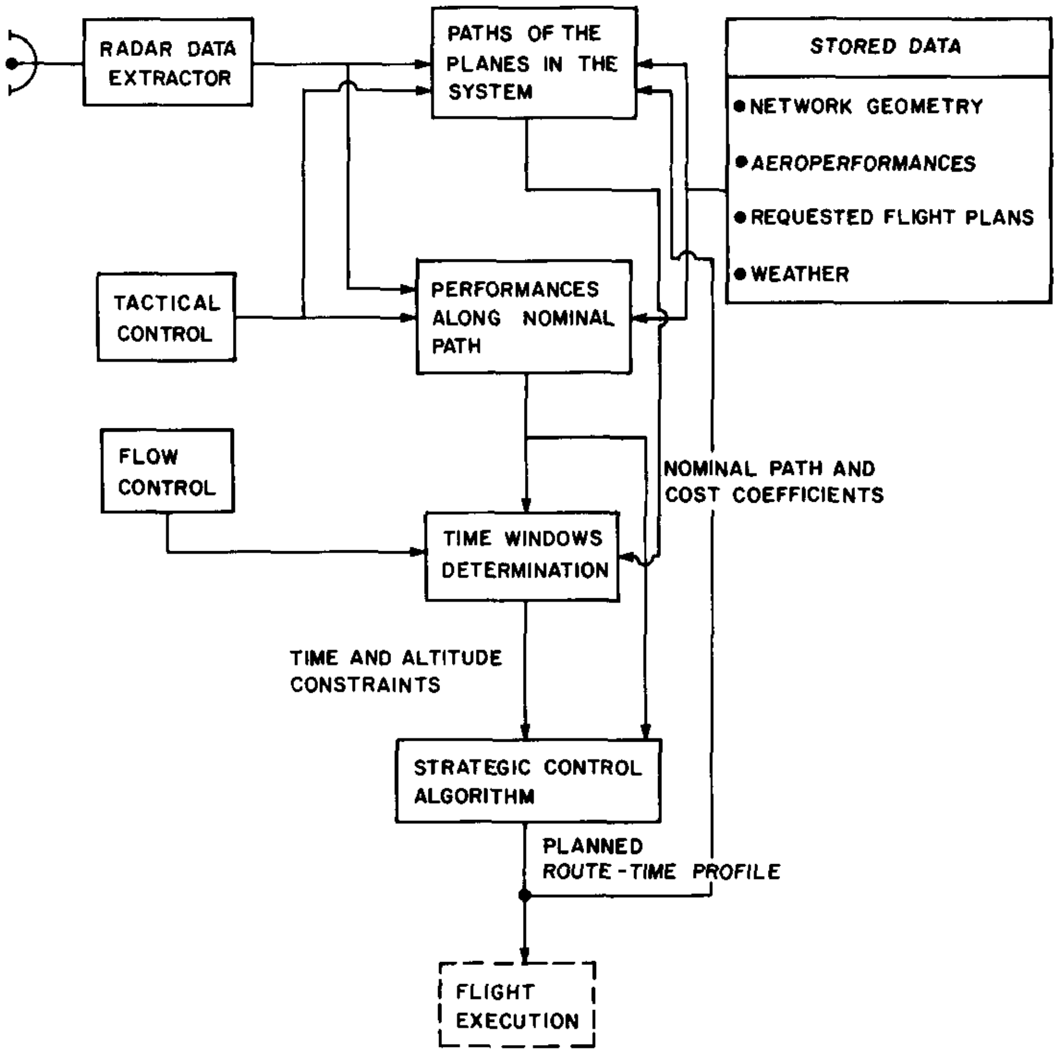

Fig. 5 - ROUTE-TIME PROFILE GENERATION SYSTEM

8. CONCLUSIONS

To sum up we can say that, even if different meanings are associated with the term "strategic control" and complete studies do not exist, there is a general agreement on the necessity of introducing a planning function in ATC systems. Presently, the main advantages that can derive from a strategic control approach, are:

- reduction in overall flights delay;
- reduction in fuel consumption;
- reduction in human workload;
- increase in the use of system capacity;
- increase in system safety.

Regarding the first two issues it is useful to point out that the strategic function may allow more regular traffic flows and (ideally for all aircraft) more economic flight paths. Consequently, a reduction both in flight delay and in fuel consumption can be obtained. One must also observe that a significant fuel saving can result from a reduction in holding times. In fig. 6 some fuel consumptions figures related to 10-minutes holding are shown. Morevover *we must also consider that, for a given delay, the related cost diminishes* the more its forecasting is anticipated (see fig. 7).

With regards to human workload, strategic control can reduce the work of controllers and pilots. In fact, a better planning of flights and the possibility of automatic generation of the flight profiles, should lead to a reduction in tactical interventions.

A better exploitation of system capacity is based on a more accurate traffic allotment due to strategic planning. Moreover, it is worthwhile remarking that all the described phenomena have, directly or indirectly, a positive effect on system safety.

A quantitative evaluation of the whole economical advantages which can come from the introduction of strategic control has been made in [7] with reference to annual traffic of Los Angeles Airport. The estimation forecasts a saving from 40 million dollars (1972) to 1,500 million dollars in (1995).

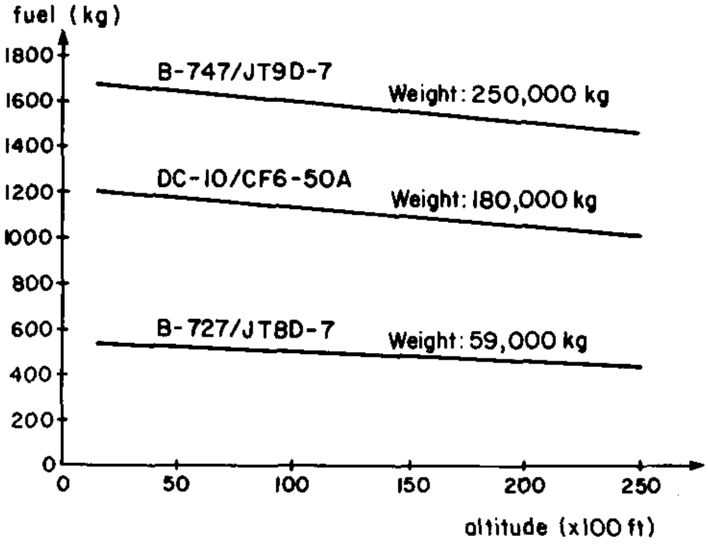

Fig.6 - FUEL PENALTY RESULTING FROM A 10-MIN HOLDING.

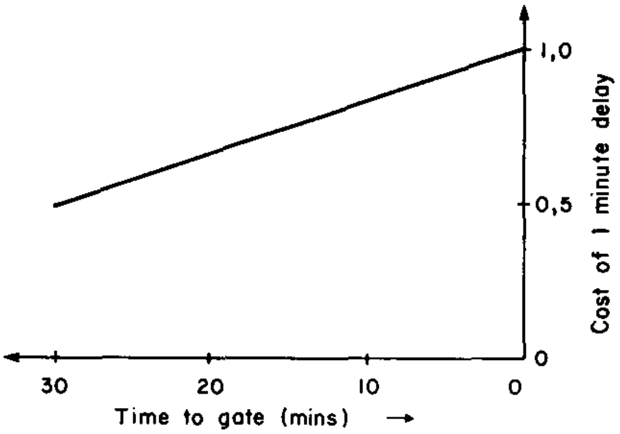

Fig. 7 - COST OF DELAY.

Nevertheless, we must admit that the implementation of a strategic control function is not easy in that it depends on numerous political, technological and methodological conditions.

In fact, a first consideration is that the effectiveness of planning action is as much significant as large is the region considered. From this follows that, generally, controlled air space interests different nations and requires a political and normative coordination taking into account different air space characteristic and traffic needs.

With regard to the technological aspects, the possibility of implementing any kind of planning function in the ATC system, as already mentioned, depends on the development of the subsystems of navigation, communication, surveillance and information processing.

Finally, as far as the methodological aspects are concerned, we need to have both mathematical models, able to descrive more adequately the system behaviour, and reliable solution methods that use optimization techniques. This work intends just to help in this last direction. However, a real use of the developed model and solution algorithm involves preliminarily an adequate testing in the operational environment and also a carefull evaluation of the human aspects in that strategic control involves modifications in the duties and responsibilities of the controllers and pilots.

REFERENCES

1. *U.S. Department of Transportation:* Fourth Generation Air Traffic Control Study, 1972, Report n. DOT-TSC-304 - 1
2. W.B. COTTON: Formulation of the Air Traffic System as a Management Problem, IEEE Trans. on Communications, Vol. COM-21, n. 5, May 1973, 375-381.
3. R.L. MAXWELL: The Advanced Air Traffic Management System Study. Proc. 19th *IATA Technical Conference, Dublin,* October 1972, Conf. 19/WP-16.
4. A. BENOIT et al.: Study of Automatic Conflict Detection and Resolution in Air Traffic Control Planning. 7th ICAS Congress, Rome, Sept. 1970.
5. A. BENOIT et al.: An Evolutionary Application of Advanced Flight Path Prediction Capability to ATC. Proc. Intern. Conference on Electronic Systems and Navigation Aids., Paris, Nov. 1977, 61-69.
6. A.J. FOSSARD, N. IMBERT: Hierarchical Approach to the Air Traffic Control Problem. "Large Scale System Engineering Applications", North Holland, 1979, 297-236.
7. R.L. ERWIN et al.: Strategic Control Algorithm Development. U.S. Department of Transportation, 1974, Report n. DOT-TSC-OST-74-3, Vol. I - IV.
8. R.L. ERWIN: Strategic Control of Terminal Area Traffic. AGARD Conference Proceedings n. 188. Plans and Developments for Air Traffic Systems, 1975, 3-1, 3-13.
9. R.M.SOWARD: Some Trends in Air Traffic Control. Proc, 19th IATA Technical Conference, Dublin, October 1972, Conf. 19/WP-47.
10. S. RATCLIFFE: Principles of Air Traffic Control, 1975, AGARD AG-209, Vol. I, 5-19.
11. L. BIANCO, M. CINI, L' GRIPPO: Pianificazione e Controllo Strategico del Traffico Aereo. CSSCCA-CNR and Istituto di Automatica, University of Rome, 1978, R. 78-28.
12. L. BIANCO et al.: New Approaches to Air Traffic Control Management. Transport Research for Social and Economic Progress, London, S. Yerrel, 1981, Vol. 4, 2373-2384.
13. L. BIANCO, M. CINI, L. GRIPPO: A Strategic Approach to Air Traffic Control. 9th IFIP Conference on Optimization Techniques, Varsaw, September 1979. Lecture Notes in Control and Information Sciences, Springer Verlag, 1980, 345-355.
14. G. ANDREUSSI, L. BIANCO, M. CINI, L. GRIPPO: Un Approccio Strategico per il Controllo in Linea del Traffico Aereo. IASI-CNR, 1981, RI-7.
15. L. BIANCO: A Multilevel Approach to the ATC Problem: the on-line Strategic Control of Flights. Seminar CEE-CNR-PFT on Informatics in Air Traffic Control, Capri, October 1985.

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CP-410

A TIME-BASED CONCEPT FOR TERMINAL-AREA TRAFFIC MANAGEMENT

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ABSTRACT

This paper describes an automated air-traffic-management concept that has the potential for significantly increasing the efficiency of traffic flows in high-density terminal areas. The concept's implementation depends on techniques for controlling the landing time of all aircraft entering the terminal area, both those that are equipped with on-board four-dimensional (4D) guidance systems as well as those aircraft types that are conventionally equipped. The two major ground-based elements of the system are a scheduler which assigns conflict-free landing times and a profile descent advisor. Landing times provided by the scheduler are uplinked to equipped aircraft and translated into the appropriate 4D trajectory by the on-board flight-management system. The controller issues descent advisories to unequipped aircraft to help them achieve the assigned landing times. Air traffic control simulations have established that the concept provides an efficient method for controlling various mixes of 4D-equipped and unequipped, as well as low- and high-performance, aircraft. Piloted simulations of profiles flown with the aid of advisories have verified the ability to meet specified descent times with prescribed accuracy.

1. INTRODUCTION

After years of research, automation of air traffic control (ATC) procedures remains a distant goal. While much progress has been made in the processing and display of information for controllers, the major decision and control functions involved in managing traffic continue to be done in the traditional way by teams of controllers who work without significant computer assistance. This situation contrasts sharply with the situation of the pilot of a modern aircraft who uses numerous automated systems for guidance, control, and navigation, including automated flight-path management.

At first, problems in ATC automation often do not appear to be more difficult than typical aircraft guidance and control problems that have been successfully solved. But then, after some promising initial successes, unforeseen problems surface and reach unmanageable complexity as more and more practical constraints are included, leading to the eventual abandonment of the effort. Yet the need to increase safety, capacity, and fuel efficiency, and to reduce controller workload in a period of rising traffic density provides a continued impetus for developing practical solutions to ATC automation problems.

Much of the difficulty in designing automated ATC systems stems from the complex and ever-changing air traffic environment. Whereas controllers usually can adapt to such an environment, automated systems have so far lacked the flexibility to adapt to it. For example, automated systems must be able to handle a range of aircraft types, from high-performance jets to low-performance, general-aviation aircraft. Furthermore, the systems must allow future aircraft equipped with four-dimensional (4D), flight-management systems to fly their optimized flight profiles while efficiently controlling aircraft with conventional avionics (referred to as unequipped aircraft). Finally, the systems must provide an intelligent interface so the decisions of the automated system can be supervised by the controller.

This paper describes an automated concept for traffic management in the terminal area that has the potential for meeting the design objectives and constraints just discussed. The design evolved from a series of studies in 4D guidance and ATC simulations conducted at NASA Ames Research Center during the past 10 years. The viability of the concept hinges on techniques which accurately control the landing times of all aircraft entering the terminal area, not just 4D-equipped aircraft. The advantage of a system based on time control is that it provides a unified framework for automating flow control and for scheduling and spacing all types of traffic. Furthermore, this time-based system is ideally suited to exploit the time-control capabilities of future 4D-equipped aircraft, whose population in the traffic mix is expected to increase steadily.

The paper begins with an overview of the concept, followed by a review of results from controller-interactive simulations of an initial design. These simulations have shed light on the question of how acceptable the various automated procedures and computer aids are to controllers and how suitable the concept is for controlling a mix of aircraft (e.g., that are equipped and unequipped, high performance and/or low performance). Finally, the design and the piloted-simulator evaluation will be described for an algorithm for controlling the landing time of unequipped aircraft--a crucial element of the concept.

2. OVERVIEW OF TRAFFIC-MANAGEMENT SYSTEM

Fig. 1 shows the major elements of the terminal-area-traffic-management system that is being studied at Ames Research Center. The two major ground-based elements of this system are primarily embodied in two computer algorithms referred to as the scheduler and the 4D profile descent advisor. The airborne elements are aircraft equipped with 4D flight-management systems and unequipped aircraft.

The scheduler generates the landing order and the conflict-free landing times for all aircraft, both 4D-equipped and unequipped. Primary input to the scheduler is the list of arrivals and their estimated arrival times at the entry point into the extended terminal area. Entry points, also known as feeder fixes, generally are located near the end of cruise flight just prior to the descent point, which

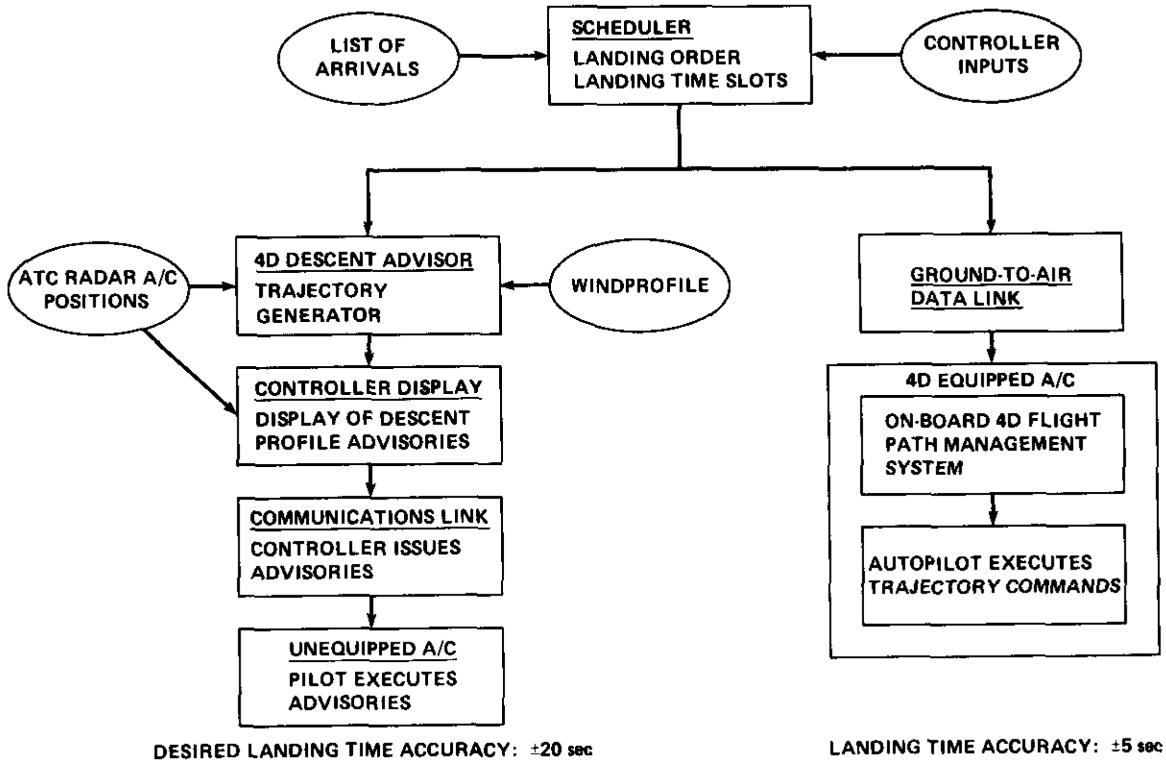


Fig. 1. Terminal-area traffic management system.

is about 120 n.mi. from the destination runway for conventional jet-transport aircraft. The most important factors considered by the scheduler in generating efficient landing times are the minimum separation times between aircraft and the landing-order criterion, as exemplified by the first-come-first-served rule.

The minimum time separations between aircraft are derived from the minimum-distance separation rules specified by the FAA and given in Table 1. These separation rules depend on aircraft weight class (small, large, and heavy) and the landing sequence. By combining the data in Table 1 with the known speed profiles of each aircraft weight class along the common final-approach path, the matrix of minimum time separation (Table 1) can be calculated. *If two consecutive aircraft are* 4D-equipped, the interarrival times given in Table 1 are used directly for scheduling purposes. However, unequipped aircraft, which cannot achieve specified landing times as accurately as 4D-equipped aircraft, are given additional time buffers to prevent separation-distance violations. Further discussion of this subject can be found in Ref. 1.

The scheduler is designed as a real-time expert system that provides for efficient interaction with a human controller. The controller monitors the time assignments of the scheduler on a graphics terminal and can override its ordering and time-assignment decisions by using a small, but flexible, list of commands. For example, controllers can delay traffic at the feeder fixes or increase the time separation if delays are being encountered in the terminal area. *Also, they can overrule the built-in* first-come-first-served rule to give landing time priority to a missed approach or emergency aircraft (Ref. 2).

The landing times generated by the scheduler are handled in one of two ways depending on whether the times apply to a 4D-equipped or unequipped aircraft. The times are *assumed to be uplinked auto*matically to equipped aircraft where the on-board 4D flight-management system translates time commands into the appropriate 4D-trajectory commands. The autopilot then flies the aircraft according to these commands, achieving a landing-time accuracy of about ±5 sec (Refs. 3,4).

Table 1. Distance- and time-separation rules

		Trailing Aircraft					
		Minimum separation distance (n.m)			Minimum separation time (sec)		
Aircraft Type		Small	Large	Heavy	Small	Large	Heavy
First to land	Small	3	3	3	98	74	74
	Large	4	3	3	138	74	74
	Heavy	6	5	4	167	114	94

The landing times for the unequipped aircraft constitute the primary input to the 4D profile descent advisor whose algorithms reside in the ATC host computer or in a minicomputer linked to the host. By using ATC radar-tracking data, wind profiles and aircraft performance models, the descent advisor generates simplified 4D trajectory commands which are displayed on the arrival controller's monitor as brief controller advisories. The arrival controller then issues the advisories to the pilot of the unequipped aircraft. When the pilot properly executes these advisories, the unequipped aircraft will arrive at the designated time-control point within acceptable error bounds. The arrival-time accuracy of the unequipped aircraft should be a reasonably small fraction of the minimum interaircraft arrival times given in Table 1 in order that the benefits of a time-based system be fully realized. This requirement led to the choice of ±20 sec as the desired accuracy.

3. ATC SIMULATIONS OF MIXED TRAFFIC

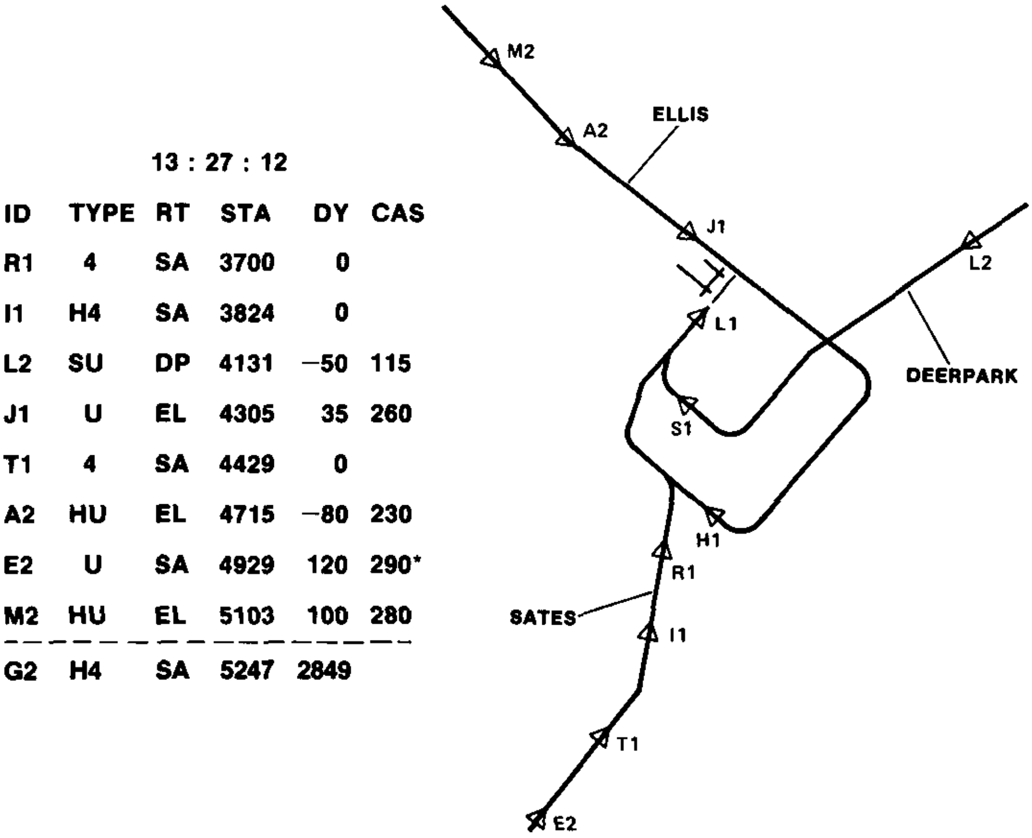
The terminal-area traffic-management concept described in the previous section has been evaluated and its design refined in a series of real-time, controller-interactive, ATC simulations. For this purpose an extensive set of software tools and simulation techniques were developed to permit the study of time-based ATC concepts under reasonably realistic conditions. Special features incorporated in the simulator include algorithms for on-board, 4D-guidance and ground-based, speed-advisory systems and interactive scheduling logic with associated graphics displays (Ref. 5).

Examples of critical issues that have been addressed in simulations are the following: 1) Effect of percentage of 4D-equipped aircraft in the traffic mix on controller workload and landing rate; 2) effectiveness of speed advisories; 3) controller procedures for handling 4D-equipped aircraft; and 4) rescheduling of missed-approach aircraft. A complete discussion of simulation results can be found in Refs. 2 and 6. The simulation scenario and controller procedures will briefly be described first.

3.1 Scenario and Controller Procedures

The terminal area simulated in these studies is based on the John F. Kennedy (JFK) International Airport in New York. The route structure and runway configuration together with information used by the controllers are shown in Fig. 2. Two routes, Ellis from the north and Sates from the south, are high-altitude routes flown by large or heavy jet-transport aircraft. Both 4D-equipped and unequipped aircraft on these routes fly profile-descent, fuel-conservative procedures, providing a mix of the same speed class on the same route. Low-performance (general-aviation) aircraft fly the Deerpark route from the east, but use the same final approach and land on the same runway as the jet traffic. The Deerpark traffic is unequipped and always constitutes 25% of the traffic mix.

In these simulations aircraft entered the extended terminal area at the feeder fix points flying at cruise speed and altitude. The total distance to be flown by high-performance jets was 120 n.mi. and that flown by low-performance aircraft was 60 n.mi. Two air traffic controller positions were established, arrival control and final control. The arrival controller controlled aircraft from all three feeder fixes and transferred traffic to the final controller at approximately 30 n.mi. from touchdown.



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ID	TYPE	RT	STA	DY	CAS
R1	4	SA	3700	0	
I1	H4	SA	3824	0	
L2	SU	DP	4131	−50	115
J1	U	EL	4305	35	260
T1	4	SA	4429	0	
A2	HU	EL	4715	−80	230
E2	U	SA	4929	120	290*
M2	HU	EL	5103	100	280
G2	H4	SA	5247	2849	

Fig. 2. Controller display showing route structure and flight-data table.

Control procedures differed for 4D-equipped and -unequipped aircraft. Controllers were instructed to monitor the progress of 4D-equipped aircraft after the time assignment had been established, and to override the automated scheduler only if necessary to ensure safe separation. Any 4D-equipped aircraft could also be controlled by conventional methods and treated as unequipped. Alternatively, a 4D-equipped aircraft which had been taken off its 4D route and time schedule could be given a waypoint to recapture a 4D route and be given a revised landing time. Unequipped aircraft were considered to be navigating in the conventional manner via very-high-frequency omnidirectional range procedures, with altitude clearances, radar vectors, and speed control.

A typical arrival controller display is shown in Fig. 2. The map portion of the display provides a horizontal display of traffic in the terminal area. Each aircraft position is shown by a triangular symbol. A block of data next to each aircraft (not shown here for simplicity) provides aircraft identification, type, altitude, and speed. The information in the flight data table in the upper-left portion of the display is generated by the scheduler and speed advisory system. At the top of the table, the time is shown in hours, minutes, and seconds. The first column shows the aircraft identification (ID), such as "R1." The second column provides aircraft type (TYPE) which includes 1) weight category (small (S), large (blank), or heavy (H)); and 2) 4D status (equipped (4) or unequipped (U)). The third column provides the assigned route (RT). The fourth column is the scheduled time of arrival (STA) at the runway in minutes and seconds. Thus, R1 is scheduled to touch down at 13:37:00. Note that touchdown times are shown for all aircraft, whether they are 4D-equipped or unequipped. For the 4D-equipped aircraft, these times are assigned by the ground-based computer system. For the unequipped aircraft, the time assignments are not given to the pilot directly; rather, the controller uses speed advisories and the known-to-be-on-time positions of 4D-equipped aircraft as they traverse their routes to achieve touchdown at the times indicated. The next column is the expected delay (DY) at touchdown in seconds. In an effort to simulate the characteristics of the current en route ATC system, which does not provide accurate time control, the unequipped aircraft were assumed to depart their feeder fixes with an initial time error uniformly distributed in the range ±120 sec. This amount is considered rather large even by today's controller experience and certainly will be less with a future en route metering system. Thus, if an aircraft departed the feeder fix 90 sec late, a DY of 90 would be displayed, indicating that unless controller action was taken, the aircraft would touch down 90 sec late. Early arrivals were indicated by a negative value in the DY column, and late arrivals by a positive value. All 4D-equipped aircraft departed the feeder fix at the scheduled departure time. In flight tests, it has been shown that 4D-equipped aircraft can meet time schedules within ±5 sec; hence, these small errors were neglected (Refs. 3,7).

The data in the last column give the calibrated airspeeds (CAS) in knots, computed by the speed advisory system. These speed advisories, which are based on current aircraft position, altitude, and wind profile, help the controller to correct the unequipped aircraft's time errors shown in the DY column. The speed advisory is recomputed once per minute using the current aircraft position as long as the delay remains larger than 20 sec. This feature gives the arrival controller the freedom to issue the advisory at a convenient time.

The speed advisory incorporated in the ATC simulation is a simplified early version of the more recently developed descent-advisor algorithm, which is detailed in a later section. It will be seen that the new algorithm also provides top-of-descent-point and Mach number advisories in addition to the CAS advisory. However, for investigating controller response and other ATC-related issues the speed advisory system used provides a sufficiently realistic substitute.

Finally, aircraft below the dotted line in Fig. 2 are aircraft which will enter the simulated control region at their respective feeder fixes within the next 5 min. The feeder-fix start times are given in minutes and seconds.

3.2 Summary of Results

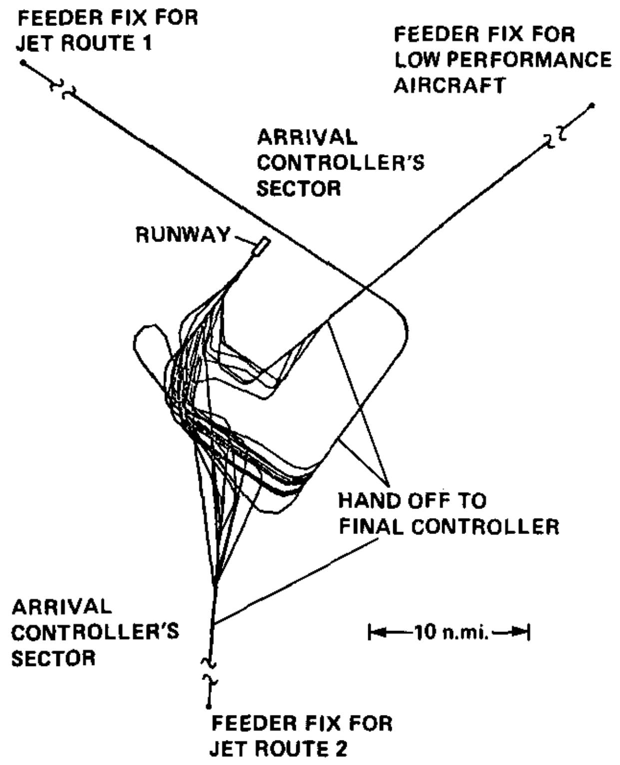
The traffic mixes examined in simulation runs, each lasting 1.5 hr, were 0%, 25%, and 50% 4D-equipped aircraft. For each mix, the total arrival rate from the three approach routes was selected to generate a full landing schedule with no excess time gaps between touchdown. This condition required arrival rates that varied from 30 aircraft/hr for the 0% or baseline mix to 33 aircraft/hr for the 50% mix. The variation is due to the time separation buffers added for the unequipped aircraft. All runs included the ±120-sec feeder-fix departure errors for unequipped aircraft.

Controllers rated all mixes as having acceptable workload, but considered the 25% mix without speed advisories the most difficult to control. This result was probably related to the controller procedures adopted for this experiment of not disrupting the planned 4D paths of the equipped aircraft unless it was necessary for safety. As a consequence, the final controller occasionally vectored an unequipped aircraft to control its distance spacing from an equipped aircraft when he would have preferred under the circumstances to vector the equipped aircraft. One solution to this problem that will be examined in future simulations is a relaxation of the "do not disrupt" rule. Then, after vectoring an equipped aircraft, the controller would assign a new 4D route and landing time to that aircraft. Some experience with this approach was recently obtained in handling missed approaches of equipped aircraft (Ref. 2).

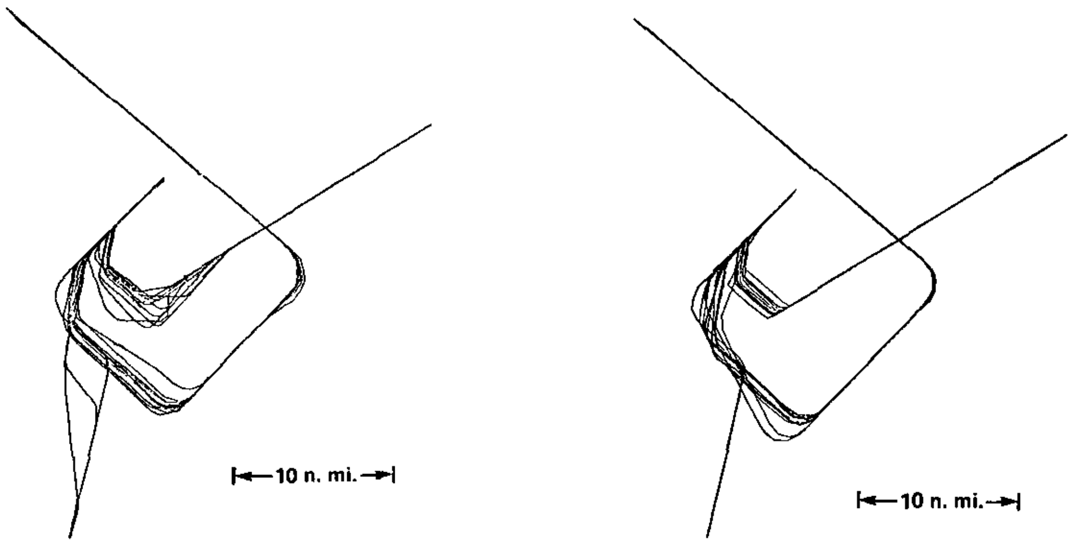
Controllers regarded the baseline mix of 0% as reasonable with respect to control difficulty, but not because of lightened workload. Rather it was the most familiar mode of operation. The controllers regarded the 50% mix as easiest to control.

Under all mix conditions, controllers found the landing order provided by the flight-data table in Fig. 2 to be helpful and generally accepted the suggested ordering. But they did not make use of the numerical landing-time data.

Further insight into the simulation results can be obtained by examining the composite plot of aircraft ground tracks generated during a 1.5 hr simulation run. Such a plot is shown in Fig. 3a for



(a) 25% 4D equipped; no speed advisories for unequipped.



(b) 25% 4D equipped; speed advisories for unequipped.

(c) 50% 4D equipped; speed advisories for unequipped.

Fig. 3. Composite trajectories from ATC simulation.

the 25% mix without speed advisories. In the arrival sector, from the feeder fixes to the hand-off points, the flightpaths are largely undisturbed, indicating that the arrival controller acted primarily as a traffic monitor. After the hand-off points, the flightpaths spread into the broad envelope which characterizes manual vectoring. This spreading is the result of the final controller issuing heading vectors that cause unequipped aircraft merging from the three routes to be properly spaced on final approach. Although the arrival controller had available the scheduled landing times for the unequipped traffic, he could not use this information to correct spacing errors before the hand-off point. Evidently, aircraft are still too far from the merge point for the arrival controller to anticipate future spacing errors. As a result, control difficulty and workload were unevenly distributed between the two control positions, with the final control position requiring higher skill and greater workload than the approach control position.

A composite plot for the 25%-mix condition, in which speed advisories were used, is shown in Fig. 3b. The advisories were issued by the approach controller shortly after unequipped aircraft with time errors exceeding 20 sec departed the feeder fixes. Typically, only one advisory was issued per aircraft. The unequipped traffic was handed off to the final controller with significantly reduced time errors. As a consequence, the final controller needed to make only minor adjustments in the flightpaths to achieve the desired spacing. The resulting improvement in the traffic flow manifests itself as a reduction in the spread of flightpaths along all three routes. Furthermore, controllers commented that speed advisories resulted in less bunching of traffic and fewer "ties" in the merging area. Traffic seemed to blend together smoothly and required fewer vectors, resulting in reduced complexity of control.

The 50% mix with speed advisories was rated by controllers as providing the most desirable control environment of all conditions evaluated. The controllers commented that it was easy to fit the unequipped aircraft into their planned time slots by vectoring or speed control in the final control sector. One controller stated that he could work and stay on top of the traffic without being overtaxed. These favorable controller evaluations are reflected in the well-ordered and narrowly distributed composite-trajectory plots (Fig 3c) obtained for this simulation run.

In conclusion, the procedures, computer assists, and information displays used in these simulations established a workable baseline configuration for efficiently controlling a mix of 4D-equipped and unequipped aircraft in a time-based environment.

4. DESIGN AND SIMULATION OF 4D-PROFILE-DESCENT ADVISOR

The following sections present the theory of design and the results of a piloted simulation of the descent advisor algorithm. The primary topics covered in the discussion of the design include selection of descent procedures, derivation of the aircraft equations of motion, the method of numerical integration, and an example output from the computer implementation of the algorithm.

4.1 Selection of Descent Profiles

The trajectories generated by the descent-advisor algorithm are based on models of fuel conservative procedures used in airline operations. In such procedures the pilot first selects the point of descent using a simple rule of thumb to estimate the idle-thrust descent distance. A rule frequently used by pilots assumes 300-ft altitude loss/n.mi. Choosing the point of descent so as to minimize level flight at low altitude is probably the pilot's most important decision for optimizing fuel efficiency. At the point of descent, the pilot reduces thrust approximately to idle and at the same time commands a pitch-down attitude so as to hold Mach number fixed at the cruise value. Thrust may be kept slightly above the idle position if there is a requirement not to exceed a descent-rate limit, typically 3000 ft/min. During this constant Mach descent, CAS will increase steadily. When CAS has climbed to a desired value the pilot ceases holding the Mach number and begins tracking the desired CAS through appropriate adjustments to the pitch attitude. As the aircraft approaches an altitude of 10,000 ft, the pilot reduces the descent rate briefly to decelerate to 250 knots calibrated airspeed (KCAS) as required by ATC regulation. If the initial descent point had been selected properly, the aircraft will be 30 n.mi. from touchdown at the end of the deceleration and the pilot will resume the descent into the terminal area.

The primary function of the descent-advisor algorithm is to select the speed profile that achieves the arrival time specified by the scheduler. A secondary function of the advisor is to provide an accurate estimate of the point of descent to optimize fuel efficiency. Later it will be seen that the algorithm accomplishes both functions in a unified computational procedure.

The algorithm selects the speed profile with the help of a parameter, σ , which determines a Mach number and CAS that falls within the speed envelope of the aircraft as follows:

$$M = M_{min} + \sigma(M_{max} - M_{min}) \; ; \qquad 0 \le \sigma \le 1 \tag{1}$$

$$V_{CAS} = V_{min} + \sigma(V_{max} - V_{min}) \tag{2}$$

The family of speed profiles generated by Eqs. (1) and (2) are superimposed in Fig. 4 upon the speed envelope of a 727 aircraft. Note that the maximum-speed boundary contains a corner at 25,000 ft where

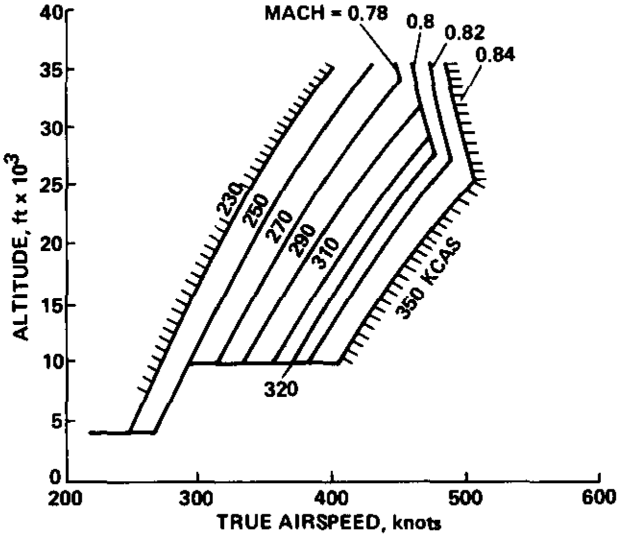


Fig. 4. Speed profiles for time control.

the maximum Mach number and maximum CAS boundaries intersect. The family of speed profiles generated by Eqs. (1) and (2) converges into this corner as σ approaches 1, thereby covering the full-speed envelope of the aircraft.

The relationship between the parameter, σ , and the arrival time at the 30 n.mi. from touchdown point is not amenable to a closed-form solution, since there are complex aerodynamic, propulsion, and atmospheric models embedded in the relationships. Thus, a procedure that computes σ iteratively has been developed. Initially, the procedure calculates the minimum and maximum arrival times by setting σ to one and zero, respectively. If the specified time falls within the feasible time range, iteration on σ by a directed trial and error technique is begun and continues until the arrival-time error falls within acceptable bounds (for example, 2 sec). Experience has shown that five iterations are generally sufficient to achieve a 2-sec accuracy. The next section will describe the equations of motion that must be integrated for each iteration of σ. (Ref. 4).

For reasons of brevity, the speed-profile selection process just described has been considerably simplified compared to the method actually implemented in the computer algorithm. The computer algorithm includes a more complicated mapping of σ into profiles that provides an appropriate transition from the cruise Mach number to the descent Mach number. It also eliminates constant Mach segments in the speed profile if the descent CAS is less than the cruise CAS.

4.2 Equations of Motion

Numerical integration of a simplified set of point-mass equations of motion has been adopted as the basic method for calculating the descent trajectory and arrival time corresponding to a given speed profile. This method is computationally intensive, but it is more flexible and more accurate than schemes that depend on analytical approximations or precomputations of trajectories. Here, no restrictive assumptions on pilot procedures, wind profiles, or aircraft performance models need be made in calculating trajectories. Potentially, it would even be possible to include the preferred procedures of individual airlines in the calculations of the descent trajectories.

To begin with, it is assumed that the aircraft is flying along a known horizontal path in space. Therefore, the problem simplifies to finding the vertical profile along the known horizontal path. Furthermore, the horizontal path is assumed to be a straight line, though it is easily modified to include curved segments. Using an Earth-fixed coordinate system with x as the horizontal axis pointing in the flight direction and h as the upward-pointing vertical axis, the components of inertial velocity u and w that must be integrated are

$$\frac{dx}{dt} \equiv u = V_T \cos \gamma_a + u_w \equiv F_1 \tag{3}$$

$$\frac{dh}{dt} \equiv w = V_T \sin \gamma_a \equiv F_2 \tag{4}$$

where V_T is the true airspeed, γ_a the aerodynamic flightpath angle and u_w the horizontal component of wind. The airspeed acceleration is calculated from the following equations:

$$\frac{dV_T}{dt} = \frac{(T - D)}{m} - g \sin \gamma_a - \frac{du_w}{dt} \tag{5}$$

$$mV_T \frac{d\gamma_a}{dt} = L - mg \cos \gamma_a \approx 0 \tag{6}$$

where T is thrust, D is drag, L is lift, m is aircraft mass, and g is acceleration of gravity. The approximation in Eq. (6) implies that accelerations normal to the flightpath are considered to have negligible effect on trajectory modeling for this application. This assumption is valid for the low-g maneuvers encountered in commercial transport operations. The value of lift computed by solving the algebraic Eq. (6) couples into Eq. (5) through the dependence of drag on lift. The last term in Eq. (5) reflects the influence of a time-dependent wind, also known as wind shear, on the airspeed acceleration. On the time and distance scale of a descent trajectory it is reasonable to assume that wind shear is only encountered during changes in altitude, implying the relationship $u_w(h)$. The drag coefficient involved in calculating the drag force was represented by seven fourth-order polynomial functions, each representing a different Mach number in small increments from Mach 0.6 to 0.9. Both tables and polynomial functions were used to model the thrust and the fuel flow as a function of engine-pressure ratio (EPR), Mach number, temperature, and pressure. Idle thrust and fuel flow were stored in separate tables indexed by Mach number and altitude. Such aircraft performance models must be developed for all major aircraft types that operate into the terminal area where the descent advisor is used to provide time control.

Another important quantity that the descent advisor uses in computing trajectories is aircraft mass. An adequate estimate of mass can be calculated from a knowledge of aircraft type, point of origin, and takeoff mass. Such information is generally contained in aircraft flight plans or can be obtained from the pilot at take-off time.

4.3 Constant Mach/Constant CAS Segments

In modeling the speed profile it was shown that pilots maintain either a constant Mach number or a constant CAS during the majority of an aircraft's descent into the terminal area. This assumption can be used to reduce the differential equation for airspeed, Eq. (5), to an algebraic relation. Consequently, only the position rates, Eq. (3) and (4), need to be numerically integrated in such segments.

Considering first the constant Mach segment, one can write from the definition of Mach number

$$V_T = a(h)M \tag{7}$$

where a is the speed of sound, which is a function of altitude. Differentiating this equation with respect to time and using the fact that M is constant, yields

$$\frac{dV_T}{dt} = M \frac{da}{dh} \cdot \frac{dh}{dt} = M \frac{da}{dh} \gamma_a V_T \tag{8}$$

where use was made of Eq. (4) and $\sin \gamma_a \simeq \gamma_a$. After replacing the left side of Eq. (5) with the right side of Eq. (8) and calculating the wind shear term in Eq. (8) as $du_w/dt = (du_w/dh)\gamma_a V_T$, an explicit expression for γ_a is obtained as

$$\gamma_a\Big|_{M \text{ constant}} = \frac{(T - D)}{m} \cdot \frac{1}{\left(M \frac{da}{dh} V_T + g + \frac{du_w}{dh} V_T\right)} \tag{9}$$

where the small angle approximation, $\sin \gamma_a \simeq \gamma_a$ has been used. For a constant Mach segment at a known altitude, all quantities needed to compute γ_a are either known or measurable. The derivative da/dh must be computed by differentiation of the speed of sound function. If this function is obtained from a table of the standard atmosphere, the derivative can be precomputed numerically, curve-fitted for the range of altitudes of interest, and permanently stored for use by the program. However, the most accurate results will be obtained by calculating the speed of sound function from the temperature profile measured at the time and location of the descent. Calculation of the wind shear term, du_w/dh, depends on knowledge of the altitude-dependent wind profile in the descent airspace. The descent advisor must compute the derivative numerically and update the derivative whenever the wind profile is updated. Thus, each terminal area where the descent advisor is used will have to provide for measuring the wind profile at regular intervals during each day. Several technical means exist for measuring the wind profile including the use of conventional weather balloons. (Ref. 8).

Considering next the constant CAS segment, an expression for γ_a can be derived in a similar manner. One begins by writing the expression relating true airspeed and CAS

$$V_T = V_T(V_{CAS}, h) \tag{10}$$

The time derivative of Eq. (10) yields a relation analogous to that for the constant Mach case

$$\frac{dV_T}{dt} = \frac{dV_T(V_{CAS}, z)}{dh} \cdot V_T \sin \gamma_a \tag{11}$$

An explicit expression for $V_T(V_{CAS}, h)$ in terms of V_{CAS}, the speed of sound, a, and the atmospheric pressure, p, can be derived from expressions found in standard textbooks on aerodynamics and flight mechanics (Ref. 9)

$$V_T = a \sqrt{\frac{2}{\gamma_{air} - 1}\left[\left(\frac{p_{SL}}{p}\left[\left(\frac{\gamma_{air} - 1}{2\gamma_{air}} \frac{\rho_{SL}}{p_{SL}} V_{CAS}^2 + 1\right)^{\frac{\gamma_{air}}{\gamma_{air}-1}} - 1\right] + 1\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} - 1\right]} \tag{12}$$

where p_{SL} and ρ_{SL} are sea-level values of atmospheric pressure and air density, respectively, and γ_{air} is the specific heat of air. Since atmospheric pressure, p, and speed of sound, a, are known functions of altitude, h, the expression for V_T in Eq. 12 is in the form required by Eq. (10). However, the complexity of Eq. (12) makes it infeasible to compute the derivative of V_T with respect to h analytically for use in Eq. (11). Therefore, the derivative is computed by a standard numerical technique.

The expression for the flightpath angle in the constant CAS segment can now be obtained by combining Eq. (5) and (11)

$$\gamma_a\Big|_{CAS \text{ constant}} = \left(\frac{T - D}{m}\right) \frac{1}{\left(V_T \frac{dV_T}{dh} + g + \frac{du_w}{dh} V_T\right)} \tag{13}$$

The last question to be settled in computing γ_a is how to determine the thrust, T, in the two expressions for the flightpath angle. In a conventionally equipped aircraft pilots hold thrust more or less constant during descent by keeping the throttle levers at their idle position. However, if the idle throttle position results in an excessive descent rate during a portion of a descent, the pilot will adjust the throttles to maintain the descent rate at a specified limit. Since both specified-thrust and specified-descent-rate segments can occur under appropriate conditions, both have been implemented and the choice between them is determined by the constraints of the descent. If the descent rate, $\dot{h}$, is specified, γ_a is computed from the relation $\gamma_a \cong \dot{h}/V_T$ and Eq. (9) and (13) are solved for the unknown thrust. It should be noted here that a pilot cannot easily fly a commanded value of γ_a directly because no readout of this quantity is provided on conventional cockpit instruments.

It is of interest to evaluate the effect of the windshear term, $(du_w/dh)\cdot V_T$ on the descent profile. For example, a decreasing tail wind $(du_w/dh > 0)$ during descent results in a γ_a that is shallower than that for a constant wind. Thus, in this case, the descent trajectory experiences an expansion of the distance to descend from cruise altitude. The opposite effect occurs for a decreasing head wind. For a typical wind shear of 2 knots/1000 ft, the calculated distance to descend from 35,000 ft to sea level would be in error by 5 n.mi. if this term were neglected.

4.4 Integration Algorithm

A fourth-order Runge-Kutta scheme was adopted for the numerical integration of the trajectory equations (Ref. 10). This scheme gives accurate results with relatively large step sizes and also does not require evaluating derivatives of the complex functions appearing on the right-hand sides of the equations being integrated. The latter property simplifies the integration of functions specified in tabular form. For the constant Mach number and constant CAS segments, which constitute the majority of the descent, only Eqs. (3) and (4) need to be integrated, as previously explained. Letting Δt represent the time increment, then the states (x_{i+1}, h_{i+1}) at the $(i+1)^{st}$ time increment are determined from four sets of sequentially computed state increments as follows:

$$\Delta_1 x_i = (\Delta t) F_1(x_i, h_i, t_i) \tag{14}$$

$$\Delta_1 h_i = (\Delta t) F_2(x_i, h_i, t_i) \tag{15}$$

$$\Delta_2 x_i = (\Delta t) F_1(x_i + \frac{1}{2}\Delta_1 x_i, h_i + \frac{1}{2}\Delta_1 h_i, t_i + \frac{1}{2}\Delta t) \tag{16}$$

$$\Delta_2 h_i = (\Delta t) F_2(x_i + \frac{1}{2}\Delta_1 x_i, h_i + \frac{1}{2}\Delta_1 h_i, t_i + \frac{1}{2}\Delta t) \tag{17}$$

$$\Delta_3 x_i = (\Delta t) F_1(x_i + \frac{1}{2}\Delta_2 x_i, h_i + \frac{1}{2}\Delta_2 h_i, t_i + \frac{1}{2}\Delta t) \tag{18}$$

$$\Delta_3 h_i = (\Delta t) F_2(x_i + \frac{1}{2}\Delta_2 x_i, h_i + \frac{1}{2}\Delta_2 h_i, t_i + \frac{1}{2}\Delta t) \tag{19}$$

$$\Delta_4 x_i = (\Delta t) F_1(x_i + \Delta_3 x_i, h_i + \Delta_3 h_i, t_i + \Delta t) \tag{20}$$

$$\Delta_4 h_i = (\Delta t) F_2(x_i + \Delta_3 x_i, h_i + \Delta_3 h_i, t_i + \Delta t) \tag{21}$$

$$x_{i+1} = x_i + \frac{1}{6}(\Delta_1 x_i + 2\Delta_2 x_i + 2\Delta_3 x_i + \Delta_4 x_i) \tag{22}$$

$$h_{i+1} = h_i + \frac{1}{6}(\Delta_1 h_i + 2\Delta_2 h_i + 2\Delta_3 h_i + \Delta_4 h_i) \tag{23}$$

At the top and bottom of the descents rapid changes in speed occur, and neither Mach number nor CAS remain constant. During these acceleration or deceleration intervals it is also necessary to integrate Eq. (5) representing rate of change of airspeed. The incremental Eqs. (14) through (23) were augmented appropriately to integrate this equation.

The integration time increment, Δt, was experimentally selected to be as large as possible to consistently give accurate and numerically stable results. The optimum step sizes were 60 sec for the constant Mach/constant CAS segments and 30 sec for the acceleration/deceleration segments.

4.5 Example Descent Profile

This section gives an example of a complete descent profile generated by the program. The aircraft model used is that of a 727-200 weighing 140,000 lb at the start point. Initially the aircraft is cruising at Mach 0.8 and 35,000 ft and is 150 n.mi. from touchdown. The time-control point is located 30 n.mi. from touchdown at 10,000-ft altitude. At this point the aircraft must have completed its deceleration to 250 knots. A descent time of 985 sec, measured from the 150 n.mi. starting point to the end of the deceleration, is specified. The wind is assumed to be zero throughout the descent.

The synthesized trajectory consists of four segments whose parameters are given in Table 2. The first segment is a level-flight segment leading from the starting point to the point of descent at 98 n.mi. from touchdown. The second segment is a Mach 0.8 descent with EPR, which controls thrust, set to near idle (approximately 1). The third segment begins at 27,603 ft where Mach 0.8 corresponds to a CAS of 320 knots. In this constant CAS segment, thrust is held at idle. The fourth segment consists of deceleration from 320 to 250 knots at 10,000 ft. The last line of data in the fourth segment shows that the time and the distance to touchdown closely match the specified values. Various other parameters relating to the trajectory synthesis such as the number of integration steps in each segment and the fuel consumed are also included in the table.

In addition to achieving the specified descent time, the synthesized trajectory is also relatively fuel efficient, requiring only 1208 lb for all four segments. Good fuel efficiency is assured by the combined benefits of an idle-thrust descent and the choice of descent point that results in the termination of the trajectory exactly at the specified altitude and distance from touchdown.

4.6 Piloted Simulator Evaluation: Experimental Setup

An evaluation of the descent advisor concept was conducted on a so-called phase II simulator of a 727-200 aircraft located in the Man-Vehicle Systems Research Facility at Ames Research Center. This

Table 2. Example of synthesized profile

Comments	Time (sec)	Dist. (n. mi.)	Altitude (ft)	Mach	V_T (knots)	V_{CAL} (knots)	EPR	Thrust (lbs)	Fuel (lbs)	Alt Rate (ft/min)
	Cruise, two integration steps									
Step size = 500 sec	0.0	150.0	35000	0.80	461	272	1.95	9824	0	0
Capture = 98.4 n. mi	402.5	98.4	35000	0.80	461	272	1.95	9824	867	0
	Constant Mach, four integration steps									
Step size = 60 sec	402.5	98.4	35000	0.80	461	272	1.06	1597	867	0
Mach, constant	462.5	90.6	32000	0.80	467	291	1.09	2173	906	-3000
Vertical speed, constant	522.5	82.8	29000	0.80	473	310	1.13	2945	954	-3000
Capture = 320 KCAS	550.4	79.1	27603	0.80	476	319	1.14	3363	981	-3000
	Constant CAS, nine integration steps									
Step size = 60 sec	550.4	79.1	27603	0.80	476	319	1.00	73	981	-3000
CAS, constant	610.4	71.4	24665	0.76	455	319	1.00	-148	1008	-2912
EPR, constant	670.4	63.9	21781	0.72	436	319	1.00	-301	1035	-2854
Capture = 10,000 ft. alt.	730.4	56.8	18952	0.68	418	319	1.00	-377	1063	-2807
	790.4	50.0	16172	0.64	402	319	1.00	-353	1092	-2752
	850.4	43.4	13448	0.61	386	319	1.00	-316	1124	-2693
	910.4	37.1	10785	0.58	372	319	1.00	-297	1160	-2637
	928.4	35.2	9999	0.58	367	319	1.00	-299	1172	-2621
	Bottom-of-Descent Deceleration, three integration steps									
Step size = 30 sec	928.4	35.2	9999	0.58	367	319	1.00	-299	1172	0
Mach, CAS not constant	958.4	32.3	9999	0.51	324	281	1.00	-125	1191	0
Vertical speed, constant	986.5	30.0	9999	0.45	288	249	1.00	17	1208	0
EPR, constant										
Capture = 250 KCAS										

simulator, manufactured by Singer-Link, is widely used by airlines for crew training. The simulator is equipped with a six-degree-of-freedom motion system and a night/dusk vision system. Computer-generated imagery of the night or dusk scene is displayed in front of the cockpit windows by four projectors which give a wide, high-resolution field of view to the pilot and copilot.

Each simulated flight consisted of a straight-in approach beginning 150 n.mi. from the runway threshold at an altitude of 35,000 ft and a speed of Mach 0.8. In all flights a tail wind of 70 knots at 35,000 ft decreasing linearily to zero at the runway was simulated. Simulated weather conditions consisted of a visibility ceiling of 1000 ft above the runway, with tops at 5000 ft and light turbulence at all altitudes. Pilots were briefed on wind and weather conditions prior to the simulation runs.

Test subjects were three current 727 pilots, one each from three major U.S. airlines. Initially, each pilot was asked to fly his own airline-recommended descent profile, which will be referred to as the baseline profile. The three pilots chose essentially the same baseline profile, consisting of a Mach-0.8/280-KCAS descent. Each pilot also estimated his top-of-descent point using the 300 ft/mi rule of thumb mentioned earlier. Range to touchdown was provided by a standard cockpit readout of distance measuring equipment (DME) range from a station located at the destination airport. All baseline profiles were flown without ATC advisories.

After completing the baseline descents, the pilots flew three types of controller-assisted descents referred as nominal, slow, and fast with speed profiles of Mach 0.8/320 KCAS, 230 KCAS, and Mach 0.85/350 KCAS, respectively. Note that the slow and fast profiles follow the limits of the speed envelope for this aircraft (Fig. 4).

Before flying these profiles in the simulator, pilots received brief, written instructions on operational techniques to be used:

1) Thrust Management. - The flight idle position is to be used in tracking the speed profile unless the descent rate exceeds 3000 ft/min. If such is the case, add only sufficient thrust to keep the descent rate from exceeding 3000 ft/min.

2) Deceleration at the Top (Slow Profile). - First, reduce thrust to idle at the descent-procedure start point; second, maintain level flight (zero descent rate) while decelerating to the specified CAS; and third, begin the descent as the specified CAS is approached.

3) Acceleration at the Top (Fast Profile). - At the descent-procedure start point (the top of descent point in this case) initiate a pitch-down maneuver to achieve a 3000-ft/min descent rate. Then, maintain cruise thrust while accelerating; as the specified Mach number is approached, reduce thrust according to 1).

4) Deceleration at the Bottom of Descent (Nominal and Fast Profiles). - As the aircraft approaches 10,000-ft altitude, decelerate to 250 KCAS in level flight and with thrust still at idle; resume descent at the 30 n.mi. to the touchdown point.

The descent advisories were issued during the simulation by a pseudo-controller located at the engineer's position in the cockpit. The advisories were issued only once approximately a minute before the start point of the procedures and specified the DME range of the start point and the speed profile. Calculated off-line by the previously described computer program, the advisories typically contained the following information, "Begin descent procedure at 108 DME; follow a Mach 0.8/320 speed profile using idle thrust."

Each type of controller-assisted descent was flown four to six times. These few simulation runs are believed to provide sufficient information to determine the feasibility of the concept. However, they are too few in number to warrant extensive statistical analysis of the results.

4.7 Discussion of Results

Errors in the predicted time of descent measured at the time-control point were the principal criterion for evaluating the effectiveness of the controller-assisted (and computer-generated) profile descent advisories. Also the instantaneous-altitude and time-tracking errors as well as the fuel efficiency of the descents provide important measures of effectiveness. Finally, the pilots participating in the simulation were asked to comment on the value and acceptability of the advisories. This simulation focused on isolating errors attributable to pilot technique. Errors caused by other sources such as wind and aircraft-model uncertainties can be determined more efficiently by analysis and fast-time simulation, and therefore are not addressed here.

The results for the various types of descents are given in Figs. 5 through 8 as composite plots of time and altitude versus range to touchdown. Figure 5 shows the composite plots for four baseline descents. Although all pilots presumably used the same procedure to fly their profiles, the data revealed significant time and altitude variations between profiles, reflecting differences in individual pilot technique. At 30 n.mi. from touchdown time-control point, the variability in time is 196 sec. Here, variability is defined as the difference between the earliest and latest arrival time for all profiles of a particular type and is used as a conservative substitute for standard deviation.

Since the typical landing-time interval between aircraft is approximately 100 sec (Table 1), a 196-sec error range implies difficulties in achieving efficient traffic flow at terminal areas where two or more streams of aircraft flying unaided profile descents are merged. Thus, unaided aircraft assigned conflict-free time slots at the top of descent by an en-route metering system would accumulate unacceptable time errors during the descent, and would therefore not be conflict free at the merge point. As a result, the controller would frequently have to interrupt the profile descents to resolve potential conflicts and ensure efficient traffic flow. Such problems have indeed been experienced in

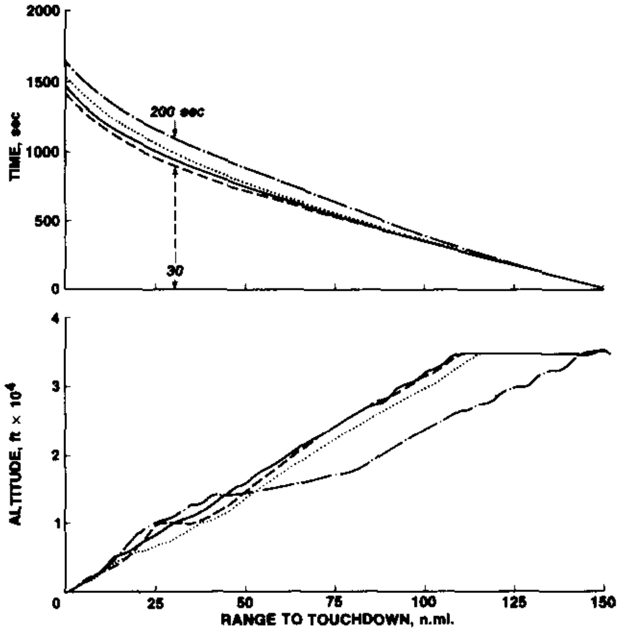


Fig. 5. Baseline descents.

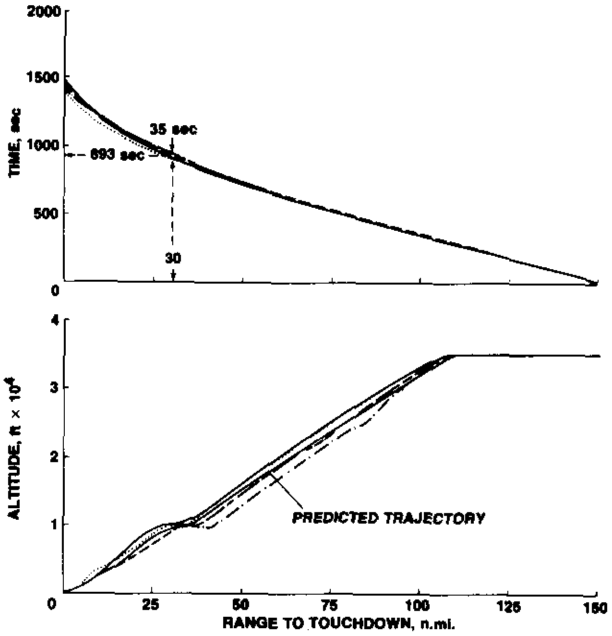


Fig. 6. Nominal descents: 0.8/320.

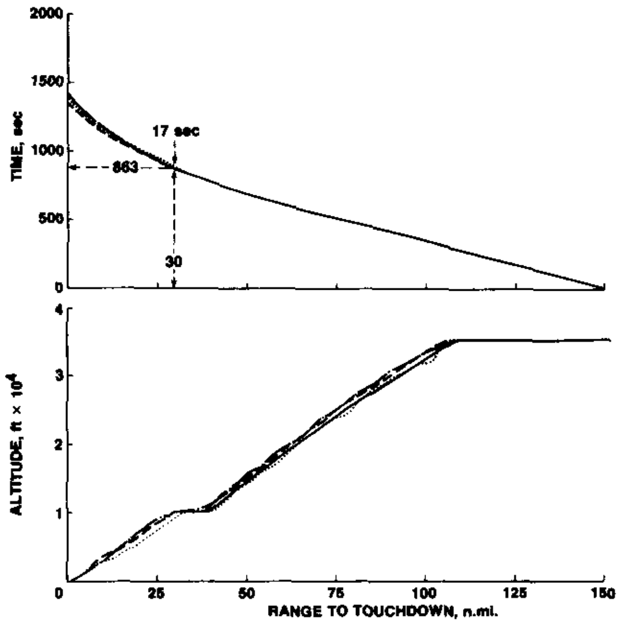


Fig. 7. Fast descents: 0.84/350.

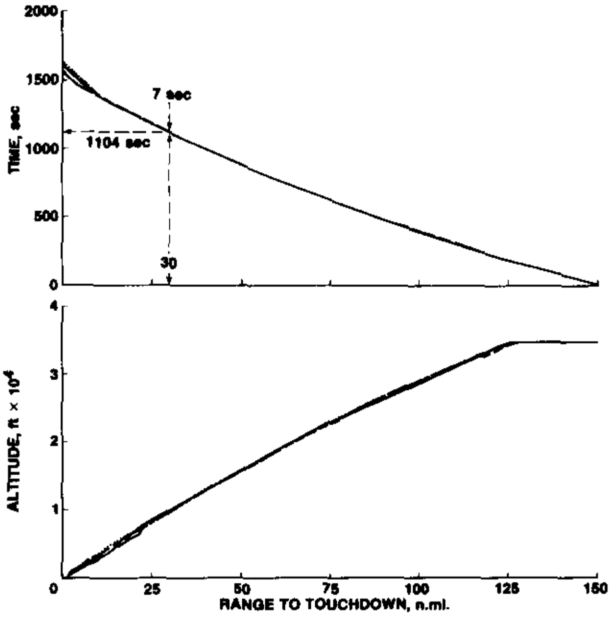


Fig. 8. Slow descents: 230.

ATC simulations of unaided profile descents (Ref. 11) and are also evident in the results of the ATC simulations discussed earlier.

As shown in the composite plots in Fig. 6, the time variability of the nominal profile descents, flown with the aid of the descent advisories, is reduced from 196 sec for the baseline descents to only 35 sec. Furthermore, the scatter in the altitude profiles is significantly reduced throughout the descent. The predicted trajectory with an arrival time of 893 sec at 30 n.mi. is also plotted in Fig. 6, but is difficult to distinguish from the simulated trajectories because of crowding of the plots. These improvements in accuracy clearly demonstrate the advantage of using the advisories. With the top-of-descent point specified, pilots could concentrate on tracking the speed profile and needed to pay little attention to thrust and altitude management. Without advisories, pilots often cross-check altitude and range and then readjust the thrust so as to minimize anticipated altitude errors at the bottom of the descent. With the advisories, pilots could maintain thrust at idle throughout, and yet be confident that the altitude target at 30 n.mi. would be achieved.

As seen in the composite plots, Figs. 7 and 8, the time variability and the altitude scatter of the fast and slow profiles are even lower than those of the nominal profile. In fact, the slow profiles have the unusually low variability of only 7 sec, which one would expect to obtain only from a closed-loop 4D guidance system. This high accuracy is probably related to the fact that they are simpler to fly than the other two types of profiles. The slow profiles are flown at a constant CAS and do not contain a constant Mach segment. Furthermore, they can be flown entirely at idle thrust, since they never exceed the 3,000-ft/min descent rate as the other two do during portions of their descent. Another simplification is the absence of a deceleration segment at the bottom of the descent. One can conclude from these results that procedural complexity has a strong impact on time-control accuracy and should be carefully considered in choosing the descent profiles.

Time accuracy and fuel efficiency of the predicted and simulated profiles at the 30 n.mi. point are summarized in Table 3. By comparing the first and second columns it can be seen that all predicted times fall within the corresponding time ranges of the simulated profiles. This comparison indicates that there is no significant bias between the predicted and simulated data.

The averge fuel-consumption data given in Table 3 show that the slow profile is the most fuel efficient and the fast profile the least fuel efficient. The nominal profile, though considerably faster than the baseline profile, consumes only slightly more fuel (17 lb) on averge than the baseline does. Thus, the trade off between time and fuel, so important in airline operations, favors choosing the nominal profile. However, the profile actually assigned to an aircraft by the air traffic scheduler will depend on the availability of a conflict-free time slot at the time of descent.

In addition to tests of the tail-wind condition reported herein, head-wind and zero-wind conditions have recently also been tested. Preliminary analysis is yielding results that are generally consistent with the tail-wind conditions. Also, the time variability between the 30-n.mi. point and touchdown was investigated for both a straight-in and a standard-approach pattern, the latter consisting of downwind, base, and final segments. Analysis of results for these conditions is still in progress.

Pilots participating in the simulation generally reacted favorably toward the profile-descent advisory concept. The pilots cited as the primary benefit the accurate specification of the top-of-descent point in the presence of complex altitude-dependent wind profiles. Moreover, the pilots considered the advisories as unobtrusive and all profiles as comfortable to fly.

The experience of this study has identified the following three guidelines for achieving accurate time control. First, descent procedures provided by advisories should be simple to execute and familiar to pilots. Second, aircraft performance and atmospheric conditions should be accurately represented in the advisor algorithm. Third, pilots should be briefed on the characteristics of the advisories and the requirement to execute them accurately.

The time accuracies achieved in the simulation would be adequate for a time-based ATC system if they could be duplicated in practice. However, uncertainty in the knowledge of the actual wind profile and inevitable lapses in pilot attention to the profile tracking task will result in larger errors than obtained in the simulation. One can attempt to estimate such time errors from analysis of ATC radar tracking data during an aircraft's descent. Then, an updated speed advisory can be issued near the midpoint of the descent to minimize these errors. With the addition of such a midpoint advisory, control of arrival time within ±20 sec appears to be feasible.

Table 3. Summary of simulation results, time (sec) and fuel (lb) to 30 n.mi. to touchdown point

Type of Profile	Time Predicted by Algorithm	Range of Times; Time Variability ( )	Average Fuel Use	Range of Fuel Use; Fuel Variability
Baseline M 0.8/280 KCAS without profile advisories	--	890-1084 (196)	1065	945-1145 (200)
Nominal M 0.8/320 KCAS top of descent: 108 n.mi.	893	880-915 (35)	1082	1064-1098 (34)
Fast M 0.84/350 KCAS top of descent: 107 n. mi.	863	854-871 (17)	1175	1169-1183 (14)
Slow 230 KCAS top of descent: 133 n.mi.	1104	1098-1104 (7)	771	764-778 (14)

5. CONCLUDING REMARKS

Studies completed to date indicate the essential feasibility of achieving the major performance objectives of a time-based, traffic-management concept. Air traffic control simulations have demonstrated that a time-based system used in conjunction with appropriate procedures, computer aids, and information displays provides an efficient method for controlling a complex mix of traffic, including both high- and low-performance aircraft as well as various percentages of 4D-equipped aircraft.

Time control offers significant benefits even at low-percentage mixes of equipped aircraft by using advisories to help maintain unequipped aircraft on an accurate time schedule. Thus, traffic in the complex final-control sector flows more orderly and is easier to control when time control methods are in use. Although the system operates internally in a time-based mode, controllers need not be aware of this situation and retain the ability to operate in their traditional distance-spacing mode.

Piloted simulations have demonstrated the effectiveness of profile-descent advisories to control the descent time of unequipped aircraft. An accuracy at the time-control point of ±20 sec, which a time-based system needs to be effective, appears attainable with the descent advisor designed according to the methods outlined in the paper.

A combined ATC and piloted-simulation test of the concept is planned for 1987. If these tests confirm performance predictions, the FAA and NASA plan jointly to conduct operational evaluations of the concept at the Denver En-Route Air Traffic Control Center.

REFERENCES

1. Tobias, L., "Time Scheduling a Mix of 4D Equipped and Unequipped Aircraft," NASA TM 84327, Feb. 1983.

2. Alcabin, M., Erzberger, H., and Tobias, L., "Simulation of Time Control Procedures for Terminal Area Flow Management," American Control Conference, June 1985, Boston, MA.

3. Lee, H.Q., Neuman, F., and Hardy, G.H., "4D Area Navigation System Description and Flight Test Results," NASA TM D-7874, 1975.

4. Erzberger, H. and Chapel, J.D., "Concepts and Algorithms for Terminal Area Traffic Management," American Control Conference, June 1984, San Diego, CA

5. Lee, H.Q. and Erzberger, H., "Time-Controlled Descent Guidance Algorithms for Simulation of Advanced ATC Systems," NASA TM 84373, May 1983.

6. Tobias, L., Erzberger, H., Lee, H.Q., and O'Brien, P.J., "Mixing Four-Dimensional Equipped and Unequipped Aircraft in the Terminal Area," AIAA Journal of Guidance, Control and Dynamics, Vol. 8, No. 3, May-June 1985, pp. 296-303.

7. Knox, C.E. and Cannon, D.G., "Development and Test Results of a Flight Management Algorithm for Fuel Conservative Descents in a Time Based Metered Traffic Environment," NASA TP 1717, Oct. 1980.

8. Menga, G. and Erzberger, H., "Time-Controlled Descent Guidance in Uncertain Winds," AIAA Journal of Guidance and Control, Vol. 1, No. 2, Mar.-Apr. 1978, p. 123.

9. McCormick, Barnes W., Aerodynamics, Aeronautics and Flight Mechanics, New York, Wiley, 1979.

10. Chuen-Yeu, Chow, An Introduction to Computational Fluid Dynamics, New York, Wiley, 1979.

11. O'Brien, J.P., Willett, F.M., Jr., and Tobias, L., "Dynamic Air Traffic Control Simulation of Profile Descent and High Speed Approach Fuel Conservation Procedures," Federal Aviation Administration Technical Center, Atlantic City, NJ 08405, Final Report FAA-RD-80-12, May 1980.

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Philosophy of Applying Automation to Air Traffic Control

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Summary: This paper summarizes the objectives of the U.S. program for applying automation to air traffic control systems, progress thus far, and plans for the future.

Introduction

Since the time in 1958 when computers were first used to print flight strips in the United States at a small number of Air Traffic Control (ATC) centers, it has been a continuing objective to capitalize on the rapidly evolving computer technologies to improve the ATC system. Our specific objectives have been to apply computers and the associated automation functions to:

- improve safety of ATC operations
- increase the efficiency of traffic management, and
- increase the productivity of ATC controllers.

The basic philosophy underlying our plans for applying automation to the ATC system has been to move as rapidly as practical, but to acknowledge that the evolution of ATC automation functions will be paced by:

- the capacity limitations of ATC computers already installed in the field, until they can be replaced with higher capacity machines
- the quality and accuracy of input data such as radar, winds aloft, and severe weather areas
- the nonuniform and relatively slow rate of equippage of aircraft with advanced avionics such as Mode S transponders, data link, microwave landing systems, and flight management computers, and
- the complexity of the design and development process for advanced levels of automation which significantly alter the work environment and functional responsibility of controllers.

The pace of automation applications has been slower than many would wish; but this does not diminish the expectations that in the long term, the ground-based ATC computers will assume a greater responsibility for traffic flow planning, traffic management, and assurance of safety. In our view, it is inevitable that the ground-based ATC system computers will eventually be linked to the airborne computers via data link to accomplish the information transfers on flight planning, traffic advisories, and ATC clearances.

Steps Thus Far in ATC Automation in the U. S.

The review of the progress to date of ATC automation in the United States illustrates a partial achievement of our objectives.

The initial use of computers in the late 1950's and early 1960's was to process and distribute flight plan data among control centers. This step substantially reduced the manpower required for this function and, in addition, improved the accuracy and timeliness of flight plan data distribution.

The next major step in the mid-1970's was to process and track digitized radar input data, and display aircraft locations with identity tags on controllers radar displays. Conformance of controlled aircraft with their flight plans was monitored automatically. Further, flight plan data were processed and flight progress strips were distributed automatically to radar control positions. The resulting improvement in controller productivity was estimated to be approximately 10-15 percent and the safety improvements were substantial due to positive identification and accuracy of displayed aircraft track information.

Additional safety improvements came in the late 1970's with track-based automated conflict alert and minimum safe altitude warning. These functions have contributed greatly to increased safety.

When the cost of fuel increased dramatically in the early 1980's, emphasis in automation development shifted to the national flow control system. Improvements were made in the automation functions which calculate expected demand for congested airports, establish arrival sequences and schedules for arriving aircraft, and shift necessary delays from airborne holds to ground holds at departure airports. Efficiency as measured by reduced airborne delays and fuel consumption was significant.

By the mid-1980's development of additional safety related automation functions was completed, but the computer capacity limititations of the installed en route computers prevented implementation. These automated functions are:

- conflict alert for encounters between Mode C-equipped VFR aircraft and controlled IFR aircraft, and
- automatic generation of conflict resolution advisories to controllers for conflicts which had been detected by the computers.

The replacement of the IBM 9020 computers in our en route centers by IBM 3083's in the late 1980's will remove the computational constraints, and implementation of these added safety functions can then proceed.

Similarly, capacity limits of the present National Traffic Management Computer, which is also scheduled to be replaced in the late 1980's, has prevented implementation of automation improvements for national flow control, namely:

- inclusion of flight plan data for nonscheduled aircraft in the demand calculations for congested airports, and
- use of computer-generated progress reports for all controlled aircraft for centralized calculation of anticipated en route sector and fix loadings.

Improved accuracy of these loading estimates is very important to the efficient centralized management of traffic flows through congested airspace and into the high density terminals.

Future Plans

The major advance planned for ATC automation in the early 1990's is the Advanced Automation System, which will include a set of automation capabilities called Automated En route Air Traffic Control (AERA) I. The AERA I functions include:

- calculation of flight paths in four dimensions (latitude, longitude, altitude, and time)
- conflict probe of planned four-dimensional flight paths 15-20 minutes into the future to provide earlier detection of flight plan conflicts and enable more orderly traffic flow and reduction of controller workload
- detection of flight plan conflicts with time-dependent, restricted airspace for the route of flight
- detection of flow and metering restrictions

This is expected to result in a far greater capability for allowing user aircraft to fly their preferred direct routes and altitude profiles than at the present time.

A follow-on automation step, called AERA II, will automatically calculate candidate solutions to detected conflicts which will:

- resolve future flight plan conflicts and perform any coordination necessary at other affected sectors, and
- present prioritized alternatives in clearance format.

The controllers will have the option to deliver these computer-generated clearances and advisories by voice or by data link to properly equipped aircraft.

Advances beyond the level of automation in AERA II will likely involve a quantum change in the ATC system procedures. To achieve our announced goal of doubling controller productivity, it will be necessary to delegate to the ATC computers some aspects of the controllers present responsibilities for direct control of aircraft. This will require a clear and unambiguous demarcation between responsibilities retained by the controller and those delegated to the ATC computer. Another obvious requirement is for a direct communications link between the ground ATC computers and airborne computers in controlled aircraft.

The alternative concepts include:

- automatic computer control of all aircraft in designated high altitude regimes
- automatic computer control of all aircraft which are equipped with advanced avionics (data link and flight management computers) and which fly through specified airspace regimes
- the ATC computer performs the separation functions for all controlled aircraft in en route airspace, while the controller uses computer aids to perform conflict free flight planning

A great deal of research remains to be done before these advanced concepts can be fully developed. Complexities derive from the:

- division of responsibilities between the controllers and computers, and the man-machine interface design

- the variety and mix of avionics and performance capabilities of controlled aircraft
- difficulties in handling unanticipated perturbations in traffic flow due to winds, severe weather, and equipment outages

Finally, before any step can be taken beyond the current mode where ATC computers provide automation aids to controllers who retain the unequivocal responsibility for control of aircraft, full and complete confidence of controllers, pilots, and the public must be achieved in not only the functional capabilities of advanced automation equipment, but also its absolute protection against equipment failures.

CP 410

COMPUTER ASSISTED ARRIVAL SEQUENCING AND SCHEDULING WITH THE COMPAS SYSTEM

by
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Summary

In a joint project carried out by DFVLR and BFS (the German Federal Air Navigation Services) the COMPAS-system (Computer Oriented Metering Planning and Advisory System) has been developed at the DFVLR-Institute for Flight Guidance. It has been tested and evaluated at the institute's air traffic simulation facility, using traffic scenarios of Frankfurt airport with upto 52 aircraft movements simultaneously.

The operational objectives of the COMPAS-system are with regard to Frankfurt airport to achieve the best possible usage of the available but limited runway landing capacity, to avoid unnecessary delays and to apply economic approach profiles whenever possible. The planning functions which today are still carried out by human controllers will be transferred to a computer. It generates a comprehensive plan for a best overall arrival sequence and schedule. The execution of this plan, however, intentionally remains the task of the human controllers. They are provided with all data necessary to control the approaching aircraft.

The systems concept, the dynamic planning algorithms as well as the operational concept for computer assistance and the man-machine interface are presented. Some preliminary results of the experiments and evaluation will be reported.

1. Introduction

Planning and control of a safe, regular and efficient flow of air traffic at high density airports is an extremely difficult task for Air Traffic Control (ATC). The increasing number of additional requirements that have to be met by ATC, such as: fuel efficiency, noise abatement procedures, wake vortex separation, capacity usage demands have made this task even more complex and challenging.

In a joint project carried out by DFVLR and BFS (the German Federal Air Navigation Services) the COMPAS-System (Computer Oriented Metering Planning and Advisory System) has been developed, tested and is now under evaluation at DFVLR.

The operational objectives of the COMPAS-system are (with regard to Frankfurt Airport) to achieve best possible usage of the available, but limited runway landing capacity, to avoid unnecessary delays and to apply economic approach profiles whenever possible. The planning functions which nowadays are still carried out by human controllers will be performed by a computer. It generates and suggests a comprehensive plan for a best overall arrival sequence and schedule. The execution of this plan however intentionally remains the task of the human controllers. They are therefore provided with all necessary data to control the approaching aircraft.

The project objective is to obtain solutions and experience in the layout and application of computer assisted systems in Air Traffic Control.

The design of a semi-automated subsystem necessitates in particular careful and feasible solutions both for the transfer of human planning and decision making functions to a computer and for the the distribution of authority between computer and controller.

2. Arrival Planning in Air Traffic Control

2.1 Human Planning in todays system

An important task in Air Traffic Control is to merge several converging streams of aircraft from different approach directions on the runway centerline (Fig. 1). On major, often congested airports this is a challenging and complex task. Although the average arrival rate may not exceed the average landing capacity, it cannot be avoided that (despite all long-term flight plan coordination and medium-term flow control) the arrivals are randomly distributed.

This would lead to

- o arrival peaks (with resulting delay),
- o arrival gaps (resulting in unused capacity),
- o uneffective wake turbulence sequencing (capacity reduction) or
- o uneconomic flight profiles

if no appropriate planning and control actions would be taken by air traffic controllers in order to establish a safe, smooth and efficient flow of traffic. The actions should be taken in due time outside the terminal area, to avoid congestion and holding procedures in the narrow terminal area, and to allow the application of economic, idle-descent profiles.

Fig. 2 illustrates in a schematic way the extended approach area of Frankfurt Airport. A typical approach commences in the vicinity of a so-called "Entry Fix" some 70-100 nm distant from the airport at flight levels between 150 and 280. The different Standard Arrival Routes are converging at three Main Navigation Aids (Clearance Limits) the so-called "Metering-Fixes".

The intermediate approach legs from those three directions finally are merged on the extended runway center line for final approach. Normally the landing sequence should be established at least some 10 nm from the runway threshold. This assumed point is called "Gate".

Today the arrival planning and control process is performed by several control units, some of them assigned the Area Control Center (units C_i and B_i) others to Arrival Control and Local Control (A_i).

The shortcomings of todays situation can be described as follows:

- The overall-planning task is distributed to several control units.
- Arrival planning is performed "stepwise" from the "outer" units (C_i to B_i) to the "inner" units (A_i).
- Some kind of tactical/ad hoc/local planning prevails in each control unit and must be coordinated with other units.
- The application of one overall planning criterion and concerted control action is very difficult to achieve, because of the very high coordination effort.
- The integration of a variety of data from many different sources has to be performed mainly in the head of the human controllers.

This leads to extremely high work load and even small disturbations which could not be matched, may result in a traffic congestion.

Splitting-up and distributing this task to more control units would require even more coordination effort.

Therefore it was envisaged to transfer at least parts of the human planning and control functions to a computer.

2.2 Computer-based arrival planning

Based upon studies at Frankfurt Airport, a concept for a computer based planning system (COMPAS), aiming to assist controllers in the comprehensive planning of arriving aircraft was developed and is now being tested and evaluated by the DFVLR Institute for Flight Guidance in cooperation with BFS - the German ATC-Authority.

The essential design principles of the COMPAS-system can be described as follows:

- The stepwise distributed planning of the controllers is substituted by one, comprehensive, overall computer planning.
- The computer planning function anticipates the traffic development for the next 30 minutes and uses one single criterion, common for all units.
- Besides the "usual" data such as radar position information and flight plan data, many other data are included in the computer planning functions, (i.e. traffic load in sub-sectors, aircraft performance and economy, actual airspace-structure etc.). The computer integrates these data and generates concentrated planning results.
- Each control unit involved is provided with its specific planning results, necessary to carry out control and to play its part in the overall plan.
- The controllers stay fully in the loop and keep their executive function. In general the computer generated plan is acceptable to the controllers. However, it is possible for the controllers to interact with the computer in order to modify the plan.

The basic structure of the COMPAS-system is shown in Fig. 3. The operational objectives of the COMPAS-system are with regard to the Frankfurt situation:

- best usage of runway landing capacity,
- delay reduction for arrivals,
- to apply economic descent profiles, if possible.

Fig. 4 shows how the COMPAS-system will be integrated into the existing ATC-system. COMPAS is designed to work in the present ATC-environment. But beyond that actual radar-data and flight-plan-data are fed on-line into the COMPAS-DP-system via special interfaces. Taking into consideration a set of other information (aircraft performance, airspace structure, wind etc.) COMPAS generates a plan and displays it to the controllers. The controller may use these COMPAS-proposals, but is not obliged to use the system. However, if he does work with it, the results should be so reasonable and convincing, that he easily can adopt these proposals for his control actions. Under normal conditions no controller-computer interaction is required. However interaction is possible, if the controller wants to modify the plan or if it is necessary to cope with unforeseen events.

A successful application of a system like this, where automated and human functions are closely interrelated, strongly depends on the development of feasible solutions for

- o the structure of the planning process,
- o the distribution of authority between controller and computer.

These topics will be discussed in more detail in the following chapters.

3. Dynamic Arrival Planning

3.1 Planning functions

The overall goal of the computer based arrival planning is to generate a plan, giving the "best" sequence and schedule and to provide information how to fulfil this plan. To work out a plan dynamically in real time in a real environment, large quantities of data are necessary. They consist of three types of data:

1. Fundamental data and models which are "static" and do not change during the planning process, i.e.
   - o aircraft performance data;
   - o airspace structure;
   - o approach procedures;
   - o separation values;
   - o wind model.
2. Event-oriented data, which change with "low frequency", i.e.
   - o aircraft entering or leaving the system;
   - o callsign, type of aircraft;
   - o flight plan data (route, way-points, estimated times);
   - o wind data (force, direction).
3. Dynamic data, changing with "high frequency", i.e.
   - o actual flight condition (position, speed, altitude, deceleration rate, descent rate).

Fig. 5 shows the main data-processing functions which are carried out in real-time.

An overview on the various sub-tasks which have to be performed for the planning is listed below. Most of them can be regarded as "auxiliary" functions for the intrinsic planning core: the sequencing and scheduling function, which will be described in more detail.

- o System monitoring and control
  - Automated DP-controller
  - Pre-processing of inputs to change basic-data; sector allocation etc.
  - Processing of DP-errors
- o Data Compilation
  - Radar target recognition, extraction
  - Flight plan data selection
  - Code/Callsign assignment
  - File inauguration and data procurement
- o Forecast
  - Speed calculation from radar tracking
  - Flight path assessment
  - Time-to-fly calculation
  - Arrival time prediction
- o Sequencing and scheduling
  - Merging of new arrivals into existing sequence and schedule
  - Time-conflict detection
  - Time-conflict resolution with "Branch & Bound" algorithm
- o Update and Fixing
  - Update of Sequence and Schedule
  - Assessment of final sequence
  - Release of unnecessary "time-tension"
  - "Freezing" of final schedule and sequence
- o Input/Output Control
  - Controller-Computer-Interaction procedures
- o Input-Processing
  - Processing of controller modifications
  - Processing and storage of parameter alterations

- Output-Processing
  - Continuous processing and display of results
  - Processing and display of data on request
- Basic-Data-Management
  - Storage, modification and provision of the valid air space structure, landing direction, landing rate, separation, type-specific performance, profile models, wind models etc.

3.2 *The Planning Algorithm*

The core of the arrival planning function is an algorithm which consists of three major elements:

1. Prediction and initial scheduling
2. Time-conflict detection
3. Time-conflict resolution

The algorithm is activated every time when a new aircraft enters the system.

3.2.1 Prediction and Initial Scheduling

When a new aircraft arrives at an "Entry" Fix", the arrival time prediction is made for the "GATE". Two arrival times are calculated:

1. The Estimated Time Over Gate (ETOGT) based upon the preferential profile (i.e. idle thrust descent) and all other actual conditions of the flight.
2. The Estimated Earliest Time Over Gate (EETOGT) taking into account all measures to advance the arrival within the performance margins of the aircraft and possible short-cuts of the flight path.

The "earliest" arrival time is used for the inital planning in order to keep the system under "time pressure" and to advance and expedite the traffic flow. With its EETOGT a new aircraft is inserted into the existing aircraft sequence and schedule for the GATE. The result is the initial plan, giving a tentative schedule and landing order. Then the time-conflict detecting function is called.

3.2.2 Time-conflict detection

The time-conflict detector is searching the entire landing order for infringements of the minimum permitted time-separation between pairs of two successive aircraft at the GATE.

It uses a data table, the so-called separation matrix (Fig. 6) which gives the minimum permitted time-separation between any combination of leading and trailing aircraft according to their wake-vortex-class.

If there is no time-conflict detected over the GATE, i.e. if the time-separation between any preceeding and following aircraft is equal or greater than the respective minimum separation the planning process is finished.

However, if a time-conflict between two or more aircraft is detected, the conflict resolution function comes into effect.

3.2.3 Time-conflict Resolution

The time-conflict algorithm works as follows:

1. It consideres the earliest time-conflict in the initial plan. If one of the two aircraft involved in this conflict has its status "frozen" (i.e.its position in the planned sequence over the Gate cannot be changed anymore), then the "non-frozen" aircraft is put behind the "frozen" one according to the separation matrix in Fig.6. If both aircraft have the "non-frozen" status, there are two possibilities for the sequence:

   - aircraft i behind aircraft j
   - aircraft j behind aircraft i.

   Both possibilities have a given delay time for the postponed aircraft. The time-conflict algorithm now first evaluates the solution with the smaller delay-time to form the revised plan (which is characterized by this delay-time).

2. In this revised plan, again the earliest time-conflict is considered (if there is one remaining). Repeating step 1, this conflict is resolved with the penalty of an additional delay time. This conflict resolution process continues until a conflict-free revised plan has been found (with a certain total delay-time).

3. In a back-tracking procedure, the algorithm has now to check all the solutions of step 1, which have been neglected in the first attempt. For each of these solutions the conflict solution process of step 2 has to be carried out until:

- either another conflict-free plan with a smaller total delay-time as that of the previous revised conflict-free plan has been found,
- or the total delay-time exceeds that of the previous conflict-free plan.

4. This back-tracking procedure is carried out for all neglected conflict solutions of step 1 and 2. The procedure terminates with a conflict-free plan with the minimum possible delay-time.

The time conflict resolution algorithm is governed by the strategy to minimize the total aircraft delay-time, according to the overall goal of the COMPAS project, to maximize the aircraft throughput. Other strategies are thinkable, e.g. to minimize the total number of time-conflicts to be resolved, thus reducing controller workload.

The described algorithm is a type of branch & bound-algorithm, which can be visualized as a heuristic-directed search in a tree, using a cost function (the total delay-time). Nodes represent plans and are labeled with the earliest time-conflict to be resolved. The arcs represent the conflict solution procedures "i before j" and "j before i", as discussed in step 1 above. The tree is developed, using the heuristics "to solve the earliest conflict in the plan first" (Step 1). The total delay-time is summed up along the branches, until a conflict-free plan is reached (Step 2).The value of the cost function for the first conflict-free plan is called "first bound". The back-tracking procedure (Step 3) leads to another branch of the search-tree, which is either closed, when its total delay-time exceeds the value of the first bound, or when a new conflict-free plan is reached with a smaller delay-time (Step 4). The result of this search procedure is a conflict-free plan with minimum delay-time. The procedure is illustrated in Fig.7.

The algorithm tries to resolve the earliest conflict first, i.e. the conflict between aircraft B an D. If one of these two aircraft has already been"frozen", in this case aircraft B, the "non-frozen" aircraft D is put behind the leading one. In the next step the algorithm checks if the delay for D has created a new conlict or if other conflicts still exist. Again the earliest conflict is selected, in the example the newly created conflict between D and E. If both sequences D-E or E-D are possible, either D or E may be delayed. The algorithm selects that sequence, where the total delay is minimum. This process is repeated until all time-conflicts have been resolved, giving a first solution for the sequence (1.branch) and the first value of the cost function (1.bound).

4. Computer-Controller Interface

The layout of the man-machine interface is of very great importance for the practicability and acceptance of a computer assisted function. The guidelines for the layout of the COMPAS-system were:

- to keep the controller in the loop (i.e. to give him the plan, but to leave the verification of the plan to his experience, skill and flexibility);
- to display just the necessary data, in a clear and understandable form;
- to minimize the need for keyboard entries.

These user requirements led to questions and proper solutions for the

- distribution of authority between controller and computer
- design of displays and controls and operational procedures.

4.1 Distribution of Authority between Controller and Computer

The requirement was to keep the controller in the loop. This led to a solution where the automated planner permanently carries out the planning functions, with the results (the overall-plan or a sub-plan) being displayed to the respective radar controllers. In the "normal" case, the plan should be reasonable and acceptable and no controller-computer interaction, not even the confirmation of receipt is required.

This means that the control authority fully remains with the controllers. The computer simply takes over the complex planning procedure and makes proposals to the controllers. Assuming that these proposals are compatible with the intentions of the controller and the "behaviour" of the aircraft, the controllers will readily accept the suggested plan, transform it into appropriate control actions, which then are carried out by the aircraft. The traffic situation will then further develop as anticipated by the automated planner. As the controller does not "inform" the computer about his control actions (via data inputs), the computer does have no direct feedback from the controllers, but only monitors and recalculates the development of the traffic situation. Only if modifications are fed in, the computer will react to controller inputs (Fig.8).

The planning function can be classified as "loose, open loop-planning", with - by intention - low accuracy, leaving much responsibility but also flexibility to the human controllers.

Other concepts with a more "tight, closed-loop-planning", are conceivable, however they require even more data, more data-processing capability, more intelligent algorithms and a higher degree of automation.

In real world operation, however, deviations and disturbances frequently occur and have also to be delt with. So, if the controller has to maintain full control authority, he must be permitted and able to "override" or modify the computer generated plan. In the COMPAS-system this can be done with some function keys. Table 1 shows the operational capabilities of the COMPAS-system without and with controller interaction.

Distributing the authority between controllers and computer causes another problem. In a computer-based system one automated planner generates one overall plan, which then is divided into several sub-plans and distributed to the respective controllers in the different sub-sectors (Fig. 9).

This means the computer has and generates some kind of "master-plan". If this overall-plan is not apparent in the sub-plans, the sub-plans might not be transparent, understandable and acceptable to the controllers. Therefore it is important to provide information on the overall-plan, be it "on-request" or permanently.

Another problem resulting from the distribution of sub-plans is, that plan modifications may originate at different places. This leads to questions of priority, of conflicting interactions and of deterioration of the general goal of the planner, and as well to the stability of the planning process. For the COMPAS experimental system with a limited number of controller working stations satisfying solutions have been worked out. In an operational system application with a great number of controller working stations this problem has to be resolved carefully.

4.2 Displays and Controls

As mentioned above the user requirements are:

- to display just the necessary data, in a clear and understandable form,
- to minimize the need for keyboard inputs.

This led to simple, but very clear displays and functions keys.

A coloured display is used. The basic version of the display for the arrival controllers is shown in Fig.10 .The display shows at top right:

- the landing direction in use; (25)
- the airport acceptance rate; (Flow 3.0 means: unrestricted flow, with 3 nm minimum separation when permitted).

The left part of the display shows a time-scale for the next 20 minutes, with the actual time (10.17h) at the bottom. The expected arrivals in this sector are displayed with their call-sign and wake-vortex-class (H). The leading aircraft is at the bottom (according to the typical arrangement of the flight-progress-strips on the strip-holder-board). The small box on the bottom left represents the GATE, giving the indication that, e.g. the JU 358 should be over the GATE right at lo.17h, followed by the AY 821 about 85 sec later, a.s.o..

The letters left of the time-scale give a rough indication of the suggested control action. Four qualitative suggestions are made to the controllers in order to establish a smooth, dense landing stream:

"X" - expedite	(30 sec up to 2 minutes),
"O" - no action	(+ 30 sec),
"R" - reduce	(30 sec up to 3 minutes delay),
"H" - hold	(more than 3 minutes delay).

As an example: the LH 880 should arrive at the GATE at about 10:26 and it should be reduced. Because the LH880 is a HEAVY-type aircraft, increased wake-turbulence-separation is planned for the succeeding JU350, which has to be expedited in order to catch its landing slot.

There is no proposal for the specific control command. Whether speed control, delay vectors or a combination of both is to be applied, is left to the judgement and experience of the controller, who will consider the entire traffic situation.

The displays for the sector controllers are configured accordingly. However, the bottom box then corresponds to the "Time over the Metering Fix". Displayed is the whole sequence, i.e. the sequence to be merged from all approach directions. According to the colour of the stripholders used in the different approach sectors the labels are presented in the respective colours, giving the controller a clear indication from which direction an aircraft could be expected and giving a hint for what reasons the computer possibly has made a different proposal than the human controller would have done with his limited knowledge of the overall situation.

In case of higher degrees of automation or in case even more sophisticated "intelligent" planning algorithms are applied, the questions of transparency and understanding become even more important, as the controller must be able to fully monitor the automated control process and to take over control at any time, in case of emergency.

In this application of a semi-automated sub-system the solutions provided for transparency and acceptance were worked out in close cooperation with the users.

As mentioned above, the controller is allowed to modify the computer generated plan if he desires or if unforeseen events have to be matched.

Fig.11 shows the small functions-keyboard which is used for controller-computer-interaction. There are 8 (2 spare) function-keys to activate the operational interventions described above. In addition there are "Clear"- and "Execute"-keys and the so-called "-/+"-keys which are used either:

- o to move a cursor down or up the time-scale, in order to identify or modify the plan of a specific aircraft, for example for a sequence change;

or

- o to increase or decrease parameter values; e.g. if the flow rate shall be changed: after pressing the FLOW-key, first the valid value is displayed on the input-control-line (bottom-right). It then can be increased or decreased with the "-/+"-keys. The desired value is activated with the EXECUTE-key.

All input procedures are performed in this same manner.

Although much more sophisticated displays and controls are conceivable and feasible from an engineering point of view (as much more information is available in the computer) the COMPAS development strictly adhered to the design-requirement of keeping the man-machine-interface as simple and clear as possible.

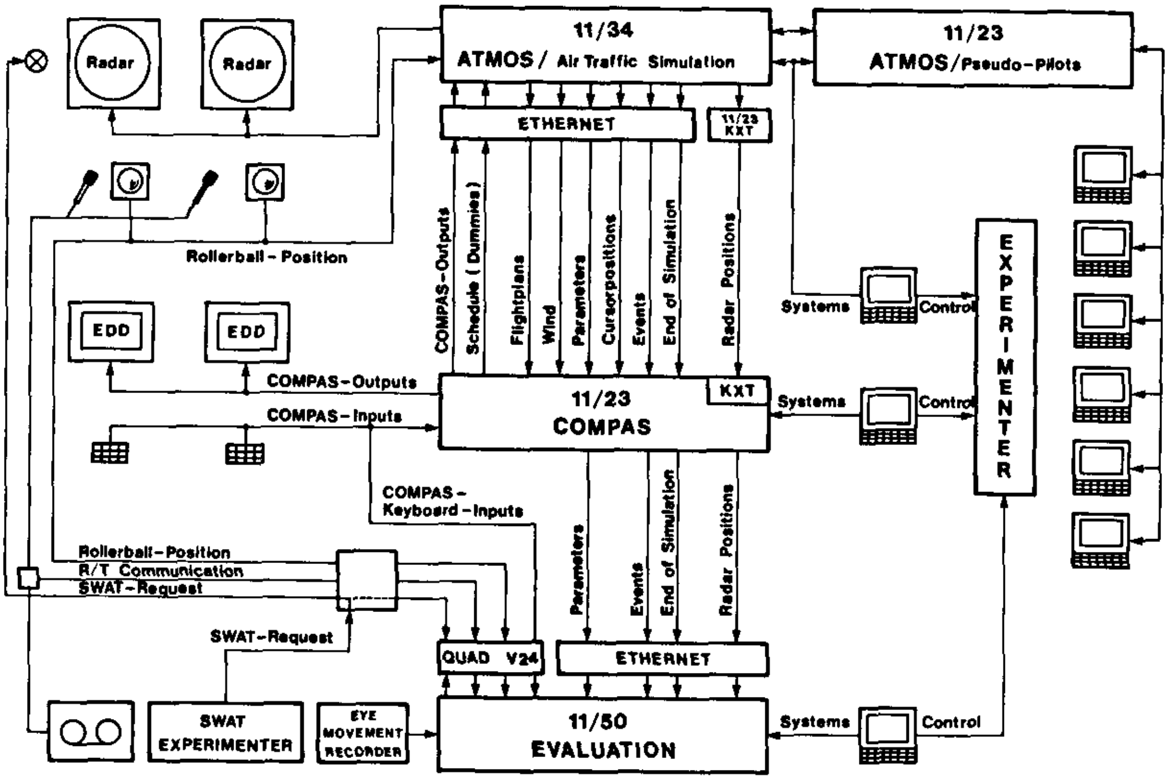
The first trials with controllers from Frankfurt are very promising with regard to acceptance and operational feasibility.

5. Conclusions

The described computer-based planning system has been developed in all its elements at the DFVLR-Institute for Flight Guidance. It has been tested and evaluated at the institute's air traffic simulation facility, using traffic scenarios of Frankfurt Airport in real-time simulations, with up to 52 aircraft movements simultaneously.

The dynamic planning algorithm as well as the operational concept for computer assistance and the man-machine interface not only proved to be feasible, but were also readily accepted by more than 30 air traffic controllers from the Frankfurt Air Traffic Control Center, who took part in the tests and evaluations.

Thus a first step towards the introduction of intelligent computer assistance for the controllers has been successfully achieved. It is however quite obvious, that this step of transferring human planning and decision making functions to a computer is still limited, with respect to the operational requirements of the user. A next step to go ahead with, is to implement some human controller heuristics in a rule-based system, which will then be coupled with the described algorithm. Essential for any operational application however are not only appropriate models and suitable computer capabilities, but in particular the careful design of elements and procedures for the man-machine interface.



COMPAS experimental system

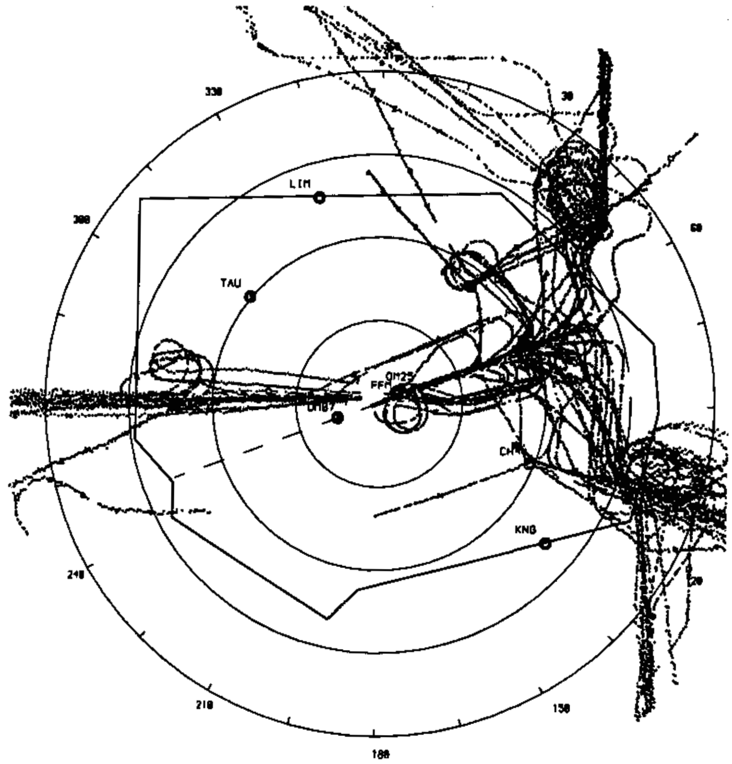


Figure 1: Radar tracks of arriving aircraft in a 90-min peak period

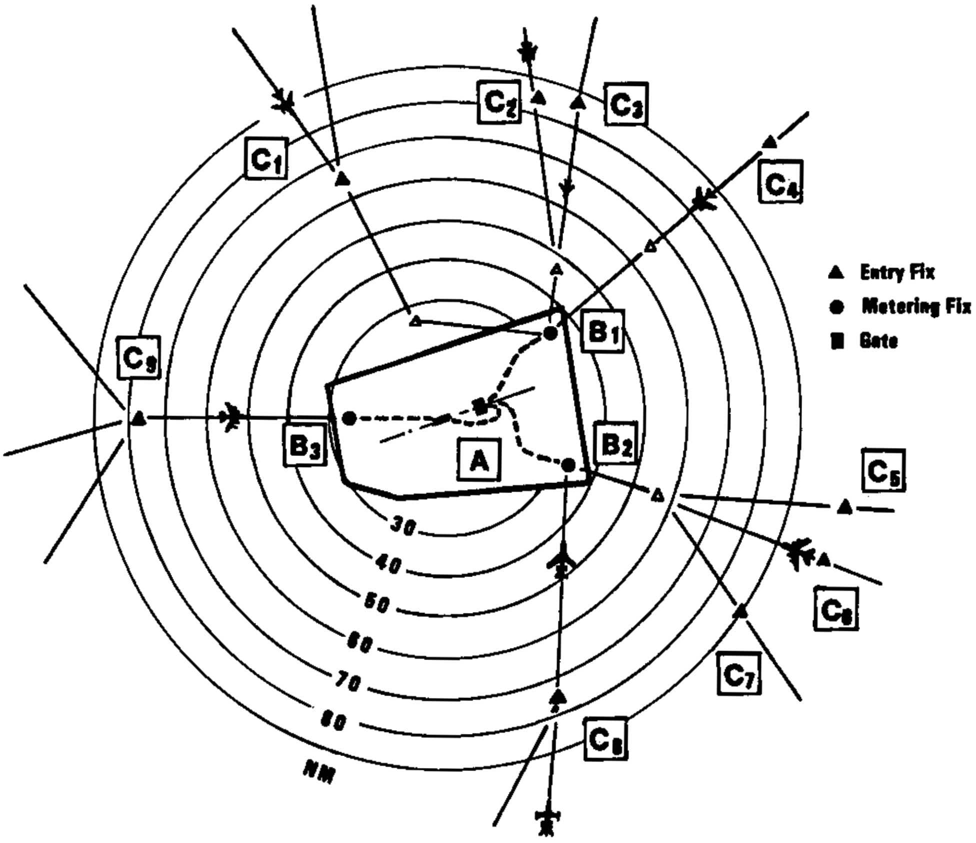


Figure 2: Structure of the Frankfurt Approach Area

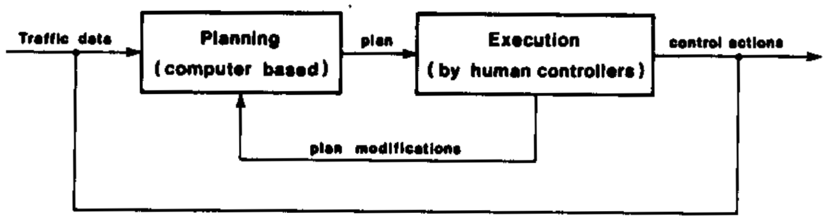


Figure 3: Planning and execution functions with COMPAS

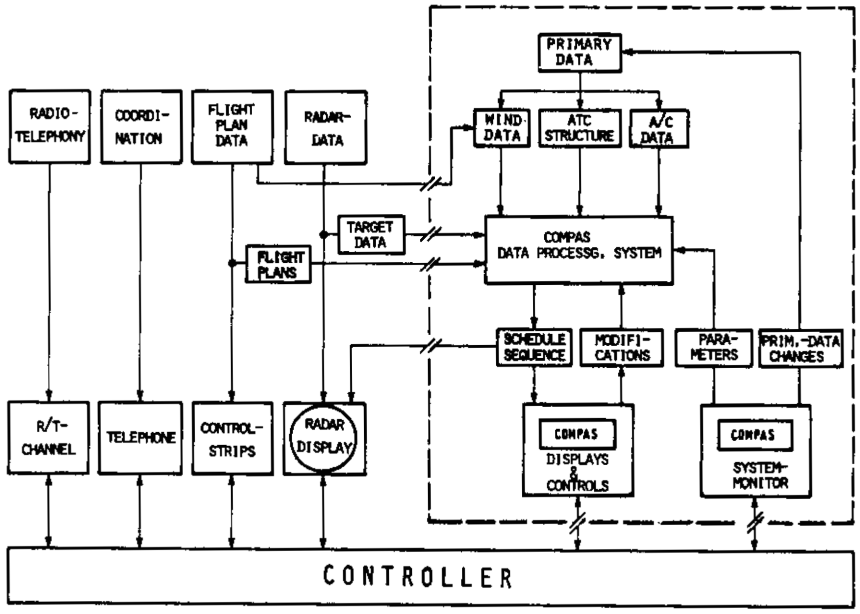


Figure 4: COMPAS as an additional function in ATC

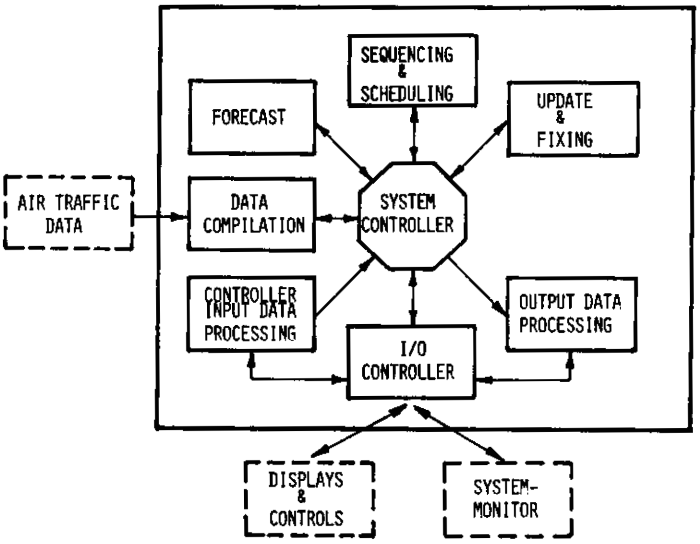


Figure 5: COMPAS data-processing functions

leading aircraft \ trailing aircraft	H HEAVY	M MEDIUM	L LIGHT
H	107	133	160
M	80	80	107
L	80	80	80

Figure 6: Minimum separation time (sec)

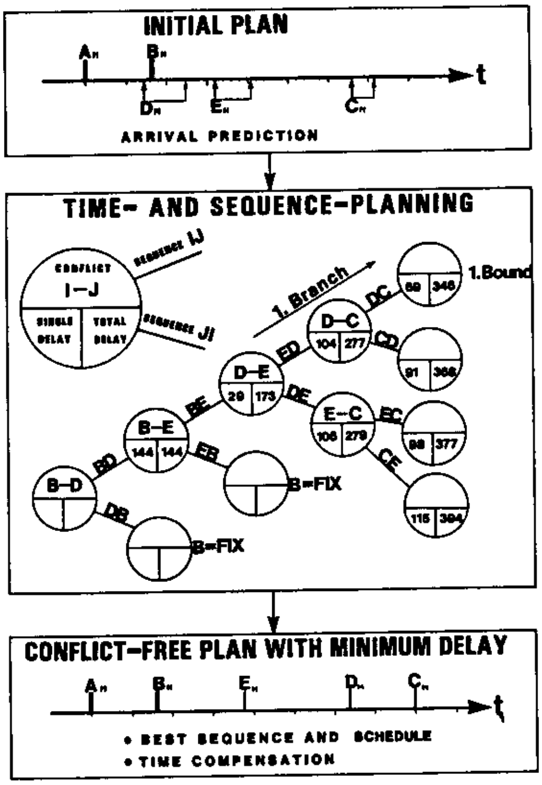


Figure 7: COMPAS-planning algorithm (Schematic)

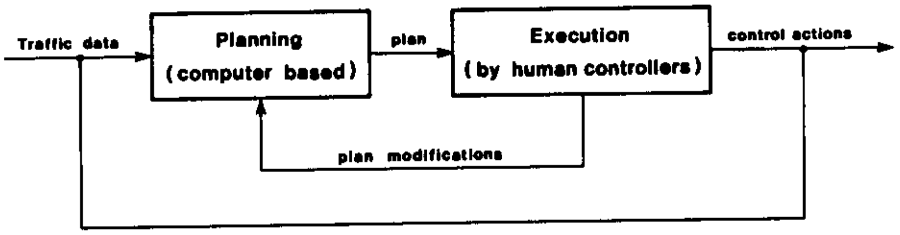


Figure 8: Distribution of planning and execution functions with COMPAS

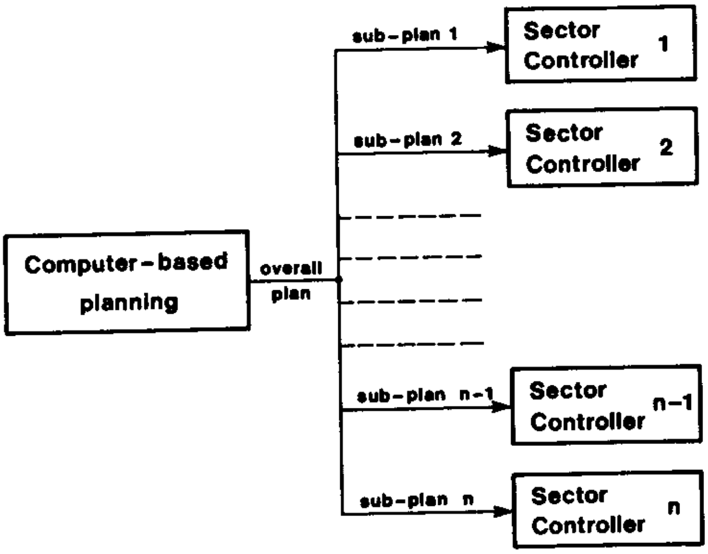


Figure 9: Sub-dividing the overall-plan

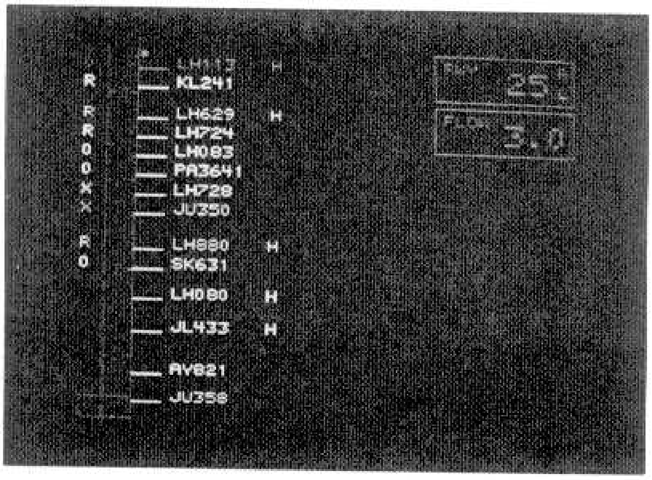


Figure 10: COMPAS-display of proposed sequence and schedule

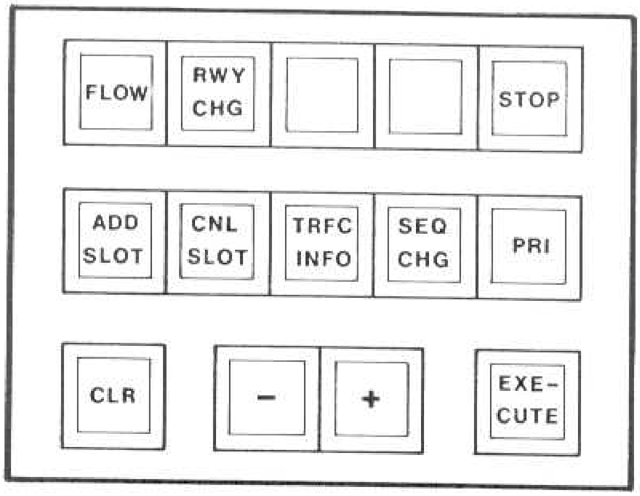


Figure 11: COMPAS-function keys

COMPAS-OPERATIONAL CAPABILITIES

CONTINOUSLY/AUTOMATICALLY

- SEQUENCING & SCHEDULING
  (SEQUENCE; ARRIVAL TIMES FOR MF AND GT)
- METERING CONTROL ADVICE
  (SPEED-, DESCENT, FLIGHT-PATH, RECOMMENDATION)
- ADDITIONAL INFORMATION (DISPLAY ON REQUEST)

IF NECESSARY, WITH CONTROLLER INTERACTION

- CHANGE OF NOMINAL SEPARATION
- CHANGE OF LANDING DIRECTION
- CHANGE OF ATC/AIRSPACE STRUCTURE
- CHANGE OF SEQUENCE
- INSERTION OF ARR. INTO SEQUENCE
- EXTRACTION OF ARR. OUT OF SEQUENCE
- EXCEPTIONAL CASES AND PROCEDURES

Table 1: COMPAS-Operational Capabilities

CONTROLE DU TRAFIC DANS LES TMA MODERNES

TECHNIQUES DE LA PROCHAINE GENERATION

Assistance automatique au dialogue contrôleur/pilote

par

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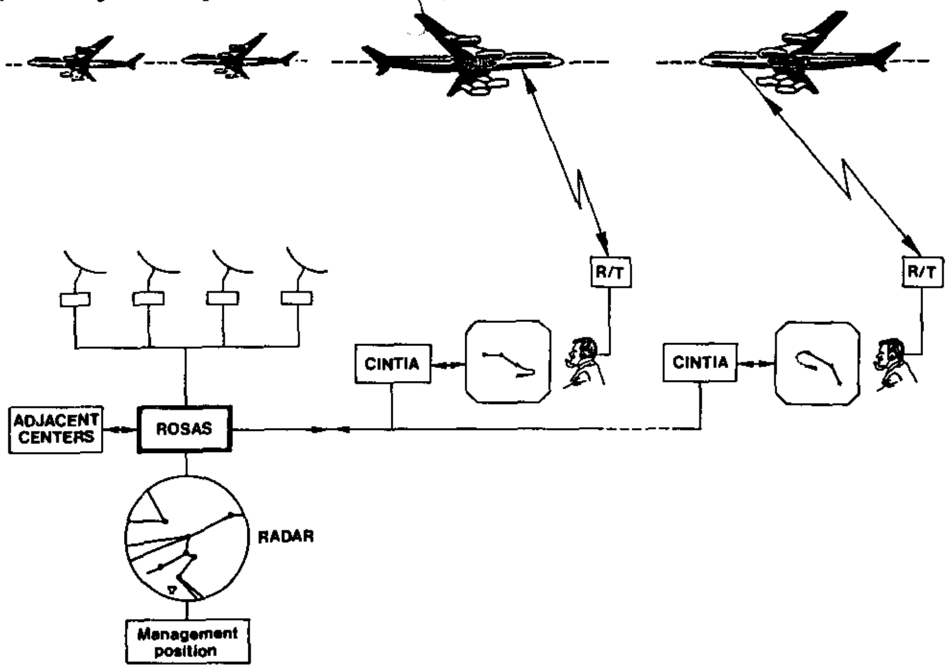
SOMMAIRE

Dans l'avenir, tout concept à mettre en oeuvre pour assurer un écoulement sûr et ordonné de la circulation aérienne (dans les conditions voulues de rapidité, d'économie et de capacité de prise en charge du système) se caractérisera très probablement par deux éléments essentiels, étroitement interdépendants. D'une part, par la gestion en direct de la circulation aérienne sur une région de grande étendue.- dont les dimensions seront au moins celles d'une Zone de Convergence mais qui pourrait s'étendre à un continent tout entier - permettra d'établir l'heure d'arrivée et de départ pour chaque aéronef entrant dans ladite région, tout en fixant les principales caractéristiques des trajectoires de vol correspondantes. D'autre part, il faudra définir une procédure opérationnelle de contrôle propre à guider chaque vol avec précision sur l'ensemble de son itinéraire dans la région soit, dans le cas d'une Zone de Convergence, depuis le moment où il y entre jusqu'au toucher des roues, en conformité avec les directives régissant la gestion de la circulation aérienne et selon les pratiques d'exploitation en vigueur (tant à bord des aéronefs qu'au sol).

Le présent document passe en revue les principales caractéristiques opérationnelles d'une procédure de contrôle qui, tout en satisfaisant aux contraintes énoncées plus haut, permet, sous réserve d'éventuelles modifications ultérieures, de respecter à 10 secondes près l'heure d'arrivée initialement prévue au moment de l'entrée dans la zone. Elaborée pour les aéronefs de transport d'aujourd'hui, cette procédure est valable tant pour l'environnement R/T actuel que pour celui, plus éloigné dans l'avenir, où les communications se feront également par liaisons de données.



Gestion de la circulation aérienne et contrôle des vols

Figure 1

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1. INTRODUCTION

Dans les années à venir, la densité du trafic aérien connaîtra probablement une augmentation continue, bien qu'il n'existe pour l'Europe occidentale aucun projet de grande envergure en matière de construction de nouveaux grands aéroports ou d'autres grandes aires d'atterrissage. Les conséquences de ce double pronostic, qui ne date pas d'aujourd'hui, ont déjà été débattues lors de précédents colloques de l'AGARD. L'analyse qui en a été faite portait sur les retards (réf. 1, 1972), sur la rapidité et l'efficacité de l'écoulement du trafic (réf. 2, 1975) et sur les possibilités d'économie, notamment de carburant (réf. 3, 1979 ; réf. 4, 1982), alors qu'il semble aujourd'hui que ce soit la capacité de prise en charge des systèmes qui repasse au premier rang des préoccupations (réf. 5, 1984 ; réf. 6, 1986).

La Direction technique de l'Organisation européenne pour la Sécurité de la Navigation aérienne EUROCONTROL a mis au point une méthode pour la gestion efficace de la circulation aérienne et le contrôle précis de chaque vol dans une région de grande étendue englobant une zone terminale importante et éventuellement plusieurs aéroports secondaires, région dénommée Zone de Convergence. Ce système comporte deux éléments essentiels, étroitement inter-dépendants :

(a) D'une part, un système de gestion du trafic appelé "Système régional d'ordonnancement-régulation des vols" ("Regional Organisation of the Sequencing and Scheduling of Aircraft System - ROSAS").

(b) D'autre part, la régulation précise, dans les quatre dimensions, de chaque vol présent dans la zone considérée, en conformité des directives établies pour la gestion du trafic. Ce deuxième élément est connu sous l'appellation "Régulation individuelle des trajectoires d'arrivée" (Control of Inbound Trajectories of Individual Aircraft - CINTIA).

Le système ROSAS/CINTIA est conçu pour répondre à un triple impératif : économie de vol, rapidité d'acheminement du trafic, capacité optimale du système de contrôle. Il satisfait aux exigences des compagnies aériennes en ce qu'il réduit à un minimum les écarts par rapport au profil de vitesse idéal pour les phases de montée, de croisière et de descente, ceci même en direct à la demande des pilotes. En outre, la situation de trafic qu'il produit offre une sécurité accrue, le nombre des conflits potentiels étant nettement réduit par rapport aux situations actuellement observées (références 7 et 8). L'élément ROSAS définit intégralement la trajectoire de chaque vol depuis l'entrée dans la région jusqu'au toucher des roues. L'élément CINTIA permet au contrôleur de la circulation aérienne d'assurer pour chacun des aéronefs présents dans la zone un guidage conforme aux directives de l'élément gestion (ROSAS) malgré l'action de perturbations nombreuses et d'origines très diverses.

Les essais menés à ce jour sur un échantillon de trafic réel observé dans les régions de Bruxelles et de Londres font apparaître que les algorithmes retenus pour le ROSAS sont à la fois efficaces et fiables. Mais, lorsqu'il s'agira d'appliquer le système en conditions réelles d'exploitation, il est évident que tout dépendra de la qualité de l'élément CINTIA : celui-ci devra constituer une procédure de navigation, de guidage et de contrôle qui, dûment coordonnée entre l'organisme de contrôle au sol et de pilote, avec intervention éventuelle de l'appareillage de bord, devra être suffisamment précise pour que l'heure d'atterrissage de chaque aéronef se situe à l'intérieur du créneau qui lui aura été attribué dans la séquence définie initialement - c'est-à-dire au moment de son entrée dans la zone - et éventuellement amendée après coup par l'organisme de gestion de la circulation aérienne ou les contrôleurs chargés du vol considéré.

Afin d'évaluer cette précision, on a procédé à la simulation de l'ensemble de la boucle de contrôle du CINTIA, avec la coopération de pilotes de ligne et de contrôleurs chevronnés. Les résultats acquis à ce jour donnent à penser que l'on peut, dans l'environnement actuel de communications radiotéléphoniques, compter sur une précision de l'ordre de 10 secondes au seuil de la piste et qu'à terme, dans un environnement automatisé avec liaisons de données, cette valeur pourra être maintenue pour des trajectoires de vol atteignant 200 NM à compter de l'entrée dans la zone jusqu'au toucher des roues. Une description succincte de la procédure de contrôle proposée - avec ses aspects techniques et les résultats de la série de tests effectués sur divers simulateurs de vol - a été présentée à de précédents colloques. Les textes correspondants (références 9 et 10) comportent en outre une bibliographie relative à des réalisations connexes. Pour l'historique de la question, ainsi que pour les détails techniques et théoriques, nous renvoyons donc le lecteur à ces publications antérieures. La présente communication traitera uniquement des fonctions opérationnelles principales du CINTIA, son objet étant d'indiquer comment il est possible d'assister par ordinateur le dialogue contrôleur-pilote et comment le CINTIA pourrait être mis en oeuvre dans tout environnement de contrôle réel, présent ou futur.

2. ENVIRONNEMENT SIMULE

2.1. Généralités : Système de gestion (ROSAS) / régulation (CINTIA)

La Figure 1 représente schématiquement l'ensemble du système de gestion et de régulation. L'élément (ROSAS, en l'occurence) attribue à chaque aéronef entrant dans la zone un créneau d'atterrissage. Celui-ci est calculé en fonction de la situation de trafic et des autres conditions d'exploitation, compte dûment tenu des impératifs et contraintes d'économie, de rapidité d'écoulement de la circulation, de capacité du système et de sécurité. Le plan correspondant est alors renvoyé aux fins de coordination aux "secteur(s)" compétent(s), où il sera contrôlé au regard de sa compatibilité avec les conditions locales.

Une fois accepté, sous réserve d'éventuels amendements, le plan est transmis pour mise en oeuvre à l'organisme de contrôle intéressé. A partir de ce moment, le contrôleur de la circulation aérienne et le CINTIA fonctionnent efficacement comme entité unique, chargée de guider l'aéronef et d'assister le pilote dans la conduite du vol jusqu'à l'atterrissage.

2.2. Régulation quadridimensionnelle des trajectoires : éléments

Le schéma de la Figure 2 représente un poste de régulation quadridimensionnelle des trajectoires d'aéronefs dans l'actuel environnement de communications radiotéléphoniques. C'est organisme de gestion du trafic aérien qui notifie l'heure d'atterrissage, laquelle pourra être modifiée dans certains cas par le contrôleur local. Pour simuler la procédure, on a recours aux éléments ci-après, dont les relations sont également indiquées sur le schéma (pour tout complément d'informations à ce sujet, voir la référence 11).

(a) La conduite des aéronefs est assurée au moyen de simulateurs de vol du type actuellement utilisé pour les compagnies aériennes, desservis par des équipages professionnels.

(b) L'information radar est transmise au CINTIA à intervalles de 5 ou de 12 secondes, de manière à simuler divers modes de poursuite radar;

(c) Les moyens de communications radiotéléphoniques sont semblables à ceux qui servent actuellement au dialogue entre les centres de contrôle et les aéronefs en vol ;

(d) Les directives de régulation quadridimensionnelle destinées à chaque aéronef sont produites par l'ordinateur du CINTIA. Affichées sur l'écran radar conformément aux usages opérationnels actuels, elles peuvent être directement traduites par le contrôleur en expressions conventionnelles agréées. Le contrôleur est en outre averti (par un changement visuel - couleurs, par exemple - et/ou par un signal acoustique) lorsque la directive est sur le point d'être transmise à l'aéronef (pour le contenu des étiquettes, les expression conventionnelles et le mode d'affichage utilisés, voir chapitres 4 et 5) ;

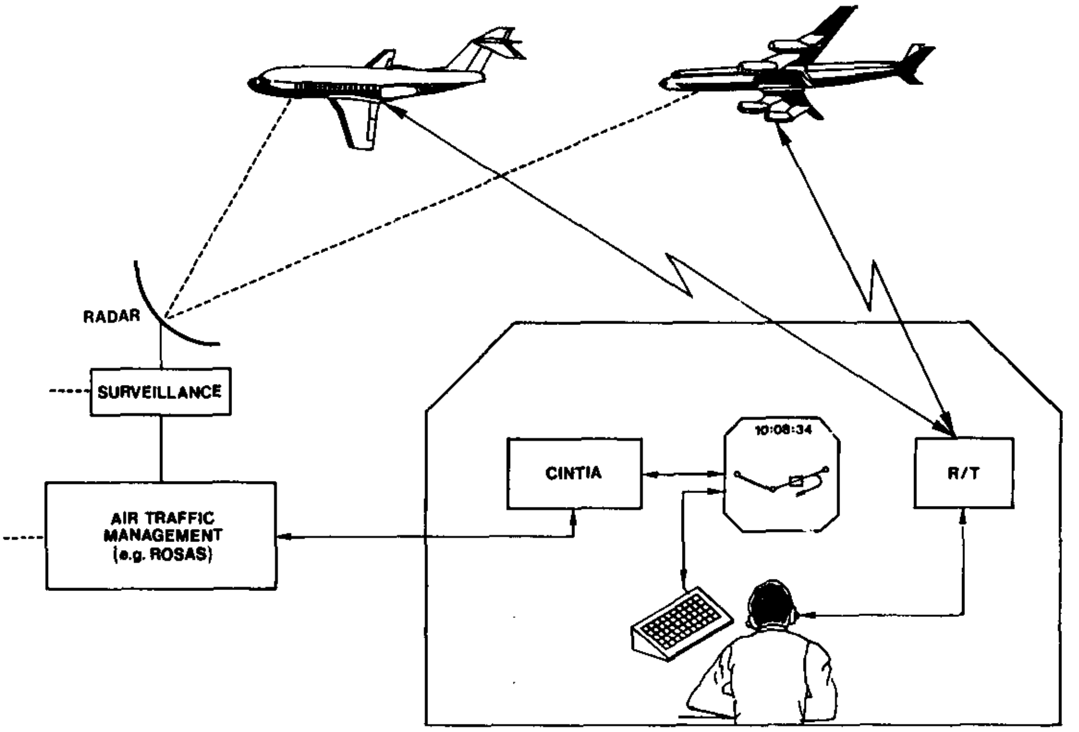
(e) Pour les vols réalisés jusqu'à présent, le contrôle effectif a été assuré par du personnel des Services belges du Contrôle de la circulatioin aérienne (Régie des Voies Aériennes / Regie der Luchtwegen) ;

(f) Le système CINTIA, tel qu'il existe actuellement, est directement adaptable à un environnement caractérisé par des communications sol-air-sol automatisées en mode numérique.

Les directives produites par le CINTIA guident l'aéronef, dans les meilleures conditions d'économie, depuis la position où elles prennent cours jusqu'au créneau qui lui a été attribué dans la séquence d'arrivée. Les indications qu'elles affichent ne sont toutefois nullement obligatoires pour le contrôleur et le CINTIA s'adapte automatiquement aux résultats des différentes décisions que ce dernier peut prendre. De fait, considérées du point de vue du CINTIA, ces décisions ne sont qu'un ensemble parmi d'autres de facteurs potentiels de perturbation.

2.3. Représentativité de l'environnement simulé

Il semble permis d'affirmer que l'environnement créé par la simulation correspond de très près à la réalité de l'exploitation, tant sur les plans techniques et opérationnels que du point de vue de l'élément humain. C'est ainsi que l'on peut créer et justifier comme suit toutes les perturbations de nature à affecter un vol régulier :



Fcontionnement du CINTIA dans l'environnement actuel
(communications en radiotéléphonie)

Figure 2

- conduite de l'aéronef : incidents créés sur les simulateurs de vol des compagnies ;
- information radar : interruptions de durée limitée ;
- occupation des fréquences radio : utilisation de telle ou telle voie à des moments critiques pour des messages urgents ;
- ambiguïtés affectant simultanément ou séparément les communications, le contrôle et la navigation à la suite d'erreurs de l'élément humain, au sol ou en vol ;
- situations de trafic appelant une intervention immédiate du contrôle, par exemple pour la prévention ou la résolution des conflits ;
- intempéries nécessitant un amendement de l'autorisation de route et/ou d'altitude, ainsi qu'un changement dans la conduite du vol (par exemple dégivrage) ;
- toutes perturbations dues à des erreurs touchant les prévisions météorologiques, les "données d'aéronef" du CINTIA (informations de performance et sur les procédures opérationnelles), les variables d'état des aéronefs (position radar et, en mode R/T, la masse moyenne), etc.

On trouvera au chapitre 5 un échantillon des trajectoires récemment parcourures sur le simulateur de vol DC-10 de la SABENA : cet échantillon donne la mesure de la représentativité de l'environnement simulé décrit dans les paragraphes qui précèdent.

3. PRINCIPES RETENUS POUR LA NAVIGATION, LE GUIDAGE ET LE CONTROLE

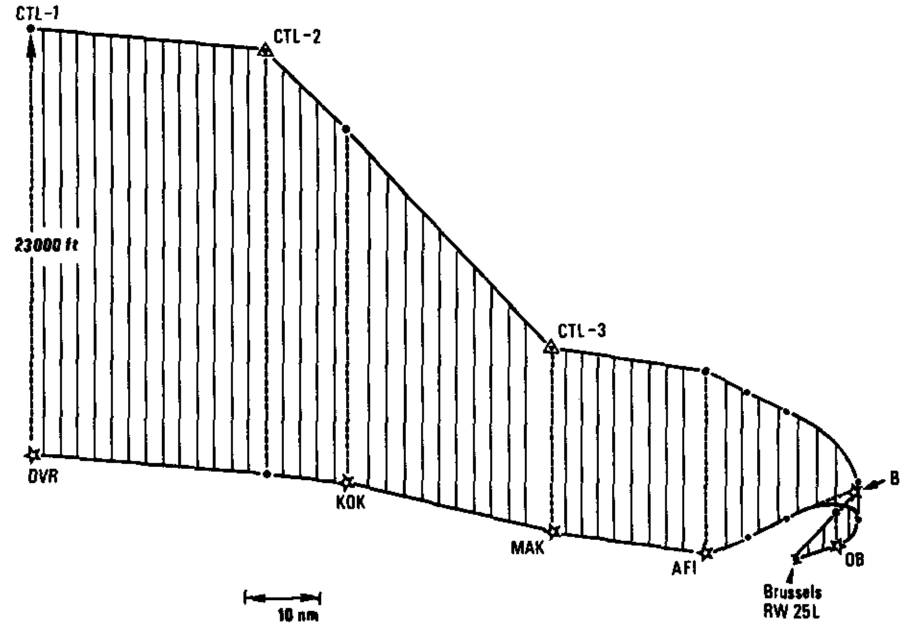
3.1. Généralités

Le schéma de la Figure 3 représente la procédure d'approche. L'aéronef en provenance de Londres à destination de Bruxelles doit suivre l'itinéraire représenté sur ce schéma : Douvres, Koksy, Mackel, Affligem, Bruno, Bruxelles. Il peut s'attendre à ce qu'on lui attribue un profil de descente et une route d'arrivée standard sur Bruxelles et à bénéficier d'un guidage radar pour l'approche ILS de la piste 25L.

L'heure d'atterrissage est déterminée au niveau de la gestion, en concertation avec les organismes de contrôle intéressés, au moment où l'aéronef entre dans la zone - ou par une coordination adéquate au moment où il passe au-dessus de Douvres. En même temps sont définies les caractéristiques correspondantes de la trajectoire (profil de vitesse en croisière, descente et approche, tracé de la trajectoire d'approche finale).

3.2. Variables de contrôle

Les deux catégories fondamentales de variables de contrôle que l'on peut mettre en oeuvre pour guider l'aéronef avec précision jusqu'au toucher des roues influent sur sa vitesse et sur le tracé de sa trajectoire. Evidemment, celle-ci peut également être affectée par un changement du profil de vol dans le plan vertical, mais il s'agit là à proprement parler d'une action sur la vitesse, encore que les directives correspondantes s'expriment par des autorisations d'altitude, comme nous verrons plus loin.



Trajectoire schématisée d'un vol à destination de Bruxelles, montrant les principaux points de contrôle

Figure 3

La base de données du CINTIA contient les caractéristiques des performances de chaque type d'aéronef, ainsi que les procédures de vol préconisées par chaque exploitant. Le système connaît également la topographie de la région et notamment les cooordonnées précises des points de route, des aides à la navigation et des aérodromes. Muni de ces connaissances détaillées, d'une bonne compréhension de l'élément humain, très bien armé pour l'extrapolation d'une trajectoire observée et pour le calcul en direct de la trajectoire la plus conforme aux exigences de la gestion, le CINTIA donne des directives directement utilisables par le contrôleur de la circulation aérienne et pleinement compatibles avec les nécessités de l'exploitation de l'aéronef.

3.3. Principes applicables aux arrivées

La Figure 3 illustre l'application du système de régulation CINTIA à un vol d'arrivée.

Lorsque l'aéronef entre dans la zone, ses autorisations d'altitude et de route sont confirmées. Pour la phase en route, c'est le profil de vitesse en croisière et en descente qui est la variable de contrôle principale. Dès lors, la vitesse en croisière fera partie intégrante de la directive de contrôle (CTL-1) soit dès l'entrée dans la zone, soit à partir d'une position ultérieure. Il reste évidemment possible de demander des changements d'itinéraire ou des restrictions d'altitude, comme nous le montrerons plus loin (raccourcissement de la route dans toute la mesure possible, mesures de résolution de conflits, évitement des zones de mauvais temps, etc.).

Après notification de la vitesse de croisière à l'aéronef, le CINTIA indique les conditions de descente en route prévues, à savoir la vitesse de descente et la position où doit se faire le passage de la croisière à la descente (CTL-2).

Pendant ou vers la fin de la descente en route, le CINTIA définit le tronçon final de la trajectoire (CTL-3). Cette définition peut comporter plusieurs éléments, à savoir des indications de vitesse (notamment au titre des règlements en vigueur dans la région) le virage d'amorce du parcours de base et le virage d'interception du faisceau ILS, comme le montre la Figure 4. Le schéma de cette figure représente le dernier tronçon - depuis Mackel jusqu'au toucher des roues, soit quelque 65 à 75 NM - de trois trajectoires effectuées sur le simulateur de vol DC-10 de la SABENA. Dans le cas (a), il n'a fallu qu'une seule directive de contrôle, laquelle correspondant à la définition du dernier virage avant interception de l'ILS. Dans le cas (b), l'approche de l'ILS s'est faite en deux étapes, à savoir d'abord un virage d'amorce du parcours de base, puis le dernier virage avant interception de l'ILS. Enfin, dans le cas (c), à la fin du second virage, le CINTIA a également proposé une réduction de la vitesse afin de respecter l'heure prévue d'atterrissage et d'assurer ainsi une séparation suffisante par rapport à l'aéronef précédent de la séquence d'atterrissage.

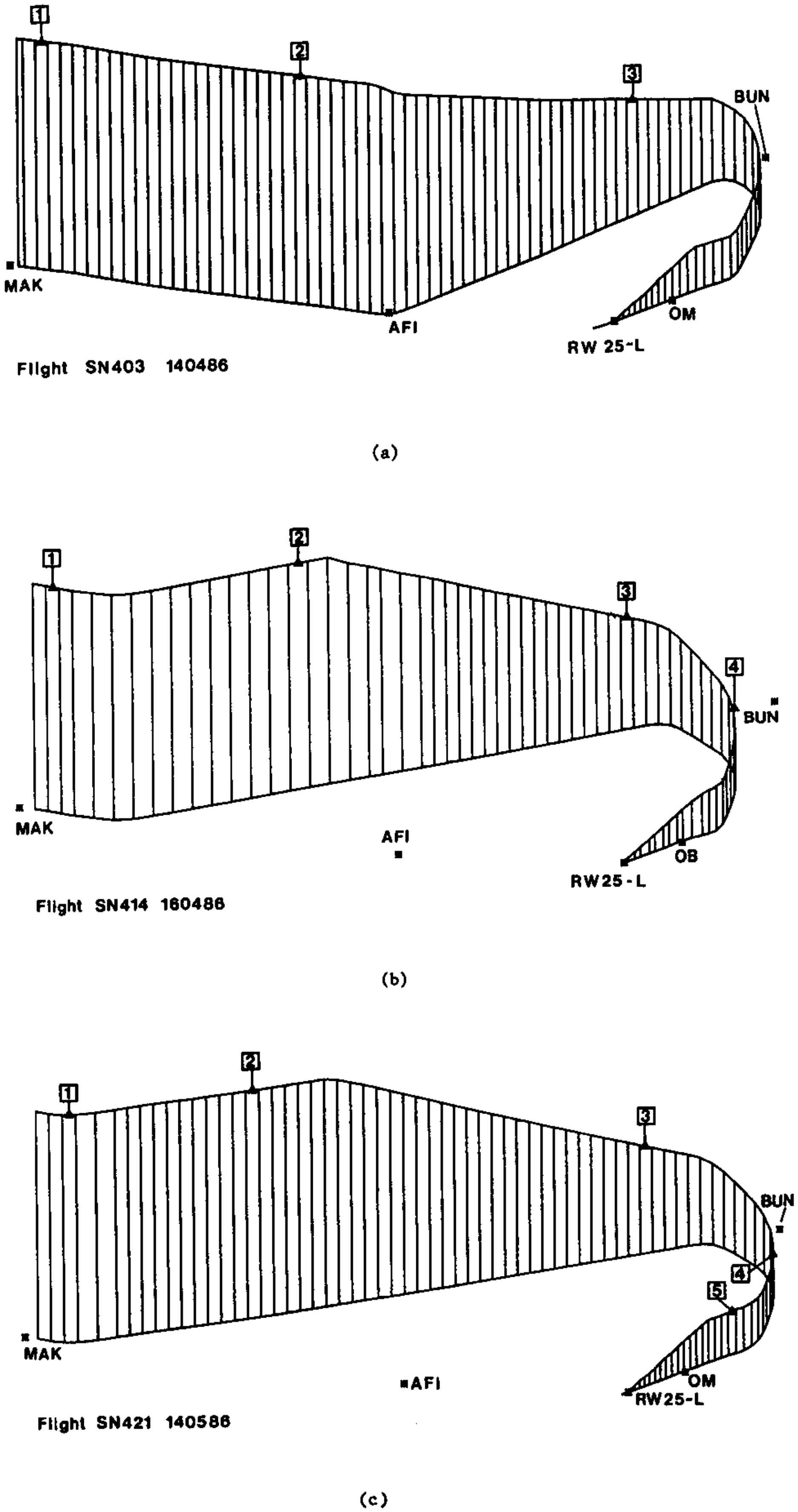
3.4. Surveillance, navigation et communications

Outre les informations radar de surveillance, qui indiquent la position de l'aéronef toutes les cinq ou douze secondes, le CINTIA prend partiellement en compte l'équipement de l'aéronef (c'est ainsi qu'il distingue entre les équipements de navigation embarqués et le calculateur de bord d'un FK-27 et ceux d'un B-757). Il exploite également plusieurs autres moyens pour la formulation et la transmission des directives de contrôle : Les diverses mesures de régulation de la trajectoire [voir plus haut les mesures de contrôle correspondant à CTL-1, CTL-2, CTL-3 (a), (b), (c)] doivent être déclenchées en des positions bien déterminées. Ces positions sont définies sous la forme de distances DME par rapport aux diverses stations normalement utilisées dans la région aux fins de navigation. Dans l'exemple de la Figure 3, ces stations sont successivement Koksy, Affligem et Bruno. En ce qui concerne les communications, deux modes d'exploitation sont envisagés. Dans l'environnement actuel (communications en radiotéléphonie), le CINTIA affiche les directives à l'intention du contrôleur, qui les transmet à l'équipage une fois qu'il les a approuvées. Ces directives sont figées quelque 30 à 60 secondes d'avance, de manière à tenir compte du délai de réaction de l'élément humain et des contraintes d'occupation des fréquences. En outre, conformément aux procédures de communications radiotéléphoniques actuelles, le CINTIA présente ses messages sous une forme qui se prête à la transmission directe aux aéronefs, après visualisation et approbation par le contrôleur, via une liaison numérique automatisée sol-air-sol (pour de plus amples informations, voir référence 12).

3.5. Interface CINTIA/Contrôleur

L'interface entre le CINTIA et le contrôleur de la circulation aérienne a été conçue avec le souci primordial de réduire autant que possible la charge de travail du contrôleur. A cette fin, il a été décidé, d'une part, d'intégrer les directives du CINTIA dans l'étiquette d'aéronef présentée sur l'écran radar plutôt que de les afficher sur un VET (visualisateur électronique de textes) séparé.

D'autre part, il était indispensable d'éviter dans toute la mesure possible que les contrôleurs aient à communiquer des informations quelconques au CINTIA. En conséquence, lorsque le contrôleur guide un aéronef sur une trajectoire différente de son itinéraire prévu, il n'est pas nécessaire d'en avertir le système. Celui-ci est en effet suffisamment "intelligent" pour suivre la trajectoire de vol effective et indiquer à tout moment quelle devrait être la directive suivante pour amener l'appareil de sa position du moment au créneau voulu dans la séquence d'atterrissage.



(a)

(b)

(c)

Régulation de la trajectoire de trois vols à l'arrivée,
avec respectivement
un, deux et trois éléments CTL-3

Figure 4

4. SCENARIO DE CONTROLE SOL-AIR

4.1. Chronologie des messages sol-air-sol

Afin de donner au lecteur une bonne vue d'ensemble de la procédure opérationnelle, il lui est proposé de suivre le déroulement des échanges de messages CINTIA-controleur-pilote pour le vol dont la trajectoire est illusrée à la Figure 3. La liste dénommée "Tableau 1" reproduit l'ensemble des messages émanant du CINTIA (messages appelant l'intervention du contrôleur et messages déjà affichés au moment où tout autre message était envoyé par les services au sol ou faisait l'objet d'une réponse de leur part), ainsi que l'intégralité des messages sol-air-sol échangés durant tout le vol depuis l'entrée dans la région jusqu'à l'atterrissage. Les messages produits par le CINTIA, qui apparaissent à gauche dans un cadre, sont la reproduction en noir et blanc des diverses étiquettes apparaissant sur l'écran radar (voir également chapitre 5). Les messages émanant de l'équipage, reproduits en caractères obliques, commencent par l'appel "BRUSSELS, SN 123". Les messages du contrôleur sont reproduits en caractères droits et commencent généralement par : "SN 123, BRUSSELS:".

Le tableau donne ainsi directement la transcription, en expressions conventionnelles ATC en clair, des directives du CINTIA apparaissant dans l'étiquette. Pour plus de clarté toutefois, nous allons en aborder brièvement quelques aspects particuliers.

4.2. Structure et teneur des messages du CINTIA

La capacité des étiquettes utilisables pour les messages CINTIA est de trois lignes de huit caractères. La teneur des messages peut varier d'une phase de vol à l'autre, mais certains éléments sont constants.

(1) La première ligne donne l'indicatif de l'aéronef considéré, soit SN 123 dans l'exemple choisi, puis la catégorie de tonnage à laquelle il appartient (H = heavy, M = medium, L = light) et, enfin, sa position dans la séquence d'atterrissage, identifiée soit par l'un des chiffres 1 à 9, soit par un astérisque lorsqu'à sa position correspond un chiffre supérieur. Ce n'est pas le CINTIA qui produit cette dernière information mais le module ROSAS, qui assure la gestion du trafic aérien.

(2) La deuxième ligne affiche généralement l'altitude, exprimée en niveaux de vol, et la vitesse-sol obtenue du radar. Sur demande, le CINTIA peut indiquer la distance à parcourir jusqu'au toucher des roues ("track-miles") au lieu de la vitesse-sol calculée ; dans ce dernier cas, le nombre est donné avec une décimale, de manière à indiquer qu'il s'agit bien d'une distance.

(3) La troisième ligne est essentiellement consacrée aux directives de contrôle du CINTIA. Bien entendu, leur teneur varie d'une phase de vol à l'autre. Le moment venu de transmettre la directive à l'aéronef, la présentation du message change, à savoir que les informations de la troisième ligne passent du jaune au rouge ou d'un affichage statique à un message clignotant, suivant le type d'équipement utilisé. Une fois passé le moment où le pilote aurait dû effectuer la manoeuvre indiquée, la présentation du message (ici encore, troisième ligne uniquement) change à nouveau, la couleur du texte passant au vert ou diminuant en intensité lumineuse, ce qui rappelle au contrôleur la mesure prévue lorsque celle-ci n'a pas été prise, par exemple si le pilote n'effectue pas son virage dans le délai imparti ; le contrôleur enverra alors un rappel et le CINTIA aura recours à toute directive de régulation encore possible pour effectuer la compensation. Remarque : Dans le Tableau 1, la marque "XXX" apparaissant à droite de la directive indique que la présentation de l'information a changé et qu'il y a lieu d'envoyer le message.

4.3. Séquence des phases de vol

Pour la commodité de la lecture, les divers messages qui apparaissent dans l'ordre chronologique au Tableau 1 ont été groupés par phase de vol.

A l'entrée dans la zone, les échanges correspondent à la pratique actuelle. Le message affiché par le CINTIA commande à l'aéronef de commencer à passer à la vitesse de croisière de 280 KIAS à 36 NM avant Koksy. Le message est envoyé au moment où il est demandé (XXX) et par la suite, le CINTIA affiche en permanence la directive de contrôle suivante, à savoir "descente prévue à ... - DME avant Koksy", indication qui marque la fin de la phase de croisière et le début de la phase de descente. La teneur de ce message peut changer, ne serait-ce que parce que les conditions de vol se sont modifiées et/ou l'élément ROSAS a attribué à l'aéronef une nouvelle heure d'atterrissage. Le CINTIA aura alors adapté le reste de ses directives afin de respecter la contrainte telle qu'elle s'établit en définitive ; exemple : "Descendez à 5 NM-DME avant Koksy à 270 KIAS" au lieu de "Descendez à 6 NM-DME avant Koksy à 280 KIAS". Pour les phases de croisière en route et de descente, le profil de vitesse doit être exprimé à la fois en nombre de Mach et en CAS. Comme on l'aura compris, l'espace limité disponible nous oblige à exprimer un tel profil sous la en forme mmm/ss, le nombre de Mach étant exprimé en centièmes et la vitesse corrigée en multiples de 10 noeuds. Pour la dernière partie de la descente, on ne peut plus utiliser le nombre de Mach. La vitesse est donc exprimée en noeuds et l'on dispose d'un espace suffisant pour afficher intégralement le code de la station DME.

Après la descente en route, le CINTIA affiche la directive suivante, à savoir les instructions définissant le virage d'amorce du parcours final, dénommé "base-turn" dans le Tableau 1. Le message indique "A 6,0 NM DME avant Bruno, virer à droite, cap 220 vers parcours de base 1". A la demande du pilote, relayée par le contrôleur de la circulation aérienne, le CINTIA indique la distance restant à parcourir. Le CINTIA prévient alors le contrôleur que, 12 secondes plus tard, il doit demander au pilote de virer au cap 220 pour intercepter l'ILS (phase dénommée "virage final et interception ILS et atterrissage" dans le Tableau 1). Après ce virage, le CINTIA calculant que l'arrivée de l'aéronef interviendra avant l'heure prévue, indique la vitesse nécessaire à la correction. Cela fait, le CINTIA calcule que l'heure d'arrivée se situera en deça de la marge d'erreur de 10 secondes et le fait savoir en affichant le message "...".

ENTREE DANS LA REGION DE CONTROLE (ZOC)

BRUSSELS CONTROL, SN123
FL 310, INBOUND TO BRUSSELS
ESTIMATING KOKSY IN 8 MIN

SN123 H*
310 410
36k /28

SN123, BRUSSELS, CONTROL
RADAR CONTACT, MAINTAIN FL 310
STANDARD INBOUND ROUTE TO BRUSSELS
EXPECT PROFILE DESCENT AND RADAR VECTORING FOR ILS APPROACH ON RWY25L

BRUSSELS, SN123
ROGER
MAINTAINING FL 310
STANDARD INBOUND ROUTE FOR RWY25L

CROISIERE

SN123 H9
310 410
36k /28
XXX

SN123, BRUSSELS
AT 36-DME BEFORE KOKSY, ADJUST SPEED TO 280KT-CAS

BRUSSELS, SN123
ROGER
AT 36-DME BEFORE KOKSY, WILL ADJUST SPEED TO 280KT-CAS

SN123 H8
311 412
6k /28

SN123, BRUSSELS
EXPECT DESCENT AT 6-DME BEFORE KOKSY

BRUSSELS, SN123
ROGER
EXPECTING DESCENT AT 6-DME BEFORE KOKSY

DESCENTE

SN123 H8
310 402
5k /27
XXX

SN123, BRUSSELS
AT 5-DME BEFORE KOKSY DESCEND TO FL 100
DESCENT SPEED 270KT-CAS

BRUSSELS, SN123
ROGER
AT 5-DME BEFORE KOKSY WILL DESCEND TO FL 100
DESCENT SPEED 270KT-CAS

SN123 H6
115 320
4afi 250
XXX

SN123, BRUSSELS
AT 4-DME BEFORE AFFLIGEM DESCEND TO 2000 FT AND
AT SAME DISTANCE REDUCE SPEED TO 250KT-CAS

BRUSSELS, SN123
ROGER
AT 4-DME BEFORE AFFLIGEM WILL DESCEND TO 2000 FT
AND WILL REDUCE SPEED TO 250KT-CAS

SN123 H6
100 300
4afi 250

SN123, BRUSSELS
CONTACT BRUSSELS ARRIVAL 118.25

BRUSSELS, SN123
ROGER

Exemple de dialogue CINTIA-contrôleur-pilote

Tableau 1

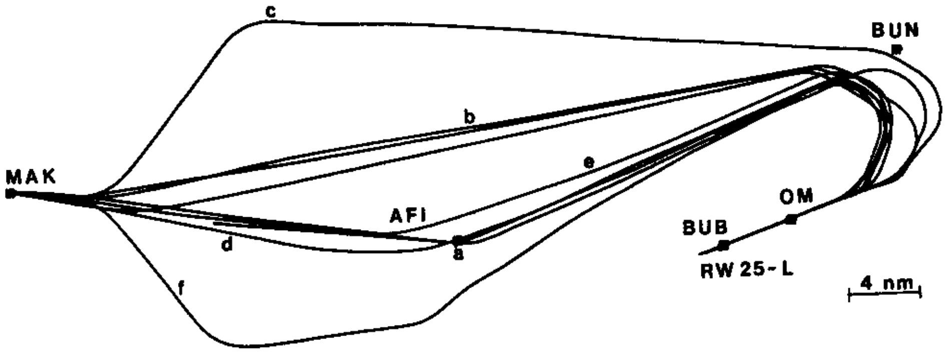
VIRAGE D'AMORCE DU PARCOURS DE BASE

SN123 H6 78 297 6.2 120		SN123, BRUSSELS ARRIVAL EXPECT BASE TURN AT 6.2-DME BEFORE BRUNO
		BRUSSELS, SN123 *ROGER* *EXPECTING BASE TURN AT 6.2-DME BEFORE BRUNO*
SN123 H5 40 280 6.0 120	XXX	SN123, BRUSSELS AT 6.0-DME BEFORE BRUNO, TURN RIGHT HEADING 120 FOR BASE LEG
		BRUSSELS, SN123 *ROGER* *AT 6.0-DME BEFORE BRUNO* *WE TURN RIGHT, HEADING 120* *WOULD YOU GIVE US THE DISTANCE TO GO ?*
SN123 H5 38 14. 6.0 120		SN123, BRUSSELS TRACK MILES TO GO: 14.
		BRUSSELS, SN123 *ROGER* *TRACK MILES TO GO 14.*

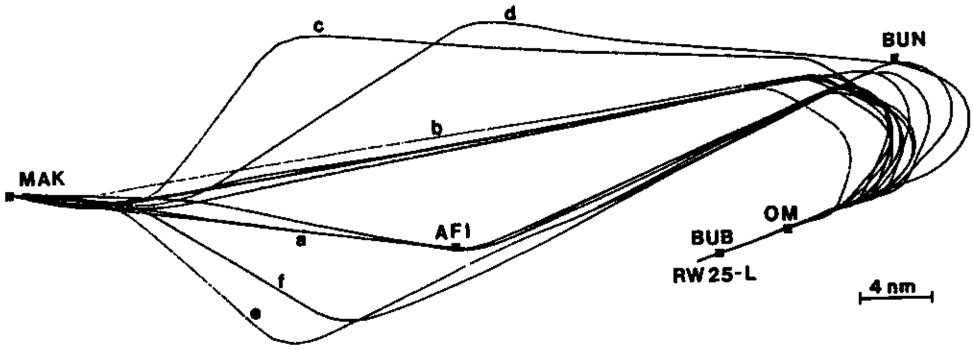
VIRAGE FINAL D'INTERCEPTION ILS ET ATTERISSAGE

SN123 H3 29 262 220 12s		
SN123 H3 27 251 220	XXX	SN123, BRUSSELS TURN RIGHT, HEADING 220 TO INTERCEPT ILS
SN123 H2 25 250 220		*BRUSSELS, SN123* *TURNING RIGHT, HEADING 220 TO INTERCEPT ILS*
SN123 H1 21 186 E 160	XXX	SN123, BRUSSELS REDUCE SPEED TO 160KT-CAS AS CONVENIENT REPORT WHEN ESTABLISHED ON ILS
		BRUSSELS, SN123 *ROGER, REDUCING TO 160* *WE WILL REPORT WHEN ESTABLISHED*
SN123 H1 20 185		SN123, BRUSSELS ROGER
		BRUSSELS, SN123 *ESTABLISHED ON ILS*
SN123 H1 16 135		SN123, BRUSSELS CONTACT TOWER ON 118.60
		BRUSSELS, SN123 *ROGER*

Tableau 1 (suite et fin)



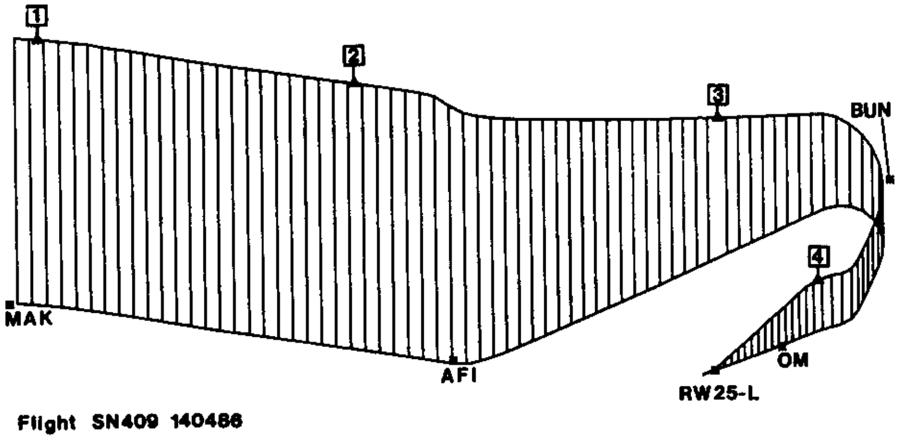
Vols du 14 mai 1986
(a)



Vols des 14 et 16 avril 1986
(b)

Echantillon typique de vols effectués sur simulateur DC-10 de la SABENA
(Projection horizontale)

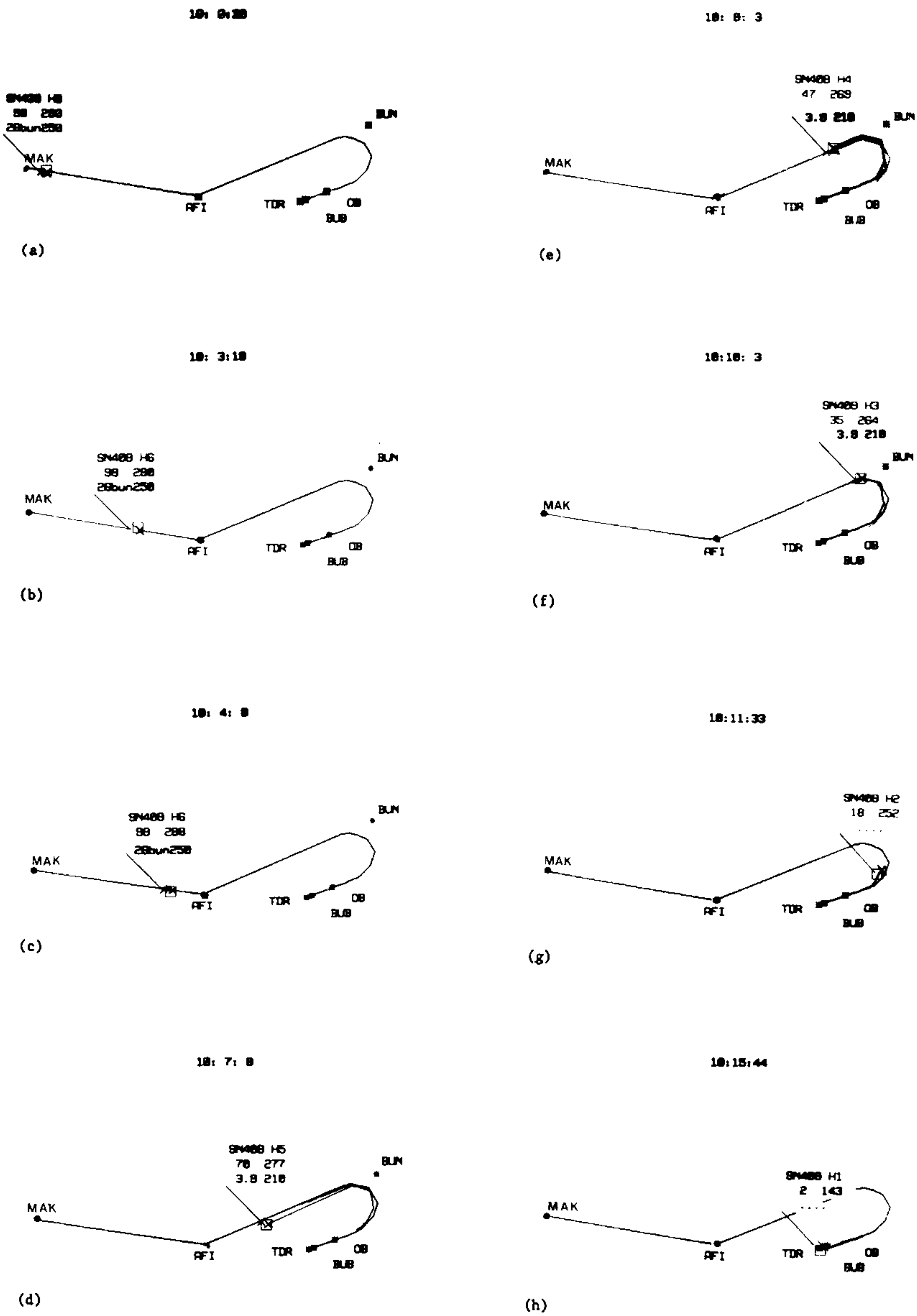
Figure 5



Représentation d'un vol en x, y et h
(a)

Affichage expérimental des messages du CINTIA

Figure 6



Ordre des messages
(b)

Affichage expérimental des messages du CINTIA

Figure 6

5. EXPERIMENTATIONS EN TEMPS REEL

5.1. Utilisation des simulateurs de vol des compagnies

Un certain nombre de simulations ont été menées sur des simulateurs de vol appartenant à plusieurs compagnies aériennes, à savoir SABENA, Belgian World Airlines, Bruxelles (Boeing B-737 et McDonnell Douglas DC-10) ; British Airways, Londres (Boeing B-757) ; Deutsche Lufthansa, Francfort (Airbus A-300 et Boeing B-737) ; NLM City Hopper, Amsterdam (Fokker F-27 et F-28) et le simulateur de vol expérimental du Laboratoire aérospatial des Pays-Bas (NLR, Amsterdam). A titre d'exemple, nous avons renvoyé aux résultats des exercices effectués récemment (les 14 et 16 avril et 16 mai 1986) à l'aide du simulateur de vol DC-10 de la SABENA desservi à chacune de ces dates par le Commandant J. PUTZ et différents membres d'équipage.

5.2. Conditions nominales de vol

Nous avons montré précédemment que la régulation précise de la phase de croisière en route et de la phase de descente peut ne nécessiter que deux ou trois interventions du contrôle (réf. 4, document 11) l'élément critique étant le tronçon final de la trajectoire, soit de 10.000 pieds au toucher des roues. C'est pourquoi les exercices les plus récents ont été limités à la phase finale définie comme suit. Les vols à destination de Bruxelles, piste 25L, étaient passés au CINTIA au moment de l'arrivée au-dessus de Mackel dans les conditions nominales (vol en palier, altitude 10.000 pieds, vitesse indiquée 250 noeuds), à quelque 65-75 NM du point d'atterrissage. Le CINTIA calcule la trajectoire théorique entre Mackel et le toucher des roues en fonction du trafic (créneau d'atterrissage) et des conditions d'exploitation (prévisions météorologiques, procédures d'approche prévues, etc.). Tout comme dans la pratique suivie pour les vols en route (voir chapitre 3) la transition du vol en palier à la phase de descente a été calculée en fonction de cette trajectoire nominale. Dans le cadre de ces exercices, on ne laissait le CINTIA exercer le contrôle effectif qu'une fois que l'aéronef allait quitter le niveau FL 100. On permettait ainsi à un nombre considérable d'erreurs de s'accumuler au voisinage du point d'amorce du virage final, ce qui rendait la régulation du dernier tronçon encore plus critique.

5.3. Echantillon de trajectoires

On trouvera à la Figure 5 les projections horizontales des vols de l'échantillon. Pour plus de clarté, cet échantillon est illustré en deux parties distinctes. A la lecture de ces figures, on peut identifier trois catégories de trajectoires.

(a) vols suivant la route prévue (Mackel, Affligem, Bruno, Bruxelles) ;

(b) vols ralliant directement Bruno ;

(c) vols faisant l'objet de déroutements importants vers le sud ou vers le nord avant d'être dirigés sur Bruno.

Les conditions atmosphériques varient d'un vol à l'autre, de même que la précision des prévisions météorologiques disponibles et un certain nombre d'autres paramètres tels que la masse de l'aéronef, laquelle n'est pas connue de l'organisme de contrôle de la circulation aérienne lorsque les communications se font en mode radiotéléphonique.

Le commandant et son équipage ont assuré la conduite de l'aéronef selon les pratiques en vigueur. A différentes reprises, les observateurs qui avaient pris place dans l'habitacle ont proposé des erreurs importantes de navigation, de même que des retards de réponse aux directives des contrôleurs au sol.

5.4. Configuration expérimentale

Pour les expérimentations, le logiciel du CINTIA a été placé sur un microprocesseur. Les données radar provenaient d'un autre microprocesseur, directement raccordé au simulateur du DC-10. Dans cette configuration, l'interface CINTIA-contrôleur se compose de deux éléments essentiels :

(a) l'affichage couleur, simulant un écran radar synthétique et montrant les positions réelles des aéronefs, assorties d'une étiquette contenant les informations du CINTIA ;

(b) le clavier, qui permet au contrôleur de commander l'affichage et de simuler les décisions du ROSAS.

Le contrôleur peut faire trois types de demandes :

- modification de l'information sur les conditions d'exploitation (affichage ou non des codes des points de cheminement de la trajectoire initiallement prévue, de la trajectoire prévue actualisée, de la positie prévue, etc.) ;
- modification du contenu de l'étiquette (par exemple, affichage de la distance restant à parcourir, au lieu de la vitesse-sol calculée) ;
- amendement de l'heure d'arrivée, en valeur absolue et en valeur relative (ceci se fait en avançant ou en retardant d'une ou de plusieurs positions le créneau d'arrivée dans la séquence d'atterrissage).

Il convient de souligner ici que les entrées mentionnées ci-dessus ont pour seul effet de modifier l'affichage et de simuler les suggestions de l'élément ROSAS. A vrai dire, le CINTIA ne s'en remet nullement au contrôleur pour la production des directives de contrôle et n'a pas besoin de savoir si une directive déterminée a été effectivement transmise à l'aéronef intéressé. A cet égard, comme nous l'avons déjà indiqué, le contrôleur ne fait pas partie de la boucle de contrôle interne du CINTIA ; il est entièrement libre de ses décisions et du moment où il les prend. Le CINTIA se bornera à suivre et à s'adapter aux situations qu'on lui crée.

5.5. Affichage des directives de l'ATC

Les étiquettes présentées sur l'écran radar - dont on trouvera un échantillon au Tableau 1 - apparaissent comme les montre la Figure 6b. La série de photographies utilisées pour cette illustration correspond au vol de la Figure 6a.

5.6. Souplesse de contrôle du CINTIA

A l'issue d'une série d'essais réalisés dans diverses conditions d'exploitation, on a fixé la marge de précision du CINTIA à 10 secondes (pour l'heure estimée d'arrivée au seuil de la piste), valeur qui a été utilisée pour l'ensemble des expérimentations décrites dans le présent exposé.

Les exercices de simulation ont porté sur 23 vols effectués en présence de représentants des Services de contrôle de la circulation aérienne. Les participants - observateurs extérieurs inclus - se sont intéressés en particulier aux réactions du CINTIA à diverses perturbations. Dans les paragraphes qui suivent, nous donnons un aperçu de celles qui ont été créées afin d'évaluer dans quelle mesure le CINTIA parvient à maintenir la sécurité du vol tout en assurant le respect de l'heure d'arrivée dans la marge prévue de 10 secondes.

En ce qui concerne les conditions atmosphériques, on a introduit des prévisions météo erronées (20° et 10 noeuds pour la direction et la force du vent ; présence de turbulences ; dégivrage). Pendant certaines périodes (allant jusqu'à 20 secondes), les informations du radar de surveillance faisaient défaut ; le CINTIA a fonctionné avec un taux de transfert d'information qui était tantôt de 5 secondes, tantôt de 12 secondes.

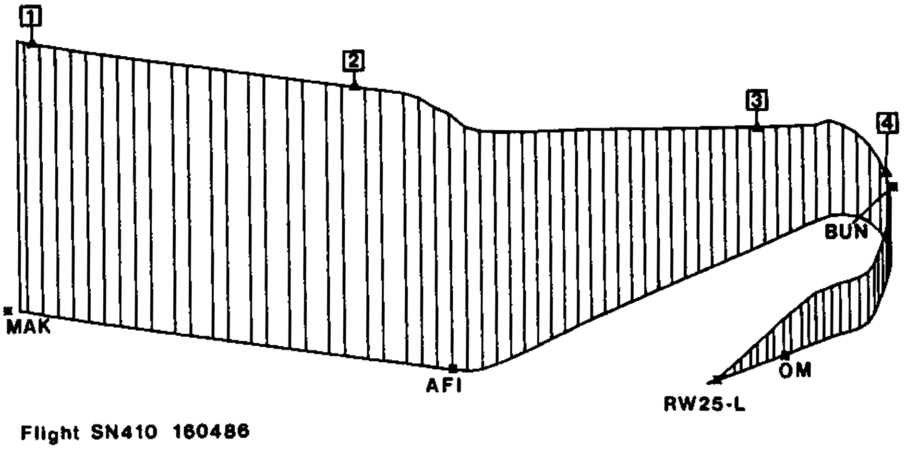
La conduite des aéronefs comportait un certain nombre d'options : conduite manuelle ou utilisation des installations automatiques pour l'accélération et la décélération, ainsi que pour la navigation et le guidage, en particulier en cours de virage et pendant les phases d'approche et d'atterrissage. On a en outre simulé des incidents à bord ; c'est ainsi que sur l'un des vols, l'approche finale a été effectuée avec un moteur en feu. La masse de l'aéronef n'était pas communiquée au CINTIA. La valeur utilisée au sol correspondait à la masse moyenne pour le type d'aéronef considéré, alors que la masse effective pouvait varier entre un minimum et un maximum.

On a délibérément introduit des éléments de nature à distraire à la fois le personnel au sol et les équipages, encore que la présence d'observateurs dans l'habitacle et dans le centre de contrôle constituait déjà en elle-même une source de perturbations. Dans la cabine, le commandant de bord retardait le début de l'action prescrite par le contrôleur jusqu'au moment où les services au sol lui répétaient impérieusement la directive ; par exemple, le retard mis à virer pour amorcer le parcours de base atteignait un mille nautique et la vitesse pouvait accuser des erreurs de 20 noeuds au cours de la croisière et de la descente. Au sol, le contrôleur omettait de transmettre l'autorisation pour la seconde partie de la descente, ce qui modifiait considérablement la composante verticale de la trajectoire.

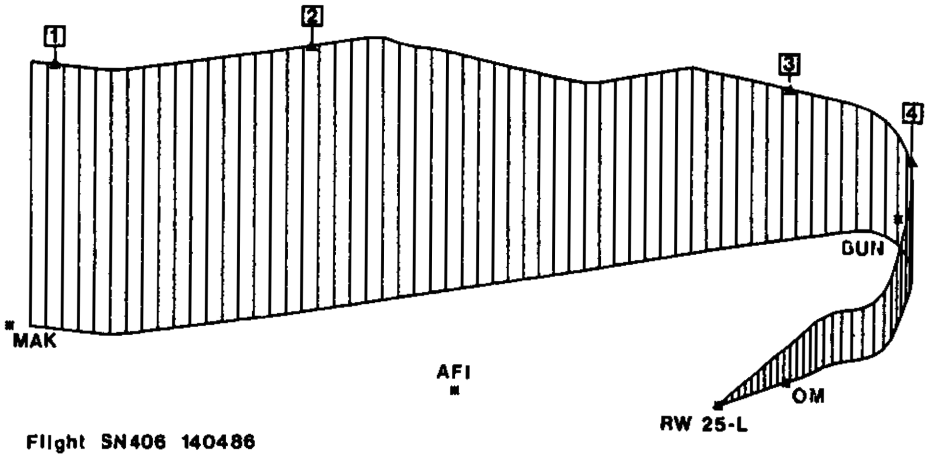
En outre, on a simulé des interventions de l'élément ROSAS destinées à tenir compte de la situation de trafic : la position de l'aéronef dans la séquence d'atterrissage était modifiée en vol et le CINTIA amendait automatiquement ses instructions en conséquence.

Les changements d'itinéraire ont été opérés soit à la demande du commandant de bord, soit à la discrétion du contrôleur. Pour les changements tels que ceux qui apparaissent à la Figure 7b, le contrôleur envoie l'autorisation ou l'instruction à l'aéronef sur la fréquence radiotéléphonique, sans entrée directe d'information au CINTIA, mais celui-ci reconnaît néanmoins le changement d'itinéraire et produit les instructions ultérieures en conséquence (de même, le CINTIA peut reconnaître les modifications de profil vertical, telles que les interruptions de descente, et amender ses prévisions).

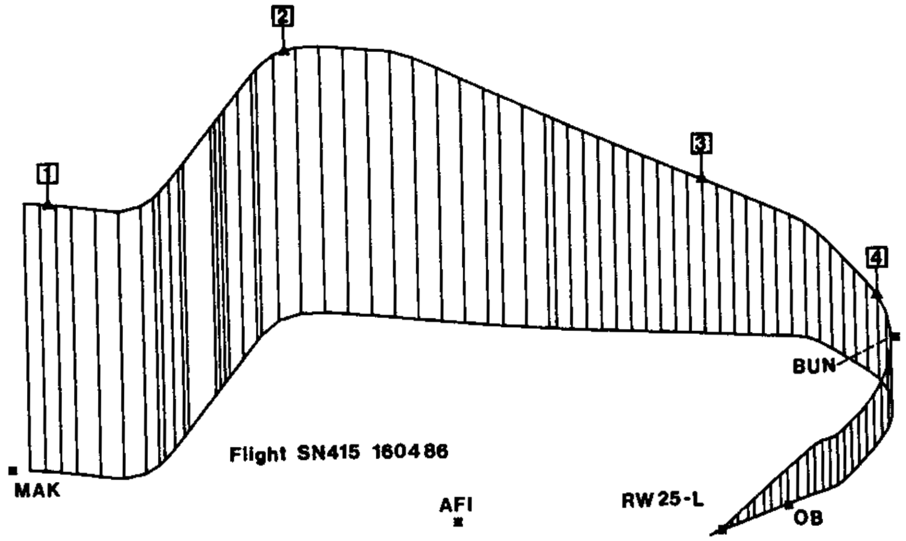
Enfin, on a provoqué artificiellement un certain nombre d'incidents conduisant à des écarts appréciables par rapport aux routes habituelles, comme le montre la Figure 7c. Ces écarts se situaient tant au nord qu'au sud de la trajectoire nominale et ont servi à simuler des résolutions de conflits, l'évitement de zones de mauvais temps ou des erreurs imputables aux effets conjugués des divers malentendus possibles entre contrôleur et pilote.



Vol suit la route initialement prévue
(a)



A sa demande, pilote autorisé à rallier directement Bruno
(b)



Vol dérouté vers le nord pour résolution d'un conflit
(c)

Exemples illustrant la souplesse du CINTIA du point de vue de la navigation

Figure 7

6. CONCLUSIONS

Tout système visant à une gestion efficace de la circulation aérienne des points de vue de la sécurité, de la rapidité, de l'économie et de la capacité de prise en charge devra pouvoir assurer la régulation précise de chaque vol dans les quatre dimensions. Le système connu sous l'appellation "Control of Inbound Trajectory of Individual Aircraft - CINTIA" (régulation individuelle des trajectoires d'arrivée) permet d'envisager un système de contrôle amenant les aéronefs au seuil de la piste avec une marge de précision de 10 secondes (sans utilisation systématique de files d'attente), bien que ce créneau soit attribué au moment de l'entrée de l'aéronef dans la zone, c'est-à-dire quelque 100 à 200 NM avant le point d'impact des roues.

La procédure initialement conçue pour être appliquée dans le cadre de la Zone de Convergence est directement transposable à tous les systèmes qui comportent une contrainte en ce qui concerne l'heure d'arrivée, c'est-à-dire en particulier tous les systèmes visant à régler au moindre coût une circulation de densité maximale dans un volume d'espace de capacité limitée.

Les expérimentations dont ce système a fait l'objet visaient à mesurer la précision de la procédure et sa stabilité en présence de perturbations d'origines diverses dont nous donnons un aperçu ci-après.

Les exercices en temps réel ont été effectués dans des conditions réalistes, avec la participation de contrôleurs d'approche et d'équipages de ligne chevronnés. Ils ont été effectués à l'aide de divers simulateurs de vol. Les illustrations qui figurent dans le présent document correspondent aux exercices effectués sur le simulateur de vol DC-10 de la SABENA, Belgian World Airlines.

Les directives du CINTIA étaient affichées dans les étiquettes apparaissant sur l'écran radar (et qui occupaient généralement une ligne de huit caractères), sous une forme que le contrôleur de la circulation aérienne pouvait aisément transposer en expressions conventionnelles courantes pour transmission aux pilotes sur les fréquences radiotéléphoniques.

On a imposé au fonctionnement du système des perturbations importantes imputables à divers facteurs :

- éléments d'incertitude des prévisions météorologiques ;
- modification des plans initiaux (changement d'itinéraire ; modification du profil vertical ; révision du créneau attribué dans la séquence des heures d'atterrissage, etc.) ;
- options concernant la conduite du vol (mode manuel ou pilote automatique) ;
- incertitude quant à la masse de l'aéronef, les contrôleurs ne connaissant que la valeur moyenne pour chaque type d'aéronef lorsque les communications se font en mode radiotéléphonique ;
- erreurs humaines, tant à bord qu'au sol (facilitées par la présence d'observateurs), induisant des erreurs assez importantes en ce qui concerne les communications, la navigation (dans les plans horizontal et vertical) et la vitesse ;
- événements et incidents particuliers (résolution des conflits, conditions météorologiques défavorables, etc.) donnant lieu à des instructions de guidage dans les plans vertical et horizontal ainsi qu'à des écarts de route importants.

A l'issue de ces essais, il apparaît que le CINTIA permet au contrôleur d'acheminer les aéronefs jusqu'au moment du toucher des roues avec une haute précision (marge de 10 secondes) et dans les conditions voulues de sécurité. Le CINTIA parvient en effet à respecter l'heure d'arrivée malgré les incertitudes inhérentes à l'environnement actuel. En outre, il adapte ses directives au contrôleur de manière à tenir compte des diverses perturbations pouvant affecter la conduite du vol. A cet égard, il présente une très grande souplesse lorsqu'il s'agit de ménager les impératifs du contrôle comme ceux de la navigation. Il s'adapte automatiquement aux plans de vol et à leurs modifications, tant dans le plan horizontal que dans le plan vertical, sans que le contrôleur doive intervenir et introduire de message particulier en machine.

Il est permis de conclure que dans les TMA Modernes de grande étendue, le CINTIA constitue un moyen efficace d'assistance automatique aux contrôleurs lorsqu'il s'agit de régler avec précision des trajectoires optimales depuis l'entrée dans la zone jusqu'à l'atterrissage. Les messages affichés par ce système sont clairs et complets et, tout en se prêtant à l'exploitation dans l'environnement actuel de communications radiotéléphoniques, ils sont directement adaptables dans l'avenir à un réseau de liaisons numériques sol-air-sol.

7. REMERCIEMENTS

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- le Département "Simulations de vol" de la SABENA, Belgian World Airlines, qui a conçu et mis en oeuvre l'interface simulateur de vol/radar/CINTIA utilisée pour les expérimentations décrites dans le présent exposé.

REFERENCES

1. "Air Traffic Control Systems".
Guidance and Control Symposium, Edinburgh, Scotland, 26-29 June 1972.
AGARD-CP-105, April 1973.

2. "Plans and Developments for Air Traffic Systems".
Guidance and Control Symposium, Cambridge, Mass., USA, 20-23 May 1975.
AGARD-CP-188, February 1976.

3. "Air Traffic Management. Civil/Military Systems and Technologies".
Guidance and Control Symposium, Copenhagen, 9-12 October 1979.
AGARD-CP-273, February 1980.

4. "Air Traffic Control in Face of Users' Demand and Economy Constraints".
Guidance of Control Symposium, Lisbon, Portugal, 15 October 1982.
AGARD-CP-340, February 1983.

5. "Automatic Conflict Detection and Resolution (SPACDAR)".
Proceedings of the 11th Meeting, 25-27 September 1984.
EUROCONTROL Doc. 842013(R), October 1984.

6. Voelckers, U. "Computer assisted arrival sequencing and scheduling with the COMPAS system".
Communication au présent Symposium, Document 54.

7. Benoît, A. Swierstra, S. "Air Traffic Control in a Zone of Convergence.
Assessment within Belgian Airspace". Congress of the International Council of the Aeronautical Sciences, Toulouse, France, 9-14 September 1984.
Also EUROCONTROL Report 842009, April 1984.

8. Attwooll, V.W. Rickmann D "A study of Conflicts within a Zone of Convergence"
Paper presented at the EUROCONTROL SPACDAR/GEDARC-11, 25-27 September 1984.
EUROCONTROL Doc. 842013(R), October 1984.

9. Benoît A. Swierstra, S. "A Cost-Efficient Control Procedure for the Benefit of all Airspace Users".
Guidance and Control Symposium, Izmir, Turkey, 16-19 October 1984.
AGARD-CP-360, February 1985.
Also EUROCONTROL Report 842011, August 1984.

10. Attwooll, V.W. Benoît, A. "Fuel Economies effected by use of FMS in an Advanced TMA".
The Journal of Navigation, Vol. 38, N° 1, January 1985.
Also EUROCONTROL Report 842003, February 1984.

11. Benoît, A. Swierstra, S. "Real-time simulation of an operational procedure suitable for the accurate 4-D control of aircraft trajectories".
EUROCONTROL Report 862018, in preparation.

12. Cox, M.R. "Possible contributions from the SSR Mode S data link to the conduct of efficient aircraft operations".
Communication au présent Colloque, Document 25.

Remarque

Les opinions exprimées dans le présent document
n'engagent que les auteurs.

CP 410

NEXT GENERATION OF CONTROL TECHNIQUES IN ADVANCED TMA

Automatic assistance for the controller/pilot dialogue

by

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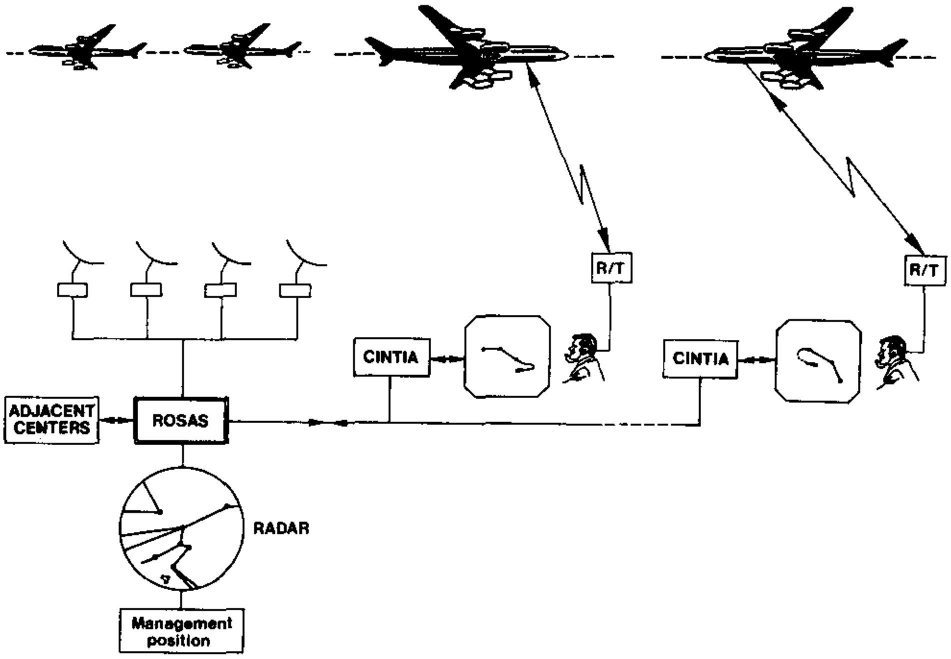
SUMMARY

It is very likely that any future concept to be used for the safe and efficient conduct of air traffic (in terms of expedition, economy and capacity) will exhibit two essential, closely interrelated components. Firstly, the on-line management of air traffic over a large area - from a Zone of Convergence type to a continental coverage - will generate the landing and departure times for each aircraft entering the area, while at the same time defining the essential characteristics of the relevant flight paths. Secondly, an operational control procedure will be required to conduct each individual flight accurately throughout the area, that is to say, in the case of a Zone of Convergence, from entry to touchdown, in agreement with the air traffic management directives and in line with operational practice (onboard and on the ground).

This paper outlines the essential operational features of a control procedure suitable to meet the above constraints while ensuring a 10-second accuracy for the time of arrival as predicted initially at entry into the zone (and possibly amended subsequently), for current air carriers in present R/T or future D/L communications environments.



Management of Air Traffic and Control of Individual Flights

Figure 1

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1. INTRODUCTION

In the years to come, the air traffic density will probably increase continuously, although in Western Europe there is no major plan for the construction of new major airports or other important landing facilities. This twofold projection has been stated in the past and its implications discussed at previous AGARD conferences. In fact, it has been analysed in terms of delays (Ref. 1, 1972), in terms of expedition and efficiency (Ref. 2, 1975), and in terms of economy, particularly fuel conservation (Ref. 3, 1979; Ref. 4, 1982), while the emphasis today seems to be placed again mainly on capacity (Ref. 5, 1984; Ref. 6, 1986).

Within the Engineering Directorate of EUROCONTROL, the European Organisation for the Safety of Air Navigation, a technique has been developed for the efficient management of the air traffic and the accurate control of each individual flight in an extended area including and surrounding a main terminal and possibly several secondary airports, this extended area being referred to as a Zone of Convergence. The system is essentially made up of two basic, closely interrelated components:

(a) on the one hand, the management of the traffic referred to as the Regional Organisation of the Sequencing and Scheduling of Aircraft System (ROSAS);

(b) on the other hand, the accurate 4-D control of each individual flight in the zone in accordance with the management directives. This component is referred to as the Control of Inbound Trajectories of Individual Aircraft (CINTIA).

The ROSAS/CINTIA system aims at meeting the three-element criterion of economy/expedition/capacity. It meets the requirements of the airlines by minimising the overall deviation from the preferred climb/cruise/descent speed profile - even on-line at the request of the pilots. In addition, the resulting traffic situation is safer, the number of potential conflicts being appreciably reduced when compared to actually observed situations (Refs. 7 and 8). ROSAS provides the definition of each flight through the zone e.g. from entry to touchdown. CINTIA makes it possible for the ground-based air traffic controller to guide each individual aircraft in accordance with the management (ROSAS) directives, in spite of the numerous perturbations emanating from a wide variety of sources.

From the tests conducted so far, using actual observed traffic in both the Brussels and London areas, the ROSAS algorithms appear efficient and reliable. Clearly, the applicability of the system to real life now relies on the quality of CINTIA, that is to say on an accurate navigation, guidance and control procedure (duly coordinated between the ground-based control unit and the aircraft pilot and possibly on-board equipment) such as to enable each aircraft to meet its landing time position within the landing time slot sequence defined initially - on entry into the zone - and possibly amended subsequently by the air traffic management unit or the controllers in charge of the flight.

For accuracy assessment, the CINTIA overall control loop has been simulated in cooperation with airline pilots and professional air traffic controllers. The results obtained to date indicate that a 10-second accuracy at the runway threshold can be expected in present R/T communications - and furthermore, in a future automated digital link environment - for flight paths from entry to touchdown extending up to 200 nm.

A summary of the proposed control procedure - the technical aspects and the results of a series of tests conducted on several flight simulators - was presented at previous conferences and the relevant proceedings (Refs. 9 and 10) also include a list of references to associated developments. The reader is accordingly referred to these previous publications for additional historical, technical and conceptual details. This paper will outline only the essential operational features of CINTIA, showing the type of computer assistance which can be expected for the controller/pilot dialogue and indicating, in addition, how CINTIA could be implemented in a real-life, present or future, environment.

2. SIMULATION ENVIRONMENT

2.1. General: Management (ROSAS) / control (CINTIA) system

The overall management/control system is schematically illustrated in Figure 1. The management component (ROSAS in the illustration) assigns a landing slot to each aircraft entering the zone. This is done in terms of traffic and other environmental conditions in accordance with the economy, "expedition", capacity and safety criteria and constraints. The related plan is then referred to the relevant "sector(s)" for coordination and checked for local compatibility.

Once accepted, subject to any amendments, the plan is sent to the control unit concerned for implementation. Thereafter, the air traffic controller and CINTIA will operate as a single efficient team in order to guide the aircraft and assist the pilot in performing the flight until touchdown.

2.2. 4-D control of trajectories: Components

A position for the 4-D control of trajectories in an R/T communications environment is shown schematically in Figure 2. The landing time is received from the air traffic management unit - on some occasions it may be modified by the local controller. For the purpose of simulating the procedure, the following components, connected as shown in the diagram, are available (additional information on this subject may be found in Reference 11):

(a) aircraft operation is simulated using current airline flight simulators operated by professional crews;

(b) radar information is sent to CINTIA every 5 or 12 seconds to simulate diverse modes of tracking techniques;

(c) R/T communications facilities are similar to those currently available between the air traffic centre and the aircraft.

(d) 4D-control directives for each aircraft are generated by CINTIA's computer. Displayed on the radar screen in a manner consistent with present-day operation, they can be translated direct into current phraseology by the controller. Further, the controller is alerted (by the changing appearance of the directive, e.g. colour changes and/or audible signals) whenever transmission to the aircraft is imminent (see Sections 4 and 5 for label contents, phraseology used and display).

(e) In the case of flights conducted to date, actual control has been provided by professional Belgian air traffic controllers (Régie des Voies aériennes/Regie der Luchtwegen).

(f) The CINTIA system as developed is directly adaptable for the purpose of automated digital ground/air/ground communications.

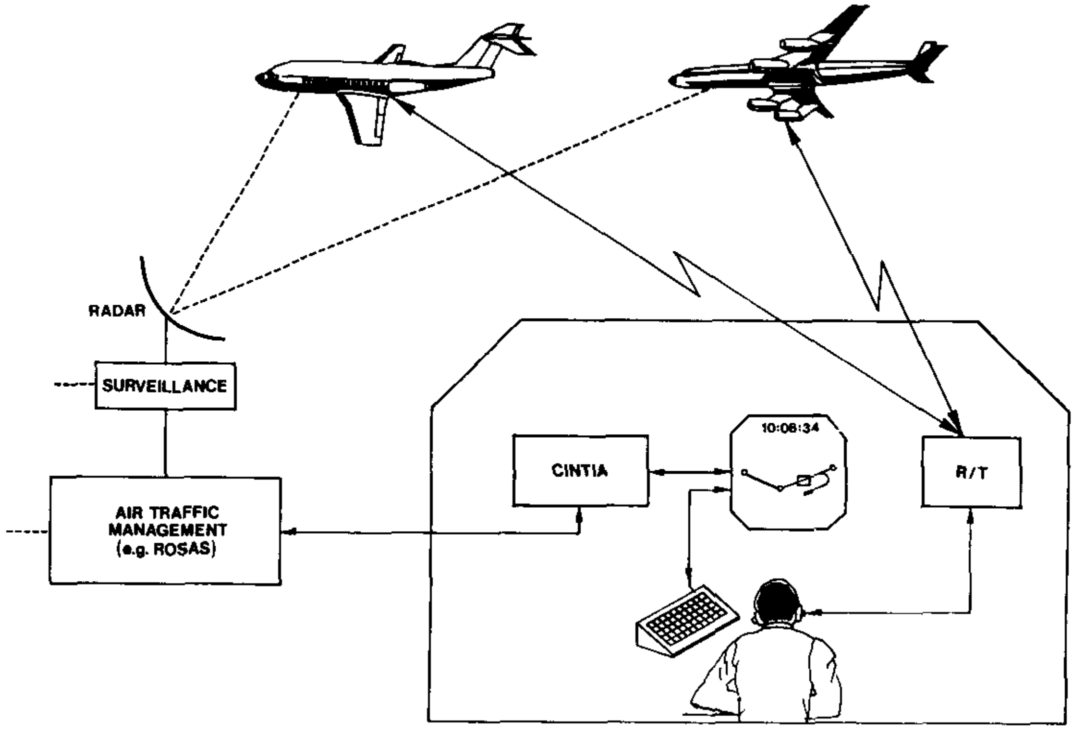
The control directives generated by CINTIA will lead the aircraft in the most economical way from its present position to arrive at the allocated slot in the arrival sequence. However, the displayed directives are by no means mandatory for the controller and CINTIA will adapt itself automatically to the results of different controller decisions. Actually, from CINTIA's point of view, these are simply considered as another set of possible perturbations.

2.3. Simulation versus real life operation

It is felt that the simulation environment which has been created reflects real life operation with a high degree of realism. This is true from the technical, operational and human viewpoints. Any disruptions which might affect a regular flight can be introduced and accounted for, including:

- aircraft operation: incidents covered by the use of the airline's training facilities;
- radar information: interruption for limited periods of time;
- radio frequency occupancy: channel used at critical moments for emergency messages;
- communications and/or control and/or navigation ambiguities resulting from human errors on the ground or in the air;
- traffic situations calling for immediate control action such as conflict avoidance or resolution;
- adverse weather conditions calling for route and/or altitude clearance alterations and change in aircraft operation (e.g. de-icing);
- any perturbations resulting from errors in meteorological forecasts, CINTIA's aircraft knowledge (performance and operational procedure), aircraft state variables (radar position and, in R/T mode, average mass), etc.

Section 5 contains a sample of trajectories flown recently on the SABENA DC-10 flight simulator: it illustrates the realism of the simulation environment as outlined in these paragraphs.



CINTIA operation in present R/T environment

Figure 2

3. NAVIGATION, GUIDANCE AND CONTROL PRINCIPLES

3.1. General illustration

The approach procedure is shown schematically in *Figure 3*. *The aircraft* coming from London, U.K., inbound to Brussels, Belgium, is scheduled to follow the route as shown (Dover, Koksy, Mackel, Affligem, Bruno, Brussels). It may expect a profile descent, a standard inbound route to Brussels and radar vectoring for ILS approach on *Runway* 25 *left*.

The landing time is determined at management level in agreement with the control units concerned when the aircraft *enters the zone - or* through adequate coordination when it passes Dover - and, at the same time, the related characteristics of the trajectory (cruise/descent/approach speed profile and final path geography) are defined accordingly.

3.2. Control variables

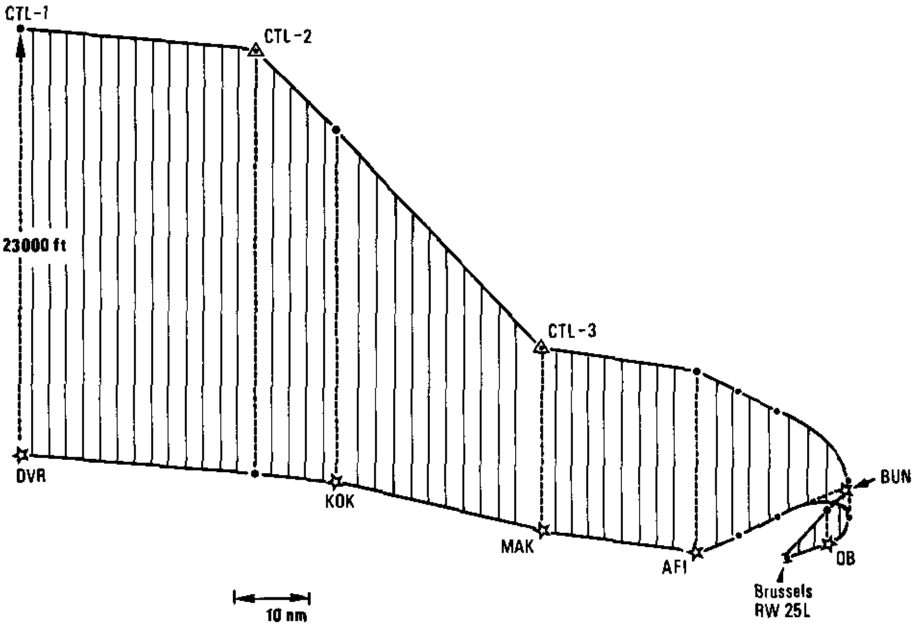
Aircraft speed and trajectory geography cover the two fundamental categories of control variables available to guide the aircraft accurately to touchdown. In addition, alteration of the *vertical profile component* may also be considered as a source of trajectory control. Strictly speaking, however, this falls within the "aircraft speed" control category even if the related directives are expressed in terms of altitude clearances, as discussed subsequently.

CINTIA incorporates the aircraft performance for each aircraft type together with the flight procedures the airline operator prefers. The knowledge *background also covers* the geography of the area including a precise definition of the way-points, navigation aids and landing facilities. With this detailed information in its mind, a good sense of human understanding, a real competence for extrapolating an observed path and a remarkable *capacity for generating* on-line the trajectory which will meet the management requirements, CINTIA provides guidance directives directly usable by the air traffic controller and fully compatible with the aircraft operation.

3.3. Principles of application to an inbound flight

The *application of CINTIA* control capability to an inbound flight is suggested in Figure 3.

When the aircraft enters the zone, altitude and route clearances are confirmed. For the en-route phase, the cruise/descent speed profile is the essential control variable. Accordingly, either at entry or at some later position, cruise speed will be part of the control directive (CTL-1). Of course, route amend-



Schematic trajectory of a flight inbound to Brussels
Illustration of the characteristic control points

Figure 3

ments may be requested, as well as altitude restrictions, as will be shown later in this paper (reduction of route length whenever possible, conflict resolution actions, adverse weather avoidance, etc.).

After notification of the cruise speed to the aircraft, CINTIA presents the expected en-route descent conditions, that is to say the descent speed and the position at which the transition from cruise to descent is to be initiated (CTL-2).

During or close to the end of the en-route descent, CINTIA specifies the final part of the trajectory (CTL-3). This may include several components, namely speed indications (including regulations applied in the area), turn to base leg and turn for ILS interception as illustrated in Figure 4. This diagram shows the final part - extending from Mackel to touchdown, about 65 to 75 nm - of three trajectories flown on the DC-10 flight simulator of SABENA, Belgian World Airlines. In case (a), only one control directive was needed corresponding to the definition of the final turn for ILS interception. In case (b), the approach to the ILS was made in two steps, firstly a turn to base leg and secondly the final turn for ILS interception. Finally, in case (c), at the end of the second turn, CINTIA also suggested a reduction of the speed to meet the allocated landing time and thus to ensure safe separation from the preceding aircraft in the landing sequence.

3.4. Surveillance, navigation and communications

Besides the surveillance radar information providing the aircraft position every 5 or 12 seconds, CINTIA accounts for part of the available onboard equipment (cf. FK-27 versus B-757 onboard navigation and computing equipments). Also it relies on and adapts itself to the following aids for the framing and transmission of the control directives.

The specific control actions (see above actions pertaining to CTL-1, CTL-2, CTL- 3:(a), (b) and (c)) must be initiated at specific positions. These positions are expressed in terms of DME distances to stations normally used for navigation purposes in the area. In the example depicted in Figure 3, these stations are successively Koksy, Affligem and Bruno.

With respect to communications, two modes of operations are envisaged. In the present mode of R/T communications, CINTIA displays the directives to the air traffic controller, who relays them to the cockpit after approval. The directives are frozen some 30 to 60 seconds in advance to allow for human response delay and frequency occupancy. In line with present R/T communications, CINTIA actually tailors its messages for direct transmission to the aircraft - after presentation to and approval by the controller - via an automated digital ground/air/ground link (this subject is discussed further in Reference 12).

3.5. CINTIA/Controller interface

The main consideration during the design of the CINTIA/air traffic controller interface was to reduce as far as possible the controller's workload. To that effect it was decided on the one hand to include the CINTIA directives direct in the aircraft label on the synthetic radar display rather than to display them on a separate EDD (Electronic Data Display).

On the other hand, it was essential to avoid as far as possible any requirement for controller input to CINTIA. Accordingly, if a controller vectors the aircraft away from the planned route it is not necessary to notify this to CINTIA. It is sufficiently intelligent to follow the flight path and consequently to suggest to the controller what, at each instance, the next control directive should be in order to arrive from the present position at the correct slot in the landing sequence.

4. GROUND/AIR CONTROL SCENARIO

4.1. Sequence of ground/air/ground messages

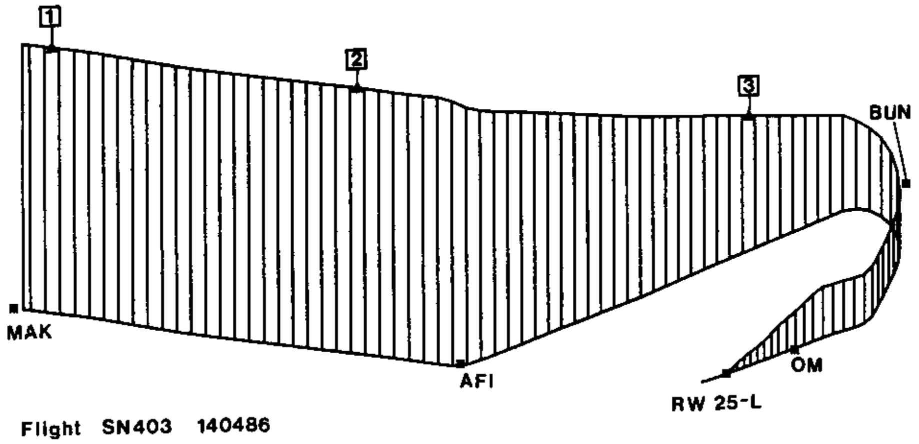
In order to give a fair idea of the operational procedure, it is proposed to follow the sequence of CINTIA - Air Traffic Controller - Aircraft Pilot exchanges for a flight whose geography is as shown in Figure 3. Table 1 lists a set of messages generated by CINTIA (those messages requiring air traffic controller action, and the messages being displayed when any other message was initiated or answered by the ground) and the complete set of ground/air/ground messages exchanged during the whole flight from entry to touchdown. The messages generated by CINTIA are placed in a rectangular frame. They are black and white copies of the label appearing on the radar screen (see Section 5). The messages originating in the cockpit are written in oblique characters and start with the call "BRUSSELS, SN123". Those sent by the air traffic controller use straight characters and usually start with the call "SN 123, Brussels:"

The translation of the CINTIA directives appearing in the label into clear ATC phraseology results directly from the table. Nevertheless, for the sake of completeness, some individual aspects will be discussed briefly.

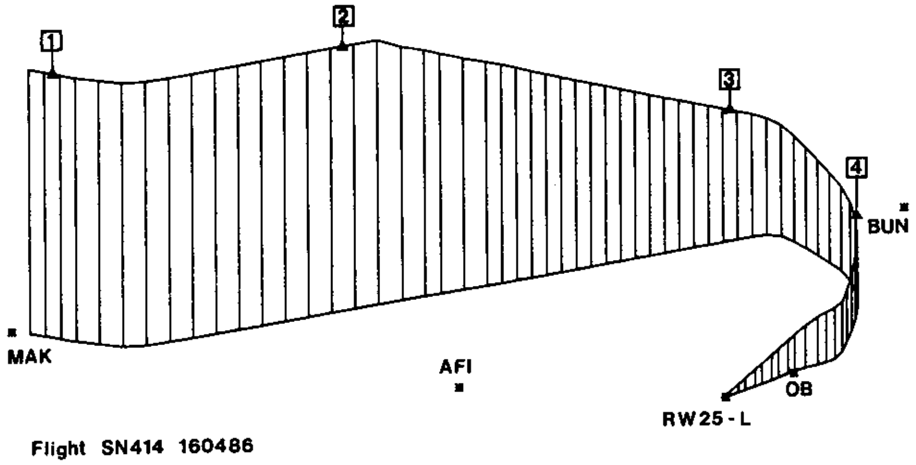
4.2. Structure and content of CINTIA messages

The labels available for the CINTIA message provide a capacity of 3 lines of 8 characters. Although their content may vary from one phase of the flight to another, there are some constant elements.

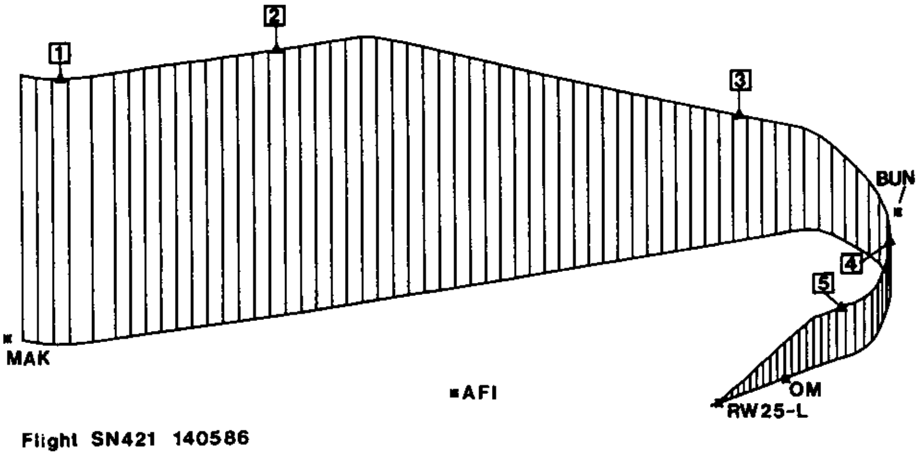
(1) The first line includes the aircraft callsign, "SN123" in the example, then the aircraft category ("H" for heavy, "M" for medium and "L" for light), and finally the position of the aircraft in the landing sequence, "1" to "9" or "*" if the aircraft occupies a position whose reference is larger than 9. This last information is not generated by CINTIA but originates from the ROSAS module which deals with the air traffic management aspects.



(a)



(b)



(c)

Illustration of inbound trajectory control
with
one, two or three CTL-3 components

Figure 4

(2) The second line usually displays the altitude expressed in Flight Levels and the ground speed as derived from radar information. On request, CINTIA will provide the distance to touchdown ("track miles") instead of the derived ground speed; in this case, a decimal point will confirm that the information displayed is distance.

(3) The third line essentially contains CINTIA control directives. Clearly, the content of the directives varies from phase to phase. When it is time to relay the directive to the aircraft, the appearance of the message (3rd line only) changes e.g. a colour change from yellow to red or from normal display to flashing depending on the type of equipment. After the time the relevant action should have been initiated by the pilot, the appearance of the message (3rd line only), changes again (e.g. to green or low intensity), which should remind the controller which action was expected if it has not been initiated - for instance, if the pilot does not turn in time the controller will send a reminder and CINTIA will use whatever control range is available to compensate. Note: In Table 1, the mark "XXX" next to the directive indicates that the appearance has changed and that the message should be sent.

4.3. Sequence of phases of flights

For ease of reference in Table 1, the various messages which follow each other chronologically have been grouped by flight phase.

At entry into the Zone, the exchanges reflect present practice. CINTIA's displayed message requires the aircraft to initiate transition to 280 KIAS cruise speed at 36 nm before Koksy. This message is sent when requested (XXX), and subsequently CINTIA presents continuously the next control directive "Expect descent at ..-DME before Koksy", which will mark the end of the cruise phase and the beginning of the descent phase. Its content may change, simply because the flying conditions have changed and/or ROSAS has allocated a different landing time. CINTIA has adapted the remaining part in order to meet the final constraint ("Descend at 5nm DME before Koksy at 270 KIAS" instead of "Descend at 6 nm -DME before Koksy at 280 KIAS"). For the en-route cruise and descent phases, speed profile is to be expressed in terms of both Mach/CAS. As already understood, the space available forces us to express such a profile in the form mmm/ss where the Mach number is expressed in hundredths and the calibrated airspeed in multiples of ten knots. For the lower phase of the descent, the Mach component is no longer applicable. The speed is accordingly expressed in knots and space is available to display the full code of the DME station.

After the en-route descent, CINTIA will display the next directive, namely the instructions defining the turn for base leg, which is called the "base turn" phase in Table 1. The message says "At 6.0 nm DME before Bruno, turn right, heading 120 for base leg". At the request of the pilot relayed by the air traffic controller, CINTIA will give the distance to go. Then CINTIA warns the controller that 12 seconds from now he should instruct the pilot to turn right heading 220 to intercept ILS (phase entitled "Final turn and ILS interception and landing" in Table 1). After the turn, CINTIA estimates the aircraft arrival to be earlier than expected and gives the speed which would bring the aircraft nto schedule. Subsequently, the time of arrival is estimated to be within the 10-second accuracy margin, and CINTIA indicates that this is so by displaying the message "....".

5. REAL TIME EXPERIMENTS

5.1. Use of airline flight simulators

A number of simulations were conducted using several airline flight simulators, viz SABENA, Belgian World Airlines, Brussels (Boeing B-737 and McDonnell Douglas DC-10); British Airways, London (Boeing B-757); Deutsche LUFTHANSA, Frankfurt (Airbus A-300 and Boeing B-737); NLM City Hopper, Amsterdam (Fokker F-27 and F-28) and the research flight simulator of the Dutch Aerospace Laboratory (NLR, Amsterdam). In order to illustrate this, reference has been made to the results of the experiments conducted recently (14 and 16 April and 16 May 1986) using the SABENA DC-10 flight simulator operated by Captain J. Putz and different crew members on each date.

5.2. Nominal flight conditions

It has already been shown previously that the accurate control of the en-route cruise and descent phases may require only two or possibly three control actions (Ref. 4, Paper 11), the critical portion being the final part of the trajectory, say from 10,000 feet until touchdown. Accordingly, recent experiments were limited to the final phase defined as follows. Flights inbound to Brussels, landing on runway 25 L, were referred to CINTIA on arrival over Mackel, nominal conditions (horizontal flight, altitude 10,000 feet, indicated airspeed 250 knots), say about 65 to 75 nm from touchdown. CINTIA computes the nominal trajectory between Mackel and touchdown in terms of the traffic (landing slot position) and in accordance with environmental conditions (meteorological forecast, anticipated approach procedure, etc.). As in en-route practice (see Section 3), the transition from horizontal flight to descent phase was computed on the basis of this nominal trajectory. For the purpose of the experiments CINTIA was allowed effective control only after the aircraft had left FL100. This allowed the accumulation of considerable errors close to the base turn point, thereby rendering the control of the final part even more critical.

5.3. Sample of trajectories

The horizontal projections of the flights included in the sample may be seen in Figure 5. For the sake of clarity, this sample is shown as two subsets on the diagram. As it appears from the figures three categories of trajectories can be identified.

(a) flights following the planned route (Mackel, Affligem, Bruno, Brussels);

(b) flights going direct towards Bruno;

ENTRY INTO ZOC-CONTROL AREA

BRUSSELS CONTROL, SN123
FL 310, INBOUND TO BRUSSELS
ESTIMATING KOKSY IN 8 MIN

SN123 H*
310 410
36k /28

SN123, BRUSSELS, CONTROL
RADAR CONTACT, MAINTAIN FL 310
STANDARD INBOUND ROUTE TO BRUSSELS
EXPECT PROFILE DESCENT AND RADAR VECTORING FOR ILS APPROACH ON RWY25L

BRUSSELS, SN123
ROGER
MAINTAINING FL 310
STANDARD INBOUND ROUTE FOR RWY25L

CRUISE

SN123 H9
310 410
36k /28

XXX

SN123, BRUSSELS
AT 36-DME BEFORE KOKSY, ADJUST SPEED TO 280KT-CAS

BRUSSELS, SN123
ROGER
AT 36-DME BEFORE KOKSY, WILL ADJUST SPEED TO 280KT-CAS

SN123 H8
311 412
6k /28

SN123, BRUSSELS
EXPECT DESCENT AT 6-DME BEFORE KOKSY

BRUSSELS, SN123
ROGER
EXPECTING DESCENT AT 6-DME BEFORE KOKSY

DESCENT

SN123 H8
310 402
5k /27

XXX

SN123, BRUSSELS
AT 5-DME BEFORE KOKSY DESCEND TO FL 100
DESCENT SPEED 270KT-CAS

BRUSSELS, SN123
ROGER
AT 5-DME BEFORE KOKSY WILL DESCEND TO FL 100
DESCENT SPEED 270KT-CAS

SN123 H6
115 320
4afi 250

XXX

SN123, BRUSSELS
AT 4-DME BEFORE AFFLIGEM DESCEND TO 2000 FT AND
AT SAME DISTANCE REDUCE SPEED TO 250KT-CAS

BRUSSELS, SN123
ROGER
AT 4-DME BEFORE AFFLIGEM WILL DESCEND TO 2000 FT
AND WILL REDUCE SPEED TO 250KT-CAS

SN123 H6
100 300
4afi 250

SN123, BRUSSELS
CONTACT BRUSSELS ARRIVAL 118.25

BRUSSELS, SN123
ROGER

Example of CINTIA/CONTROLLER/PILOT dialogue

Table 1

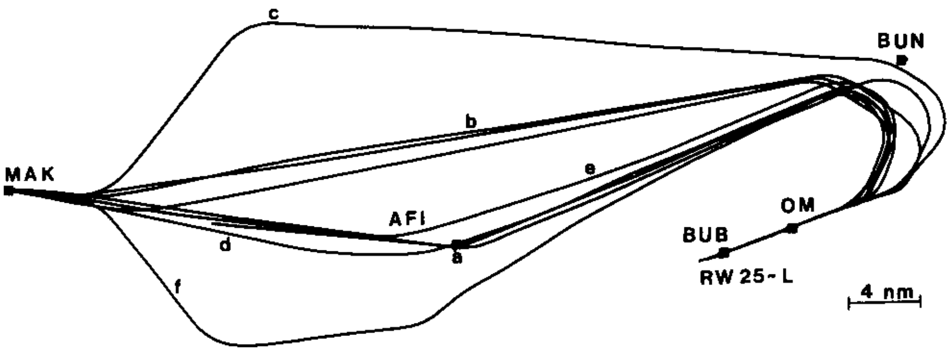
BASE TURN

SN123 H6 78 297 6.2 120		SN123, BRUSSELS ARRIVAL EXPECT BASE TURN AT 6.2-DME BEFORE BRUNO
		BRUSSELS, SN123 *ROGER* *EXPECTING BASE TURN AT 6.2 -DME BEFORE BRUNO*
SN123 H5 40 280 6.0 120	XXX	SN123, BRUSSELS AT 6.0-DME BEFORE BRUNO, TURN RIGHT HEADING 120 FOR BASE LEG
		BRUSSELS, SN123 *ROGER* *AT 6.0-DME BEFORE BRUNO* *WE TURN RIGHT, HEADING 120* *WOULD YOU GIVE US THE DISTANCE TO GO ?*
SN123 H5 38 14. 6.0 120		SN123, BRUSSELS TRACK MILES TO GO: 14.
		BRUSSELS, SN123 *ROGER* *TRACK MILES TO GO 14.*

FINAL TURN FOR ILS INTERCEPTION AND LANDING

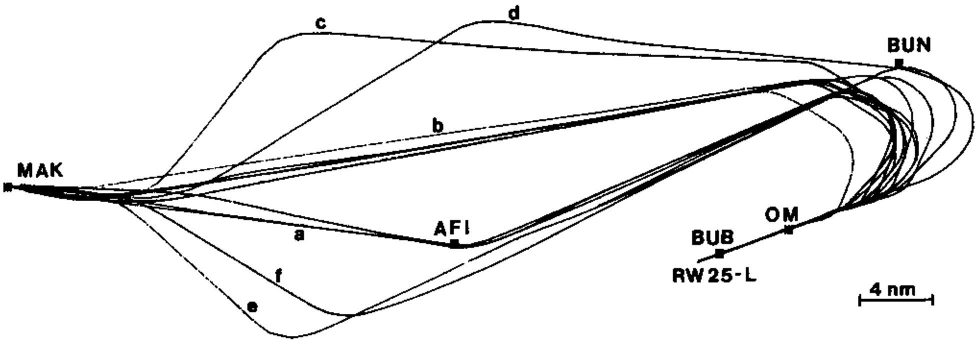
SN123 H3 29 262 220 12s		
SN123 H3 27 251 220	XXX	SN123, BRUSSELS TURN RIGHT, HEADING 220 TO INTERCEPT ILS
SN123 H2 25 250 220		*BRUSSELS, SN123* *TURNING RIGHT, HEADING 220 TO INTERCEPT ILS*
SN123 H1 21 186 E 160	XXX	SN123, BRUSSELS REDUCE SPEED TO 160KT-CAS AS CONVENIENT REPORT WHEN ESTABLISHED ON ILS
		BRUSSELS, SN123 *ROGER, REDUCING TO 160* *WE WILL REPORT WHEN ESTABLISHED*
SN123 H1 20 185		SN123, BRUSSELS ROGER
		BRUSSELS, SN123 *ESTABLISHED ON ILS*
SN123 H1 16 135		SN123, BRUSSELS CONTACT TOWER ON 118.60
		BRUSSELS, SN123 *ROGER*

Table 1 (cont.)



Flights conducted on 14 May 1986

(a)

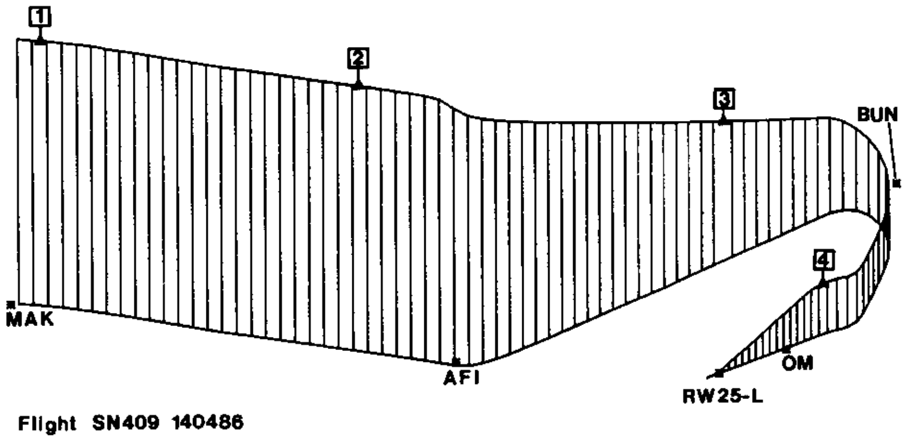


Flights conducted on 14 and 16 April 1986

(b)

Illustrative sample of trajectories flown on the SABENA DC-10 flight simulator
(Horizontal projection)

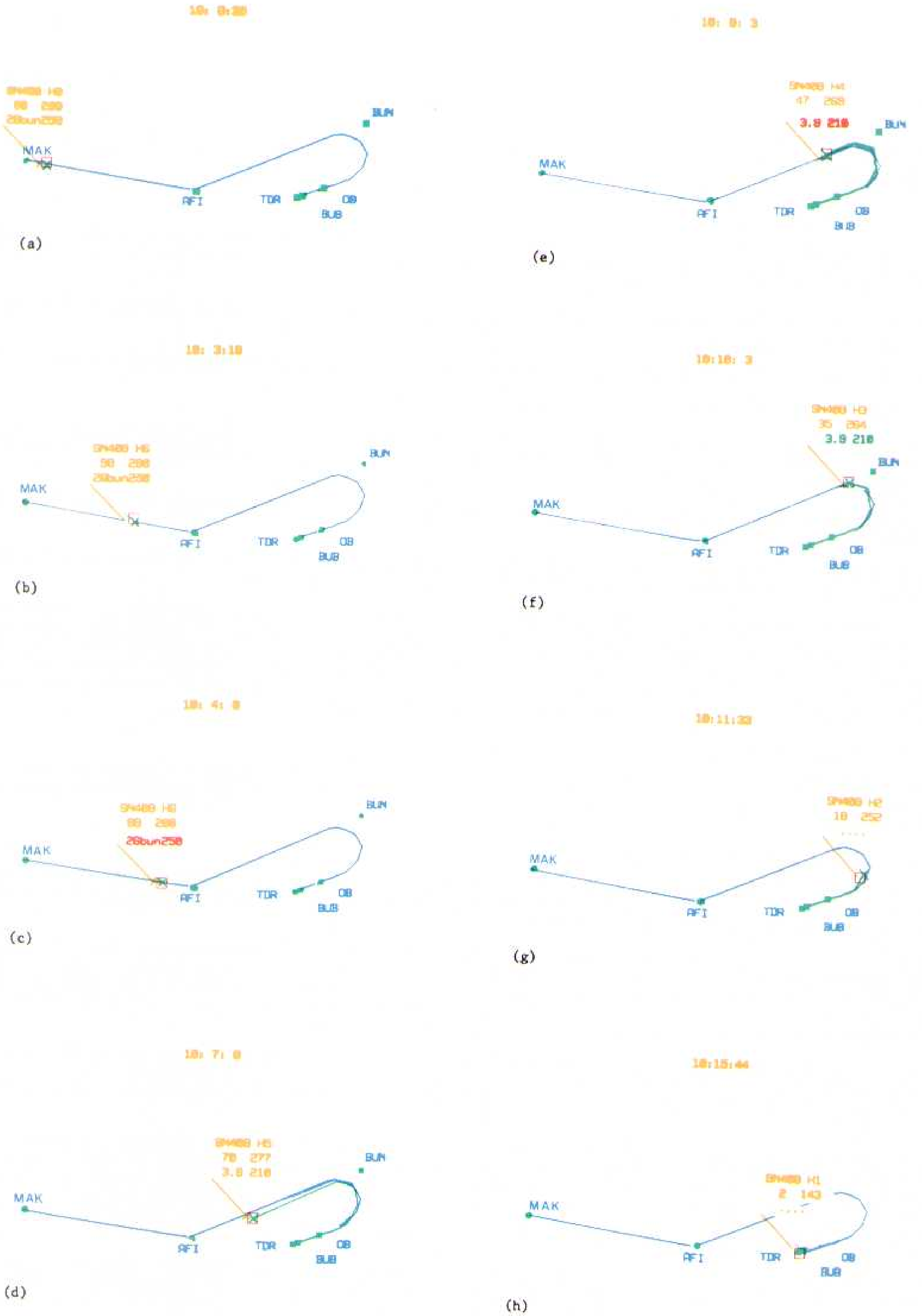
Figure 5



Flight (x, y, h) illustration
(a)

Experimental display of CINTIA messages

Figure 6



(a) (b) (c) (d) (e) (f) (g) (h)

Sequence of messages

(b)

Experimental display of CINTIA messages

Figure 6

(c) flights subject to major diversions to either the North or the South before being directed towards Bruno.

Atmospheric conditions vary from flight to flight, as do the accuracy of the meteorological forecasts available and a number of other parameters, such as the mass of the aircraft, which in the R/T communications mode is not known to the air traffic control unit.

The captain and his crew followed current practice for the operation of the aircraft. On several occasions, onboard observers suggested major navigation errors, as well as delays in responding to the ground controller's directives.

5.4. Experimental setup

For the experiments, the CINTIA software was installed on a microprocessor. The radar data were provided by another microprocessor directly connected to the DC10 simulator. In this setup the CINTIA/CONTROLLER *interface is made up of two main components:*

(a) the colour display simulating a synthetic radar display which shows the actual aircraft position and the label containing the information from CINTIA;

(b) the keyboard allowing the controller to control the display aspects and simulate ROSAS decisions.

The controller may make three types of requests:

- alteration of the background information (display or not of the way-point codes; display or not of the initially planned trajectory; display or not of the currently predicted trajectory; display or not of the predicted position, etc.);

- alteration of the label contents (for instance display of distance to go instead of derived ground speed);

- amendment of the time of arrival, either in absolute value or relatively, that *is to say by advancing or* delaying the arrival time in the landing sequence by one or several positions.

It should be stressed here that the inputs mentioned above only affect display aspects and simulate ROSAS suggestions. Basically, CINTIA expects no controller inputs for the generation of control directives nor does it *require an acknowledgement of whether or not* a specific directive has been actually transmitted to the aircraft. As said before, in this respect the controller is not part of CINTIA's internal control loop and the air traffic controller has complete freedom as to which decisions he actually takes, and when. CINTIA will just follow and adapt itself to the new situation.

5.5. Display of ATC directives

The labels presented on the radar display - of which a sample is used in Table 1 - appear as shown in Figure 6(b). The sequence of photographs used for this illustration pertains to the flight shown in Figure 6(a).

5.6. CINTIA's control flexibility

After a series of tests conducted in various operational conditions, CINTIA's accuracy level has been set to 10 seconds (for the expected time of arrival at the runway threshold), this value being used for the set of experiments referred to in this paper.

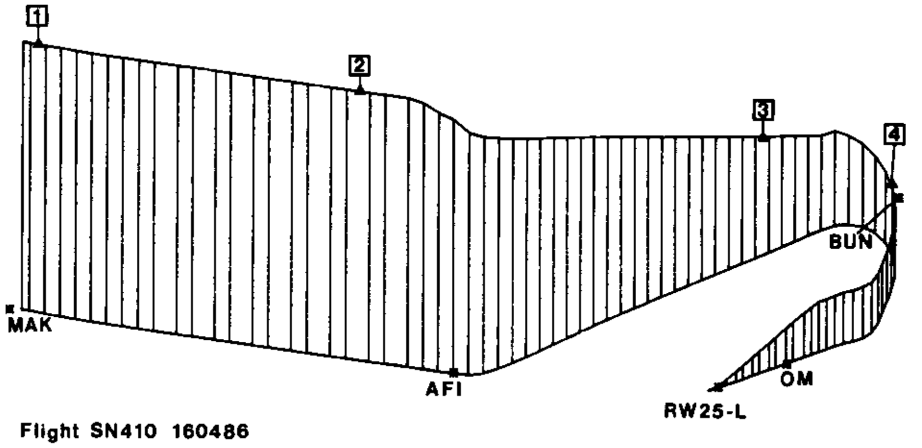
During these simulation sessions, 23 flights were made in the presence of representatives of the Air Traffic Services Authorities. The interest of the participants - external observers included - covered, in particular, CINTIA's response to various perturbations. The following paragraphs aim at outlining the disturbances injected to assess the capability of CINTIA to maintain safe conduct of the flight while ensuring the arrival time *within the expected 10-second accuracy.*

Regarding the atmospheric conditions, meteorological forecasts were in error (20 deg. and 10 kt for the wind orientations and magnitude respectively; presence of turbulence; requirements for de-icing). The surveillance information was missing on occasion (for up to 20 seconds); the CINTIA operated on both 5 and 12-second transfer rates.

Aircraft operation included a number of options such as manual conduct or use of automatic facilities for acceleration and deceleration phases, similarly for navigation and guidance, especially in turns and during approach and landing phases. In addition, incidents were generated in the aircraft; for instance, during one flight the final approach was made with one engine of the aircraft on fire. The mass of the aircraft was not communicated to CINTIA. The value used on the ground corresponded to the average mass for this particular aircraft, while the aircraft mass could vary between the minimum and maximum limits.

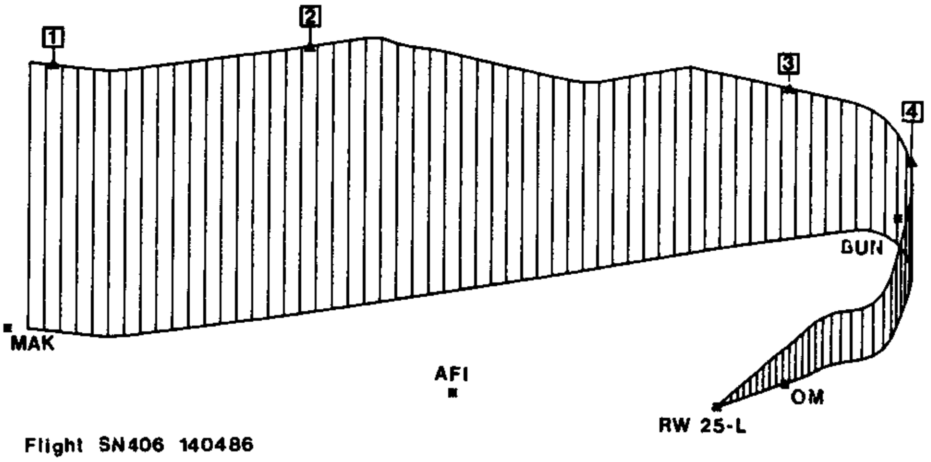
The Human concentration both on the ground and in the air was deliberately disturbed - although the presence of observers in the cockpit and at the air traffic control unit already constituted a source of perturbation. In the cockpit, the captain delayed the initiation of action required by the controller till the ground directive was repeated imperatively - for instance, delays for turning to base leg reached one mile and there were errors of 20kt on the speed during cruise and descent. On the ground, the controller omitted to clear the aircraft for the second part of the descent, which appreciably altered the vertical component of the trajectory.

Also, in view of the traffic situation, ROSAS inputs were simulated, the position of the aircraft in the landing time sequence was modified in the course of the flight and CINTIA automatically amended its instructions accordingly.



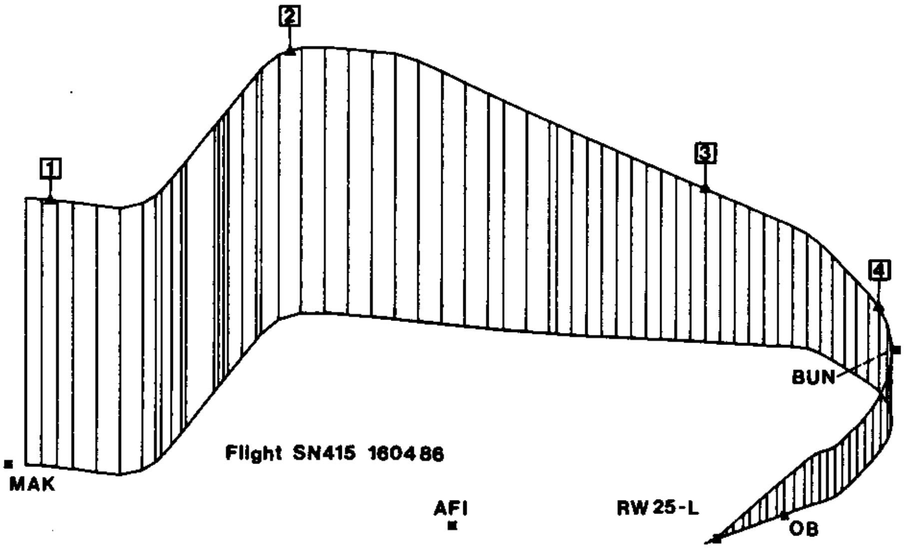
Flight follows initially-planned route

(a)



On pilot's request, flight is allowed to proceed direct to Bruno

(b)



Flight guided northwards for conflict resolution

(c)

Illustration of CINTIA's navigation flexibility

Figure 7

Changes in route were initiated either at the request of the captain or at the discretion of the controller. For changes of route such as those shown in Figure 7(b), the controller sends the authorisation or instruction to the aircraft by R/T, without direct input to CINTIA. Nevertheless, CINTIA will recognise the change of route and generate the subsequent instructions accordingly (similarly, CINTIA would recognise changes in the vertical profile, such as descent interruptions, and amend its predictions).

In addition, a number of incidents were created, leading to appreciable deviations from the usual routes, as may be seen in Figure 7(c). Deviations were made both northwards and southwards, simulating conflict resolution, adverse weather avoidance and other errors resulting from a coincidence of possible misunderstanding between the controller and the pilot.

6. CONCLUSIONS

The accurate 4-D conduct of flight will become a prerequisite of any system aiming at managing air traffic efficiently in terms of safety, expedition, economy and capacity. The Control of Inbound Trajectories of Individual Aircraft (CINTIA) makes it possible to envisage the delivery of aircraft at the runway threshold within a ten-second accuracy (without systematic use of stacking facility), even though landing slot allocation is effected at entry into the zone, some 100 to 200 nm from touchdown.

The procedure initially developed for application in the Zone of Convergence context is directly applicable to all systems involving a time-of-arrival constrained component, that is to say, in particular all systems designed to accommodate maximum traffic density with limited capacity at minimum cost.

Experiments have been performed in order to assess the accuracy of the procedure and its stability in the face of various perturbations originating from a variety of sources as summarised below. The real-time experiments were conducted in a realistic manner with the participation of professional approach controllers and airline crews. Simulations were made using various flight simulators. The illustrations used in this paper derive from the experiments conducted on the SABENA, Belgian World Airlines, DC-10 flight simulator.

CINTIA's directives were displayed in the labels on the radar screen (essentially one line of eight characters) in a form easily translated into current phraseology by the air traffic controller for R/T transmission to the aircraft pilot.

The operation of the system was appreciably disturbed. The causes of perturbation included:

- uncertainties in meteorological forecasts;
- alteration of initial plans (route changes; vertical profile modifications; revision of position in landing time sequence, etc.);
- aircraft operation options (manual or autopilot modes);
- uncertainty regarding aircraft mass, of which only the average value for the particular aircraft type is known in the R/T mode of communications;
- human fallibility both in the air and on the ground (aggravated by the presence of observers), leading to appreciable errors in communications, navigation (horizontal and vertical) and speed;
- particular events and incidents (conflict resolution, adverse weather conditions, etc.), leading to vertical and horizontal guidance instructions and appreciable off-route deviations.

As a result of these tests, it appears that CINTIA enables the controller to guide the aircraft safely to touchdown with a high degree of accuracy (10 sec.). CINTIA would maintain the time-of-arrival in spite of the uncertainties inherent to the present setup. Furthermore, CINTIA would adjust its instructions to the controller to take account of the various perturbations which may affect the conduct of the flight. In this respect, CINTIA offers a wide range of control/navigation flexibility. It will adapt to plans and alterations automatically, both horizontally and vertically without any specific computer input by the controller.

In conclusion, CINTIA provides efficient automatic assistance to the controller to ensure the accurate conduct of optimum trajectories from entry into an extended advanced TMA until touchdown. The messages displayed by CINTIA are clear and comprehensive, suitable for operation in the present R/T communications environment and directly adaptable to future automatic digital ground/air/ground links.

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- The flight simulator/radar/CINTIA interface used for the experiments referred to in this paper was developed and implemented by the Flight Simulation Department of SABENA, Belgian World Airlines.

REFERENCES

1. "Air Traffic Control Systems".
Guidance and Control Symposium, Edinburgh, Scotland, 26-29 June 1972.
AGARD-CP-105, April 1973.

2. "Plans and Developments for Air Traffic Systems".
Guidance and Control Symposium, Cambridge, Mass., USA, 20-23 May 1975.
AGARD-CP-188, February 1976.

3. "Air Traffic Management. Civil/Military Systems and Technologies".
Guidance and Control Symposium, Copenhagen, 9-12 October 1979.
AGARD-CP-273, February 1980.

4. "Air Traffic Control in Face of Users' Demand and Economy Constraints".
Guidance of Control Symposium, Lisbon, Portugal, 15 October 1982.
AGARD-CP-340, February 1983.

5. "Automatic Conflict Detection and Resolution (SPACDAR)".
Proceedings of the 11th Meeting, 25-27 September 1984.
EUROCONTROL Doc. 842013(R), October 1984.

6. Voelckers, U. "Computer assisted arrival sequencing and scheduling with the COMPAS system".
This Symposium, Paper 54.

7. Benoît, A.
Swierstra, S. "Air Traffic Control in a Zone of Convergence. Assessment within Belgian Airspace". Congress of the International Council of the Aeronautical Sciences, Toulouse, France, 9-14 September 1984.
Also EUROCONTROL Report 842009, April 1984.

8. Attwooll, V.W.
Rickmann D "A study of Conflicts within a Zone of Convergence"
Paper presented on the EUROCONTROL SPACDAR/GEDARC-11, 25-27 September 1984.
EUROCONTROL Doc. 842013(R), October 1984.

9. Benoît A.
Swierstra, S. "A Cost-Efficient Control Procedure for the Benefit of all Airspace Users".
Guidance and Control Symposium, Izmir, Turkey, 16-19 October 1984.
AGARD-CP-360, February 1985.
Also EUROCONTROL Report 842011, August 1984.

10. Attwooll, V.W.
Benoît, A. "Fuel Economies effected by use of FMS in an Advanced TMA".
The Journal of Navigation, Vol. 38, N° 1, January 1985.
Also EUROCONTROL Report 842003, February 1984.

11. Benoît, A.
Swierstra, S. "Real-time simulation of an operational procedure suitable for the accurate 4-D control of aircraft trajectories".
EUROCONTROL Report 862018, in preparation.

12. Cox, M.E. "Possible contributions from the SSR Mode S data link to the conduct of efficient aircraft operations".
This Symposium, Paper 25.

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CP-410

EXPLOITING THE CAPABILITIES OF FLIGHT MANAGEMENT SYSTEMS IN SOLVING THE AIRPORT ARRIVAL PROBLEM

by

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SUMMARY

Increasingly Flight Management Computers are becoming standard fit on present day passenger aircraft (737-300, 757, 767, A310, A300-600). Avionic update programmes which incorporate Flight Management Computers, are in hand for 747 and MD 80 and new aircraft programmes A320, MD 11, 7J7, A330 and A340 are or are likely to include Flight Management Computing as standard fit. As these aircraft come to dominate the traffic entering and leaving major airports there is potentially a new level of information and of control available to the air traffic controllers whose task it is to schedule the aircraft flow into and out of the terminal area. This information flow and the consequent control actions should enable the traffic to be handled in a manner to minimise delay, thus enhancing the available traffic handling capacity of an airport.

1. FLIGHT MANAGEMENT COMPUTING

The features of a Flight Management System are

- Position determination with continuous assessment of the likely accuracy.
- Ability to construct a flight plan, or to amend one in response to pilot entered commands.
- Ability to calculate guidance commands which cause the aircraft to acquire and subsequently to follow the defined route.
- Ability to calculate a flight trajectory which meets the constraints imposed by the flight plan, by the pilot and by ATC and allows a pilot selectable cost criterion to be minimised.
- Ability to provide trajectory predictions of the aircraft condition at down path waypoints.
- Ability to present information to the pilot in both alphanumeric and in graphical form.

of these characteristics those which are particularly relevant to the present discussion are

- Position Determination
- Flight Plan Construction and Amendment
- Guidance to the Flight Plan
- Predictions Along the Flight Plan

(a) Position Determination - Flight Management Systems determine position using at all times the best available set of information. Current systems combine information from on board IRS with radio fix information to give either DME/DME position using up to four different DME distances or in the absence of such information VOR/DME position. Future systems may be expected to add GPS position to this.

The selection which DME stations the receivers in the aircraft shall be tuned to, is made by the Flight Management Computer given the aircraft's current position and track and the positions of available DMEs. The latter are known to the Flight Management Computer from its Navigational Data Base.

The computer contains error models for each type of position fix eg. DME/DME VOR/DME and IRS and for whichever the current mode of position determination the computer has an estimate, at a 2 sigma confidence level, of the accuracy of the position indication it has calculated.

(b) Flight Plan Construction and Amendment - Flight Management Systems represent flight plans as a sequence of legs as defined in ARINC 424. Individual legs may define a:-

fixed track
fixed heading
DME arc
great circle
direct to
holding pattern
procedure turn

The set of legs and the permissible linkings are shown in Fig 1. The data items associated with each leg are shown in Fig 2. Although in present Flight Management systems routes stored in the data base can utilise all legitimate combinations of leg types, the revisions to a flight plan are restricted to

- DF legs (direct to fix) for revisions from present position.
- TF legs (great circle between two fixes) for revisions from fixed points.
- Holds at either present position or some fixed route point.
- Orbits at present position.

[The author is aware of one programme for which it is at present planned to provide the pilot with freedom to insert any legitimate ARINC leg type].

In addition some of the parameters associated with a leg (Fig 2) can be set under pilot control if the values drawn from the data base are to be countermanded.

The means which the pilot has to inspect his flight plan and to define amendments is the CDU which provides a selectable repertoire of data displays associated with the flight plan and the functioning of the Flight Management Computer Fig. 3 and also provides the pilot with the means to input data and to generate or revise flight plans (Fig 4).

(c) Guidance to Flight Plan - given the flight plan which has been defined either directly by the pilot or indirectly by calling from the data base some stored routing, and given the current estimate of aircraft position the Flight Management System is able to calculate guidance commands to cause the aircraft to capture and subsequently to follow the route. The guidance takes into account overfly, turn direction as may be specified for a transition and includes all standard entry procedures to holds. It is a complete guidance function which satisfies the requirement of the plan.

In the vertical plane constraints at waypoints or at altitudes are satisfied.

In summary, the defined flight plan, whatsoever it may be, is followed and if the requirement cannot at any point be met then this is indicated to the pilot on the CDU and on EFIS.

(d) Predictions Along the Flight Plan - a capability central to the operation of a Flight Management System is to predict the down route situation. This is an essential component in the calculation of the Top of Descent point as well as being important in predicting the fuel remaining at the destination.

Predictions take account of

- The current state of the aeroplane.
- The current wind as estimated by the Flight Management System.
- Any down route estimates of wind which have been entered into the Flight Management Computer.
- Current temperature and estimates of temperature at down route points which have been entered into the Flight Management Computer.
- The requirements of the flight plan as known at this time (altitude changes, speed constraints, etc.).

An important feature of a Flight Management System is the concept of the Temporary Flight Plan. With this feature a revision to a flight plan can be made and the predictions associated with that revised flight plan inspected while the aircraft is continuing to fly the unrevised flight plan. Only when the pilot is satisfied with the consequencies of the revision will he EXECUTE the revision and the aircraft will begin to fly to the revised plan.

In normal operation such a feature is not used extensively since the revision to the plan is demanded by ATC eg. make your approach to RW 102 using STAR XYZ. But even in this case the pilot is able to see the new routing on his EFIS map display and a CDU prior to EXECuting the revision. It provides a visual check prior to committing the aircraft to new routing (Fig 5).

2. THE AIRCRAFT ARRIVAL PROBLEM

If the traffic into an airport is sufficiently light then as each aircraft arrives in the terminal area there is no requirement for the routing and timing of an individual aircraft's descent and approach to be amended as a result of the presence of the other arriving aircraft. As the traffic density increases the average separation of the aircraft in the terminal area will decrease and the situation would arise in which one or more of the separations would reach or infringe minimum values set by consideration of safety. It is to prevent this that ATC control exits and their control is exercised by observing where aircraft currently are, and scheduling their temporal placement so that they fit into an ordered and properly separated sequence for landing. This process inevitably causes delay to some, perhaps to all, aircraft.

As traffic density increases the task of ATC becomes more difficult and the need for some automated support for that task becomes more urgent.

The objective of such an automated aid can be expressed as that of

- reducing the average delay suffered by aircraft, when the TMA is handling a given level of traffic, while maintaining aircraft separation in accordance with the rules of safety.

or

- enabling an increase in the volume of traffic which can be handled while maintaining a given average level of delay, and maintaining aircraft separation in accordance with the rules of safety.

The essential components of an effective means of traffic control are

- means of obtaining accurate predictions of the movement of aircraft toward and within the terminal area.
- Means of simulating from these predictions of incoming aircraft the interactions which would occur if they performed their planned descent and approach procedures.
- A strategy for amending these planned descent and approach trajectories in order to resolve the perceived interactions.

This could involve:

- Changes in time of arrival of individual aircraft into the TMA.
- Changes in the routing of individual aircraft in the TMA.
- Changes of speed, height etc.
- A means of instructing individual aircraft of these changes to their flight plan.

This whole process will need to be iterated both to compensate for errors in the initial information and to make fine adjustments in the trajectory of aircraft as they progress toward the final approach.

The next sections will discuss the first and the last of these components

- Obtaining predictions
- Instructing flight plan modification

(a) PREDICTIONS

It has been pointed out that a Flight Management System possesses a set of information associated with the present state of the aircraft and its predicted future movement.

Table 1 shows the suggested content of a buffer of data which could be output by a Flight Management Computer in order to report the present state and future movement.

TABLE 1

ITEM	LENGTH
Flight Number	6 bytes
GMT	3 bytes
Present Posn.	3 bytes
Altitude	2 bytes
Cleared Altitude	2 bytes
Accuracy Parameter	1 byte
TO Waypoint	
- Identifier	6 bytes
- Distance nm	2 bytes
- bearing	2 bytes
- Estimated time at	3 bytes
NEXT Waypoint	
- Identifier	6 bytes
- Location Lat, Long	3 bytes
- Estimated time at	3 bytes
Continuing by Routing	4 bytes
Termination	6 bytes
Estimated time at	3 bytes
Top of Descent	
- Time at	3 bytes
- Location Lat, Long	3 bytes
Destination	
- Identifier	4 bytes
- Estimated time at	3 bytes
Current State	
- Ground Speed	2 bytes
- Track	2 bytes
- Wind estimate	3 bytes
- Altitude (FL)	3 bytes
- Temperature	1 bytes
	79 bytes

Adding say 20 bytes for redundant bits, checksums etc. this information, output, say, every 5 seconds gives a data rate of 160 bits/second.

If a link is time shared between, say, 200 aircraft this would require a rate of 32,000 bits/sec.

(b) Data Exchange - the value of the predictions that an individual Flight Management equipped aircraft can provide depend upon the accuracy of the information upon which it bases the estimates.

One of the components of this information for which the system is totally dependent upon external sources is the meteological data.

A service which broadcasts temperature and wind information over a grid would enhance the validity of all estimates which aircraft is that region could produce.

Clearly the source of such information would be the down loaded data discussed in 2.(a) as received from all aircraft.

Table 2 shows a possible data file for broadcasting to aircraft.

TABLE 2

METEOROLOGICAL DATA

ITEM	LENGTH
GMT	3 bytes
Origin Lat. Long (X_oY_o)	3 bytes
Grid Size nm.	1 byte
Altitude	2 bytes
x_oy_o Wind, Temp	5 bytes
x_1y_o " "	
x_2y_o " "	
x_3y_o " "	
$x_{-1}y_o$ " "	
$x_{-2}y_o$ " "	
$x_{-3}y_o$ " "	= 35 bytes
x_oy_1 " "	
x_1y_1 " "	
etc.	= <u>245 bytes</u>
Repeated for 6 altitude	= 1470 bytes
Say 1500 bytes of data	= 12000 bits
If transmitted every 30 secs.	= 400 bits/sec

(c) Flight Plan Modification - supposing now that the ATC ground facility having received the present position and prediction data from all the aircraft in and approaching the terminal area has run its 'conflict simulator' and identified a number of conflicts which will occur, has applied its resolution strategy, checked on the simulator that the conflicts previously predicted will thereby be resolved. It then possesses a set of flight plan modifications which are to be be transmitted to some at least of the aircraft.

The communications will be directed to the individual aircraft concerned. Consider the way in which these flight plan modifications are handled in the aircraft.

It is clear that any modification to a flight plan cannot be allowed to become effective without the Captain/First Officer understanding the change and then endorsing it.

The principal component modifications are speed changes and path changes.

i) Speed Changes - the change Δt in arrival time consequent upon a change ΔV in the ground speed V when the distance to be travelled is d is

$$\Delta t = - d/V^2 \ \Delta V \tag{1}$$

This means that the technique is most effective when the distance is large. Thus with d = 100 nmiles, V = 300 kn, a 10 kn change in V gives Δt = 40 sec.

ii) Path Change - the change Δt in the arrival time is proportional to the change Δd in path length

$$\Delta t = \Delta d/V \tag{2}$$

The path lengthening can be effected by introducing an orbit, a hold or by effectively replacing a straight segment of path by a dog leg which diverts from the straight path by a distance x.

The latter gives:

$$\Delta d = 2x^2/d \tag{3}$$

where x is the cross track amplitude of the dog leg over a distance d.

Clearly path shortening is only possible if the basic routing contains legs which can be effectively bypassed by going direct.

In order that the ATC controllers, themselves can monitor the operation of the automatic system on the ground, it is suggested that there will be long and short delta routings for each basic STAR which will provide an approximate plus or minus one minute of flight time. These delta routings will be named and stored in the Flight Management Computer data base. Communication with the aircraft can then use these names, the system can construct the route as a Temporary Flight Plan for pilot inspection and configuration. In this way the need for time consuming pilot entry procedure at a time of already high work load will be avoided. Table 3 shows a typical message.

TABLE 3

Item	Length
Flight Number	6 bytes
GMT	3 bytes
Planned Arrival Time	3 bytes
Correction to Last Reported	3 bytes
Last Reported Ground Speed	2 bytes
Required Speed	2 bytes
Routing Change	
Hold at	
Identifier	6 bytes
Inbound Course	2 bytes
Length/Time	1 byte
Number of circuits, L/R	1 byte
Orbit at	
Identifier	6 bytes
Number of circuits, L/R	1 byte
STAR, Delta	
Identifier	6 bytes
Cleared Altitude	2 bytes
44 bytes	

With an update interval of, say, 5 seconds gives 30 bits/second.

Any such modification will, if is proposed, create a temporary flight plan which will be presented to the pilot on both CDU and EFIS.

The EXECuting of this temporary will cause the aircraft to begin flying the modified plan.

3. CONCLUSIONS

It has been suggested that the data existing in Flight Management Computer equipped aircraft can provided an ATC ground based computer with the raw data it needs to predict potential conflicts before they arise.

Further it is suggested that amendments to the flight plan generated by the ground computer in order to resolve these conflicts can be readily handled by the already existing capabilities of Flight Management Computers.

The most urgent task is to establish the communication means which will allow this data and these modification instructions to be exchanged between ground and air.

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CURRENT/NEXT LEG TRANSITIONS

NEXT LEG

CURRENT LEG

	AF	CF	DF	FA	FM	HA	HF	HM	PI	TF	VA	VD	VI	VM	VR	IF
AF	1		4						▨							▨
CF		D	4							6						▨
DF			4													▨
FA	▨	D		D	D	▨	▨	▨	▨	▨						2
FM	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
HA						▨	▨	▨	▨							▨
HF						▨	▨	▨	▨							▨
HM						▨	▨	▨	▨							▨
PI	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
TF		D	4							6						▨
VA	▨	D		D	D	▨	▨	▨	▨	▨						2
VD		D		D	D	▨	▨	▨	▨	▨						2
VI			▨			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
VM	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
VR	▨			D	D	▨	▨	▨	▨	▨						2
IF	▨	D	3	▨	▨	▨	▨	▨	▨	5						▨

SHADED BOXES - IMPERMISSIBLE TRANSITIONS

D - THESE TRANSITIONS CAN GIVE RISE TO GEOMETRIC DISCONTINUITY. IF THIS EXCEEDS 2nm, THE TRANSITION IS NOT PERMITTED.

1 - AF ⟶ AF TRANSITION IS ALLOWED ONLY WHEN THE SAME DME REFERENCE, ARC RADIUS AND TURN DISCRETE IS SPECIFIED FOR BOTH AF LEGS.

2 - WHERE THIS TRANSITION IS REQUIRED, THE IF LEG SHOULD BE CODED AS DF LEG.

3 - IF ⟶ DF TRANSITION SHOULD BE CODED AS SINGLE TF LEG.

4 - TRANSITIONS PERMITTED ONLY WHEN OVERFLY SET FOR THE CURRENT LEG.

5 - TF LEG WITHIN SI DATA BASE CONTAINS START AND END FIX.

6 - TRANSITIONS SHOULD NOT BE CODED WHERE CURRENT LEG HAS CONDITIONAL ALTITUDE TERMINATION.

FIG 1

DATA REQUIRED FOR LEG TYPES

LEG / DATA ITEM	TURN DISCRETE	OVERFLY	RECOMMENDED NAVAID	CONDITIONAL ALTITUDE	MAXIMUM ALTITUDE	MINIMUM ALTITUDE	SPEED	ORIGIN FIX	TERMINATING FIX	MAGNETIC COURSE	MAGNETIC HEADING	LEG LENGTH	HOLD	DME RADIUS	MAGNETIC RADIAL
AF	√		√	▨				⧅	√	⧅	⧅	⧅	⧅	√	⧅
CF								⧅	√	√	⧅	⧅	⧅	⧅	⧅
DF				▨				⧅	√		⧅	⧅	⧅	⧅	⧅
FA				▨	②	②		√	⧅	√	⧅	⧅	⧅	⧅	⧅
FM				▨				√	⧅	√	⧅	⧅	⧅	⧅	⧅
HA	√			▨	②	②		√	⧅	⧅	⧅	⧅	√	⧅	⧅
HF	√			▨				√	⧅	⧅	⧅	⧅	√	⧅	⧅
HM	√			▨				√	⧅	⧅	⧅	⧅	√	⧅	⧅
PI	√			▨				③	⧅	√	⧅	√	⧅	⧅	⧅
TF								√	⧅	⧅	⧅	⧅	⧅	⧅	⧅
VA				▨	②	②		⧅	⧅	⧅	√	⧅	⧅	⧅	⧅
VD			√					⧅	⧅	⧅	√	⧅	⧅	√	⧅
VI				▨				⧅	⧅	⧅	√	⧅	⧅	⧅	⧅
VM				▨				⧅	⧅	⧅	√	⧅	⧅	⧅	⧅
VR			√					⧅	⧅	⧅	√	⧅	⧅	⧅	√
IF				▨				√	⧅	⧅		⧅	⧅	⧅	⧅

STANDARD DATA ITEMS

OPTIONAL DATA ITEMS

▨	NOT PERMISSIBLE	⧅	NOT APPLICABLE
√	REQUIRED	BLANK	OPTIONAL (SET TO DEFAULT IF NOT SPECIFIED)

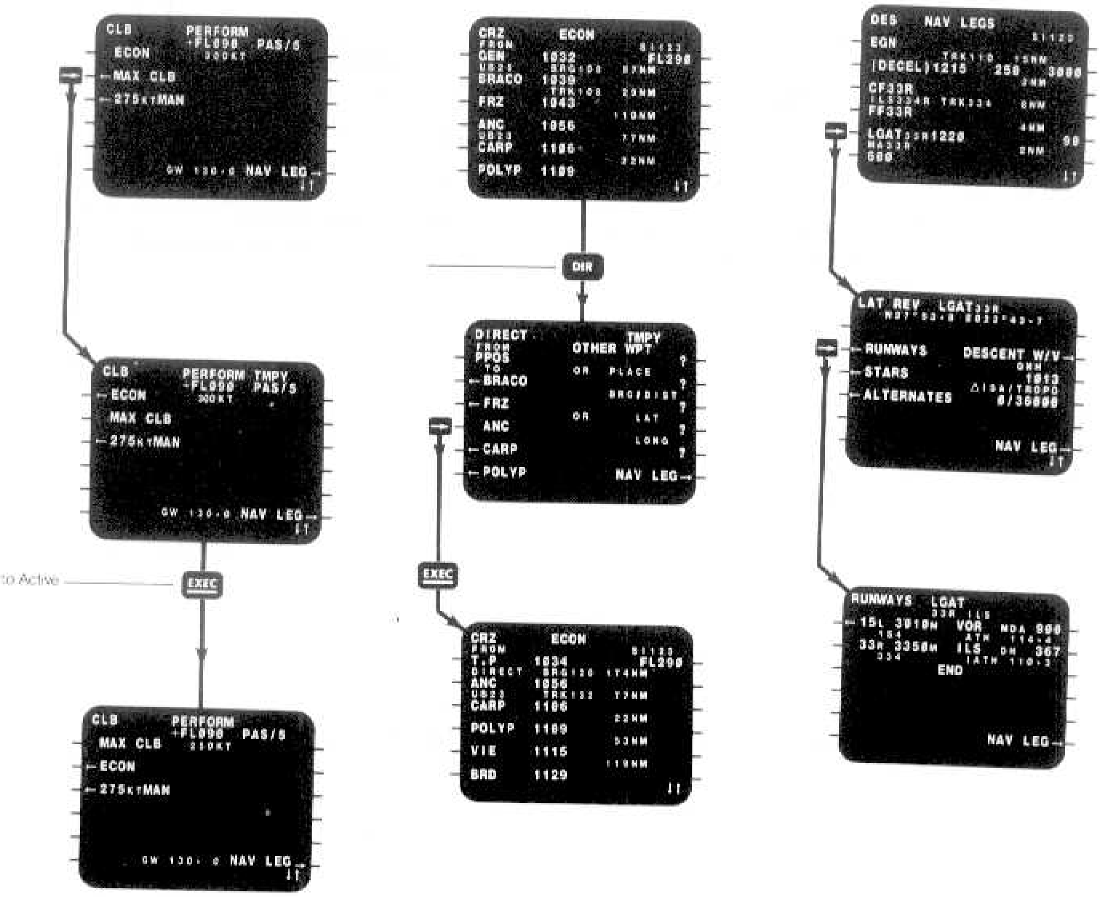
② TERMINATING ALTITUDE IS REQUIRED. MAX, MIN ALTITUDES MUST BE SET TO SAME VALUES.

③ FIX FOR PI LEG IS REQUIRED, THIS IS SPECIFIED IN SUBSEQUENT CF LEG ONLY

FIG 2

CONTROL AND DISPLAY UNIT

FIG 3



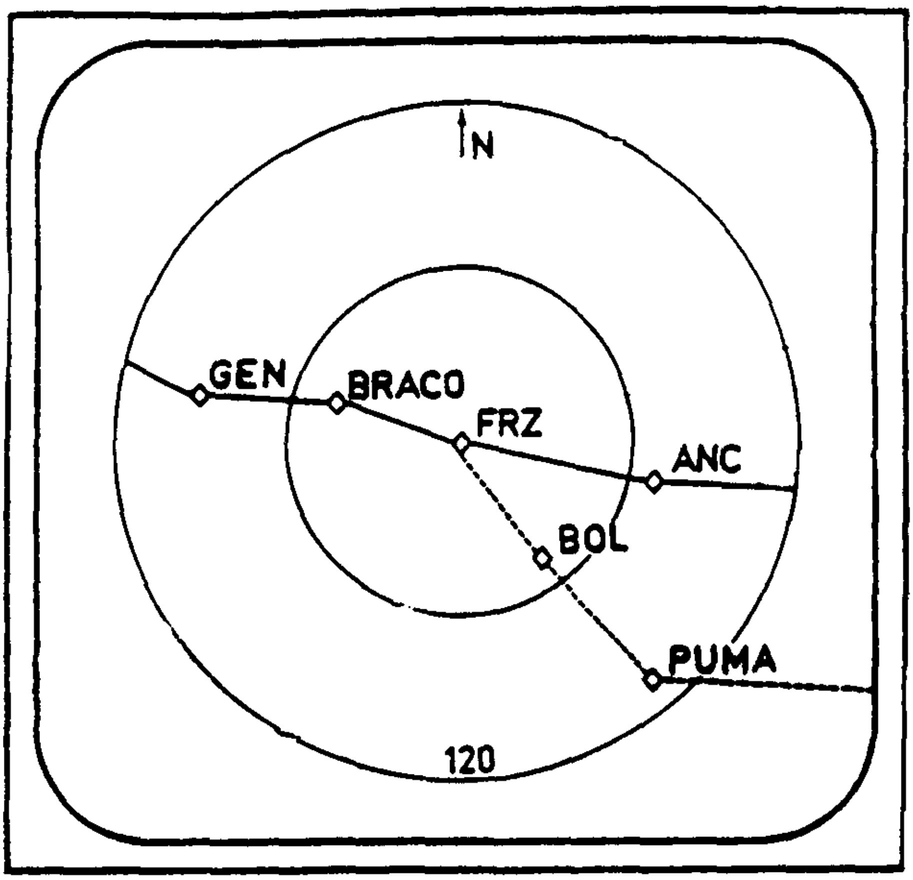
CLIMB MODE

GO DIRECT

DESTINATION R/W

TYPICAL FLIGHT PLAN REVISIONS

FIG 4



EFIS CHART DISPLAY SHOWING ACTIVE AND TEMPORARY FLIGHT PLANS

FIG 5

CP-410

APPLICATION OF FLIGHT PERFORMANCE ADVISORY SYSTEMS TO U.S. NAVY AIRCRAFT

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SUMMARY

The U.S. Navy, in its Aircraft Energy Conservation Research and Development Program, is currently investigating various methods for improving the fuel efficiency of existing and future Navy aircraft. Fuel saving concepts under development include an aircraft integrated flight performance advisory system, a pre-flight mission planning program utilizing a desk type computer and an aircraft performance advisory system using an HP-41 CV hand-held calculator.

The integrated flight performance advisory system for the F/A-18, the A-7E, and the S-3 are described in detail by reviewing the displayed outputs to the pilots and describing the required inputs and their sources. Features of each aircraft system are described in accordance with the development status of the program. The pre-flight mission planning program utilizing an HP-9845 desktop computer is described for the P-3C aircraft. The approach to weather, takeoff and cruise are described by specifying the input and output data. Sample displays are also shown. The hand-held HP-41 CV calculator utilized for flight performance predictions is described for the P-3C. All the calculator functions are described for the takeoff and cruise flight modes of this aircraft. The operational status of these three programs and plans for other Navy aircraft are also specified.

INTRODUCTION

The U.S. Navy, in its Aircraft Energy Conservation Research and Development Program, is currently investigating various methods for improving the fuel efficiency of existing and future fighter, attack, search and patrol aircraft. Fuel savings concepts under development include an aircraft integrated Flight Performance Advisory System (FPAS) to provide real time aerodynamic performance data to the crew, a pre-flight mission planning program called Fuel Optimization Routines for Energy Management (FOREM) and an on-board aircraft performance advisory system using a hand-held HP-41 CV calculator called the Pocket-Size Aircraft Performance Advisory Computer (P-S APAC).

FLIGHT PERFORMANCE ADVISORY SYSTEM (FPAS)

The FPAS program commenced with an analysis of the quantity of fuel used by Navy and Marine aircraft based upon aircraft type and mission. Using this information, high utilization aircraft which will be in the inventory for the next 10 to 15 years were identified for possible incorporation of the FPAS.

The basis of the FPAS operation is a set of pre-determined algorithms which describe the aerodynamic performance of the aircraft in flight modes such as take-off, climb, cruise, loiter, descent and landing. The system is implemented on the aircraft by the use of a computer, a control and display unit, and interface provisions to the aircraft sensor data.

With the availability of the algorithms and the technology level of the aircraft there are two basic system implementation techniques. The coupled system or Flight Performance Management System drives an autothrottle and autopilot directly, controlling the aircraft altitude and airspeed to attain the most efficient operation. Presently a management system is not being considered for Navy aircraft. The advisory system or Flight Performance Advisory System provides a display to the aircrew of the optimum altitudes, airspeeds and other parameters pertinent to conserving fuel while reducing crew workload. Fuel saving can also be translated to additional mission capability or additional flight training hours. This FPAS system through its integration with other systems and sensors on the aircraft can also provide in a military situation, return to base data, alternative base flight information and performance data for an aircraft degraded by combat damage or a system malfunction.

The FPAS type of system utilizes sensor information about atmospheric conditions, aircraft weight and drag configuration and any other variables needed by the operating algorithms. The FPAS must also provide an interface with the aircrew which simplifies the task of operating the aircraft efficiently. In most systems the interface provides for the selection of an operating flight mode and observing the results. In an austere system the aircrew may have to perform many entry tasks and fly the aircraft in response to the advisory outputs. Examples of data input to the computer are zero fuel weight, fuel weight, drag configuration, wind speed and direction, temperatures and pressures, navigational waypoints, stores inventory, and engine sensor data. Examples of data output are optimum speeds and altitudes for maximum specific range and endurance flight modes, power settings, climb and descent speeds, distance to top of descent, optimum number of engines, fuel remaining at waypoints, time and range for current and optimum conditions and fuel required to return to base or alternate waypoint.

The operating limits of the above input and output values are consistent with the established Naval Air Training and Operating Procedures Standardization (NATOPS) Flight Manual operating range. The performance equations developed for each aircraft are based upon the aircraft performance data contained in the NATOPS manual. This paper presents a summary of the FPAS programs developed for the S-3A, the A-7E and the F/A-18. These aircraft, while representing the search type, the attack type and the fighter attack also illustrate the different levels of implementation possible with aircraft of advancing technology levels. As the F/A-18 aircraft will have the most sophisticated FPAS, it will be emphasized during the presentation.

F/A-18 FPAS

The approach to implementation of the F/A-18 FPAS is to identify the alternative methods, that is, what systems are available that can provide the computational, display and control assets. On the F/A-18 this resolved into using the mission computer and the cathode ray tube (CRT) of the Horizontal Situation Display (HSD) and the Digital Data Indicator (DDI) display. Due to the technical sophistication of this aircraft all sensor information can be automatically provided. Introduction of the FPAS to this aircraft is a software only modification to the Operational Flight Program (OFP) tape and will require approximately 6000 words of memory in the computer. Analysis has determined that this system promises to be cost effective in that the fuel saved will pay for the system during the remaining life of the aircraft. Fuel savings are estimated to be three (3) per cent and based on 500 aircraft with fuel at $1 per gallon could equal $5M saved per year or eleven (11) additional flight hours per year for each aircraft.

The F/A-18 FPAS displays to the pilot on the Horizontal Situation Display Figure 1, the fuel remaining at a selected waypoint, the descent distance to the selected waypoint and the distance, time and bearing to the waypoint. This information is calculated from whatever source of navigational data the pilot has available or chooses to select.

On the Digital Display Indicator, Figure 2, the pilot can select FPAS from the displayed menu. With a predetermined fuel reserve he can obtain total range and endurance at his current Mach number and altitude, the optimum Mach number at his current altitude with respective range and endurance, and the optimum Mach number and altitude with their range and endurance. The optimum climb and descent indicated air speed (IAS) and mach number are also provided on the Heads Up Display (HUD) when the climb/descent key on the Horizontal Situation Display is depressed.

Features included in this system are actual stores configuration weight and drag count. The aircraft will automatically decrement the stores weight and drag as the stores are deployed.

The system is also adaptive in that range and endurance data is adjusted by using the actual fuel flow. Initial predictions are calculated using the fuel flow algorithm. Then the calculated fuel flow at current flight conditions is compared to the actual fuel flow and the variation is applied to the predicted values. In this manner the system more nearly represents the actual aircraft performance regardless of whether it is due to engine or airframe inefficiencies. All calculations include the effect of current winds with off course winds included in the waypoint fuel remaining calculation.

Each mission profile is also optimized, that is, the range and endurance at the optimum altitude includes the effect of climb, and all range and endurance predictions include the effect of descent. For example, the range utilizing optimum altitude and mach number would include fuel and distance for climb, acceleration and descent.

The F/A-18 FPAS is now in the development stage. The displays have been very well received by fleet pilots. A suggestion by the pilots that single engine performance be included is being implemented. This will take the form that should an engine fail, the data presented would be for single engine performance with appropriate drag modifications. This system is expected to become operational in 1988.

The F/A-18 FPAS is the most sophisticated FPAS system presently in development for Navy aircraft. It requires no manual inputs by the pilot. The pilot selects FPAS from a menu and all information is continuously displayed to him in real time.

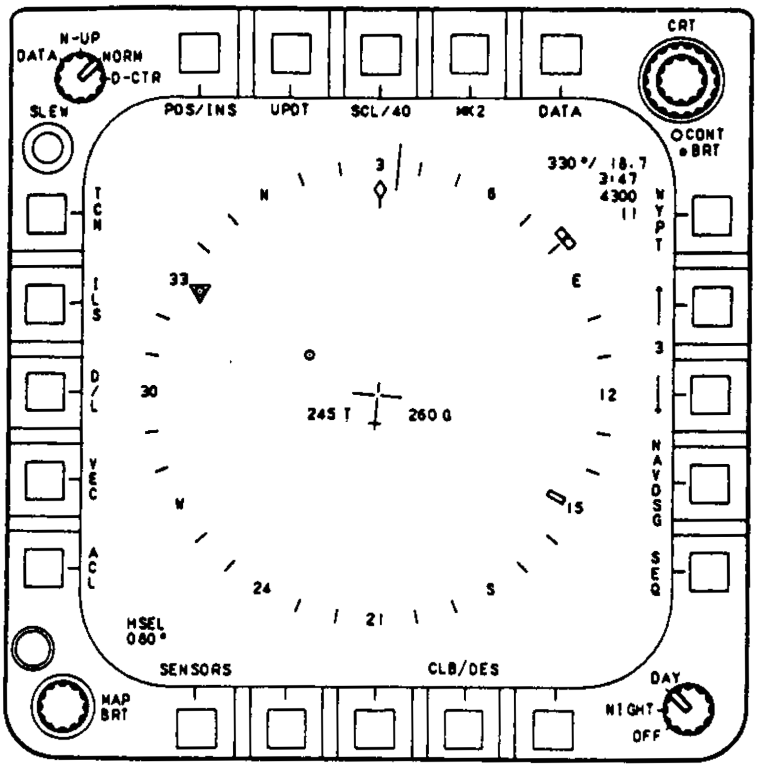


FIGURE1. F/A-18 HORIZONTAL SITUATION DISPLAY (HSD)

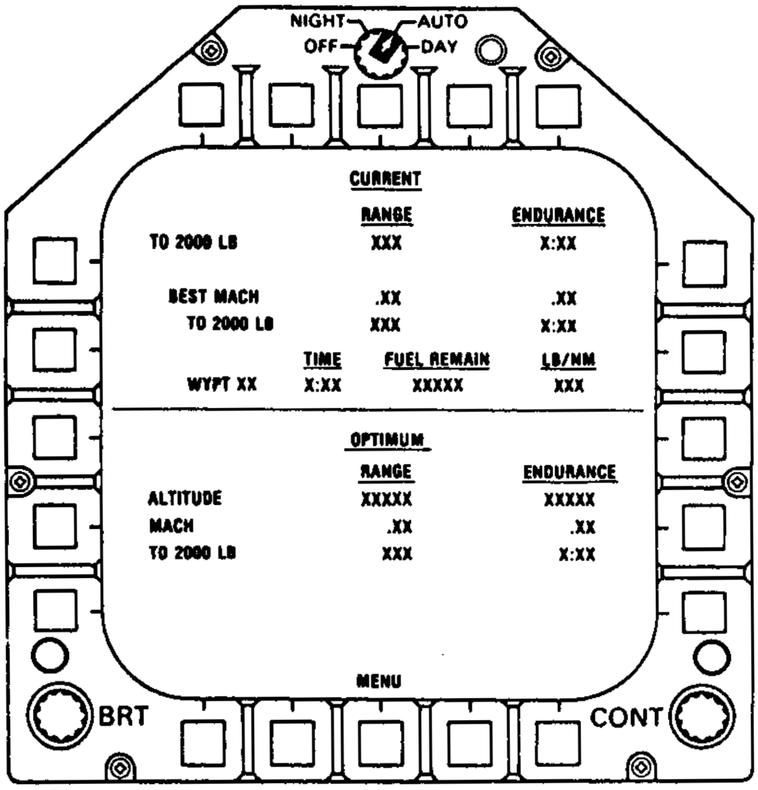


FIGURE 2. F/A-18 FPAS DIGITAL DISPLAY INDICATOR (DDI)

A-7E FPAS

The A-7E FPAS illustrates the development of a performance advisory system on an aircraft of significantly older technology than the F/A-18. As in the F/A-18, the approach for the A-7E FPAS specified a software only modification. The system has been developed and is in the test and validation phase now. It is expected to be introduced into the fleet late this year. The system consists of imbedded software in the Operational Flight Program tape and is an integral element of the tactical/navigational computer. The pilot interface is via a computer keyboard and data display. The system is limited but does provide data to advise the pilot of the optimum airspeed and altitude and the optimum airspeed at the current altitude. This data is presented for both the cruise and endurance flight modes. For both of the combinations the optimum and current specific range and the optimum and current specific endurance is presented to the pilot. The current fuel flow and current true airspeed are also displayed.

On the pilot's control display, Figure 3, there are only two windows for presenting flight data. The pilot must key in a numeric code on the keyboard for the flight parameters he wishes to see. This additional workload is judged to be acceptable for the information provided. The A-7E computer does not have fuel weight information available to it for the performance calculations. Therefore, the pilot enters the initial fuel weight and the fuel flow algorithm is integrated as a function of time to determine the instantaneous fuel weight. The pilot modifies the instantaneous fuel weight by comparing the calculated fuel flow with the actual, entering the actual, and having the computer apply the difference to the flight parameters. The accuracy of this procedure has been validated by flight testing on an instrumented aircraft. The drag count, stores weight and current wind are also maintained.

For this aircraft the maximum fuel savings is $2M in a single year and then decreasing as the aircraft goes out of service.

S-3 FPAS

The third aircraft for which an FPAS is planned is the S-3. This is a twin turbofan search type aircraft operating from land and carrier bases. The system for this aircraft is in the early development stage. This FPAS modification will also be a software only modification. The FPAS system will utilize a Communication Control Group (CCG) processor which is a recent replacement for a logic unit type communication system. This new CCG system has computer assets and a control and display, Figures 4 and 5, ideally suited to and in good cockpit position for use as an FPAS. It is planned to integrate this system with the mission computer and other sensor sources thereby minimizing pilot workload. The goal will be to present parameters as alike to the F/A-18 as possible. To date, the performance algorithms have been developed by digitizing the data in the flight manual and an FPAS with all manual inputs has been demonstrated on the control communications group hardware. Success of the system is dependent on the level of increased pilot workload.

FUEL OPTIMIZATION ROUTINES FOR ENERGY MANAGEMENT (FOREM)

The pre-flight mission planning FOREM system uses a Hewlett Packard 9845 desktop computer to provide aircrews with a convenient and accurate means of flight planning. The HP 9845 computer was selected because it was already widely used at Navy installations. The computer is no longer available from the manufacturer. Present plans call for transition to the Hewlett Packard 9020 which has been designated as the Navy Standard Tactical Desktop Computer. The 9020 is a 32 bit machine using disks vice the 9845 which is a 16 bit machine using cassette tapes.

The goals of the FOREM system are to promote fuel savings and to reduce mission planning time. Fuel savings of at least one per cent are expected by providing crews with a convenient method of accurately computing mission fuel requirements and fuel efficient flight parameters. The reduction of mission planning time to ten minutes or less is expected by computing flight parameters that aircrews presently obtain via tedious manipulation of NATOPS aircraft performance graphs and tables.

P-3C FOREM

Using the P-3C as an example, the two methods of mission planning currently available are the aircraft performance graphs and tables contained in Section XI of the P-3C NATOPS Manual or use of the Optimum Path Aircraft Routing System (OPARS). The P-3C NATOPS Flight Manual contains flight performance data which can be used to accurately plan the fuel requirements and optimal flight parameters of a mission. However, the time required to do so discourages crews from thoroughly planning missions.

OPARS does not provide detailed planning for tactical missions and when OPARS is busy the system response time is several hours.

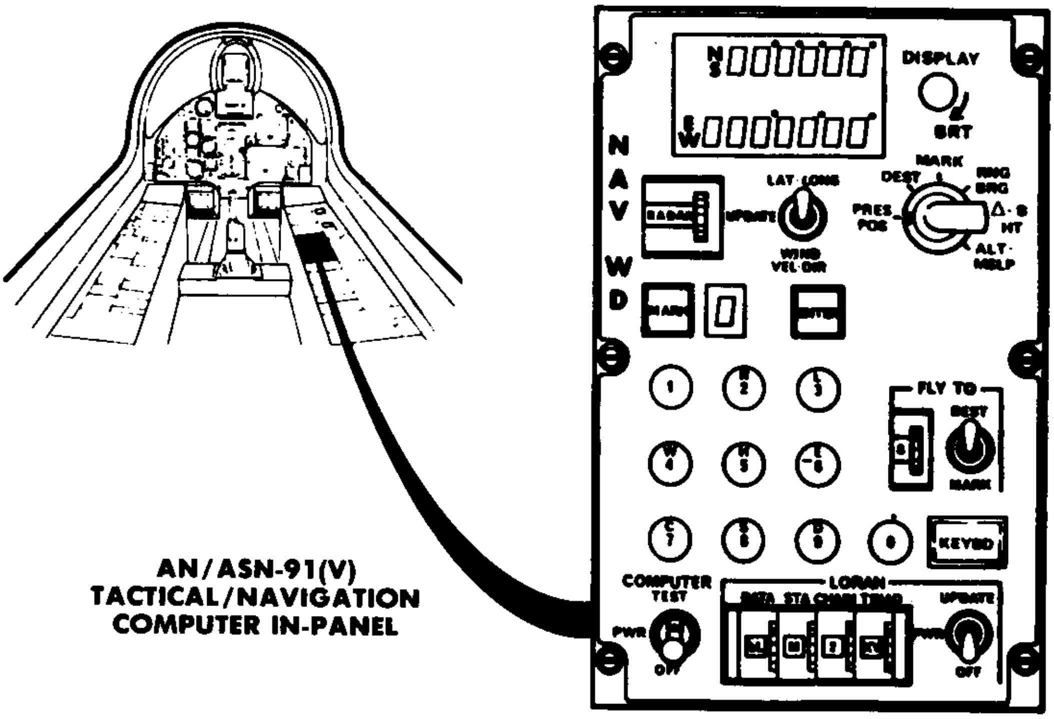


FIGURE 3. A-7E PILOTS CONTROL AND DISPLAY

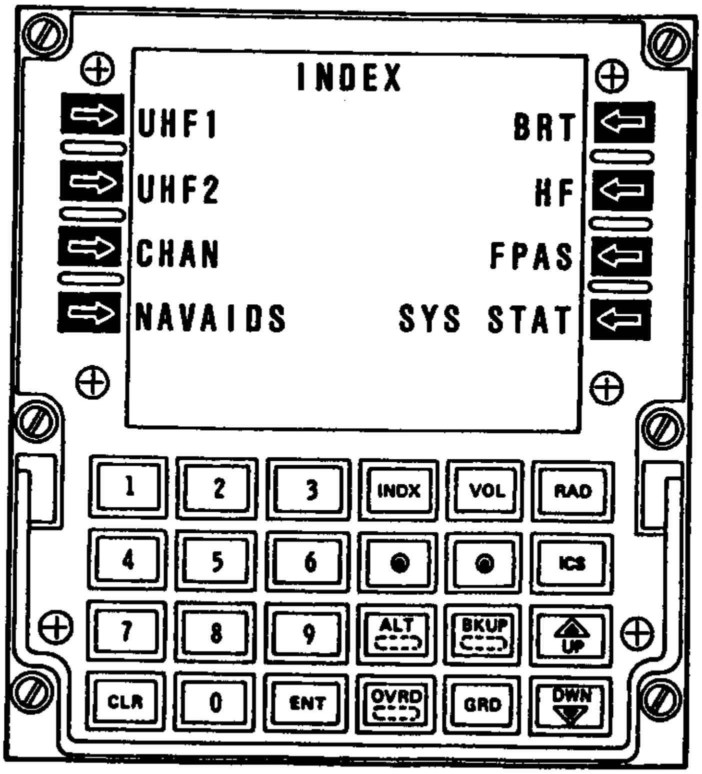


FIGURE 4. S-3 CCG/FPAS CONTROL AND DISPLAY

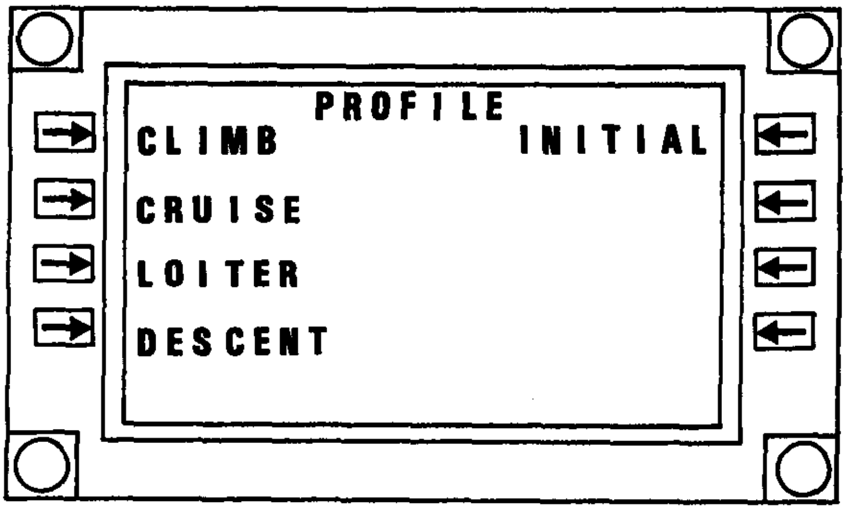
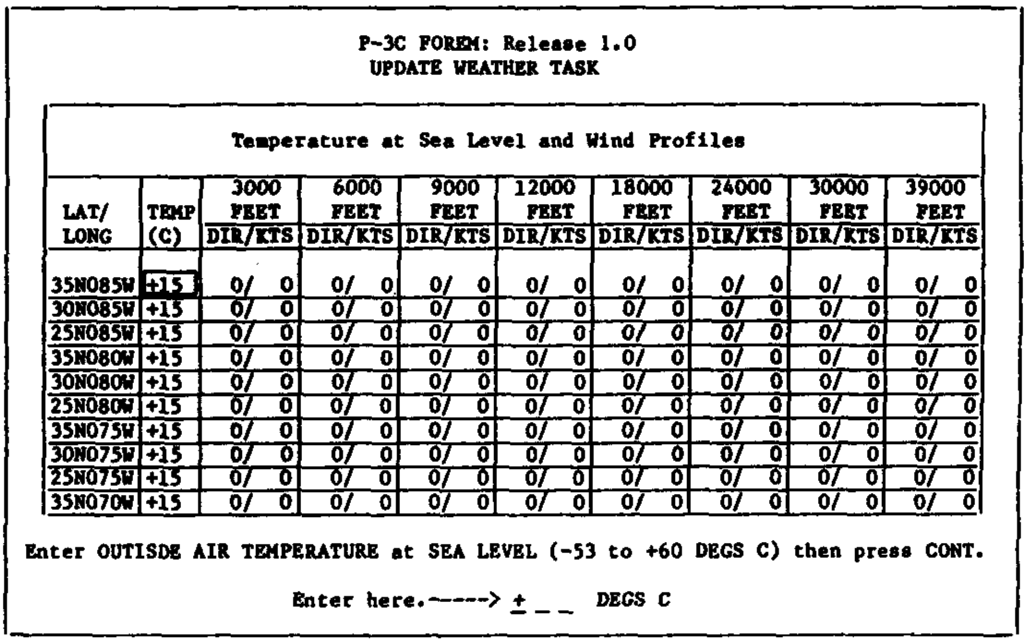


FIGURE 5. S-3 FPAS DISPLAY



P-3C FOREM: Release 1.0
UPDATE WEATHER TASK

Temperature at Sea Level and Wind Profiles

LAT/ LONG	TEMP (C)	3000 FEET DIR/KTS	6000 FEET DIR/KTS	9000 FEET DIR/KTS	12000 FEET DIR/KTS	18000 FEET DIR/KTS	24000 FEET DIR/KTS	30000 FEET DIR/KTS	39000 FEET DIR/KTS
35N085W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
30N085W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
25N085W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
35N080W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
30N080W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
25N080W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
35N075W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
30N075W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
25N075W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0
35N070W	+15	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0	0/ 0

Enter OUTISDE AIR TEMPERATURE at SEA LEVEL (-53 to +60 DEGS C) then press CONT.

Enter here.-----> ± _ _ DEGS C

FIGURE 6. P-3C UPDATE WEATHER TASK TABLEAU

The FOREM system is designed to be computationally sophisticated yet simple to learn and operate. The system consists of a Hewlett Packard HP 9845B desktop computer, a Hewlett Packard HP 2631B printer and a series of magnetic tape cartridges. Two tape cartridges contain the P-3C FOREM program. Other tape cartridges hold a library of planned missions. Another cartridge is used to store local weather forecasts. The system is organized in a task menu format and tells the user exactly what to do each step of the way via instructions displayed on the CRT. After automatically loading the program into the computer, FOREM instructs the user to eject the two P-3C FOREM program tape cartridges. Next, the user is instructed to select one of the six tasks performed by the P-3C FOREM. A brief explanation of the purpose of each task is displayed as follows:

CATALOG LIBRARY ----- Print out the date, author and a brief description of each mission on a mission library tape.

ERASE LIBRARY ----- Erase one or more missions from a library tape.

COPY LIBRARY ----- Copy entire contents of one library tape to another. Select this task to update the Spare Copy of your mission library tape from the Master Copy.

PLAN MISSION ----- Compute the flight plan for new mission or recall, modify and recompute one of the missions in the library.

PLAN TAKEOFF ----- Compute takeoff speeds, distances, shaft horsepower (SHP), etc.

UPDATE WEATHER -----Enter the latest winds and temperatures for the local area for use in computing local flights.

Upon selection of a task, a sequence of displayed instructions directs the user in carrying out that task. There are no limits as to the number of times and order in which the tasks can be selected. The three tasks of Update Weather, Plan Takeoff and Plan Mission are discussed in further detail.

UPDATE WEATHER

The Update Weather Function task is used to enter the local area forecasts into the memory of the computer for use in computing local flights. The user is instructed to enter area temperatures at sea level and the winds at eight altitudes ranging from 3,000 feet to 39,000 feet. The user also indicates the time period for which the forecast is valid. The user can request FOREM to record the entered forecast on the P-3C FOREM weather tape. When a new forecast is similar to the previous day's forecast, the user need not enter the new forecast from scratch. If the previous forecast was recorded on tape, the user can simply read the recorded forecast back into the memory of the computer and then modify it.

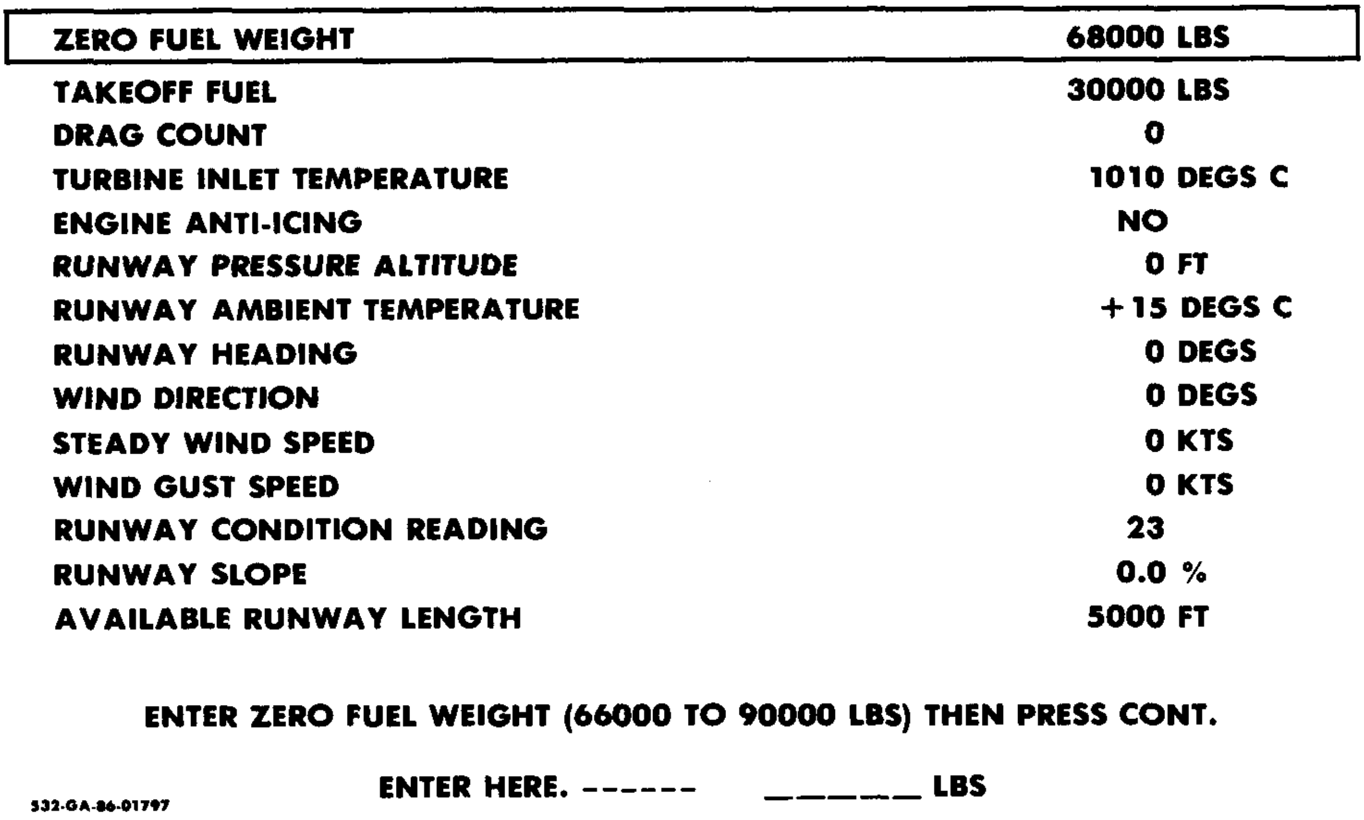
The weather tape presently contains data representing three geographic areas, Moffett Field, Jacksonville and NADC/NATC, at which FOREM is now in use. Following the selection of a weather area the display indicates the time period for which the forecast is valid. On the next display FOREM gives the temperature and wind data for the applicable weather area. Each weather area is defined by eighteen positions. These positions are separated by five (5) degrees of latitude and five (5) degrees of longitude. The weather tableau containing the applicable positions is displayed on Figure 6.

Due to the limited size of the CRT display, the user initially enters data for the first ten positions. The display is then cleared and the user enters data for the remaining eight positions. If the common data base does not contain a forecast for the selected area, temperatures at sea level are set to +15 C (standard day) and winds are set to zero.

PLAN TAKEOFF

In the Plan Takeoff function task, the user enters aircraft weight, drag count, Turbine Inlet Temperature (TIT), pressure altitude, temperature, runway heading, wind direction, wind speed, Runway Condition Reading (RCR), runway slope and runway length. FOREM then computes decision speed, refusal speed, rotation speed, liftoff speed, 3 engine climbout speed, 4 engine climbout speed, minimum control groundspeed, minimum control airspeed, stall speed, distance at 80 knots, distance at refusal speed, 4 engine liftoff distance, 95 percent SHP at 80 knots, 100 percent SHP at 80 knots, 3 engine military power rate of climb, crosswind and headwind/tailwind. Following selection of the Plan Takeoff task, the takeoff inputs list is displayed as shown in Figure 7.

The list appears exactly as shown in Figure 7 the first time the Plan Takeoff task is selected following loading of the program. Upon subsequent selection of the Plan Takeoff task, the values displayed in the list are the values entered by the last user to plan a takeoff. Also, following the computation of each planned mission in the Plan Mission task, the takeoff zero fuel weight (ZFW), takeoff drag count and

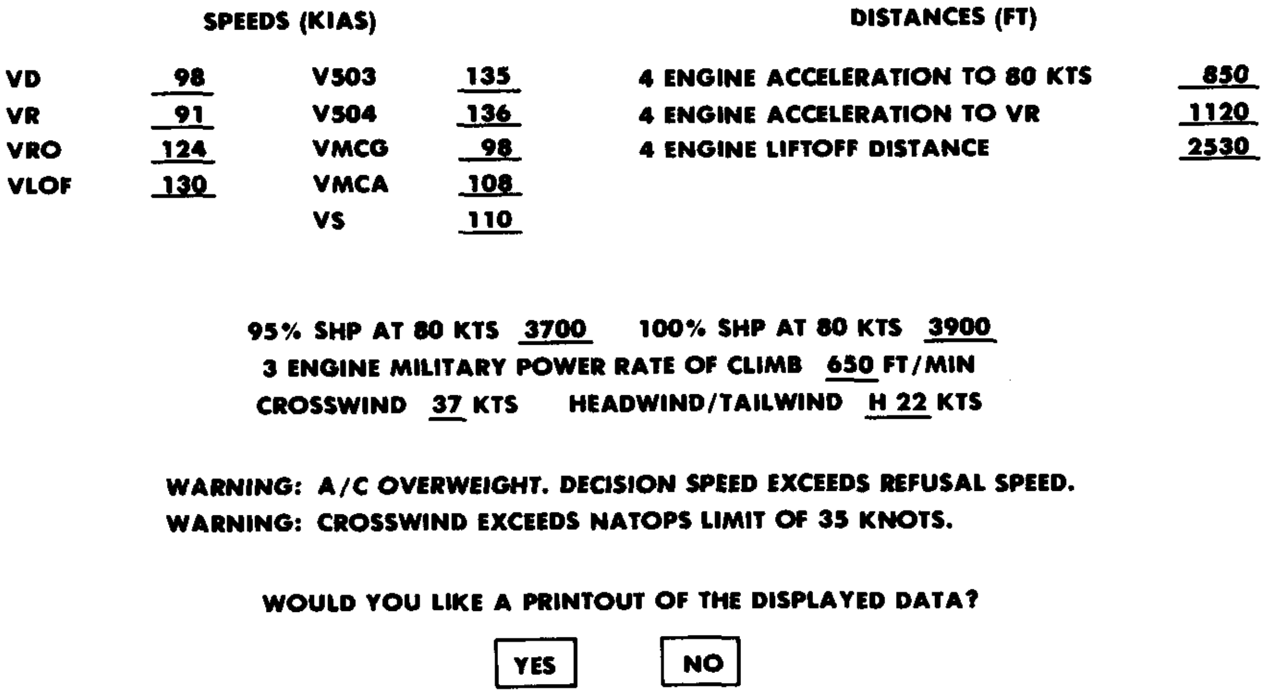


```
ZERO FUEL WEIGHT                                  68000 LBS
TAKEOFF FUEL                                      30000 LBS
DRAG COUNT                                            0
TURBINE INLET TEMPERATURE                          1010 DEGS C
ENGINE ANTI-ICING                                    NO
RUNWAY PRESSURE ALTITUDE                              0 FT
RUNWAY AMBIENT TEMPERATURE                          +15 DEGS C
RUNWAY HEADING                                        0 DEGS
WIND DIRECTION                                        0 DEGS
STEADY WIND SPEED                                     0 KTS
WIND GUST SPEED                                       0 KTS
RUNWAY CONDITION READING                             23
RUNWAY SLOPE                                        0.0 %
AVAILABLE RUNWAY LENGTH                            5000 FT

      ENTER ZERO FUEL WEIGHT (66000 TO 90000 LBS) THEN PRESS CONT.

532-GA-86-01797    ENTER HERE. ------       ______ LBS
```

FIGURE 7. P-3C PLAN TAKEOFF TASK INPUTS



```
             SPEEDS (KIAS)                           DISTANCES (FT)

VD       98       V503    135     4 ENGINE ACCELERATION TO 80 KTS     850
VR       91       V504    136     4 ENGINE ACCELERATION TO VR        1120
VRO     124       VMCG     98     4 ENGINE LIFTOFF DISTANCE          2530
VLOF    130       VMCA    108
                  VS      110

        95% SHP AT 80 KTS  3700     100% SHP AT 80 KTS  3900
          3 ENGINE MILITARY POWER RATE OF CLIMB  650 FT/MIN
        CROSSWIND  37 KTS      HEADWIND/TAILWIND  H 22 KTS

    WARNING: A/C OVERWEIGHT. DECISION SPEED EXCEEDS REFUSAL SPEED.
    WARNING: CROSSWIND EXCEEDS NATOPS LIMIT OF 35 KNOTS.

         WOULD YOU LIKE A PRINTOUT OF THE DISPLAYED DATA?

                      [ YES ]       [ NO ]
```

FIGURE 8. P-3C PLAN TAKEOFF TASK OUTPUTS

takeoff fuel used to compute the mission are automatically transferred to the takeoff inputs list via the common data base. The takeoff output values are then computed and displayed as shown on Figure 8. The computed speeds are defined as follows.

VD ---- Decision Speed: NATOPS chart value for slope and wind. If VD is less than refusal speed (VR), VD is set equal to VR. If VD is greater than rotation speed (VRO), VD is set to VRO.

VR ---- Refusal Speed: NATOPS chart value adjusted for slope and wind. If VR is greater than rotation speed (VRO), VR is set equal to VRO.

VRO --- Rotation Speed: NATOPS ALTERNATE TAKEOFF SPEED SCHEDULE value. VRO exceeds minimum control airspeed (VMCA) by at least 5 percent.

VLOF -- Four Engine Liftoff Speed: NATOPS ALTERNATE TAKEOFF SPEED SCHEDULE value.

V503 & V504 -- Three Engine and Four Engine Climbout Speeds: NATOPS ALTERNATE TAKEOFF SPEED SCHEDULE values. V503 and V504 exceed zero-thrust stall speed by at least 15 percent.

VMCG -- Minimum Control Ground Speed.

VMCA -- Minimum Control Airspeed: (1 engine inoperative, 5 degree favorable bank angle).

VS ---- Stall speed (power on, 18 degree flaps, 0 bank angle).

The following alerts are displayed when applicable.

WARNING: A/C OVERWEIGHT. DECISION SPEED EXCEEDS REFUSAL SPEED.

WARNING: CROSSWIND EXCEEDS NATOPS LIMIT OF 35 KNOTS.

If the user answers YES to the printout option, the computer takeoff outputs are then printed on the thermal printer.

PLAN MISSION

The Plan Mission Function task provides planning for ASW (Anti-Submarine Warfare), SSSC (Surface/Subsurface Surveillance Coordination), mining and transit missions containing up to twenty waypoints. For ASW and SSSC missions, planning is provided for up to two loiter stations. For each mission, the user either specifies the takeoff fuel weight or request FOREM to compute the optimal takeoff fuel.

The user may enter a cruise flight level, cruise speed, percent time engine anti-icing in use, temperature and winds for each leg of the mission. A leg is defined as the flight segment from one waypoint to the next. For the cruise flight level, the user either specifies a level or requests FOREM to compute the maximum range IFR (Instrument Flight Regulations) level. When the maximum range flight level is requested, FOREM also performs step climb calculations. For cruise speed, the user either specifies a speed or requests FOREM to calculate the maximum range speed. FOREM adjusts cruise fuel flows for the indicated amount of engine anti-icing.

For ASW and SSSC missions in which the user specifies the takeoff fuel weight, the following values are computed to aid the user in the determination of maximum time-on-station.

- Fuel remaining upon arrival on station.

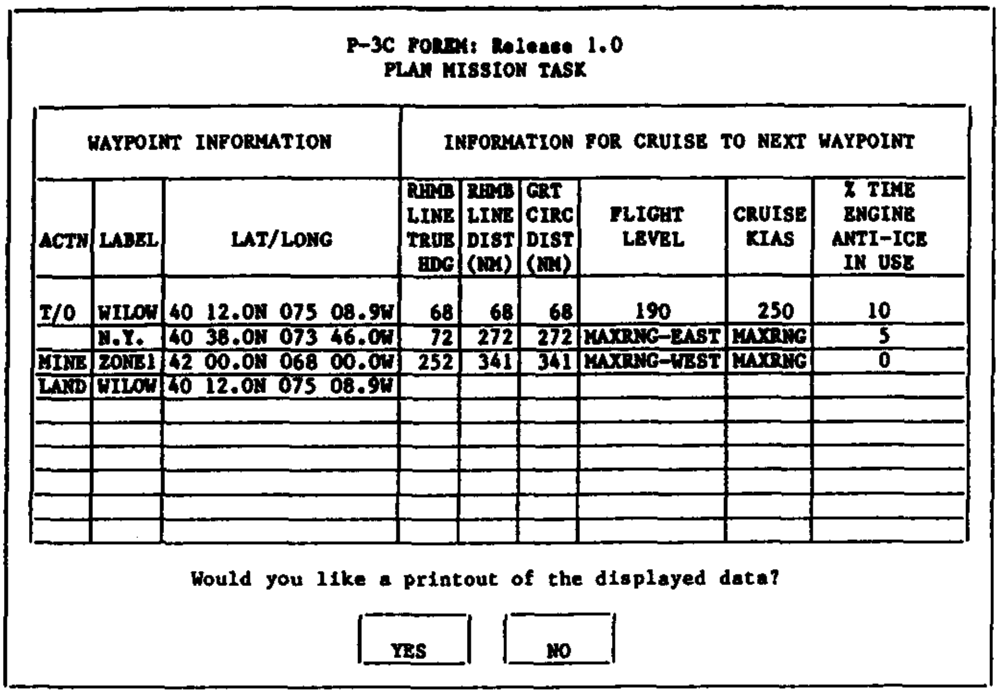
- Fuel required for the cruise-from-station.

- Fuel available for loiter for both normal and Prudent Level of Endurance (PLE) scenarios.

- Maximum endurance speeds, engine configurations and fuel flows.

The Waypoint Tableau contains the navigation and cruise parameters for the mission. If the user has recalled a mission or the user has opted to plan another version of a mission, the Waypoint Tableau (containing the previously entered parameters) is displayed.

FOREM provides for the entry of up to 20 waypoints per mission. Waypoint number 1 is the position upon takeoff. The final waypoint is the position upon landing. A sequence of instructions directs the user to enter information for each waypoint. Due to the limited size of the CRT display, the user initially enters data for up to 10 waypoints. If the mission requires more than 10 waypoints, the display is then cleared and the user enters data for the remaining waypoints. The PLAN MISSION TASK display is shown in Figure 9. If the user has recalled a mission or the user is

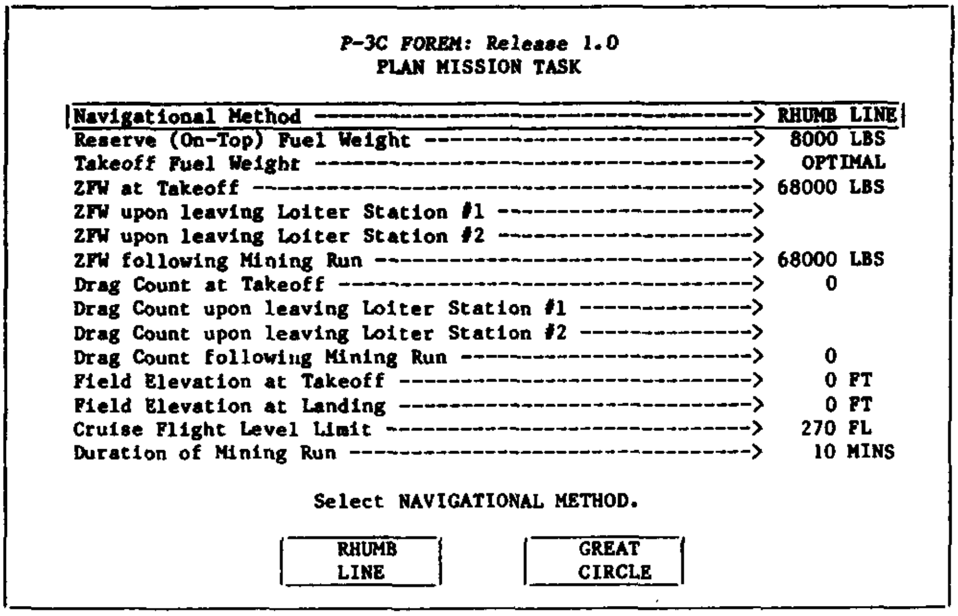


P-3C FOREM: Release 1.0
PLAN MISSION TASK

WAYPOINT INFORMATION			INFORMATION FOR CRUISE TO NEXT WAYPOINT					
ACTN	LABEL	LAT/LONG	RHMB LINE TRUE HDG	RHMB LINE DIST (NM)	GRT CIRC DIST (NM)	FLIGHT LEVEL	CRUISE KIAS	% TIME ENGINE ANTI-ICE IN USE
T/O	WILOW	40 12.0N 075 08.9W	68	68	68	190	250	10
	N.Y.	40 38.0N 073 46.0W	72	272	272	MAXRNG-EAST	MAXRNG	5
MINE	ZONE1	42 00.0N 068 00.0W	252	341	341	MAXRNG-WEST	MAXRNG	0
LAND	WILOW	40 12.0N 075 08.9W						

Would you like a printout of the displayed data?

FIGURE 9. P-3C PLAN MISSION TASK WAYPOINT INPUT DATA



P-3C FOREM: Release 1.0
PLAN MISSION TASK

```
Navigational Method -----------------------------------> RHUMB LINE
Reserve (On-Top) Fuel Weight ---------------------------> 8000 LBS
Takeoff Fuel Weight ------------------------------------>  OPTIMAL
ZFW at Takeoff -----------------------------------------> 68000 LBS
ZFW upon leaving Loiter Station #1 --------------------->
ZFW upon leaving Loiter Station #2 --------------------->
ZFW following Mining Run -------------------------------> 68000 LBS
Drag Count at Takeoff ---------------------------------->    0
Drag Count upon leaving Loiter Station #1 -------------->
Drag Count upon leaving Loiter Station #2 -------------->
Drag Count following Mining Run ------------------------>    0
Field Elevation at Takeoff ----------------------------->    0 FT
Field Elevation at Landing ----------------------------->    0 FT
Cruise Flight Level Limit ------------------------------>  270 FL
Duration of Mining Run --------------------------------->   10 MINS
```

Select NAVIGATIONAL METHOD.

FIGURE 10. P-3C PLAN MISSION TASK DATA LIST

planning another version of a previously entered mission, the data list containing the previously entered data is displayed. If the user has not recalled a mission and is not planning another version of a previously entered mission, the data list containing default values is displayed as shown in Figure 10.

The major output of the Plan Mission task is a "Howgozit" tableau shown in Figure 11. The tableau contains the computed elapsed time, flight time remaining, distance remaining, fuel remaining, fuel flow, flight level, TIT, SHP, IAS, TAS, ground speed, specific range, indicated outside air temperature and headwind or tailwind component at the end of each climb, cruise, descent and loiter segment of the mission. Hourly checkpoints are also included for cruise and loiter segments. Space is provided in the Howgozit tableau for the user to record the actual values at each checkpoint during the flight.

The Plan Mission task enables the user to quickly and easily plan several versions of a mission. This is useful when planning missions with unknown parameters. For example, if no wind data is available or the winds forecast is questionable, the user may wish to plan three versions of the mission (best case, worst case and probable case). The three Howgozits would be carried on board and the most appropriate Howgozit then used.

Following the printout of the Howgozit tableau, the user can request FOREM to add the mission to the mission library. Missions recorded on the library tapes can be recalled, modified and recomputed at any future date. Future mission planning time is greatly reduced by building a library of the missions most often flown by the squadron.

POCKET-SIZE AIRCRAFT PERFORMANCE ADVISORY COMPUTER (P-S APAC)

A commercially available HP-41CV computer containing a specific Read Only Memory (ROM) module advises aircrew members of those in-flight parameters, such as altitude and airspeed, that permit optimization of available fuel. The ROM module contains a software program based on the performance curves of the NATOPS manual.

By keying in vital inputs as they are prompted on the computer's display, various flight mission segments can be optimized. These inputs include aircraft weight, drag index, fuel on board, wind speed and direction, and air temperature, for take-off, cruise, loiter, descent and bingo flight modes. The P-S APAC can be used as a quick pre-flight mission planning tool or can be used in flight to advise aircrews of altitude and airspeed changes. Each P-S APAC ROM module and interactive program is customized to each type, model and series aircraft in the Navy. The HP-41CV computer is completely independent of the aircraft's electrical system, and is lightweight, portable and inexpensive.

The objective of this program is to optimize fuel use. It is estimated that limited use can inspire better than 1% fuel savings per year. This translates into about $8-10 million per year. The computer and development program can be amortized by a small fraction of this savings.

P-3C P-S APAC

The P-S APAC for the P-3C aircraft will be described to further illustrate this program. Based upon user input of aircraft and weather data, the APAC will calculate and display optimum flight parameters for climb, cruise, loiter and descent. Additional information provided by the APAC includes weight and balance conditions, takeoff parameters, a wind calculation and a temperature calculation. The APAC is used in the battery operated HP-41CV calculator, programmed to support flight planning. The calculator face is modified with a special overlay which provides labels that identify APAC-peculiar keys (see Figure 12).

The operating keys are used to input data into the APAC and to obtain data previously input or output. The operating keys perform the following functions.

The ON key turns the APAC on in the USER mode and also turns it off.

The USER key activates the USER and NORMAL modes depending upon which mode is in use.

The YES/GO key enters input values and affirmative responses to prompts. It also stops the calculations when a program is running; starts calculations when a program is not running.

The NO key enters negative responses to YES/NO prompts (e.g., T.I.T = 1010 Y/N). If a prompt has only two possible responses, it automatically inputs the other choice.

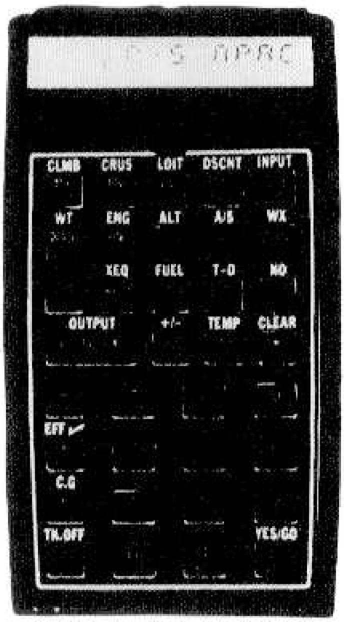
The +/- key changes the sign of a displayed value (e.g., negative delta T and headwind).

P-3C FOREM: Release 1.1 VP- ______ A/C SIDE # ________ NAME: ______________________________

Plan Mission Task. Howgozit Tableau MTH/DAY/YR: _____/_____/_____ LIBRARY TAPE/FILE # ______________/________

CHECKPOINT	TIME	FUEL REMAIN X 1000	FLIGHT LEVEL	KIAS	IOAT (C)	HEAD/ TAIL WIND	FUEL FLOW	TIT	SHP	TAS GRS SR	LEG/TOT MILES REMAIN	LEG/TOT TIMES REMAIN
30 14.1N 081 40.5W JAX Takeoff	0+00	20.0									180 904	0+34 2+55
Top of Climb Begin Cruise	0+14	18.6	230	248	- 3	T 4	4500	923	2350	357 361 80	119 843	0+20 2+41
29 50.0N 078 15.0W PT A Begin Climb	0+34	17.1	230								158 724	2+21
Resume Cruise	0+40	16.7	270	224	- 13	H 6	3900	909	2030	345 339 87	130 696	2+15
Begin Descent	1+02	15.3	270								9 575	1+53
29 07.5N 075 20.5W PT B Continue Descent											114 566	
29 05.0N 073 10.0W AREA1 Begin Mining	1+21	14.1	3	300	+ 31		6570	790	2700			1+34
29 05.0N 073 10.0W AREA1 End Mining	1+28	13.3	3								114 452	0+26 1+27
Top of Climb Begin Cruise	1+42	12.3	260	220	- 16	H 7	3520	824	1760	331 324 92	61 399	0+12 1+13
29 07.5N 075 20.5W PT B Continue Cruise	1+54	11.4	260	213	- 15	T 6	3470	821	1730	329 335 96	158 338	0+28 1+01
29 50.0N 078 15.0W PT A Continue Cruise	2+22	9.7	260	218	- 13	T 2	3470	824	1720	330 332 96	180 180	0+33 0+33
Begin Descent	2+46	8.3	260								46 46	0+09 0+09
30 14.1N 081 40.5W JAX Landing	2+55	8.0									0 0	0+00 0+00

FIGURE 11. P-3C "HOWGOZIT" TABLEAU



- **ALPHA/NUMERIC DISPLAY**
- **CONTINUOUS MEMORY**
- **PORTABLE & LIGHTWEIGHT**
- **DURABLE**
- **USER ASSIGNED KEYS**
- **PLUG-IN ROM MODULES**
- **32K ROM AVAILABLE**

FIGURE 12. P-3C POCKET-SIZE AIRCRAFT PERFORMANCE ADVISORY COMPUTE (P-S APAC)

The CLEAR key erases the last entered digit from the display. The entire value displayed can be erased one digit at a time by repeatedly pressing the key.

The INPUT key initiates the display of the current flight mode followed by the values previously entered for that function. This is not operative in the takeoff and C.G. functions.

The OUTPUT key initiates the display of the current flight mode followed by the outputs previously computed. This is not operative in the takeoff and C.G. functions.

The XEQ key executes flight parameter calculations after updates.

The SHIFT key deletes the entire display in a single step when used with the CLEAR key. The SHIFT key is the gold unlabeled key on the calculator. (It is white in Figure 10).

The function keys are used to activate equations which compute flight performance parameters specific to each mission phase (climb, cruise, etc.). Pressing a function key initiates a series of prompts. The responses to the prompts are used to compute flight planning outputs. All flight functions are performed with the USER program activated. Some values are carried from one function to another, if a total memory clear is not performed. The APAC does not sum fuel, time, or distance values across flight functions. These must be calculated by the user. The function keys are: CLMB, CRUS,LOIT, DSCNT, WIND, TEMP, TK.OFF, and C.G.

The CLMB key activates the climb function which computes a near-optimal climb profile including climb fuel and optimal airspeed.

The CRUS key activates the cruise function which computes optimal cruise altitude and airspeed, and related flight parameters.

The LOIT key activates the loiter function which computes optimal loiter altitude and airspeed, and related flight parameters.

The DSCNT key activates the descent function which computes optimal descent airspeed and descent distance.

The TK.OFF key activates the takeoff function which computes NATOPS takeoff parameters.

The C.G. key activates the weight and balance function which computes percent mean aerodynamic chord, zero fuel weight, gross weight, and total moment.

The WIND key activates the wind function which computes the wind component and automatically inputs it into the cruise and descent modes.

The TEMP key activates the temperature function which computes delta T from altitude, airspeed, and indicated outside air temperature inputs.

The update keys are used to change flight variables after initial inputs into the APAC flight functions. This allows updates of values without repeating the entire input sequence. When an update key is activated, the APAC initiates a series of prompts. The update keys are: WT (Weight), ENG (Engines), ALT (Altitude), A/S (Airspeed), and WX (Weather).

The operational range keys are used to supplement the data output from flight functions. The operational range keys are T-D (Time-Distance, e.g., time and range available for fuel burn-off of a specified number of pounds) and FUEL (e.g., fuel required for a specified nautical mile leg of a flight segment).

TAKEOFF

As noted above, the APAC provides the following P-3C functions: weight and balance, takeoff, climb, cruise, loiter, descent, a wind calculation and a temperature calculation. The takeoff and cruise function will be described in some detail. The takeoff function is operable by depressing the takeoff key which initiates a series of prompts for the inputs required to compute NATOPS takeoff parameters. Turbine Inlet Temperatures (TIT) of 1010, 1049, or 1077 degrees can be specified during the takeoff function. After the TIT is specified, the system prompts for the following input data: percent engine efficiency, runway pressure altitude, anti-ice on or off, zero fuel weight, fuel on board, drag count, the available runway length, the bank angle allowance, the runway slope, the runway condition reading, runway temperature, the takeoff runway number, the wind direction and wind speed. The headwind and crosswind are then momentarily displayed and the calculator goes into a standby mode for a computation time of 31 seconds. A tone sounds when calculations are complete and the following information is displayed: the shaft horsepower at 80 knots, the rotation speed, the liftoff speed, the four engine airspeed at 50 feet, the three engine airspeed at 50 feet, the refusal speed, the three engine rate of climb, the distance to 80 knots, the distance to refusal speed, the distance to rotation speed, the distance to liftoff speed, the decision speed, the minimum ground control speed, the minimum control speed in air for three engines, the minimum control speed in air for two engines and the power-on stall speed.

CRUISE

The cruise function is operable by depressing the CRUS key which initiates a series of prompts for inputs required to calculate the cruise altitude, cruise airspeed, shaft horsepower, actual TIT, fuel flow, and ground speed. Optimum outputs are automatically calculated for altitude and airspeed by retaining the zero values displayed in the input prompts. If altitude and airspeed are constrained, all the other outputs are based on the specified altitude and airspeed.

Outputs are computed for three or four engine cruises, with TIT limits of 925 or 1010. Temperature deviation from standard day and wind component factors are used in the computations. Cruise distance and time are estimated, given cruise fuel. Cruise fuel and time are estimated, given cruise distance. Cruise outputs can be updated, after initial outputs are calculated, by using the update keys to change weight, engines, altitude, airspeed, and/or weather inputs. Additionally, the WIND and TEMP function keys can be used to provide input to the cruise function. The operational range keys, T-D and FUEL, can be used during the cruise function. The FUEL key can be used to determine the cruise time and fuel burn on the basis of estimated cruise distance. The T-D key can be used to determine cruise time and distance on the basis of estimated cruise fuel.

The input prompts as they appear on the calculator are as follows: the turbine inlet temperature (TIT), the zero fuel weight (ZFW), the fuel on board (FOB), the drag count (DRAG), the cruise altitude (CRUISE.ALT) select value or retain zero for computed optimum, cruise indicated airspeed (CRUISE.IAS) select value or retain zero for computed optimum, the number of engines operating (ENG.OP), the temperature deviation (DELTA T) and the headwind or tailwind component (WIND).

The word STANDBY is then displayed for approximately 46 seconds while the APAC computes the outputs. A tone sounds when this is completed and the following outputs are displayed: the optimum cruise altitude or the selected cruise altitude (CRUISE.ALT), the optimum airspeed or the selected airspeed (CRUISE.IAS), the shaft horsepower (SHP), the turbine inlet temperature (TIT), the fuel flow (F/F) and the ground speed (GRSPD). At this point the prompt for the operational range input can be obtained by depressing the FUEL key. The computer prompts for cruise distance (DIST) and after being entered computes and displays the outputs of cruise fuel (FUEL) and cruise time (CRUISE.TIME). If the T-D key is depressed, prompts are displayed for determining time and range available for fuel burn-off of a specified number of pounds. Other parameters that can be updated are airspeed (A/S), altitude (ALT), weight (WT), number of engines (ENG) and weather (wind component and the temperature deviation) (WX).

PROGRAM STATUS

All of these programs are in various stages of development. The A-7 FPAS is scheduled for introduction in the fleet in July 1986. The F/A-18 FPAS program schedule calls for first use in late 1988. The S-3 FPAS is in the early stages of development with a planned introduction into the fleet in 1989. Use of FPAS by other Navy aircraft will be dependent on extent of avionic updates which can provide the necessary computational assets and sensor input data necessary to support an on-board Flight Performance Advisory System.

One of the FOREM systems, the P-3C, will have completed its technical evaluation by June 1986 and be ready for fleet wide use. The S-3 FOREM program will at that time be starting its 90 day technical evaluation. FOREM systems for 14 other Navy aircraft are planned.

The P-S APAC for the P-3A is operational and the P-3C will be operational in June 1986. The KC-130C is expected to have completed technical evaluation by June 1986 and be ready for fleet use. Development of the P-S APAC for 14 other Navy aircraft is continuing at various stages of development. A total effort of 24 P-S APACs is planned.

DESIGN CRITERIA FOR MULTI-LOOP FLIGHT CONTROL SYSTEMS

by

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Abstract

The problems of design criteria and architecture of multiloop flight control systems are discussed for a realized system to achieve precise flight path guidance, safe and economic control of the aerodynamic flow (airspeed, angle of attack and lift coefficient control) and passenger comfort. Joint root locus and quality criteria design will be presented.

The structure of the presented multiloop flight control system consists of nonlinear open loop control for flight performance and flight management purpose, superposed quasi linear state vector feed back and six control surfaces (aileron, rudder, elevator, trim, throttle, direct lift/drag control).

Contents

1. Introduction
2. Symbols
3. Control system structure
4. Non linear open loop control
5. Design criteria and procedure
6. Flight test results
7. Literatur
Appendix

1. Introduction

Flight control systems are more or less a conventional tool to improve the aircraft characteristics as well as to provide a more precise guidance and control. The range of application is extrem wide. In order to improve the handling qualities and low stability margins of uncontrolled aircraft, damper and stabilizer are state of the art. F lutter control systems may reduce the structure load of the aircraft structure and can improve life cycle time. For many applications in guidance and control the improvement of flight accuracy for air traffic control and 3D/4D navigation is essential. Weapon delivery requires excellent attitude and speed control. Also for safe and economic flights, the control of the aerodynamic flow condition via airspeed, angle of attack or lift coefficient is of great importance. Additonally, many military and all civil aircraft need control systems to improve passenger comfort and the safety margin when flying in adverse wheather conditions e.g. turbulence, wake vortices, wind shear and poor visibility.

Design criteria for adequate flight control systems to fullfill the discussed requirements are contradicting in general and an acceptable compromise has to be found /1/.

These design problems will be discussed for a multiloop flight control system that can achieve a precise flight path guidance and a safe aerodynamic flow control. The structure of this flight control system consist of

- nonlinear open loop control for flight performance and flight management purpose
- superposed linear state vector feed back control
- six control surfaces (aileron, rudder, elevator, trim, direct lift/drag, throttle)

The flight control system as a digital experimental system, is installed in a twin engined propeller driven research aircraft of the Technische Universität Braunschweig. Up to now the system has been tested in cruise flight, approach and landing.

2. Symbols

2.1 Control theory

$\underline{A}$, $\underline{B}$	System matrix
D	observation period
$\underline{D}_c$	disturbance vector
$\underline{G}_c$	guidance input vector
t	time
σ^2	variance

2.2 Flight mechanic

C^*	handling quality criterion
C	derevativ
F	Thrust
g	earth acceleration
H	altitude
$\dot{H}$	rate of climb
$\ddot{H}$	vertical acceleration
n	load factor
m	aircraft mass
S	wing area
q	pitch rate
q_p	dynamic pressure
u	orthogonal speed component
v	
w	

V	airspeed	
V_K	ground speed	
V_W	wind speed	
α	angle of attack	
γ	flight path angle	
ϕ	roll	attitude angle (Euler)
θ	pitch	
ψ	yaw	
η	elevator displacement	
δ_f	flap displacement	
ρ	air density	

2.3 Indices

c	Command
d	disturbance
D	drag
L	Lift

o	open loop
w	actuator open loop command
α	angle of attack

3. Control system structure

Design criteria and control system structures are difficult to be presented in general, as they vary due to the application. In this paper we will concentrate the discussion on the precise control of the flight path and the safe control of the aerodyamic flow condition. Flight path and flow condition can vary over a wide range in short time periods.

The basic command inputs in the flight control system are flight path and airspeed. The pilot or an outer loop air traffic control system may vary this command inputs.

To achieve a proper response of the controlled aircraft six control surfaces (actuators) are applied, as there are aileron, rudder, elevator, elevator trim, throttle, and direct lift device (fast landing flap control). For optimum control, all relevant control information has to be fed to all relevant actuators. Therefore the adequate control system for this task is a strongly cross-coupled multi-loop control system.

For the mathematical presentation of general cross-coupled higher order multiloop systems the state space may be adequate. In this space presentation all state element have equal status. It is typical for the aircraft dynamic response that some state element have different status. Generally speaking the aircraft dynamic response can be presented as a cascade system. Each loop of this cascade system has a different and specific response charakteristic. The different loops can be characterised by their frequency domains. Beginning with the highest frequency domain as the inner cascade loop, four different loop can be identified.

1. Structural dynamic

In the relativ high frequency dynamic response of the elastic aircraft flutter control, structural strength reduction and partly loadfactor control as well as gust alleviation are typical applications.

2. Rotational dynamic

In the frequency range of the short period mode, dutch roll and roll mode the handling qualities are of great importance. In this frequency regime an enormous knowledge exists to specify and design special control systems, as there are damper, stabilizer, gust alleviation, direct lift control.

3. Energy dynamic

In the frequency regime of the phugoid and spiral mode, energy transfer is important. Throttle control, speed control and wind shear suspression are typical applications in this area. Additionally some cross coupling effects between lateral and longitudinal motion, e.g. turn flight, are of interest as well as some effects of direct drag and lift control.

4. Flight path management

In the extrem low frequency regime, flight management, 3D and 4D navigation and partly air traffic control dominate this outer cascade loop.

In the past, most of the applied flight control systems are specified and designed for relativly small cascade element (e.g. damper for cascade Nr. 2 and autothrottle control for cascade Nr. 3) as single loop control systems. As the interaction between the cascades can not be neglected, the control efficiency of such single loop control can be improved significantly in applying a multi-loop control structure. For example, the poor control dynamics of conventional flight control system for transport category aircraft in the energy cascade loop require a long stabilized flight profile for approach and landing /2/. Already small energy disturbances e.g. moderatly curved flight path or wind shear can effect such type of control systems very much.

The well known modern control theory /3/ based on a state space presentation of the aircraft may overcome some of the discussed problems. The general problem in application of the modern control theory is the cascade behaviour of the aircraft dynamic, where each cascade loop askes for its specific design procedure. The application of different design procedures in one control systems shall be discussed in chapter 5 more in detail.

The knowledge concerning the aircraft response is in general excellent. The relevant discipline is known as flight mechanics. But only a small part of this knowledge is implemented in flight control systems. This lack of information may cause problems in dynamic response quality and precision.

Most flight control systems use only information to adapt variing parameters as dynamic pressure or Mach number.

The theoretical approach to incorporate flight mechanical knowledge in the flight control system is simple in principle. We assume that the characteristics of total cascade can be described in state space

$$\underline{\dot{x}} = \underline{A}\,\underline{x} + \underline{B}\,\underline{u}\ . \qquad (1)$$

If, for specific manoeuvres, the state vector $\underline{x}_c$ is specified, the required optimal control deflection uc can be calculated in prinziple.

$$u_c = (\underline{\dot{x}}_c - \underline{A}\,\underline{x})\,\underline{B}^{-1}. \qquad (2)$$

This ideal equation cannot be solved in general. The phenomen is known as the inversion of the transfer function of time delayed systems.

Most flight control applications eq.(2) can be simplified in a way, that a mathematical solution is possible.

If we observe the information flow in the cascade loops, we find that primary the information will flow from the outer loop to the inner loop. Therefore the dynamic presentation of the outer loop is more important for the knowledge implementation. As the outer loop responds much slower than the inner loops, a quasistationary approximation of eq.(2) may solve the problem. Because the equation of aircraft motion is non linear the approximation of eq.(2) has to be non linear.

With such an quasistationary non linear open loop control the closed loop design is easier. The required feed back gains are small compared with control systems without an adequate open loop control. For example, the aleviation of gust and windshear can be a part of the open loop control.

The less the presentation of the aircraft dynamic in the open loop, the greater are the required feed back gains to fullfill the task. An example for such an open loop control system is given in chapter 4.

4. Non linear open loop control

A more detailed discussion of the loop control shall demonstrate some practical aspects.

The cross-coupling effects between lateral and longitudinal aircraft motion are relative small for conventional transport aircraft. Primary the coordinated turn flight influences the load factor

$$n = \left[\frac{\ddot{H}}{g} + \cos\gamma\right]\frac{1}{\cos\phi} \qquad (3)$$

and body fixed rate sensors produce coupled output signals. For example in the output of a pitch rate sensor

$$q_s = \dot{\theta}\cos\phi + \dot{\Phi}\sin\phi\cos\theta \ . \qquad (4)$$

To simplify the discussion, only the longitudinal aircraft motion shall be pointed out more *in detail*.

There exist two major tasks of the open loop control (see fig. 1 and fig. 2)

- Calculation of the commanded state vector element $\underline{x}_c$
- *Calculation of the open loop control surface displacement* $\underline{u}_o$

A typical set of state vector elements of a flight control system may be

q	pitch rate
θ	pitch attitude
α	angle of attack
H	altitude
$\dot{H}$	vertical speed
$\ddot{H}$	vertical accelleration
$\underline{\dot{V}}_K$	horizontal accelleration

To achieve a precise control with adequate dynamic behaviour, each state vector element should be compared with a commanded state vector element.

The commanded state vector $\underline{x}_c$ has to be calculated as a function of

the <u>guidance</u> input vector $\underline{G}_c$

H_c	flight path command
V_c	airspeed command

and the <u>disturbance vector</u> $\underline{D}_c$

Φ	roll angle
δ_f	wing flap deviation
ρ	air density
W	aircraft weight
V_W	wind and turbulence velocity

The function between $\underline{x}_c$, $\underline{G}_c$ and $\underline{D}_c$ is part of the flight performance calculation. In general the complete set of the aircraft motion equation (see appendix) is necessary to realize the performance calculations. A simple example shall demonstrate this in a procedure that is well known in the flight mechanics community.

The required lift L is in equilibrium with the weight W of the aircraft and the load factor n

$$L = n\,W \ . \qquad (5)$$

The lift is a function of dynamic pressure

$$q_p = \frac{\rho}{2}\ V^2 \qquad (6)$$

wing area S and lift coefficient C_L

$$L = \frac{\rho}{2}\ V^2\,S\,C_L \ . \qquad (7)$$

The lift coefficient itself is primary a function of angle af attack α and flap deflection angle δ_f

$$C_L = C_{Lo}(\delta_f) + C_{L\alpha}\,\alpha \ . \qquad (8)$$

The combination of equation (5) to (8) gives the element α_c of the commanded state vector $\underline{x}_c$

$$\alpha_c = 2\,W_d n_c \left[V_c^2\,S\,C_{L\alpha} + C_{Lo}\,(\delta_f)\,C_{L\alpha}{}^{-1} \right]^{-1} . \qquad (9)$$

The commanded airspeed V_c is an element of the guidance vector. The weight W_d is an element of the disturbance vector. The load factor n_c has additionally to be calculated in relation to eq.(3).

An example for the open loop throttle control may be derived from the "drag equation" of the aircraft (see appendix). The required thrust is:

$$F_c = W \left[n\,\frac{C_D}{C_L} - n\,\frac{w_W}{V}\,\cos\gamma - \left(1 + n\,\frac{u_W}{V}\right)\sin\gamma + \frac{\dot{V}_K}{g} \right] . \qquad (10)$$

The drag lift to drag ratio is a function of the angle of attack, flap position and Mach number. The load factor n is in relation to eq.(3) a function of vertical accelleration $\ddot{H}$, roll angle Φ and flight path angle γ. The effect of vertical wind w_{Wg} (e.g. downburst) is as well implimented as horizontal wind u_{Wg} Horizontal wind influences the required thrust only in climb or descend conditions. The effect of required thrust in a windshear situation shall be discussed more in detail. In windshear the airspeed V of an aircraft shall be constant ($\dot{V} = 0$) for safety reasons. As the ground speed V_K is a superposition of windspeed V_W and airspeed

$$\underline{V}_K = \underline{V} + \underline{V}_W . \tag{11}$$

The time derevation is

$$\dot{\underline{V}}_K = \dot{\underline{V}} + \dot{\underline{V}}_W .$$

With $\dot{V} = 0$ the requirement exists, that $\dot{V}_K = \dot{u}$. This means, that in a windshear situation the aircraft has to be accelerated or decelerated in the same way as the wind itself. We introduce this effect into eq.(10). For small flight path angle γ we get

$$F_c = W \left[n \frac{C_D}{C_L} - n \frac{w_{Wg}}{V} - (1 - n \frac{u_{Wg}}{V})\gamma + \frac{\dot{u}_{Wg}}{g} \right] . \tag{10a}$$

These equations are the basis for a precise and effective open loop control.

With the todays computer power in digital flight control systems these coupled non linear equations can be calculated in real time without any significant problems.

The modern control theory /3/ gives precise answers concerning the optimal structure of linear feed back: All state vector elements $\underline{x}$ have to feed back to all actuators. The practical problem is to define the six elements of the state vector and to measure the state variables. These very interesting problems can only be mentioned without going into details.

The state vector size depend on how many cascade loops are necessary to present the aircraft characteristics. In most cases the actuator dynamics must be added yet. In contrast to this the sensor dynamic may be neglected.

The aircraft measurement technics /4/ are well developed so that most state vector elements can be measured directly. On the other hand the modern control theory provides powerfull methods to observe unknown state vector elements. The design of observers /5/ for flight control systems is a very interesting task. The designer has to find a compromise between expensive sensors and moderate system knowledge.

Figure 1 shows a block diagramm of all essential control loop elements.

5. Design criteria and procedure

For a given control system structure the control parameters have to be calculated. To design a non linear open loop control is relativly simple. The set of nonlinear equations can be solved for example with a numerical minimum variance methods /6/.

In contrast to the open loop control, the closed loop control design can in theory be very complicate. The todays design procedure for complex flight control systems is more art then an application of a proper theory. I shall illustrate this private statement more in detail.

The design criteria in the "rotational dynamic cascade" are well formulated in the handling qualities criteria of aircraft. An excellent example of handling qualities requirements is the well known military specification MIL 8785 /7/. Most of the handling quality criteria can be expressed as eigenvalues and eigenvectors of the relevant modes (short period, dutch roll, roll mode). The MIL 8785 gives clear rules, where the eigenvalues (roots) have to be placed.

In contrast to the adequate root method of the rotational dynamic cascade the design of the energy dynamic cascade and parts of the flight management cascade can be formulated only unsufficiently by eigenvalues. Problems of speed and flight path deviation as well as of throttle activity may be formulated by variances of deviations. For example the difference between the commanded airspeed and the measured airspeed is a clear and simple measurement for speed control accuracy. The variance of the speed derivation is $\Delta V = V_C - V$

$$\sigma_V^2 = \frac{1}{D} \int_t^{t+D} \Delta V^2 \, dt \tag{12}$$

is easy to calculate. Throttle activity is an important human factor in flight control design and acceptance. A high throttle activity bothers both pilot and passengers /1/. S ome additional research is required to formulate an adequate mathematical equation to describe throttle activity. A sufficient measurement is thrust rate $\dot{F}$

$$\sigma_{\dot{F}}^2 = \frac{1}{D} \int_t^{t+D} \dot{F}^2 dt \; . \tag{13}$$

Passengers or pilots comfort is an additional important human factor, both in civil and military aviation. In general it is difficult to find an acceptable mathematical formulation for human factors. The well known C^*- Criteria /8/ for short periods response design represents passenger comfort quite well.

$$C^{*2} = \ddot{H}^2 + (V_p\, q)^2 \tag{14}$$

$$\sigma_{C^*}^2 = \frac{1}{D} \int_t^{t+D} C^{*2}\, dt \tag{15}$$

As difficult as the correct mathematical formulation of the relevant effects in the energy dynamics cascade is the weighting of these effects. The simple question what is more undesirable: a speed deviation of 1 knot or a flight path deviation of 10 ft is very difficult to answer. Due to the flight envelope different weighting are worthwhile. A practical approach is the equal weighting of the relevant energy-deviations

- kinetic energy $\Delta V \cdot V$
- potential energy ΔH

This energy weighting produce acceptable flight test results /9/.

More difficult is weighting the precision (H, V) on one hand and the human factors (throttle activity, passenger comfort) on the other hand. Many experience in calculation, simulation, flight test and operation are necessary to fix the weighting factors.

When the weighting factors $\underline{K}$ have been fixed, variance of the control qualtiy Q

$$Q = \int \Delta \underline{x}\, \underline{K}_x\, \Delta x^T dt + \int \Delta \underline{u}\, \underline{K}_u\, \Delta u^T dt \tag{16}$$

can be minimized with different powerfull procedures.

Recording many application, a fixed set of weighting factors is not adequate for the total flight regime. Each area of the flight envelope requires its specific weighting matrix. The superposed calculation of different flight regimes and a joint minimisation of the quality criteria can give sufficent results. Todays powerfull computer are the necessary tool for this job.

As problemized earlier, complete flight control system requires different design procedures, root methods for the inner cascades and minimum cost methods for the outer cascades. No theory exists to solve both problems at the same time. If we use the different characteristics of the cascade we will find, that the control parameters of the inner loops affects strongly the dynamic characteristics of the outer loop but not vice versa. The control parameter sensivity move in the opposite way compared to the control information. Based on this axiom, we design complex multiloop control systems step by step.

The first step is the design of the inner loop (flutter suspression, damper, stabilizer) with root methods based on aircraft handling quality specifications. In a second step the outer loop control parameters are calculated by cost function minimization, where the inner loop control parameters are fixed. In most applications two or three iterative circles including flight test are sufficient.

6. Flight Test results

The results of the discussed design procedure for complex multiloop flight control systems shall be demonstrated for a realized flight control system for scientific applications. This flight control system has been developed in the Institut for Guidance and Control, Technical University Braunschweig /10/. The design targed was an extrem precise flight control system for flying nap-on-the-earth profiles to measure wind, windshear and turbulence on board of the aircraft.

The test aircraft is an institute owned, twin engine propeller aircraft (fig. 3). The aircraft is fully equiped with sensors, digital and analog computer and actuators for elevator, aileron, rudder, horizontal fin trim, throttle and direct lift (fig. 4). In the presented version of the flight control system, the aerodynamic flow condition was measured via the angle of attack. The task of air data computing, flight augmentation and thrust control will be done in one central computer (Typ Norden, DEC PDP11 compatible). The sample rate is 23 cycles per second.

Figure 5 demonstrates the high accuracy of the flight control system in smooth air. In a 9 minutes flight period, the maximum altitude deviation was less then 1 m. The altitude deviation is in the range of the resolution of the barometric altimeter. Figure 6 shows the aircraft response in altitude, airspeed and thrust at the begin of a turn flight in moderate turbulence. In figure 7 the aircraft energy situations were heavily disturbed by setting the landing flaps. An altitude-acquire manouevre shows fig. 8 for strong turbulence. An automatic landing is demonstrated in fig. 9. Typical for this test aircraft is the gust sensitivity of the uncontrolled aircraft due to the low wing load and on the other hand its high pitch angle variation due to tail-wheel landing gear.

An older version (with a simple open loop control) is shown in fig. 10 in an curved MLS-approach /11/ passing a moderate wind shear.

7. Literatur

1.	Schänzer, G.: Böhret, H.	Integrated flight control system for steep approach and short landing. AGARD, GCP-Symposium, Geilo, Norway, Sept. 73.
2.	Clifford, D.R.:	Approach path control for reduced noise and improved traffic capacity. AGARD, FMP-Symposium, Baden-Baden, Germany, 1971.
3.	Tou, J.:	Modern Control Theory. Mc, Graw-Hill Company, New York, 1964.
4.	--	Flight Test Instrumentation. AGARD-AG-160-VOL 1-11, ISBN-92-835-1386-1.
5.	Luenberger, D.G.:	An introduction to observers. IEEF Transactions on Automatic Control 16. pp. 596-602, 1971.
6.	Jacob, H.G.:	Rechnergestützte Optimierung statischer und dynamischer Systeme. Springer Verlag Berlin, Heidelberg, 1982.
7.	Hoh, R.H.: et alii	Proposed MIL Standard and Handbook Flying Qualities of Air Vehicles. Technical Rep. AWAL-TR-82-3081 Flight Dynamic Laboratory Wright Patterson Air Force Base.
8.	Rang, E.R.:	A nonvarying C^* -control scheme for aircraft. J. Aircraft 8 (1971), pp. 679-680.
9.	Schänzer, G.:	Auslegung von Autopiloten durch Zustandsrückführung. Zeitschrift für Regelungstechnik, S. 73-83, März 1978.
10.	Redeker, A.:	Beiträge zur Verbesserung der Führungsgenauigkeit von Flugreglern. Thesis, Technische Universität Braunschweig, 1986.
11.	Schänzer, G.:	Influence of Microwave Landing Systems on Guidance and Control. AGARD GCP-Symposium, Cheltenham, UK, May 1976.

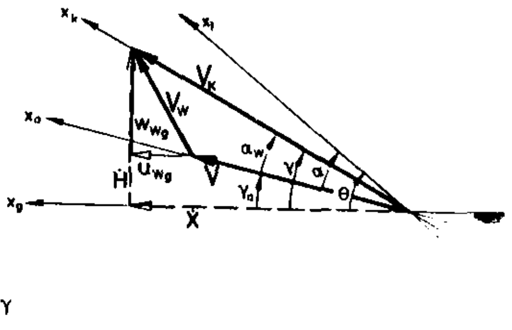
Apendix

A1 Aircraft equation of motion (translational) (simplified)

$$m \dot{V}_k = F - D + L \sin \alpha_W - W \sin\gamma \qquad (A1)$$

$$n G = L \qquad (A2)$$

A2 Velocity vector geometrie



$$\underline{V}_K = \underline{V} + \underline{V}_W \qquad (A3)$$

$$\sin\alpha_W = -\frac{w_W}{V}\cos\gamma - \frac{u_W}{V}\sin\gamma \qquad (A4)$$

A3 Thrust equation (superposition of eq (A1), eq (A2), eq (A4))

$$F = W \left[n\frac{C_D}{C_L} - n\frac{w_W}{V}\cos\gamma - \left(1 + n\frac{u_W}{V}\right)\sin\gamma + \frac{\dot{V}_K}{g} \right]$$

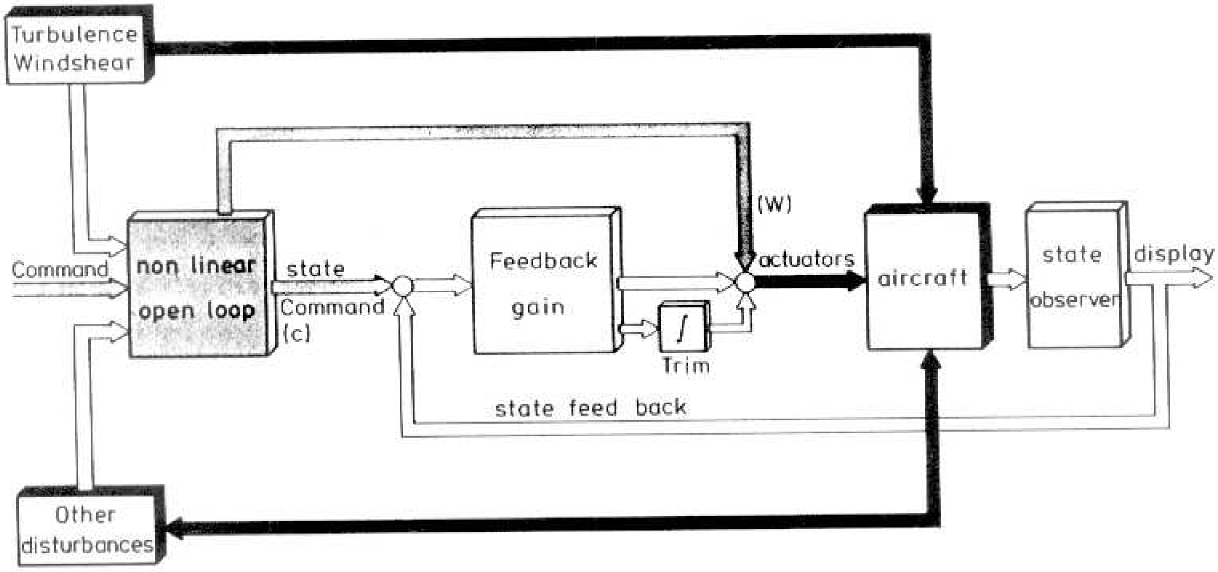


fig. 1 Block diagramm of the control loops

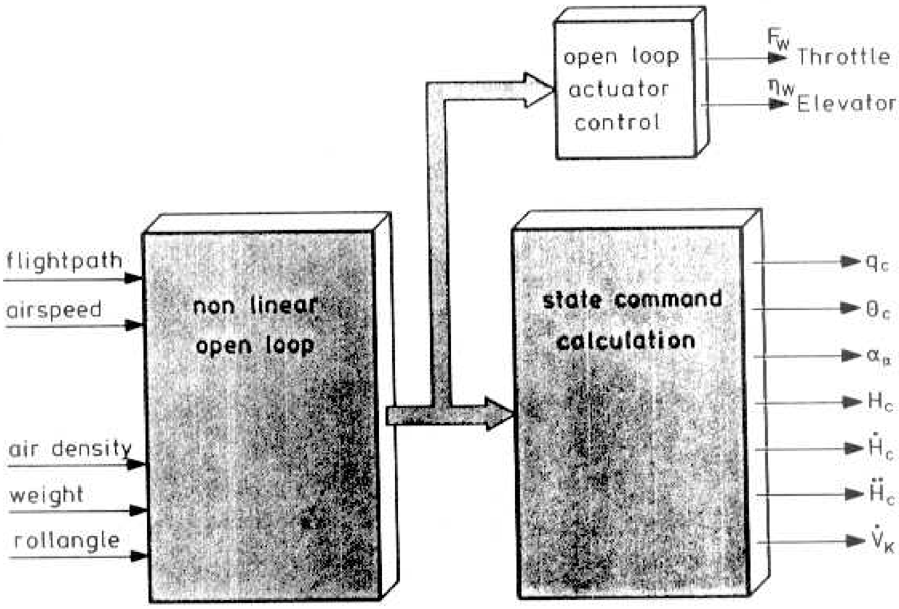


fig. 2 Non linear open loop control state and state command calculation

fig. 3 The DO 28 research aircraft

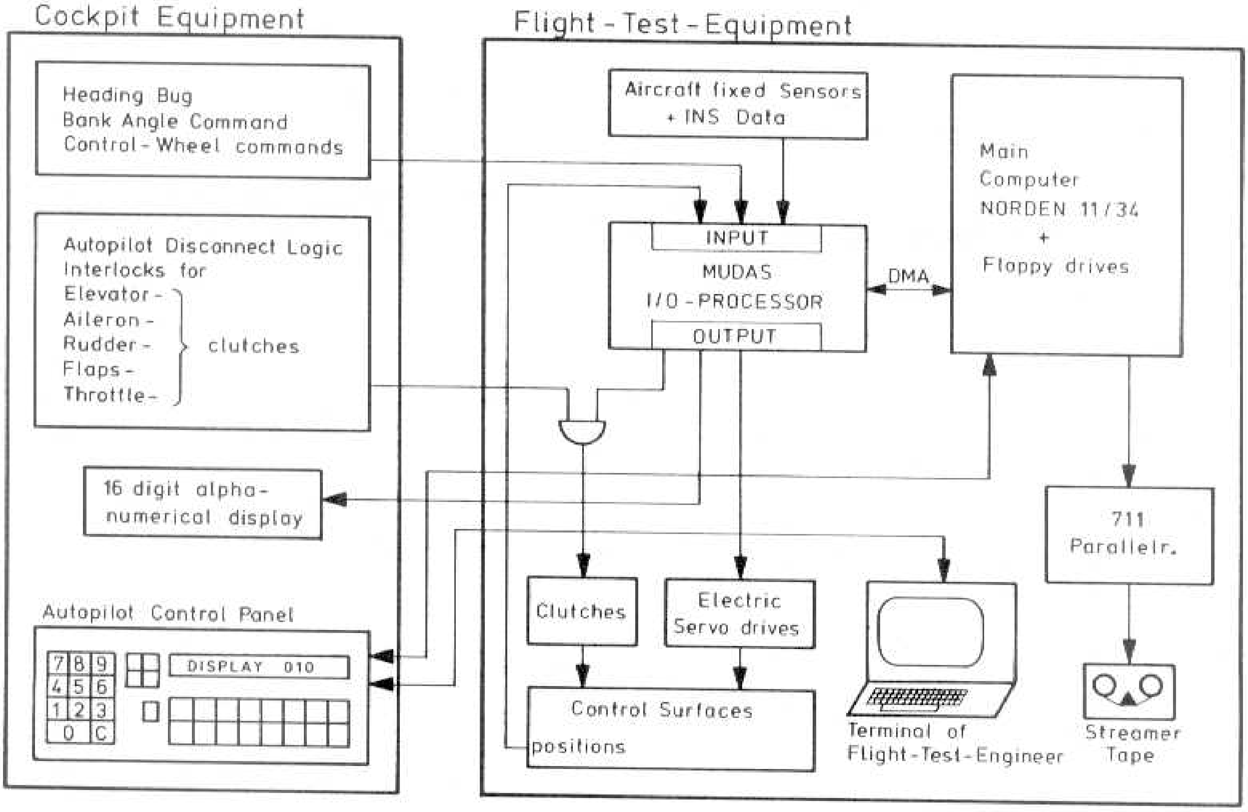


fig. 4 Equipment of the DO-28 research aircraft

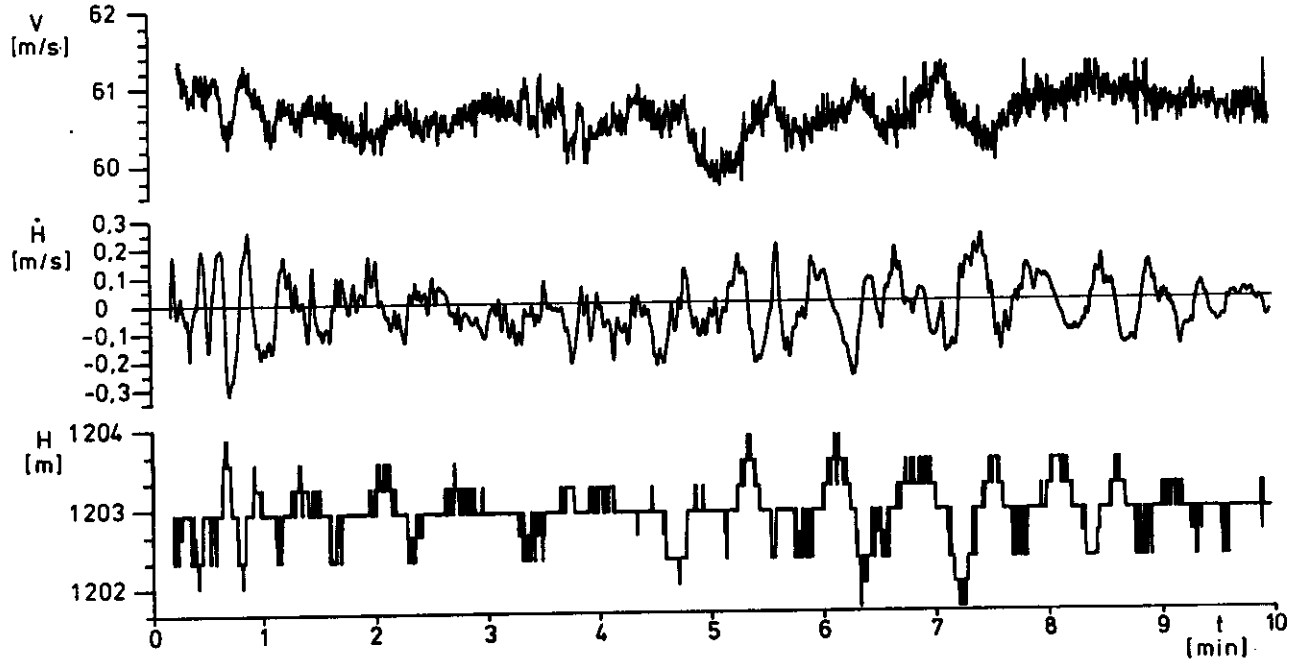


fig. 5 Altitude and speed hold (calm air)

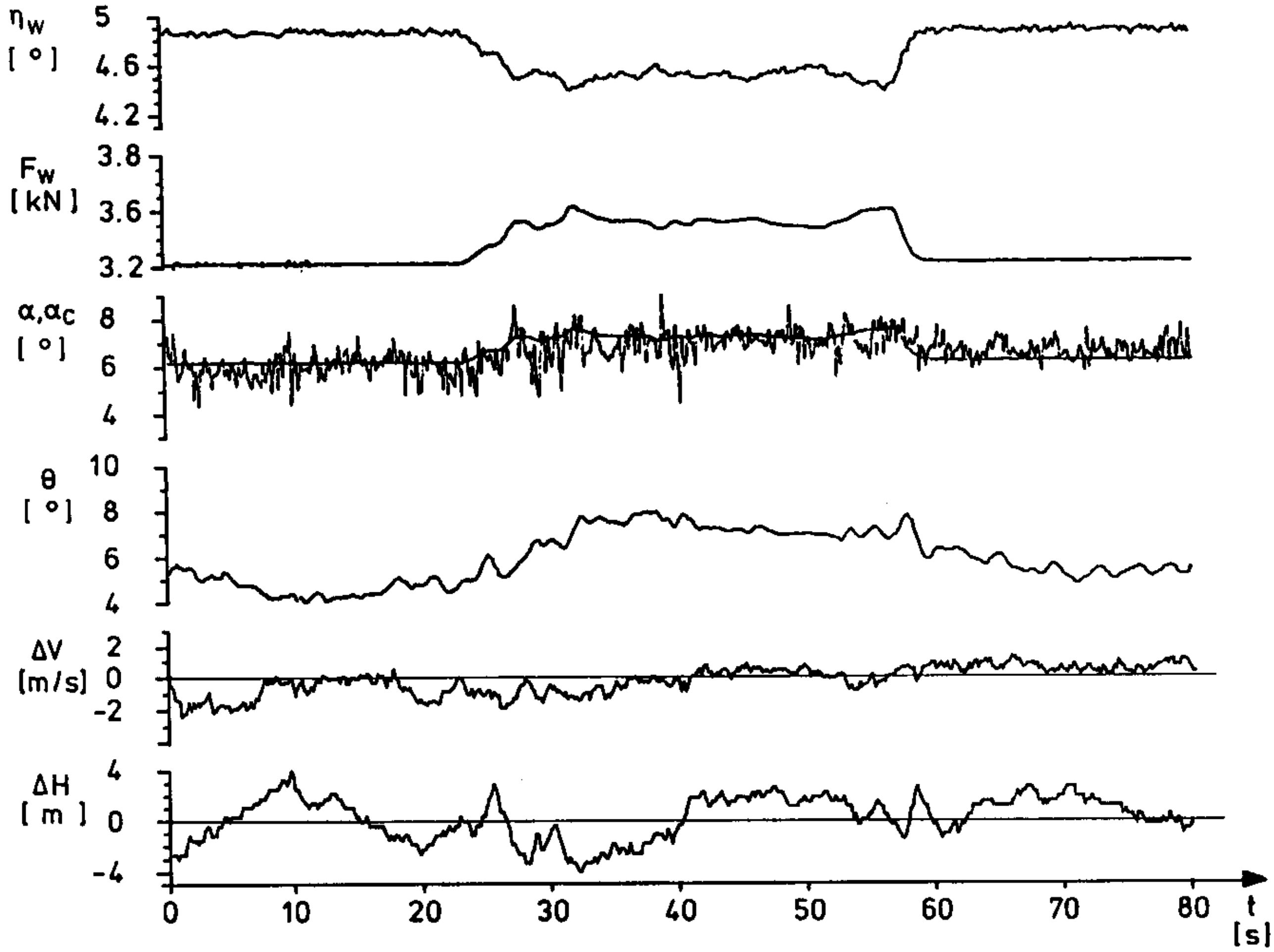


fig. 6 Altitude and speed hold in turn flight (moderate turbulence)

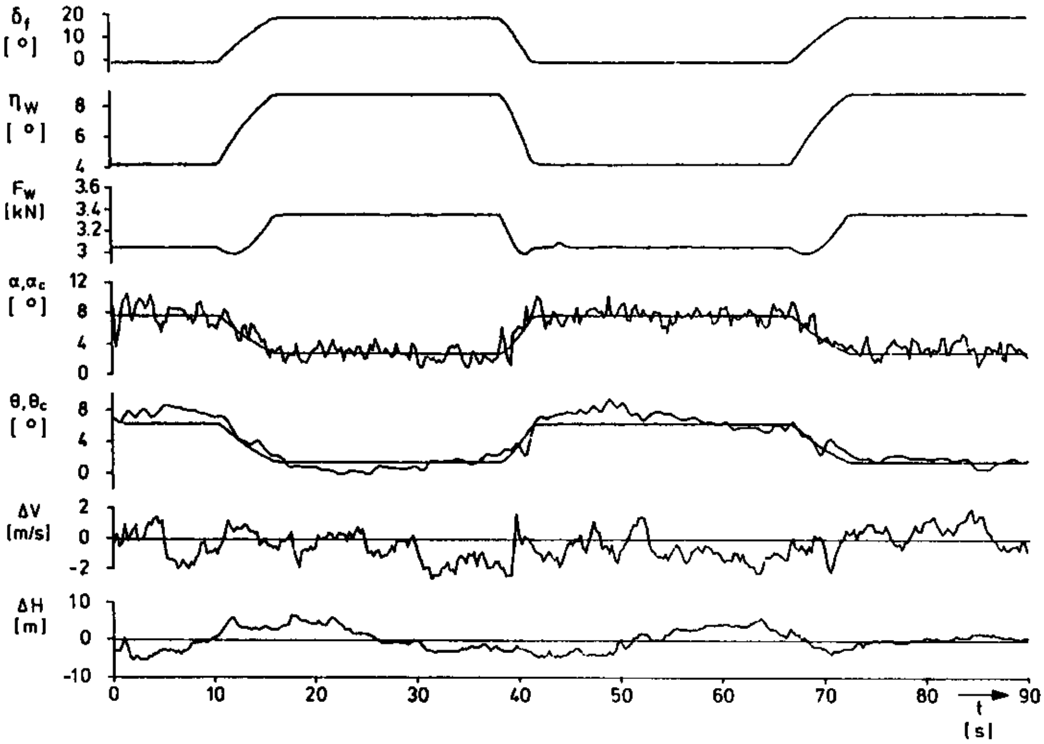


fig.7 Altitude and speed hold at flap setting

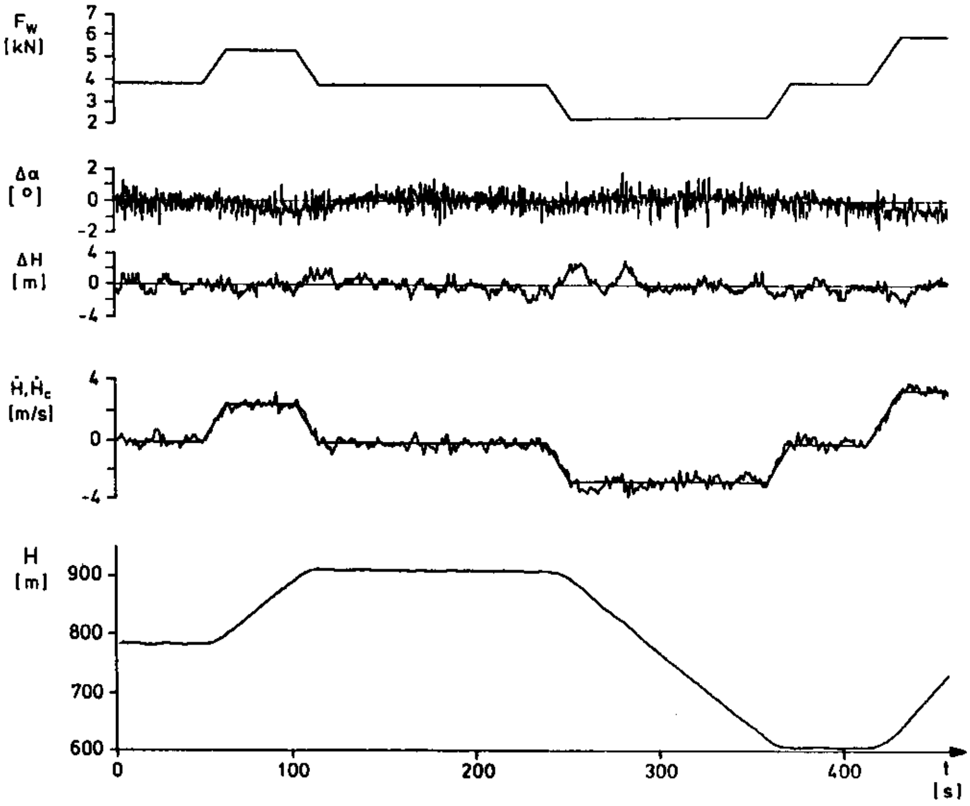


fig.8 Altitude acquire (strong turbulence)

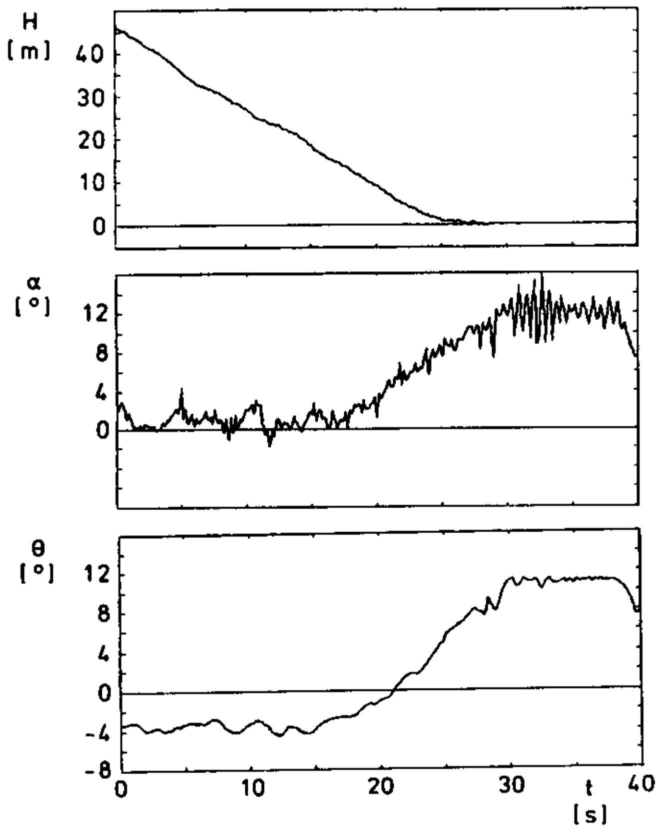


fig. 9 Automatic landing
(flap position $\delta_e = 52°$)

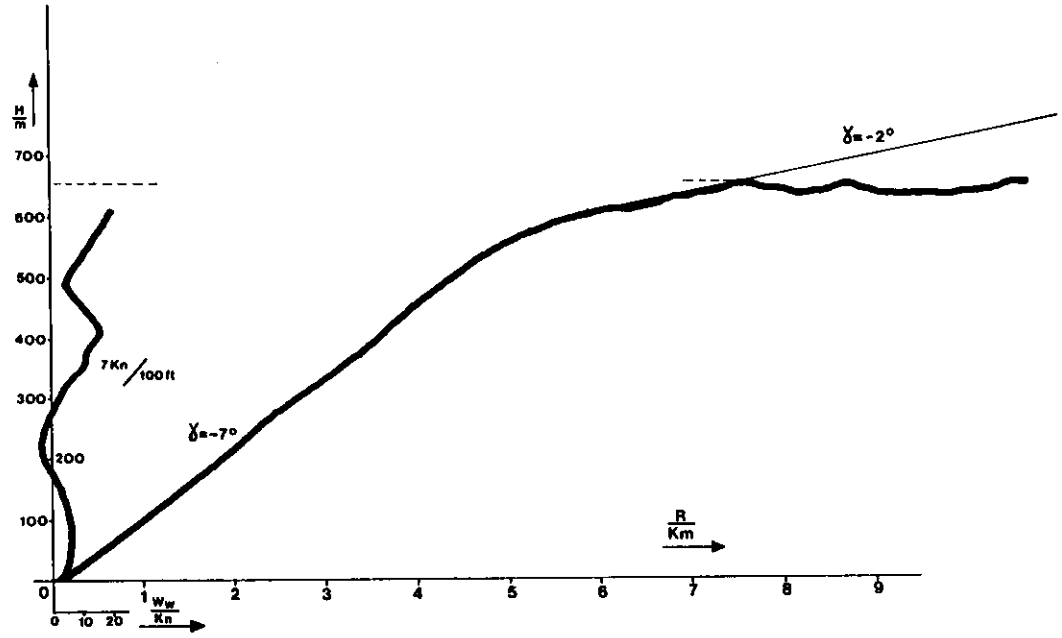


fig. 10 Curved MLS approach (passing a moderate windshear)

CP-410

SOME EXPERIENCES IN INTEGRATING AVIONIC SYSTEMS ON THE CIVIL FLIGHT DECK

by

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SUMMARY

The Paper describes some of the work carried out in the Civil Avionics Research programme at RAE Bedford. After describing some of the factors that are leading to a future Air Traffic Management system, the Paper reviews the activities in navigation, flight management, displays and novel human input techniques. The progress made and some of the lessons learned are also described. The Paper concludes with a view of how a future Air Traffic Management system might operate.

1 INTRODUCTION

The Civil Avionics Section of Operational Systems Division at RAE Bedford carries out a programme of research on behalf of the UK Department of Trade and Industry. The aim of the research, which enjoys the support and cooperation of industry, is to enhance the technological base of the UK avionics industry, particularly those firms seeking to operate in the civil market. Almost all the products and concepts which arise are subjected to flight testing in the section's BAC 1-11 flying laboratory aircraft. Without such realistic final proving there is often little hope of convincing hard-headed operators that the ideas will work.

Inevitably there has to be considerable emphasis on improving the efficiency of airline operation because airlines and their customers are very cost conscious and have aircraft and equipment purchasing policies that reflect this. These policies have led to the procurement of dramatically improved airframes and engines and also a great proliferation of electronic aids on the flight deck. This trend towards greater complexity will continue and, in our view, the sophistication of the ATC environment will also increase; it is this trend that makes necessary the research to exploit these growing capabilities and to make them manageable and useful.

2 ECONOMIC PRESSURES ON AIRLINES

The last 25 years has seen major changes in the patterns of civil aviation. The best known and most widely publicised influence for change has been the rapid increase in the price of crude oil and the aviation fuel derived from it. Fig 1 shows the oil and aviation fuel price movements since 1960, the recent downturn in fuel prices can probably at best be regarded as a temporary reprieve from the upward movement in basic energy costs. Over the same period the cost of aircraft and their equipment has risen steeply as manufacturers have sought to reduce fuel burn per passenger seat/mile and yet despite this the real cost of air travel has fallen as the example of the cost of a N Atlantic crossing shows.

The contribution of avionics to aircraft operating economy began in the 1970s with the introduction of area navigation (RNAV) systems originally intended to provide a navigation capability that would allow direct routings and thus break the dependence on fixed air routes based on the location of ground navigation aids. It is perhaps ironic that only now, in the 1980s, are direct routings becoming acceptable to ATC authorities and that the savings associated with RNAV systems have instead been realised by virtue of precise navigation and flight control along airways. Examples of the possible improvements that can be made can be seen by contrasting observed airway performance (Fig 2) with our own flight results based on DME/DME navigation (Fig 3); this contribution alone reduces track miles by 0.5-1.0%. Correct turn anticipation, rather than turning after the beacon overhead position can save a further 1-3% of track miles depending on route structure.

Also started in the 1970s was the adoption of Performance Management Systems to provide guidance to the pilot or autopilot for optimum climb, cruise and descent strategies. Some users have attributed fuel savings of 3% to such systems. Recently even more sophistication and precise control has come to the flight deck with the widespread adoption of Flight Management Systems in the 1980s.

The potential savings are so large in cash terms that it has been estimated that at least 70% of major civil transport aircraft will have either RNAV or FMS fitted by 1990 and over 80% will be so fitted by the year 2000[1].

You can easily imagine the frustration of airlines as they find that, despite the sophisticated computation available on the flight deck and the CRT based instrument display systems that so vividly portray the enforced departures from the planned route, significant further savings are being denied them because the ATC system cannot provide the routings, flight levels and optimum climb and descent profiles that they would like. It has been calculated that in Europe a further 5-10% of route miles could be saved if true direct routing was possible[1] and Attwooll and Benoit[3] have calculated that at one busy UK airport 10 tonnes of fuel per hour in the peak period could be saved by ideal, non interrupted descent paths and yet current airline experience suggests that only 20% of descents into that airport are uninterrupted.

This emphasis on economic operation has made life very different for the pilot; he is now concerned with the minimising of fuel burn by feeding and obeying his flight computers in addition to his other tasks, thus the mental workload has increased. The contribution to reduced pilot workload and increased situation awareness provided by the Electronic Flight Instrument Systems (EFIS) on modern aircraft has largely offset this and the importance of this technique cannot be over emphasised, but the ergonomics of the Control and Display Units used to communicate with the FMS and other systems are still appalling. As the complexity of the future ATM system increases, including the use of four-dimensional trajectories, the pilot-machine interface will become more complex and more critical if the man is to remain in effective control of his systems, rather than the other way round.

3 SOME ATC PROBLEMS

The most important function of ATC is to ensure safe, orderly and expeditious flow of air traffic. The keyword 'safety' naturally makes ATC authorities conservative organisations, this conservatism being further reinforced because they must work within international rules. The system that we see now has evolved over many years from basically procedural forms of control (which are well suited to low traffic density, low workload environments) to the modern high traffic density, high workload tactical radar control experienced near major airports and airway junctions. The system is based on the human judgement exercised by Air Traffic Controllers who, with experience, actually achieve astonishingly good performance. The methods of control, especially in busy periods, involve accurate mental estimation of positions and velocities and are very communication intensive, the communication being by voice over RT or telephone links. As traffic flows increase any one controller will reach a limit which can be loosely described as a 'headful' of information beyond which he cannot picture and control the situation. The classic response to this problem is to reduce the volume of airspace that he controls, and this remedy is effective until the overhead of communicating with adjacent sectors begins to dominate his workload. Major airports and intersections have probably reached this point and yet all traffic forecasts predict significant traffic increases in the years ahead; for example, in Europe up to 50% increase by the year 2000, and for some types of traffic in the USA even more than this[1,2]. Clearly this will present a major problem.

It is fortunate that improving technology, both in the air and on the ground, offers at least partial solutions to this problem.

Some simple guidelines that could govern the transition to future solutions are:

(a) Safety must at least be preserved at each step.

(b) Each step must be an evolutionary one and offer compatibility with previous solutions and, ideally, be capable of justification on cost benefit grounds at each stage.

(c) The system must be able to cope with a wide range of demands and with unexpected perturbations.

(d) For the foreseeable future men will remain in the loop both in the air and on the ground.

(e) Greater capacity will be achieved through greater precision in the knowledge of aircraft current and future positions. The exploitation of this precision will in turn demand computer based systems, both in the air and on the ground, for prediction and execution of trajectories that will be specified in three and four dimensions. These trajectories will be based largely on continuous descents that are close to fuel optimal.

(f) This implies a shift to more strategic rather than tactical forms of control, and the necessary numerical specification of trajectories will require a data link to support the resulting air-ground exchange of information. The exchange of data will almost certainly provide the means for improved short term weather forecasts needed for economical four-dimensional control.

These predicted changes, leading towards a full Air Traffic Management (ATM) scenario, pose considerable demands on research and development; amongst these are how to specify and achieve the necessary man-machine interfaces (both air and ground) that allow this information to be understood, agreed and monitored by pilots and air traffic controllers.

It is against this vision of the future that our programme should be viewed, seeking to provide the technical building blocks which will eventually be assembled into a future system.

4 RESEARCH PROGRAMME

The Civil Avionics research programme is 100% funded by the Department of Trade and Industry, and on a short-term basis provides a flight test, development and demonstration facility for UK Avionics manufacturers, enabling them either to install and operate equipment on a stand-alone basis, or to integrate their equipment fully with other systems already operating in the BAC 1-11 aircraft. On a longer term basis, a major aim of the programme is to investigate the role and integration of avionic systems for the more demanding air traffic environment of the future. Our programme is therefore concerned with developing and demonstrating a total aircraft system that will be compatible with future ATC systems. These will need to cope with the expected large increases in traffic demand and provide more economic aircraft operation in terms of fuel savings and reduced delays, while at the same time improving, or at least maintaining current levels of safety. Although the emphasis of our research is on systems integration, it is convenient for descriptive purposes to break down the programme into a number of main topics which are detailed below.

4.1 Navigation

The navigational aspect of our programme is concerned with how accurately aircraft can position-fix and fly a defined two-dimensional route. The work has included an assessment of the accuracy and characteristics of currently available ground navigation aids[4], and also extensive measurements of automatic navigation performance when using various combinations of radio aids augmented by on-board sensors[5]. These measurements confirmed the high level of accuracy provided by DME/DME position fixing, (of the order of 0.25 n mile 1 sd), which is now used by most area navigation systems when operating in areas of good DME coverage. Our navigation work is now concentrating on methods of improving the accuracy achievable in regions less well-equipped with ground aids.

4.2 Flight Management

The essential feature of a Flight Management System (FMS) is to combine the requirements of lateral, vertical, speed and time demands, in order to obtain an optimum overall result in terms of aircraft operating efficiency, within the constraints imposed by Air Traffic Control. The lateral requirement is to track automatically along airways and to follow defined Standard Instrument Departure (SID) and Standard Arrival Routes (STAR) in the terminal area. Vertical control facilities should enable the pilot to define and achieve any required climb and descent profiles. Speed control needs to take account of the vertical profile requirements in order to maintain optimum speed accurately and with minimum throttle activity.

Time control within current ATC systems generally involves path stretching manoeuvres within defined holding areas in order to absorb unavoidable delays. A number of flexible path stretching methods have been investigated and developed allowing any specified delay to be achieved accurately within the airspace presently allocated for such manoeuvres. More fuel efficient methods of meeting time constraints are under development, involving strategic speed control (often referred to as four-dimensional control or time-slot following), and most of our research effort in the flight management area is being concentrated on this aspect[6].

4.3 Man-machine interfacing

4.3.1 Displays

As civil aircraft become fitted with more comprehensive facilities in terms of route navigation, vertical, speed and time control, it is essential to provide sufficient information in the cockpit to enable the flight crew to monitor and control these automatic systems adequately. Displays research is aimed at providing a fully integrated presentation of Primary Flight and aircraft systems data, including mode indications and failure warnings, in such a way that information is always available when needed, but is not displayed otherwise. This avoids clutter and possible confusion. Colour CRT displays have been used to provide this major interface between the pilot and the various sensors and systems needed to operate the aircraft, with the emphasis being on developing navigation display formats suitable for the FMS functions described in section 4.2 above.

4.3.2 Workload reduction

As well as informing the pilot of the present position and status of his aircraft and its systems, it is also necessary to enable him to easily input the data and commands required for overall system management. The keyboard entry methods currently used are time-consuming and error-prone, especially in high workload situations, sometimes causing frustration as well as sore fingers. Alternative input techniques are being tried, including the use of a joystick or roller-ball to drive a cursor symbol on the CRT screen in order to change the defined navigation route more rapidly, for example.

Methods of utilising speech recognisers to allow direct voice input to control selections and insert commands and data to various automatic systems are also under investigation. Initial results appear promising but much work is required in this area to determine the combination of input techniques probably needed to provide the speed and flexibility demanded by pilots.

4.4 Air Traffic Management

It is vitally important that the systems and capabilities provided for airborne use are compatible with, and form part of, future Air Traffic Management systems, and the Civil Avionics section therefore has a joint programme with the Royal Signals and Radar Establishment at Malvern, to consider how future ATC systems might develop in order to utilise the capabilities of modern well-equipped aircraft. Of particular interest is the potential use of a two-way data link between the ground and the aircraft, for passing the more detailed information expected to be needed for efficient operation of future ATC systems. Initial trials are being carried out using commercial modem equipment with VHF radio transceivers in the BAC 1-11 aircraft, to investigate the integration of data link information with ATC, the on-board avionic systems and the flight deck crew. Later a mode S data link will be used in these experiments.

4.5 Flight control

Research on flight control aspects is largely concerned with non-linear control laws and energy management techniques and seeks to achieve tighter control performance with less control activity and fuel burn. This work is currently independent of the other research topics and is therefore outside the scope of this paper.

5 THE BAC 1-11 RESEARCH AIRCRAFT

The programme centres on a BAC 1-11 200 series aircraft, equipped with a multitude of facilities that make a 20 year old aircraft a versatile research tool, ie a flying laboratory. The present installation lends itself to research into such topics as navigation techniques, flight management system assessment, flight control and more recently the man-machine interface including research into the use of electronic flight deck displays and Direct Voice Input (DVI). For ease of access and maintenance, the majority of equipment, excluding power and cooling systems, has been fitted into the passenger cabin. To preserve flexibility, the philosophy of routing signals and data via junction boxes has been adopted.

On entering the cockpit, a striking feature is the contrast between the port and starboard pilot panels. The starboard pilot position retains conventional instrumentation and systems and is the safety pilot position. By this means considerable freedom to modify the remainder of the cockpit has been obtained. The port side is dominated by two colour displays which conform to ARINC 725 format D (8 inch × 8 inch). One of these is normally devoted to the display of normal primary flight information, the other is used as a navigation display. The generation of the navigation display format is shared between a symbol generator unit and a general purpose digital computer. The basic data for this navigation display comes from an area navigation (RNAV) system. The navigation computer has been expanded with additional memory for experimental use and, with the numerous software changes since its purchase, now provides a Flight Management System (FMS) capability. The controller for this FMS/RNAV installation is situated in the centre pedestal of the cockpit; for monitoring purposes and software updating an additional controller is installed in one of the rear observer's control desks.

The navigation sensor package for the RNAV/FMS and other systems includes two VOR receivers to ARINC 579, a VOR to ARINC 711, three DME receivers to ARINC 568, two frequency agile DME receivers to ARINC 709, an inertial navigation system to ARINC 581 and a digital air data system.

A low cost RNAV system receiver has also been installed into the aircraft. Trials have been conducted in collaboration with the manufacturer, to assess the performance of such equipment.

Situated next to the FMS controller in the cockpit pedestal is a Radio Management System (RMS) based on an integrated control and display unit. This forms part of the on-board comms/nav suite. This prototype system not only provides the pilots with a tactile controller with space saving benefits but also an interface between the speech recognition system and the Tx/Rx units.

A duplex analogue autopilot offers full autoland capability; in addition, a microprocessor and a digital computer, that can drive the autopilot servo systems, provides a flexible and readily programmable autopilot for experimental purposes. The aircraft has been modified to provide a direct lift capability, using the standard spoilers; pitch compensation is also available using an elevator series actuator.

In-house control research is supplemented by UK Industry participation and recently a prototype high integrity flight control computer has been installed. This joint programme between RAE and Industry will investigate the use of such systems on a civil aircraft.

Two dual flight observer stations are positioned forward in the passenger cabin. From these stations, the flight observers can conduct the trial and also monitor the aircraft's state by means of a full set of flight instruments and displays. The recording of most parameters, including the aircraft intercom, is also controlled from these stations.

As the programme has broadened to include Air Traffic Management and man-machine interface aspects more equipment has been recently installed, including:

(a) Experimental data link systems based on VHF/modems as a precursor to mode S, capable of linking experimental ATC systems to the aircraft.

(b) Advanced speech recognisers.

Comprehensive instrumentation as well as a large number of signal conditioning units have been provided. The primary recording system is a digital magnetic tape system. Online analogue pen recorders are also available. The synchronisation of the aircraft records with other sources, such as tracking radar installations, is achieved by a standard time radio clock receiver. In addition to the normal aircraft supplies, two static inverters provide 4 kW of UK domestic electrical power at 240 V x 50 Hz. Seventeen passenger seats are provided in the rear of the cabin allowing flight demonstrations; the nature of the BAC 1-11 with ventral stairs and auxiliary power unit also give the aircraft a convenient ground demonstration role.

6 PRESENT POSITION ON RESEARCH TOPICS

6.1 Navigation

DME/DME navigation is now widely used in area navigation and flight management systems, giving an accuracy of around 0.25 n mile when operating in areas moderately well-equipped with ground aids. In other areas (eg Mediterranean and Northern Scandinavia) the number of ground aids is severely limited, with the result that automatic position fixing systems are forced to revert to VOR/DME operation, or even to dead-reckoning, for long periods of time. Measurements taken in the Mediterranean area, using a frequency agile DME receiver fitted in our BAC 1-11 aircraft, showed that intermittent DME data was frequently available from a number of ground stations, even though signals from two stations giving a satisfactory cut-angle for DME/DME operation could not be maintained for any significant length of time.

Our recent navigation research has therefore been concentrated on developing techniques for utilising the capability of frequency agile DME receivers, so that whatever range information is available at any particular time can be combined with other aircraft data to provide a best estimate of present position. As the data tends to be intermittent in nature, and could be coming from continuously changing sources, the navigation technique for combining the data has become known as 'data puddle'. Position fixing algorithms to combine distance information from up to five ground stations have been developed, together with the necessary station selection algorithms for determining the preferred five stations when operating in areas well-equipped with aids. The selection criteria are based on achieving an even spread of ground stations around the aircraft whenever possible, rather than simply accepting the aids closest to the aircraft. If range information is only available from five or less ground stations, then all the available data will be utilised and no selection is necessary. Obviously this situation applies in those areas sparsely equipped with ground aids.

Initial flight trials using data puddle in a good nav aid environment have proved that the concept works, and there are signs that the expected improvement in accuracy compared with DME/DME position fixing is being achieved, although no absolute accuracy measurements have been made at this stage. Data puddle performance on flights in sparsely equipped areas shows equal promise, with position fixing from two or more stations being maintained for much of the time that conventional DME/DME navigation proved impossible. There were, however, times when the available aids were located close together and therefore gave very small subtended angles, which could lead to poor position fixing accuracy. There were other times when only one DME station could be received or even none at all. Methods for improving navigation in these circumstances are discussed in section 8.1.

6.2 Flight Management

The ability to fly a defined route accurately, with no overshoot at turn points, is already providing many airline operators with cost savings as a result of fitting RNAV or FMS equipment. Automatic track following of complex SID and STAR routes is now available on modern FMS systems, and therefore no significant research effort is taking place in terms of lateral flight management capabilities.

Similarly, adequate vertical and speed capabilities are now available, with the pilot able to define any climb or descent profile by inputting a cruise flight level and required heights at waypoints along the route. Demanded speed will be maintained to any value set by the pilot, and automatically changed as necessary for different flight conditions (eg reduced to optimum holding speed as the aircraft enters a holding pattern). A vital safety back-up is provided on our vertical control system. Each time ATC clear the aircraft to a particular altitude or flight level, the pilot inserts this cleared value on his instrument display. The same information is fed to the FMS, so that any height profile pre-programmed into the system is then over-ridden and the aircraft automatically levelled at the cleared altitude.

Our recent FMS research has concentrated on time control. The need to absorb delays by path stretching is necessary within to-day's ATC system and will almost certainly remain so in future systems, although hopefully to a lesser extent than at present. To meet this requirement a cruise level speed control algorithm as well as an automatic holding capability have been developed which, together, enable the pilot to insert any desired hold exit time. The FMS system then computes the size of holding pattern (up to a maximum of 6 min), and how many times the aircraft needs to fly round the pattern. If necessary, airspeed is automatically adjusted on the inbound leg of each orbit to prevent accumulation of timing errors during the sequence. Flight measurements of the time-keeping accuracy achieved by the system gave an exit time error of ±5 s. The major contribution to these errors was the track keeping inaccuracy during the curved segments of the pattern, where a lateral error of only 0.1 n mile can lead to a 10 s time error. The accuracy of DME/DME position fixing is such that a 6 min hold can be contained in a protected area somewhat smaller than that required for a standard pattern. Also, because aircraft position is known relative to the pattern without having to overfly the aid defining the hold, it has been possible to implement a revised set of entry procedures, allowing automatic joins from any direction without going outside the racetrack pattern[7]. Adopting these procedures would eliminate the need to allott airspace to protect hold entry manoeuvres specifically. To cater for delays of less than 3 min, a U-shaped manoeuvre has been developed, which again is contained within the defined holding area, so the FMS is fully capable of absorbing any required delay using conventional path-stretching techniques.

Of perhaps greater significance to future air traffic management systems, is the development of strategic speed control (four-dimensional or time-slot following) aimed at providing a more fuel efficient method of meeting time constraints in situations where the need to delay is known well in advance. While at cruise altitude, the pilot can nominate an end of descent waypoint and insert any altitude, speed and time constraints associated with it. The system then calculates the constant calibrated airspeed required to achieve these constraints, together with a top-of-descent point from which idle thrust should be maintained throughout the descent, with allowance made for a deceleration segment towards the end of the descent. Of vital importance to the efficient performance of the descent, is the prediction of the wind conditions the aircraft will meet during the descent. Forecast winds issued by, for example, the Met Office at Bracknell cover a six hour period and can be based on data up to 12 hours old, so it is essential to combine the actual wind, as measured in the aircraft, with the forecast wind, in order to obtain a reasonable prediction. Fairly large errors in forecast wind at high altitude can be overcome with only small speed changes, but similar errors at low altitude lead to significant speed changes because of the limited time left before reaching the constraint point. The time-keeping performance currently being achieved is impressive, typically within ±5 s at the end-of-descent point, but this accuracy is only achieved with thrust changes at the lower altitudes and is therefore less fuel efficient than we would like. Some improvements may be possible by refining the wind prediction algorithm, but the biggest improvement would come from more accurate forecasts of the wind profile along the descent path, or by relaying over a data-link actual winds experienced by a preceding aircraft that has recently descended through the same airmass.

6.3 Man-machine interfacing

6.3.1 Displays

Two colour CRT displays, each 8 inch square, and using shadow-mask tubes with cursive writing, have been operating in the 1-11 aircraft since June 1981[8]. The large screen size enables all primary flight information to be displayed on just one display. Airspeed, height and vertical speed are presented in a conventional circular analogue fashion, with aircraft attitude information in the centre of the display, and a heading scale along the bottom. No new research effort has been put into this primary flight display, and although not optimum in some areas, it presents a sharp contrast to some more recent attempts to provide the same information using vertical strip scales on smaller displays. We feel that care must be taken to present these critical flight parameters in the best possible way. Additional display area should be provided to meet the presentation requirement, rather than compromising the presentation in order to squeeze it into too small a space.

The second display is used for navigation data, and it is in this area that our displays research has been concentrated. A full-screen map display has been developed showing the intended route of the aircraft including any holding patterns, with track lines joining the waypoint symbols. Present position is indicated by an aircraft symbol positioned towards the centre of the screen, thereby providing considerable look-behind capability. This gives pilots a greater awareness of position along the route and is especially useful when flying complex SIDs and STARs within terminal areas.

Additional data can be selected by the pilot as and when required, including the display of all navigation aids, all waypoints contained in the data base, and VOR or ADF bearing pointers for flying non-precision approaches or for monitoring the simplex navigation computer driving our map display. Full scales from 15 n mile up to 300 n mile are available, and the map orientation can be heading-up, track-up or north-up. A look-ahead or planning mode, has been provided, allowing the pilot to examine any part of the route easily and in fine detail. This is especially useful for checking the programmed arrival procedure well before entering a terminal area. In this look-ahead mode, the pilot can move the map origin to any desired position using a roller-ball mounted on his armrest. He can also, of course, change the map scaling as required.

Danger areas are automatically drawn on the map if the aircraft is likely to pass close to them. In a similar way, safety altitudes have been included in the data base so that if the aircraft comes close to infringing any of these altitudes, the relevant area is drawn on the map, together with the minimum allowable height within that area.

Vertical information has been incorporated on the map display by writing demanded altitudes alongside each waypoint symbol, and colour coding the route track-lines, using blue for climb segments, white for level flight or cruise segments, and brown for descent segments, which gives extra emphasis to the vertical structure. Also available, by pilot selection, is a full-screen vertical display which allows detailed checking of the vertical profile in much the same way as with the azimuth look-ahead mode.

Time-slot following information can also be presented on the map. This includes the computed top-of-descent point, the end-of-descent waypoint together with speed, height and time constraints, time estimates for all waypoints in the route, and the display of any time errors together with an indication of where the aircraft should be in order to meet the constraints.

As well as controlling map position in the look-ahead mode, the roller-ball can also be used to position a cursor symbol on the map, to nominate any point held in the data base, or to generate new waypoints for insertion into the route. This rapid and flexible entry method has also been combined with direct voice input techniques and is discussed further in section 6.3.2.

The current map display, while still capable of improvement and further development, provides a very versatile method of presenting considerable quantities of navigation data to the pilot and, by giving an instant picture of present position without the need for mental interpretation of range and bearing from ground aids, achieves the biggest workload reduction seen in civil cockpits for many years.

6.3.2 Workload reduction

The research thrust has been directed towards methods of data input and system control other than conventional CDUs, keyboards, knobs and switches. Most effort has been directed at evaluating the capabilities of the modern Automatic Speech Recognisers (ASRs) in the airborne environment and then to explore their integration with other cockpit systems to provide an experimental Direct Voice Input (DVI) capability of considerable authority.

After initial testing with an early speaker dependent isolated word recogniser, it was clear that connected or continuous word recognition was required to maintain the natural aspect of using speech for control purposes. This early recogniser also suffered unacceptable recognition error rates in the noise environment of a cockpit.

At about that time a UK firm was developing a then advanced connected word recogniser that was also speaker dependent but employed dynamic time warping to allow for within speaker variability. This machine, the SR 128, was delivered in mid 1982 and was subjected to laboratory testing. The recognition performance was so encouraging that the same equipment was installed in the aircraft for flight testing two weeks later. Similar recognition performance was obtained during flight conditions and, as a result, the SR 128 was integrated with the cockpit displays and this degree of DVI was demonstrated successfully at the SBAC Air Show in 1982. A vocabulary of 32 words was used. Pilot reaction to DVI in this early stage was very favourable, to the extent that other systems were considered for voice control. A prototype Radio Management System (RMS) was described in section 5. Experiments using this menu driven CDU based system having been completed, it was decided to attempt DVI control of the radio and navigation equipment via this system. This allowed the pilot DVI control of two UHF/VHF radios, two VHF radios, two ADF receivers, two ILS receivers, two VOR receivers and an SSR transponder.

The vocabulary size required to control the comms/nav equipment and the cockpit electronic displays was now 106 words. To assist recognition the syntax adopted was structured as shown in simplified form in Fig 4. It will be noticed that the vocabulary is split into two parts, display commands or Comms/Nav commands, requiring two keywords (DISPLAY or COMMS) to be said before the remaining command. The pilots commented that the syntax was too restricting, and the necessity for key words aggravating. The syntax that was eventually adopted is shown in Fig 5. The pilots found the revised syntax easier to remember and use but the recognition performance was degraded due to the increase in the number of words at some syntax nodes. For example, in the first syntax the number of possible words after the command 'BOX' was 23, whereas in the revised syntax this increased to 54.

A test was conducted to examine the impact on recognition performance of these two syntaxes. A standard test was devised consisting of typical connected word commands such as BOX 1 1 2 3 DECIMAL 4. Three pilots conducted the same test with both versions of the syntax during flight using the same training templates. The difference in recognition word error rate for the two syntaxes is shown in Fig 6. Not only are there differences in performance for the two syntaxes but also significant variations between pilots. The reason for the range in operator performance is believed to be speaker variability; it is hoped that future speech recognition algorithms may be more robust.

As the general reaction to DVI on board the BAC 1-11 was still favourable, it was decided to attempt integration with the FMS.

The implementation of route changes through the FMS keyboard is a time-consuming and cumbersome process, and therefore it was in this area that we concentrated our DVI integration efforts. A variety of route changing options are available to the pilot by

(e) Response time to pilot inputs must be short; there should be no limit on the rate at which the pilot can enter data. Also, at the completion of any input sequence, the system should provide any computed information, demanded as a result of that input, within 5 s.

Experiments with time control algorithms have shown that a high degree of accuracy (typically ±5 s) can be achieved in meeting time constraints at an end-of-descent waypoint[6]. This accuracy is only achieved by using engine thrust in excess of flight idle or unwanted throttle activity in some wind conditions. It has proved difficult to predict the wind structure accurately during a descent, when using a combination of forecast wind along the descent path and actual wind being experienced by the aircraft at its current altitude. Considerable improvement in the accuracy of forecast wind data is required if such tight time constraints are to be met in a fuel efficient manner.

7.3 Man-machine interface

7.3.1 Displays

The clarity, sharpness and colour definition produced by shadow mask CRT displays make a very favourable impression on all pilots. The use of colour enables far more information to be presented without clutter and potential confusion, than can be displayed on monochrome displays. Nevertheless, care must be taken to display only essential information at any time. Even with colour discrimination, it is easy to achieve a cluttered presentation if the temptation to display desirable, as opposed to essential, features is not strongly resisted.

For civil applications we feel that the colour chosen for a particular feature is not critical. Of more importance is ensuring that a consistent colour code is applied throughout all display modes and also from one display to another. Primary colours have been found to be too harsh, and are more acceptable when desaturated. Pilots generally prefer the softer tones of colours like cyan and yellow. Magenta is considered by many to be a harsh colour and could therefore be useful for highlighting purposes, although the conventional use of amber for caution and red for warning appears to work well and has, of course, been readily accepted.

Flashing any symbol on and off is very attention-getting and is therefore effective for alerting purposes. It is, therefore, essential to avoid inadvertent flashing of symbols on the display (eg if a parameter is dithering at one end of its displayed scale, it is necessary to add hysteresis to prevent it flashing on and off).

Electronic instrument displays are still in a very early development stage and therefore, in our view, it would be premature to attempt to standardise on the symbology and colour coding in use on civil aircraft. The flexible nature of CRT displays should be fully utilised. The optimum choice of colour and symbology will largely depend on the exact combination of airborne equipment and capabilities, together with the type of operation any particular aircraft is designed to perform.

Apparent symbol movement can occur on the displays (in the form of sudden jumps in the apparent position of one symbol relative to another) if symbols positioned close to one another on the screen are drawn at significantly different times (more than about 4 m sec time difference), Some people are more susceptible to this effect than others. Time differences between drawing various symbols are a function of the screen refresh rate, and problems of this sort are not usually apparent if refresh rates greater than 60 Hz are employed.

The uniform brightness level of all displayed information is a feature much appreciated by pilots. This particularly applies in night conditions, when CRT displays compare favourably with the standard of panel lighting found in most cockpits using conventional instruments. CRT displays must, however, be designed to operate without flickering when set to the very low brightness levels required for night flying.

Large CRT displays (8 inch x 8 inch in the 1-11) give a wider choice of formats for presenting data compared with smaller displays. This has proved important in two areas. On just one display it has been possible to present all primary flight information, using conventional circular analogue counter-pointer formats for speed, height and vertical speed. The second area concerns the map display, where it has been possible to position the aircraft symbol towards the centre of the screen, rather than close to the bottom. By this means a good look-behind capability is provided without unacceptably compressing the range scaling of the map.

It is worth again emphasising the overall benefit of the map display. Its introduction on the civil flight deck is considered to have produced the largest reduction in pilot workload for many years.

7.3.2 Workload reduction

A cursor symbol on the map, which can be driven to any required position in order to designate already defined points for inclusion in the route, or to generate totally new waypoints, has added considerably to the speed and flexibility of route changing compared with keyboard entry. Driving the cursor with a roller-ball controller was found to be a

On a longer-term basis we are cooperating with the UK Civil Aviation Authority and Eurocontrol to investigate a mode S type of data link. It is hoped that this programme will provide a prototype airborne mode S transponder together with a Data Link Processor Unit for installation in mid 1987. In the meantime we have installed a two-way data link in the 1-11, using radio modem equipment connected to VHF transceivers, which we intend to develop as a mode S simulation. By this means, we are able to demonstrate how routing demands and constraints might be passed to the aircraft from some future ATC system. We can also investigate the man-machine interface problems associated with data link. Currently, we present the data-link message on the pilot's map display. Required routing together with any constraints, are manually input to the FMS by the pilot, who then checks that the demanded speed to meet these constraints is within the aircraft's capability. In the future he will be able to reply over the data link, either accepting the route and constraints, or requesting a different time slot or alternative routing.

7 LESSONS LEARNED

7.1 Navigation

Position fixing systems, using range information from two DME ground stations, achieve mean errors of about 0.25 n mile, while systems using multiple DME ground stations have a potential for achieving mean errors of perhaps about 0.1 n mile. These accuracies depend on knowledge of ground station position and accurate reply delay. Published coordinates are sometimes in error, and sometimes differ depending on the source of information used (eg whether civil or military documents are consulted). The integrity of ground station coordinates in airborne data bases will become very important if DME navigation systems are used as a means of reducing track separations to increase airspace capacity. Another potential source of error lies in the method of defining these station coordinates in terms of latitude and longitude. Different countries use different grid coordinates for surveying purposes. We believe a variety of earth models are used for converting from grid coordinates into latitude and longitude. This can lead to differences of up to 0.5 n mile in defined position. Coordinate conversion problems of this sort could affect other accurate position fixing systems such as GPS, and indicate a need for common conversion standards.

To avoid receiving range information from other stations on the same frequency, some navigation systems only tune stations when the aircraft is within the protected range published for each station. Other systems ignore the protected range figure, but carry out validity checks on both range and range rate before accepting data as coming from the selected ground station. This latter method may well have benefits in areas sparsely equipped with ground aids, as any validated information can be utilised for position fixing irrespective of range from the ground station.

An electronic map giving estimated aircraft position, provides a very compulsive and believable display to the pilot. It is therefore essential that any degradation in the position fixing accuracy (eg as a result of reverting from DME/DME to VOR/DME mode) is suitably indicated to the pilot. Ideally, the probable error in estimated position (based on navigation mode in use, or time since last position fix) should be calculated and clearly displayed when greater than some residual level (say 0.5 n mile).

The use of a frequency agile DME for multi-DME position fixing brought to light two problems. First of all, some difficulties were experienced in positively relating a particular range value with its associated ground station frequency. This problem stems from lack of adequate data word identification in the ARINC specification for airborne equipment. The range data from a particular ground station is output on the DME data highway immediately after the data word containing the frequency of that ground station. Difficulties can arise in the event of failing to receive some data words, with a danger of associating the wrong range data with a particular frequency. This problem would not have arisen if each data word had been uniquely tagged. The second problem area concerns the polar diagram of DME airborne aerials. Reception in some directions is inevitably better than in other directions. This can lead to a less than optimum spread of available aids around the aircraft and therefore a reduction in position fixing accuracy. It may be desirable to consider feeding agile DME transponders from more than one aerial if maximum accuracy is required.

7.2 Flight management

The capability of flight management systems to control the azimuth, vertical and speed components of an aircraft's flight path satisfactorily has been demonstrated adequately, with a number of such systems already in airline service. Because of the wide range of options available to the pilot and the complex interactions between the many different operating modes, provided by these automatic systems, it is clear that conventional multi-function keyboards do not provide an ideal interface between the pilot and the computer system. Although they may appear self-evident, it is worth stating the main requirements of any future FMS man-machine interface.

(a) System current operating state and engaged modes must be displayed clearly.

(b) Options available for selection must be shown.

(c) Methods for obtaining required data must be logical and obvious.

(d) Methods of inputting, storing and displaying data must be consistent.

keyboard operation, and most of these were made available as direct voice commands (see Table 1). The pilot could, therefore, enter the required form of route change by voice, together with relevant waypoints defined by name, latitude and longitude, or by range/bearing from a known waypoint. He could verify correct speech recognition using the DVI visual feedback display on the coaming in front of him. To ensure that his commands had been transmitted correctly from the recogniser, through the associated microprocessor, to the FMS, the demanded route modifications were shown on the colour map display in the form of dotted lines, with the current route still displayed in solid lines. When satisfied that his commands had been correctly interpreted, the pilot would then use voice to execute the route change, with the map then displaying the new route in the conventional way (ie with solid lines).

Also integrated into this FMS/DVI route change system, was the roller-ball/map-cursor combination described in section 6.3.1 above. The cursor position could be used to nominate a pre-designated waypoint or define a new one. These positions, combined with DVI commands to state what should be done with each waypoint, provided a flexible and convenient method of modifying the existing route. The procedure was found to be particularly useful for constructing entirely new routes involving input of many waypoints.

In addition to route changing functions, DVI has also been introduced to control FMS mode selection and to insert any commanded values needed for operation in these selected modes. This application of DVI, where voice is used to control systems which have a direct effect on aircraft attitude, height, heading and speed, is more relevant to military aircraft than to the civil flight deck, where it is generally easy to select modes and demanded values using simple switches and knobs. The principle adopted for route changing, where the pilot verifies that the system has understood his voice command before he executes that command, was also applied to the control of FMS modes and inputs.

The concept of using voice input to control any of the aircraft systems and facilities was proved feasible and was readily accepted by the pilots. However, delays between uttering commands and obtaining aircraft or system response were found to be unacceptably long in most cases. These delays were caused by a combination of the time taken for speech recognition and the long transmission and handshake times between the experimental equipments used to implement the commands.

The vocabulary required for the control of electronic displays, comms and nav and the FMS by voice is now 235 words. This size of vocabulary has caused certain problems not only for the ASR but also memory problems for the operator. These problems are discussed in section 7.3.2.

6.4 Air Traffic Management

Research into integrating airborne FMS capabilities with future strategically-based air traffic management systems is going on in a number of countries. Within Europe a GARTEur Action Group (FM AG03) with members from the Netherlands, West Germany and the UK research establishments, has recently produced a future ATM scenario in order to provide a framework to help assess the benefits of integrating FMS and ATM systems. This scenario identifies a number of broad areas where changes to present ATC systems are expected. These include improvements in en-route capacity through exploitation of more accurate three-dimensional navigation, and use of longitudinal (time or four-dimensional) navigation and control to increase capacity of junctions and terminal areas. To meet these and other expected developments, the scenario suggests that three distinct levels of communication will be required:

(a) Background level - for automatic exchange of data between air and ground computers with no direct human intervention.

(b) Strategic level - for human initiated exchange of strategic ATC planning and clearance information.

(c) Tactical level - for exchange of information requiring short-term response, eg ATC tactical instructions.

It is recognised that for some time to come voice R/T will remain the primary channel for tactical transmissions. However, data link is considered to be the most appropriate mechanism for the background and strategic communication requirements of future ATM systems. As any change to ATC systems must take place in an evolutionary manner, it follows that an early introduction of data link features into the present mainly tactical ATC system could be of benefit in developing the necessary formats, procedures and equipment. Passing weather data from the ground to aircraft and confirmation of R/T clearance and control messages are examples of where data link could be introduced in to-days environment.

Data link research using our 1-11 aircraft started with the installation of a Data Buffer Unit which interfaces with a SSR-type transponder unit, to provide a down-link of aircraft parameters to the ground. This airborne-derived data is being used to assist development of the ground SSR network required for future mode S operation, and this work will continue in conjunction with RSRE Malvern.

considerable improvement compared with using a joystick. Pilots find positioning the cursor is easier when using direct position control, as in the roller-ball case, compared with using the rate control necessary with a spring-loaded-to-centre joystick.

No agreement has been reached over the direction in which the cursor should move when the roller-ball is rotated in a fore-and-aft direction. Some pilots want the cursor to move up the screen for a forward movement of the roller-ball, while others want the reverse sense. The same disagreement on convention also exists for joystick control of the cursor.

Rotatable knobs for dialling pilot selected values need to be positioned next to the visual display of the value selected, so that the pilot can see the knob and the value at the same time. Selected values may therefore need to be displayed on, for example, the coaming area alongside the knob, as well as on the pilot's primary flight display.

The experiments on the integration of DVI have indicated the great potential of speech which can exploit a modality of human to machine communication which is so far unused. Work so far has indicated that the applications for DVI must be chosen with care, as certain tasks can already be done more quickly and accurately by other means, for example, a simple switch setting. Also needed is some feedback from the recogniser to the speaker, together with a simple means of correcting mistakes. Visual display feedback has been used so far, to good effect, but the role of audio feedback needs to be explored. Syntax is used at present purely to improve recognition performance, if it remains necessary it must not be obtrusive or restricting; ideally it should become more intelligent and equate more to the human use of context to improve understanding. Error rates for current recognition algorithms are about 1% or 2% per word for good subjects; algorithms need to be made more robust to cope with less consistent speakers and need to cope automatically with the changing background noise that is experienced in flight. Vocabulary size also presents an interesting problem in that a human can easily remember say 50 words, and would be unlikely to stray outside an unstructured vocabulary of say 1000 words. Between these extremes are vocabularies like ours of about 250 words for which the human cannot remember without being prompted which words and sequences are permitted.

The combination of a roller-ball driven cursor, to designate waypoints on the map and DVI, to define to the flight management system the exact form of route change required, was found to have great potential for overcoming keyboard entry problems. It is by combining the best features of particular input techniques in this way that the pilot can be provided with the most effective methods of interacting with the automated systems at his disposal. He may wish to use different input techniques for a particular task, depending on the workload he is under at the time, and therefore the man-machine interface must remain flexible with a variety of modalities available to him.

Recognition and implementation delays have been found frustrating, with total system delays of up to 6 s being experienced on occasion. Tolerable delays are probably less than 1 second for a complete operation. To achieve this not only will faster recognisers be needed but more efficient computing architectures will be required for system processing.

8 FUTURE PROGRAMME

8.1 Navigation

Further development of the data puddle concept will form the main part of our future navigation work. Special algorithms need to be developed to improve position fixing accuracy, when all available DME stations are situated in approximately the same direction relative to aircraft position, thus giving very small subtended angles and poor position fixing. The use of range rate information, in conjunction with aircraft track angle and ground speed, to compute aircraft bearing from each ground station, will be investigated to determine potential benefits. This technique will also be tried in situations where range from only one DME ground station can be obtained.

Additional sensor inputs will also be incorporated into the data puddle system. These will include VOR bearing information as well as data from an inertial navigation system.

Because wide variations in position fixing accuracy will occur using data puddle, from very high precision in areas well equipped with DME ground stations to relatively low accuracy when only one aid is available (or even non at all), it is important to provide the pilot with an indication of the probable error in estimated position. A method needs to be developed for computing this probable error taking into account the confidence level attached to each element of data contributing to the best estimate of position.

Other position fixing systems are expected to play a significant role in future civil air transport operations. These include MLS and GPS, and our research programme will include integration of position data from these sources with the on-board FMS, together with consideration of any display and pilot interfacing requirements resulting from such integration. We plan to install a GPS receiver in the 1-11 for flight trials during 1987.

8.2 Flight Management

To achieve maximum airspace utilisation, it will be necessary for aircraft to conform accurately with altitude, speed and time constraints at particular route locations, such as at airway intersections and end-of-descent points. Our programme will continue to investigate methods of complying with such constraints in a fuel-efficient manner. In lightly loaded traffic situations, it may be possible for Air Traffic Control to define a four-dimensional 'window' at the constraint point, such that the aircraft can arrive at the defined position within a particular height band, with speed held within certain limits, and somewhere between defined earliest and latest arrival times. In this way the airborne system would have more freedom to follow an optimised flight profile and could absorb errors in wind forecasting in a cost-effective manner more easily. We will be investigating techniques for meeting constraints defined in this way, and will extend the work to include multiple constraint points in the route. Our work will provide a logical step towards the concept of future ATC systems issuing aircraft clearances in the form of four-dimensional tubes in space, as envisaged in the GARTEur future scenario.

The structure of present flight management systems often makes it difficult to introduce new features and to interface with other systems, for experimental purposes. Some effort may be spent in exploring alternative FMS structures that could provide greater flexibility, allow easier modification and, therefore, be more suitable for our research programme.

8.3 Man-machine interfacing

The emphasis of our future man-machine interfacing work will be on integration of displays and inputting techniques, to provide the pilot with flexible options for controlling and monitoring the aircraft and its systems. The aim is to combine the best features of particular inputting techniques to obtain satisfactory overall solutions to the many different situations faced by the pilot (the combination of roller-ball driven cursor symbol and direct voice input is one example of a possible solution).

A large experimental display area will shortly be provided in the centre of the 1-11 cockpit coaming, with CRT displays with touch-sensitive screens being fitted initially. These will be replaced by flat-panel displays as soon as suitable devices prove worthy of flight evaluation.

There is scope for improvement in current map displays, particularly in terms of better presentation and integration of vertical information, possibly leading to some form of 'path-in-the-sky' display. There is also a need for improved display of heading information on the map, as some pilots miss the level of orientation provided by conventional compass rose displays. The integration of weather radar data on the map is another important aspect, but can only become part of our programme if funding for suitable radar equipment is made available.

Improvements are expected in the capabilities of automatic speech recognisers, and new systems will be assessed as they become available. It is particularly hoped that improvements will be evident in their capability to cope with changes in background noise level, and that faster computing will reduce recognition delay times. Our programme may also investigate the use of audio feedback of DVI recognition to supplement the present visual feedback method.

One long-term aim of our research is to develop a 'flying desk' cockpit environment in the 1-11 aircraft. This would involve removing the control column on the port side of the aircraft and installing a sidestick or ministick controller. By this means the space around the pilot becomes more accessible, and allows greater freedom for introducing new display technology and improved interfacing techniques. We are constructing a ground rig to enable full testing, development and integration of alternative display and inputting methods to take place before installing the most promising systems in the 1-11 for flight testing.

8.4 Air Traffic Management

The future scenario suggested by GARTEur Action Group FM AG03 will be used as an overall guide to our air traffic management programme. This will be carried out in cooperation with other agencies such as CAA, Eurocontrol and GARTEur, as it is vital to evolve international solutions to ATM problems, as well as achieve compatibility between the ground and airborne elements. The principal aim of the programme is to improve overall operational efficiency, which involves increasing airspace capacity and allowing aircraft operators to achieve individually optimised flight profiles.

Our flight programme investigating the use of data link will continue, in conjunction with RSRE Malvern, by providing airborne-derived data to assist development of the ground SSR network required for future mode S operation. We will also continue to develop a mode S simulation capability, using radio modem equipment, with the aim of demonstrating the concept of a ground-based data network being linked to the aircraft with its airborne data network. Methods of integrating the data link system with the avionic network will be investigated, including any display and hard-copy requirements. Provision of automatic entry of data-linked ATC routing commands and constraints into the FMS albeit after acceptance by the pilot, is one example of the integration required.

9 A LONG TERM FUTURE LOOK

This Paper has concentrated on current and projected developments in avionic technology. There are corresponding developments emerging from research into ATC, examples include better radars and radar processing which will allow more precise monitoring in busy airspace. Also, algorithms for automatic conflict prediction and resolution will be combined with refined automatic scheduling, to provide a complete computer-based source of ATC advice. Here too, better man-machine interfaces will be needed, large full colour displays and direct voice input will almost certainly have a role to play in these improved interfaces.

It is assumed that, with computer-based systems on the ground and in the air, digital data links will form the obvious and ideal basis of air/ground communication, with voice RT being reserved for special functions such as emergency actions or perhaps even reassurance.

There is as yet no agreement on how a future ATM system would operate, but the following proposed sequence may well serve to illustrate our own thinking for the years beyond 2000 and also to provoke further discussion.

(a) The aircraft approaches a control boundary and makes a bid for a preferred route and timing.

(b) The ground system checks the request against the known traffic situation and offers a trajectory and time slot; this may or may not be the one the aircraft requested.

(c) If necessary, data link based negotiation ends with an agreed description of the trajectory, defined in four-dimensions all the way to the runway threshold.

(d) This trajectory description includes data on the allowed tolerances, _ie_ the size of the defined tube in space. Low density traffic allows loose tolerances which the aircraft can exploit to minimise its operating cost; conversely high traffic densities will demand a tightly constrained or narrow tube to meet traffic needs.

(e) The aircraft then executes the trajectory and is monitored by the ATC system, with intervention only needed for deviations or emergencies.

Even these simple statements pose many problems in the technical, human engineering and possibly political arenas and, as yet, the cost benefit studies needed to justify such major change have not been carried out.

The future arrival of satellite based systems for communication, navigation and surveillance, such as are being considered by the ICAO FANS committee, provides a common reference for such operations rather than altering the ATM concepts.

10 CONCLUSIONS

This Paper has attempted to describe the problems and resulting trends that have led to the existing level of avionic sophistication in the latest generations of civil aircraft. These standards of avionics have quite short economic payback times and would appear to have fully justified the investment involved. However, airlines have realised that still greater savings could be realised if ATC would allow procedures more compatible with modern aircraft and systems. As a result, pressures are mounting on ATC authorities to move this way. ATC, at the same time, is facing problems due to already saturated bottlenecks in the system and yet is facing substantial predicted increases in traffic demand.

The solutions to both economic and traffic problems would appear to be with increased dependence on computer-based advice and automation. Given the assumption that pilots and air traffic controllers will remain in the loop, then a whole new range of nam-machine interface problems have to be solved. The civil avionics research programme at RAE Bedford has been working for some time in the technologies and their integration needed for a future air traffic management system; this Paper has concentrated on some of the technologies that will be present in future civil flight decks.

Some important lessons emerging from this largely experimental work can best be summarised under a series of headings:

NAVIGATION

There is still substantial development potential in conventional radio aid based navigation but there are problems to be faced with the accuracy and integrity of data bases. It is probable that a completely new system based on satellites would also suffer from these problems.

FLIGHT MANAGEMENT

Current FMSs are very capable, perhaps even over complex. Future developments must include better man-machine interfaces. Good, fuel efficient, four-dimensional descents need better wind and other atmospheric data than is given by current forecasting techniques.

DISPLAYS

The arrival of full colour CRT displays on the flight deck is an enormous advance, and here as elsewhere big displays provide more opportunity for an integrated presentation than do small ones. The electronic map is very powerful and will be the medium which will make future complex trajectories comprehensible.

WORKLOAD

Modern cockpits with their clean, uncluttered presentations are very good indeed, but a future ATM scenario will be more complex than at present and will require greater dialogue between the pilot and his computing systems. Direct voice input and other techniques offer great potential in this dialogue, but they must be used carefully if this potential is to be realised.

Finally, it is worth pointing out again that all of these developments are driven by the demands for additional traffic capacity and improved efficiency and that therefore additional efforts to quantify the benefits are needed.

REFERENCES

1 Chief Scientists' Division, Civil Aviation Authority, 'Report of the UK Air Traffic Management Working Group'. 1981

2 Federal Aviation Authority', 'The USA National Airspace System Plan'. 1981

3 V. Attwool, A. Benoit, 'Fuel economies effected by the use of FMS in an advanced TMA'. The Journal of Navigation, Vol 38, No 1, January 1985

4 R.C. Rawlings, R.A. Harlow, 'Flight trials to determine the overall system performance of distance measuring equipment'. 1979, RAE Technical Report TR 74140

5 R.A. Harlow, 'Flight measurement of RNAV system performance using various combinations of ground aids and airborne sensors'. 1980, IEEE, Position, Location and Navigation Symposium, Atlantic City, New Jersey

6 N. Witt, 'A flight investigation of avionic systems for future air traffic management'. 1985, RAE Technical Memorandum FS(B) 606

7 R.C. Rawlings, 'Entry and exit procedures for RNAV holds'. 1986, RAE Technical Memorandum FS(B) 635

8 N. Witt, E. Strongman, 'Application and experience of colour CRT flight deck displays'. Displays Journal, April 1983

Table 1

OPTIONS AVAILABLE TO THE PILOT BY VOICE COMMANDS

(a)	Route change procedures	
	1	Go direct from present position to new waypoint
	2	Go direct from one waypoint to another waypoint
	3	Insert a new waypoint after an existing waypoint
	4	Change one waypoint for another waypoint
	5	Delete existing waypoint(s)
(b)	Selection of lateral, vertical, speed and time modes	
(c)	Insertion of commanded values relevant to each mode	

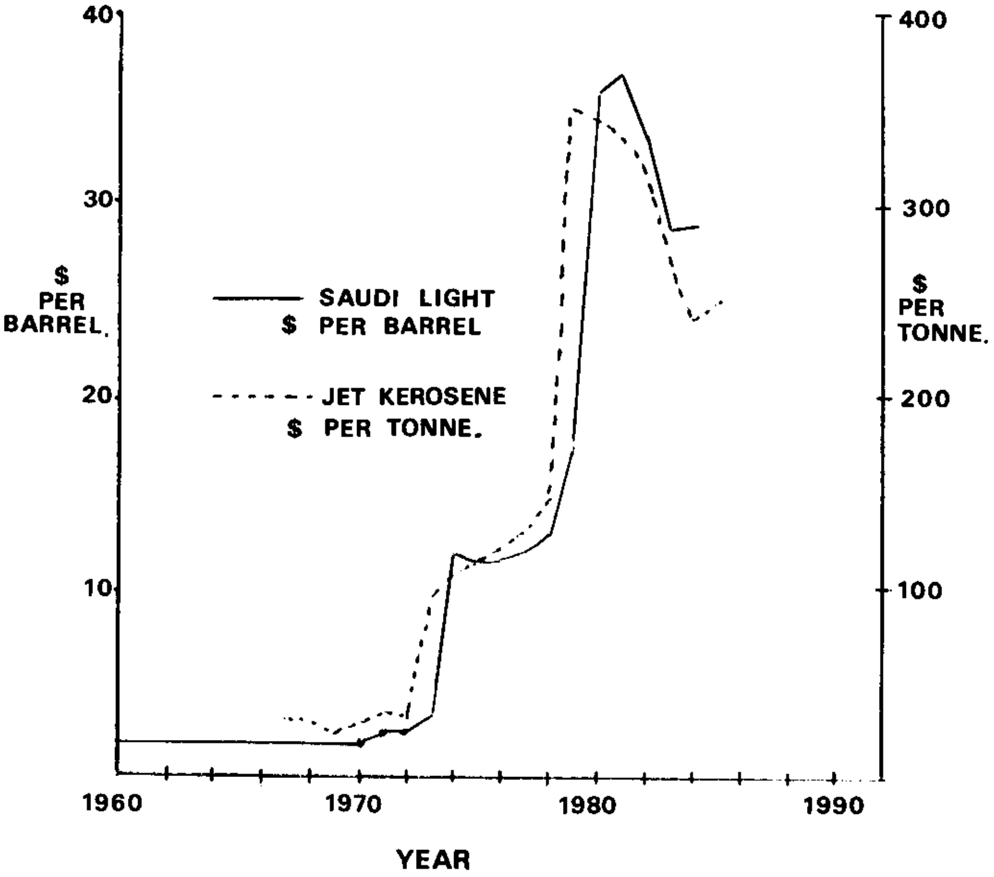

FIG 1 ROTTERDAM SPOT FUEL PRICES.

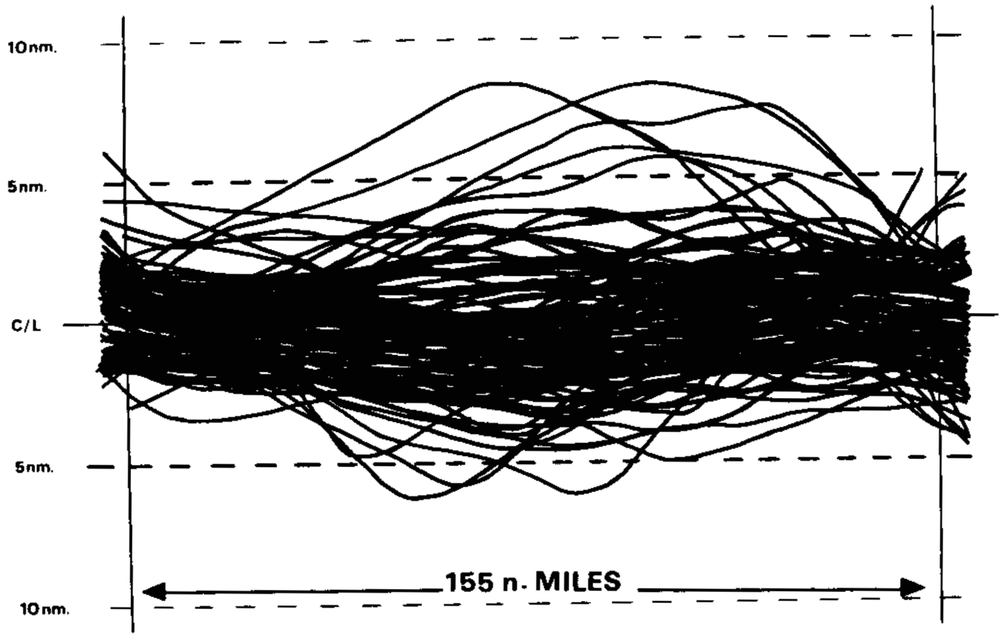

FIG 2. OBSERVED ON AIRWAY PERFORMANCE USING VOR.

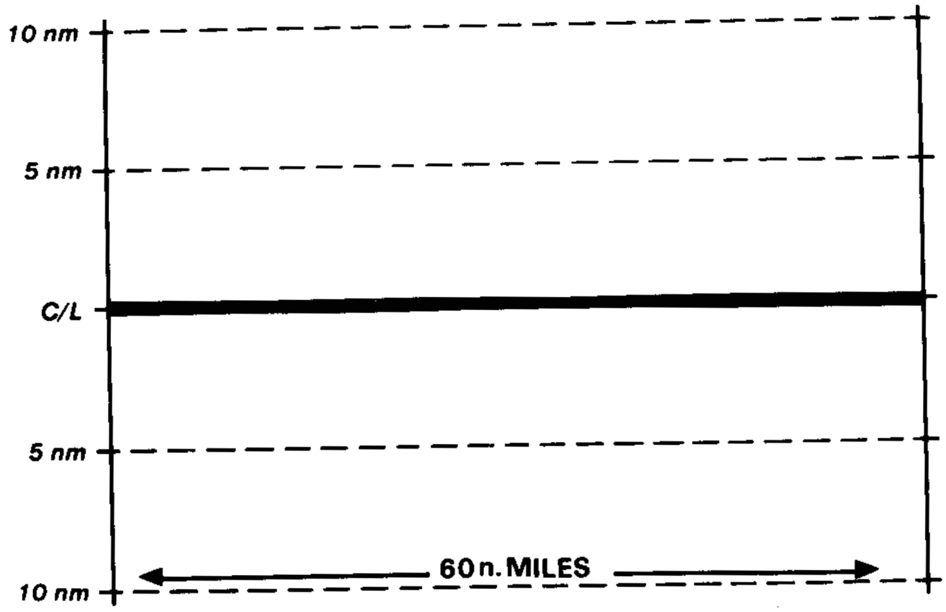

FIG 3. OBSERVED FLIGHT PERFORMANCE USING DME/DME.

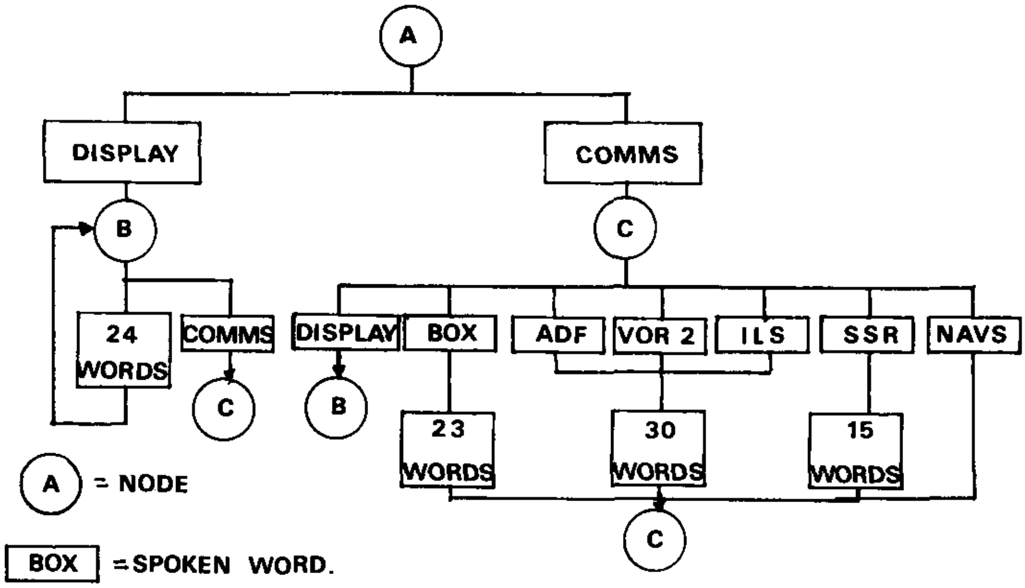

FIG 4. BLOCK DIAGRAM OF DVI SYNTAX A [COMMS AND DISPLAY]

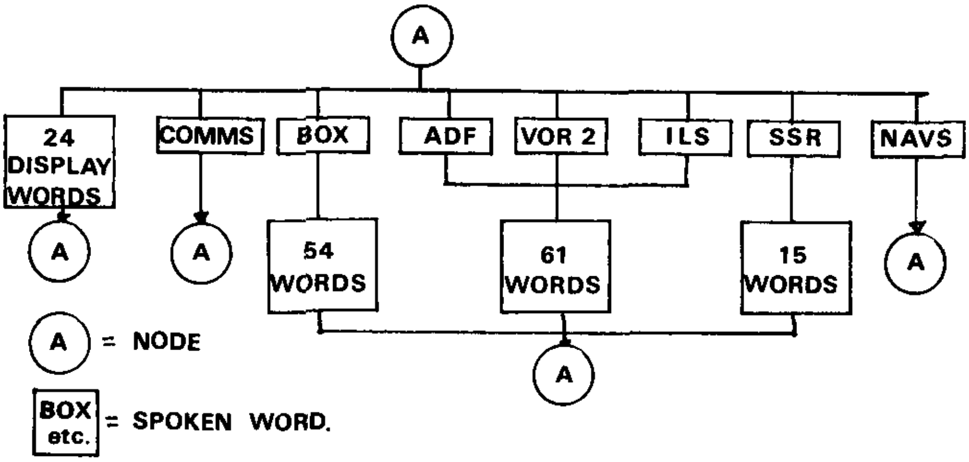

FIG 5. BLOCK DIAGRAM OF DVI SYNTAX B [COMMS AND DISPLAY]

PILOT	NO OF COMMANDS	NO OF ERRORS	% WORD ERROR RATE
SYNTAX A:			
A	278	2	0.7
B	283	3	1.1
C	273	12	4.4
SYNTAX B:			
A	228	4	1.7
B	229	10	4.3
C	208	18	8.6

FIG 6 INFLIGHT RECOGNITION RESULTS OF SYNTAX A AND SYNTAX B

CP 410

SEMI-AUTOMATIC CROSS-CHECKING BETWEEN DIFFERENT COPIES OF THE SAME FLIGHT PLAN

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SUMMARY

A flight-plan usually exists in several different forms, in the aircraft flight management system, as hard copy on the flight-deck, in one or more ATC data processors, and distributed over flight-progress strips (or their electronic equivalents) in one or more control centres. Any discrepancies between various versions of the plan are potentially hazardous. Given that the flight plan is already stored, for one reason or another, in at least one computer, it is proposed that each computer should also be used to generate a "check word" which can easily and rapidly be compared with that stored as hard-copy or in some other machine. The check word might consist of four alpha characters which can easily be remembered and passed by voice. The paper discusses possible algorithms for generating check-words, and gives the results of some laboratory trials of a prototype system.

ERRORS IN GENERAL

Air traffic control does not have a monopoly over clerical errors, and the technique outlined in this paper may well be applicable in other areas, but work has so far concentrated on flight plan data, where undetected errors, although rare, can have major safety implications. A discrepancy between the flight plan used at route qualification briefing and that supplied to the flight management computer on the day, was a factor in the disaster to New Zealand flight TE901, which flew into the side of an Antarctic volcano, Mt. Erebus, in November 1979. Measures have recently been introduced in the UK to ensure that controllers are reminded, by a suffix to the radio call sign, when an aircraft is flying to a plan that differs from a version earlier stored by ATC. The European Air Navigation Planning Group are reviewing the procedures more generally. It seems likely, therefore, that problems have been encountered in ATC as well as on the flight deck.

The problems of validating copies of important documents must have arisen very early in history, when manual copying was virtually the only method by which a document could be duplicated. If there is a task more boring than the meticulous copying of a lengthy document, it must be the subsequent collation of the copy and the original in the process of checking for possible errors. A number of techniques were accordingly devised which, whilst not guaranteeing to detect all possible errors, had the advantage that they could detect many errors by a simple check. Such simplicity not only saves time, the process is more likely to be carried out correctly. The so-called SECUNDO FOLIO method was based on a comparison of the leading words of the second or subsequent pages of two nominally identical documents, on the grounds that, given reasonable standardisation of letter size and spacing, a discrepancy at the top of the two "second pages" would point to a repetition or deletion from some earlier page. Each page of the hand-drawn scrolls of the Jewish Bible, the TORAH, is believed to incorporate a means whereby the scribes can check that the page contains the correct number of words.

Such checks, no doubt, rapidly draw attention to many of the errors likely in handwritten copy. They do not serve to catch other errors common in typing, such as the transposition of two adjacent characters. Such mistakes are easily detected and corrected by human readers of plain language text, but an error in, for example, a call-sign, SSR code, or a waypoint co-ordinate in an aircraft flight plan may more easily escape detection, although such an error is potentially dangerous. Errors in messages sent by teleprinter or other telegraphy channel may contain, in addition to normal typing errors, one or more corrupt "bits" in the string of characters received. Such errors can be detected by means of an error-detecting code in the transmission mechanism. If the errors are sufficiently sparse, they may even be corrected on reception. In its simplest form, an error-correcting code is formed by adding a redundant bit to the seven-bit code that is essential to define an ASCII or ISO (CCITT Alphabet No. 5) character. The redundant bit enables a single-bit error in the character to be detected, but correction is only possible by demanding a replay of part of the message. More elaborate codes are possible, such as the frame check sequence used by the Common ICAO Data Interchange Network, CIDIN (1), or that proposed for SSR Mode S. These are capable of detecting a moderate number of independent errors, and the faulty bit can often be precisely identified, thus enabling the correct message to be reconstructed at the receiver. These mechanisms can only detect errors that arise after the redundant bits have been incorporated in the message, "garbage in, garbage out" still applies.

Given a message such as a Flight Plan, which has a defined structure and which is handled by computers which can be programmed to test the validity of the message content, further checks are possible. For example, one can check that the cruising level and airspeed are within the aircrafts' capabilities, that successive waypoints along the route are not too far apart, and so on. These checks on the stored flight plan cannot do more than establish that the flight plan is credible, it does not have to be correct:

yesterday's flight plan would pass the credibility checks as easily as today's. Given a suitable data link, it is possible, in principle, automatically to check that the data in the flight management computer is consistent with that held in the ATC processor, but it will be much more difficult to check that the computer data is consistent with a hard-copy version.

Reference 2 pointed out a drawback to the present N. Atlantic position-reporting system, where waypoint co-ordinates (latitude and longitude) are quoted as integer multiples of a degree, corresponding to the lateral separation standard, 60 nm. The effect is that many errors in inputting waypoint data will result in a plausible but incorrect figure being delivered to the computer. If the lateral tracks were separated by 59 nm, say, transposition of two latitude digits would yield a result that was not an integral multiple of 59 minutes, and the error could easily be detected. Unfortunately, it is difficult to see how the ATC system could now make a transition from 60 nm to 59 nm spacing.

THE USE OF "CHECK-WORDS"

The present paper is primarily concerned with the detection of differences between two or more versions of a given message. The proposed method is quite general, and does not need access to any data other than the message itself. An algorithm has been devised which generates, at the end of the message, or at the end of a page if the message is long, a "check-word" consisting of four alphabetical characters, say. The check-word is easy to compute, and the result can be printed at the end of hard-copy versions of the message, or displayed at the output of any computer holding the same text. The four-letter check-word is suggested as a suitable length for most purposes, but there is no problem in making the word longer or shorter if desired.

The four-letter check-word, supposing we are confined to the 26 alphabetical characters in the ICAO alphabet (3), is capable of taking any one of 456,976 combinations. Let us, for the moment, consider some numerical representation of the check-word, hereafter referred to as the "value" of a given text. The text will, in general, have more than 26 different characters, if we include the numerals 0-9, punctuation marks and, for some applications, diacritical signs (represented by a letter, backspace and some agreed symbol) used to denote accented characters not found in the alphabet defined in reference 3. The alphabet used in the original text is not important so long as there exists some agreed method of representing each character in the alphabet by some numeral unique to the character. This number is then multiplied by a "weight" chosen in accordance with some rule to be discussed below. The product, here termed the "value" of the character, is added to that of all other characters in the message, and the total, the "value" of the message as a whole, is used to define the check-word, by some means to be discussed later. The simplest possible algorithm for converting a text into a check value is to give each character the same weight, unity say. Unless the value thus derived exceeds 456,976, the check value is a reliable test that two copies of a given message contain the same characters, but there is no check that the characters are in the same order in the two versions. If the resulting value exceeds 456,976, the value used for check purposes is the remainder obtained on division of the original figure by 456,976. There is therefore a risk that two different messages may yield the same check word. This situation is inevitable, since the number of possible messages is infinite, and the possible permutations of a limited number of characters forming a check word is finite. The probability of a coincidence can be reduced to any desired level by making the check word long enough. For the present purposes, it is suggested that, since the probability of the error which the check word is to detect is itself low, a reduction in the resulting risk by a factor of 100,000 may be more than adequate.

To overcome the danger of failing to detect transposition of a pair of characters, the algorithm that generates the check value must be more complex than suggested above. Transposition of two adjacent digits can be detected by giving different weights, eg 1 and 3, to alternate characters. The difficulty remains that many simple errors, such as 412 for 214 will escape detection. A better method is to give each character a different weight, at least until some practical upper limit is reached. This can be achieved by giving each character a weight equal to the character's position in the message. For a long message, it will eventually be necessary to restart the numbering process to avoid the need to handle inordinately longer numbers, but see below.

Having computed the value of the whole message, it is now proposed to convert it to a group of alphabetical characters, four say. Four alpha characters can represent more than 400,000 combinations, and is easier to remember than a group of six numerals. An obvious method of conversion is to express the value in radix 26. Just as in the normal decimal convention, the four digits of a number, 2345, say, denote (1000 * 2) + (100 * 3) + (10 * 4) + 5, in radix 26 the digits would denote $(26^3 * 2) + (26^2 * 3) + (26 * 4) + 5$. Instead of ranging from 0 to 9, the individual digits can each range from 0 to 25 and substitution of alpha characters is now a trivial task.

A weakness of this system is that a single error, such as the substitution of FL 270 for FL 290, is likely to change only a single character in the check-word: the "most significant" letters will change only slowly as characters are added to, or subtracted from, the text to be checked. Indeed, since a typical flight plan requires only a short message, some of the letters in the check word may rarely change at all. An error can cause the check value to change in either direction. If a single error results in only a small change in the check word, there is a significant risk that two errors in the message may leave the check word unchanged. This situation can be improved by using weights which vary rapidly over a considerable range between successive characters, the object being to produce weighted character values which are spread over the entire available range, even for short messages.

The use of a pseudo-random number generator to generate a sequence of weights does not easily satisfy the requirement. We need an algorithm which enables all conceivable types of computer to generate the same random sequence. Further, the suggested scheme would lead to calculations involving large integers, and multiple-length arithmetic would be needed in many machines, with a subsequent penalty in processor time. An alternative approach, that involves only arithmetic on small integers whilst avoiding the problems involved in generating standardised pseudo-random integers, will be discussed in the following section.

THE PROPOSED SOLUTION

It is proposed to compute, not one "value" for the message, but a separate value for each character in the check word, using a different weight for each. It will be shown that, given a check word based on an alphabet of 26 characters, and a message alphabet of, say, 40 characters, only integers are involved in the calculation and none need exceed about 1040. Most of the numbers involved can be stored and processed as a single 8-bit word. The final step in converting each message value into a single alpha character is to divide the value by the number of available letters in the alphabet and to discard everything but the remainder. If there are M characters, this remainder will, in what follows, be referred to as the value (MODULO M). It can be shown that the value (MODULO M) of the difference, the sum, or the product of two integers is not changed if any multiple of M is subtracted from either or both of the integers before the calculation is commenced. The truth of this assertion is obvious, for MODULO 10, at least. The value (MODULO 10) of any integer is simply the least significant digit of the number as normally written, and it is easy to see that this digit in the result of an addition, subtraction or multiplication depends only on the least significant digits of the numbers input to the calculation. It is not necessary for the programmer to reduce his numbers to MODULO M at each step, but he is free to do so whenever the integers become inconveniently large.

From the argument given above, it is clear that, with the suggested method of generating the check word, there is no point in having a weight greater than M, since the outcome of the weighting process depends only on the weight (MODULO M). It follows, similarly, that if the number of characters in the alphabet used for the text (including numerals and other signs which are to be taken into account when computing the check word) is greater than M, there must arise situations where different characters in the text have the same value (MODULO M). For example, with a 40 character alphabet for the text and M = 26, no less than 14 characters will have synonyms when converted (MODULO 26).

This ambiguity can be resolved by using different values for M in generating the various letters for the check word. It can be arranged that if the 'true' and 'false' versions of a given character give the same value in the calculation of one character in the check word, the two versions of the text will result in different values in computing the other three characters. In the experimental version, the four letters for the check word are calculated for M equal to 26, 25, 23 and 21. The number of possible combinations of weights is equal to the number of check words now available, the lowest common multiple of the four values chosen for M, ie 313,950. We have resolved the ambiguity at the expense of a reduction in the number of possible check words from 456,976. The method of generating successive weights has been designed to ensure that each weight changes rapidly over the available range and that there is no correlation between changes in the weights used to generate different characters in the check word. Successive values of each weight can be calculated by a method which requires only the addition and/or subtraction of integers, so that the outcome will not depend on characteristics of the host processor.

EXPERIMENTAL RESULTS

For purposes of experimental work, the immediate source of test messages is the output of a word-processor, resident in a 16-bit micro. Most word processor software is so designed that it is difficult for an outsider to penetrate its workings. A simple method of appending additional software for check word generation is to use a second microprocessor to emulate the printer to which the word-processor output is normally delivered. This second machine can perform the necessary check word claculations on each character before passing it to the printer mechanism. The additional processing need have no serious effect on printing speed. At the end of the text, the emulator software appends the check word to the original text. This technique may be of interest to other workers wishing to test a check word system without disturbing some existing software package. The emulator can even be driven directly from a teleprinter.

Figure 1 shows a short section of the sequence of weights generated by the experimental word-check algorithm. The four numbers printed in each row correspond to the four characters in the check word. The pattern in the left-hand column repeats after 26 rows, that in the second after 25 rows, and those in the third and fourth rows after 23 and 21 respectively. Since these four numbers have no common factors, the pattern as a whole will repeat only after 26 x 25 x 23 x 21 rows.

Figure 2 shows a rather improbable message consisting of 24 rows of 40 identical characters, whose numerical equivalent in the software is unity. The check word, GAVJ, is shown below the text of the message.

25	19	15	20
6	6	13	15
3	13	19	2
22	20	20	17
21	15	5	18
8	21	14	16
1	22	1	1
18	3	13	5
4	2	8	12
7	17	18	11
12	23	17	7
17	1	7	13
23	5	9	14
15	24	2	4
9	11	11	19
13	7	12	8
19	8	4	9
11	16	10	6
5	9	22	3
10	13	21	8
1	10	16	10
14	12	6	20
24	18	3	15
2	14	15	2
16	4	13	17
20	19	19	18
25	6	20	16
6	13	5	1
3	20	14	5

FIGURE 1. Sample Weightings

```
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

FIGURE 2. GAVJ

In Figure 3, a single character has been changed from "A" to "B" (numerical equivalent 2). Note the change in every character of the check word, GAVJ has become HRCK.

Table 1 gives the probability that a single radome error in the text will change any given number of characters in the check word.

Characters Changed	*Probability*
4	67.2%
3	29.3%
2	3.38%
1	0.14%
0	0.0036%

TABLE 1

Effect on a 4-Character Check word of a Random Change in One Character in the Text

```
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAABAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
```

FIGURE 3. HRCK

Table One was obtained experimentally, using the algorithm explained above, for 330,000 trials each involving one random change to a character selected at random in a 100-word text. The probability of failing to change even a single character in the check word is about 10 times greater than when the same algorithm is used with a text drawn from a 26-character alphabet, thus avoiding synonyms.

OUTSTANDING PROBLEMS

This paper has concentrated on "the flight plan". In fact, a flight plan is a relatively complex document containing assorted data not all of which is relevant to the tasks of every user of the data. It is not normally necessary, for example, to tell a flight management computer the type of aircraft in which it is fitted. Similarly, ATC authorities are principally concerned with details of the route by which an aircraft plans to pass through their particular jurisdiction. Although the check word proposal might be useful even to a single airline using the system purely for its own purposes, much greater benefits might arise if the technique was used by the majority, though not necessarily all, of the civil aircraft in a given region, not only for checks within the airline or the ATC organisation, but also for overall checks between aircraft and ATC. It will then be necessary to agree on those features of the flight plan for which checks are essential and carefully to frame rules to ensure that any interested party can base his check word calculation on the same elements of the text.

The flight plan is not the only message to which this technique can be applicable. ATC clearances, which frequently require manual inputs to a computer by pilots and controllers, may also lend themselves to the technique. There may be other applications. To explore the possibilities will require an international and interdisciplinary study beyond the capability of the present author's small team.

When the application has been more clearly defined, numerous protocol problems will require study. It may be found that not all users of a particular text wish to store the display characters in the same format. It is then necessary to compute the check word by a method that is not sensitive to the layout of the text as displayed or printed. This may involve, for example, treating any mixture of "carriage return" and "line feed" characters as synonyms for "space". Problems also arise if data is not stored as a string of characters, or if the data in the character string is not kept up-to-date. For example, numerical values can be written in a number of different styles, all mathematically equivalent, which yield different check words. A waypoint may be given as 0010N00500W, where the leading zeros in both latitude and longitude serve to draw attention to any confusion between latitude and longitude. Within a computer, the co-ordinates could well be broken up into their latitude and longitude components, the angles being expressed as degrees and fractions of degrees, or even as radians.

Real numbers, ie those involving some fractional part, present another obvious problem. Clearly, if two systems perform their calculations to different levels of precision, difficulties arise if a check word is used to determine whether two numbers are "identical". It will be necessary, before computing the check word to round-off any fraction to some agreed level of precision. This problem is common when attempting to make a comparison between numbers that have undergone some transformation before storage in a database, eg when 20 minutes of arc has become 0.33333... degrees. It will also be necessary for users to agree on a standard method of expressing numeric quantities as a string of characters, at least for purposes of computing the check word.

It may be argued that ICAO (4) has standardised number formats for use in flight plans, ATC clearances, etc, to the point where the above differences do not arise in the present context. Since this symposium is looking to the future, it should be appreciated that we may face higher accuracy navaids combined with more precise flight management systems, and ATC systems wishing to carry out more *detailed planning*. One way or another, these are likely to lead to a demand for more precise specification of aircraft co-ordinates, and the format problem may then raise its head.

Figure 4 shows a small sample of flight-plan derived data, as stored in an ATC computer, with a check word printed under each plan.

```
BA690 B737/C 420 EGLL P1055 330 EGLL.URIN..UG24N..R23.EPWA
     RAEA

BD774 SH36/C 205 EGLL P1105 060 EGLL.A1.EGBB
     RIDD

KM815 B737/C 420 EGKK P1110 330 EGKK.UA1..UA3W..UR16..UR46.MEDAL..TORLI..RO
TUN..GIANO..PAL.UA18.LMML
     YJFF

GAF1004 B707/C 468 TOLKA P1100 310 EDDK.UW39..UB1..EGL.CYYR :TACAN TO TOLKA
     NJPF

BA845 BA11/C 370 LIFFY P1125 170 EIDW.B1.EGCC
     EYRU

BA5445 BA11/C 400 EGNT P1130 230 EGNT..POL.A1.MID.A1E.LFPG
     OVGQ

UK703 FK27/C 240 EGNM P1130 150 EGNM
     HOKO

BA147 L101/C 494 EGLL P1030 330 EGLL.UG1.UB6..UB1W..UB5..UA4..VA4..VG8..VA16.
.VB15..W10..A21..R19..B54.OKBK
     VIJC

GBOAD CONC/C M200 EGLL P1200 600 EGLL. SWB2.5107N/0715W..5110N/0645W..4920N/
0600W..4946N/0353W..5008N/0149W..ASPEN.UR14..UR8..W38.NORRY..EGVN
     CMPR
```

FIGURE 4.

CONCLUSION

It was not intended to put forward a paper in which the check word was presented as the outcome of some mysterious process known only to the author. The description of the algorithm used in the experiments has been given in terms that were meant to be intelligible to readers unfamiliar with number theory. A better qualified mathematician, writing for similarly qualified readers, could, no doubt, have produced a more concise description.

The given algorithm is not the only means of generating a check word, and better *methods may present themselves*. The immediate object was to build a demonstrator system which might provoke discussion of the possible uses of this technique by ATC.

From the trials so far, it appears that the check word generator should have the following properties:

(1) It should be easy to implement in any microprocessor having a word length of 8 or more bits.

(2) It should require only integer arithmetic in the processor, thus ensuring that the *check words* generated are independent of the hardware in which the software is resident.

(3) It should be possible to determine the probability that an error of a given type, eg one erroneous character, will pass undetected. If this is not possible, *there* must be, at least, a known upper bound on the possibility.

(4) The probability, *as determined under item (3)* above, must be acceptably low.

(5) The check word is significantly easier to remember if it does not contain more *than* about four characters.

The present phase of the work on this scheme is near completion. It seems very likely that a reduction in the frequency of errors in inserting or amending flight plans is desirable. The question is how desirable? Having more precisely *defined the problems* to be solved, the next question is what will it cost? Neither of these questions can be answered by a small team working in isolation. The object of the present paper was, hopefully, to encourage *discussion of*, at least, the first of these questions.

ACKNOWLEDGEMENTS

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REFERENCES

1. ICAO; Aeronautical Telecommunications; Annex 10 to the ICAO Convention Vol.1, April 1985, p.120.

2. Ratcliffe, S.; "Precise Navigation for Air Traffic Management", Conference Proceedings No. 273, AGARD October 1979.

3. ICAO; Aeronautical Telecommunications; Annex 10 to the ICAO Convention Vol.2, April 1985, p.17.

4. ICAO; "Rules of the Air and Air Traffic Services", Doc. 4444-RAC/501/12, 12th Edition 1985.

CP 410

THE APPLICATION OF INTELLIGENT KNOWLEDGE BASED SYSTEMS TO AIR TRAFFIC CONTROL

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SUMMARY

This paper considers the need to explore the approach of Intelligent Knowledge Based Systems (IKBS) towards meeting the pressures for change in future Air Traffic Control Systems. The discussion includes the role of automation in ATC and the suitability of IKBS within a shared approach between controller and machine. Areas selected to provide practical experience of IKBS applied to ATC include Air Traffic Flow Management, Conflict Resolution and Training. Finally, guideline concepts for the introduction of a new technology to ATC are outlined.

1. Introduction

There is now increasingly worldwide interest in Artificial Intelligence (AI), with the Japanese 5th generation project, the European ESPRIT project, United States programmes supported by the Department of Defense, the Federal Aviation Authority, NASA, and the United Kingdom Alvey programme. Interest in a subset of AI - Intelligent Knowledge Based Systems (IKBS) - within the United Kingdom Civil Aviation Authority, has been fostered by the Chief Scientist who in 1985, placed two IKBS study contracts with Industry [1],[2]. These studies investigated potential applications of IKBS to Air Traffic Control (ATC); this paper includes the findings and strategies developed from these studies for gaining experience of concepts and for the introduction of IKBS technology.

Additionally, the Civil Aviation Authority sponsors a programme in Air Traffic Systems research, including IKBS, at the Royal Signals and Radar Establishment, Malvern, and in human factors at the RAF Institute of Aviation Medicine.

The paper examines the UK Air Traffic System for potential applications; there are, however, conclusions drawn which relate to ATC in general. On an even wider scale the implications of introducing a new technology are considered, where issues of safety, expedition and human factors interaction are paramount.

2. Air Traffic Services Within the United Kingdom

ATC Centres

Air Traffic Control, Advisory and Information Services within United Kingdom airspace are divided into the London and Scottish Flight Information Regions, (FIRs). Within the FIRs airspace is controlled from the London Air Traffic Control Centre, LATCC, West Drayton with a subcentre at Manchester, from the Scottish ATC Centre, ScATCC, and the Oceanic Area Control Centre OACC both at Prestwick.

The Civil Operations Room at LATCC has control suites for each sector of airspace and the north and south London TMA, and the Air Traffic Flow Management Suite, incorporating Departure Flow Regulation and the Expected Approach Time Unit. Military Operations are conducted separately but co-ordinated where necessary at the London ATCC.

Airports and Aerodromes

The United Kingdom National Air Traffic Services provides ATS for all British Airports Authority airports, also at some local authority airports and at all the Scottish aerodromes. Each airport provides aerodrome control and approach control services which include ground movement planning, ground movement control, alerting service and flight information services.

Pressures for Change

Pressures for change aimed at improving the air traffic control system are listed in Figure 1.

The increasing demand for air travel continues, despite fluctuations caused by economic and political factors. This increase is fundamental to initiatives directed at improving the air traffic control system. A recent estimate of the forecast increase in the number of passenger Air Transport Movements through the British Airports Authority airports is shown in Fig 2 [3]. This shows a steady increase with a mean expectancy of 25% growth by 1995 and 55% by the year 2000.

Continued expansion in the variety of aircraft also has major implications for ATC with increasing numbers of "low and slow" public transport traffic.

Airfield capacity studies [4] for the London TMA show that the limitations are in the amount of "concrete", and runway configuration as well as by vortex wake separations and environmental factors.

The capability of the existing ATC system to deal with such increased pressures is limited and requires new methods of control.

Further pressure for change comes from the airlines which are investing in aircraft with sophisticated navigation, flight management and collision avoidance systems. There is also a view that investment and application of technology for the ground control environment is lagging significantly behind that on the flight deck.

3. Current Considerations

Developments in civil aviation take place reasonably slowly and long timescales are to be expected. Major changes in ATC can only be achieved through an incremental approach while maintaining safety and continuity of service at all times. It is the requirement for a longer term view which makes it necessary to consider supportive research and planning now for possible implementation in the years beyond 1995.

IKBS has a relatively long history, almost as long as data processing itself, with early attempts starting in the 1960's in University research departments. At that time processing hardware was far from being sufficiently powerful to support significant applications, and the subject remained largely academic until the late 1970's. Several significant Artificial Intelligence systems then began to emerge with commercial exploitation developing momentum in the early 1980's. Currently there is much interest in both military and civil areas, including ATC, [5],[6] in the anticipation of much more powerful computers becoming available.

It is by no means certain that many of the claims made for IKBS will be fulfilled in the near future, if at all, and it is likely that there is an undue degree of optimism in many recent statements [7]. It is therefore necessary to explore the possibilities carefully within a research or prototype development environment.

Dominant considerations when introducing a new technology to ATC are listed in Fig 3. The introduction of any new technology must maintain and, if possible, enhance safety features. Secondly, the CAA, supported by UK airline interests, currently believes in ground-based control. In the 1960's, prior to the FAA large commitment to a ground-based control philosophy, there was active exploration of an air-based system with the belief that only such a system would meet the capacity demand in air traffic. This movement did not succeed and the FAA confirmed its belief in a ground-based control philosophy. Another well established UK view is to adopt an integrated human-machine system, as distinct from either manual control or full automation. The US shared control concept is similar to this. Additionally the UK has to consider the interaction with continental neighbours. Finally, the UK is also a member State of Eurocontrol and of ICAO; developments in aviation and avionics affect all ATC authorities.

4. Computer Assistance and its Limitations

There already exists a significant amount of computer assistance within the 'manual' Air Traffic Control System. Examples of present and planned assistance in the UK are given in Fig 4. The role of automation in ATC, however, requires examination.

Potentially, there exists a continuum between the completely manual system and a theoretically possible completely automatic system. Pressures to increase automation are manifold. With present traffic levels, the area and volume of traffic which a controller can handle are governed by his communications load and by the limitations on his span of comprehension, his ability to keep track of a complex situation, and to integrate information from a wide variety of sources, as in Fig 5. It is not possible to overcome these limitations by continually subdividing the airspace into smaller sectors since each new sector boundary increases the communications load substantially. Some communications problems between sectors could be aided by establishing an automatically updated flight plan data base while sector team restructuring could also improve co-ordination.

Complete automation of controller functions would appear to remove the problem of human error, but in reality this is simply a transfer of error origin to the systems designer and to the software. While the controller is directly and consciously accountable for his actions, is highly motivated and can take immediate action in a crisis, ATC is a secondary area of expertise to the system designer who is not directly in the control loop and so would be unable to make a direct response should a crisis occur. Unfortunately experiences in the nuclear industry have made us all too aware that we cannot design error free systems or even identify all possible error conditions.

Increasingly, it has been acknowledged that some compromise to additional automation is necessary [8], [9]. There are at least three approaches to the introduction of automation. Initially, attempts were made to assign tasks to man and machine on the basis of their respective strengths. Recently the increasing capability of technology has allowed it the potential to assume more of these tasks. If the technology is exploited then man becomes reduced, initially, to a supervisor of the system's behaviour, and as more planning and strategic functions become possible (perhaps through IKBS), finally to a monitor with nothing to do until a crisis occurs. Concern about the man's ability to intervene in such circumstances has been expressed in ATC and in the aircraft cockpit where similar problems are evident.

As processing power has become cheaper, manpower costs have become a consideration. However, when safety is involved, other cost criteria have to be considered. Hopkin, [10], has pointed out that with this decrease in computing cost, it is no longer prohibitive to allow both the man and machine to perform tasks in parallel with more fluid switching between them. Despite the problems in ensuring consistency of control in such circumstances, there are advantages in that two such different methods of problem solving, through two different processing media, provide a very powerful error checking method.

A second approach to the role of automation is envisaged by this parallel function: the 'electronic cocoon' concept (11) currently being considered in the US for the flight deck. The pilot flies the aircraft within his cocoon which is constantly monitoring all the details of the aircraft's progress. Intervention only comes from the system when it decides that the pilot has made an oversight or has not become aware of some emerging situation. This method has the advantage of retaining all the pilot's existing skills, providing him with a satisfying job, and keeping him deeply involved in the situation which may be vital if his perception and improvisational abilities are required. The system may however have difficulties in recognizing that the pilot is already resolving a crisis especially if a novel solution is required.

A third approach to the role of automation, and the current mainstream, is represented by work within the CAA and elsewhere, which moves the emphasis away from tactical ATC and towards strategic and planning functions. In essence this shifts the limitations on the controller's comprehension by shifting the level of description upwards to a more global level where fewer concepts and objects describe the same situation. This approach uses automation to filter the data and present it to the controller in different ways. It may have advantages in that the individual controller can deal with a larger area in a more efficient way, and it retains involvement, motivation and responsibility in the hands of the individual but it does create a new task which may require new skills. Anticipating the nature of these skills, their consequences for a smooth transition for retraining and for the selection of personnel, may present significant problems.

In summary, total automation is unlikely to be feasible, or acceptable in the foreseable future. There are a number of approaches to partial automation some of which are suspect because of difficulties in keeping the controller actively involved, but all of which require a great deal more exploration and consideration. The next section considers the suitability of IKBS in such a role.

5. Properties of Intelligent Knowledge Based Systems (IKBS)

Until recently computers have been usefully applied in areas where human capabilities are limited, ie in high speed calculations and in storing and retrieving large volumes of data. The computers run algorithmic programs - completely defined, step-by-step procedures for solving problems.

IKBS have demonstrated their special potential in several application areas such as medical diagnosis, structural chemistry, and genetics. In each of these applications computer programs were developed which were capable of performing tasks which would normally be described as requiring the application of human knowledge or experience.

IKBS may have many conventional computing components but are unique in the way they can draw conclusions from a store of task specific knowledge. This knowledge consists of rules and concepts similar to those used by specialists when they make decisions in their field of expertise. An example of expert system rules is shown in Fig 6. IKBS encode knowledge directly in a symbolic, ie non-numerical, form, and draw conclusions principally through logical inference, not by numerical calculation. In this way IKBS are not restricted to a pre-defined decision path; they can choose from alternatives in their search for a conclusion. They can weigh facts and assumptions, and in a sense, make choices appropriate for each problem presented to them.

IKBS can also organize knowledge of classification systems or the relationships between real objects. One of their most significant features is the display, on request, of their line of reasoning; thus the user can examine the suitability of the computer's decision process. The potential for better forms of computer assistance by improving the relationship between the controller and the computer is considerable since familiar techniques for problem solving can often be incorporated in the program.

A pre-requisite for building and maintaining an IKBS is the human expert or specialist in the domain of interest. The success of the IKBS depends on how well it captures not only "textbook" knowledge but also the "heuristics" of human experts, ie, informal rules, and "rules of thumb" based upon experience, together with methods for dealing with uncertain information and ill-defined or multiple goals and constraints. All of this information makes up the "knowledge base" on which the "inference reasoning mechanism" operates. Often acquisitioning such information is the bottleneck in building an IKBS.

It is most important that the human expert, the controller, should be able to obtain explanations of the IKBS behaviour on demand and to help improve the system interactively in the light of operational results. It is therefore essential that the knowledge is represented explicitly in the program code. This is a major difference between IKBS programs and more "conventional" computer programs. Conventional programs usually contain information that can be described as "knowledge", but this knowledge is distributed throughout the program and is, therefore, not recognisable or accessible to anyone other than the programmer.

Where conventional computing systems are starting to reach their limits, IKBS can provide extra capabilities such as deductive reasoning and data organization which simplify some parts of system building. Consequently IKBS can be regarded as using very high level languages which describe problems in a more readily understandable form, and may provide solutions which are less optimal than mathematical solutions, but generally much easier to understand.

6. Application Areas for IKBS

Over the past 20 years many potential applications for computing have been found in ATC but have been limited by technology. From this experience and from a requirement to identify potential IKBS growth areas which can remain separate from the planned implementation programmes, and still have a reasonably high chance of successful implementation in the longer term, several Operational Support and Off-line examples have been selected for further study.

During the selection process a wide range of applications was considered. These applications covered both specific tasks such as arrivals sequencing and metering, departure flow regulation and control, clearances, conflict detection and resolution, emergency situations, radar monitoring, and general tasks such as a Controller Help Interface, Airspace Structure and Procedure Expert, and Training.

The particular examples selected for further study are:

Air Traffic Flow Management
Conflict Resolution
Departure Flow Regulation
Ground Movements Planning and Control
Training
Maintenance

Of these, Air Traffic Flow Management, Conflict Resolution and Training are being actively pursued.

Air Traffic Flow Management is concerned with the means and measures to improve the flow of Air Traffic. On a local or regional basis this includes obtaining air traffic demand data and available route information. Strategically this is being done through the Eurocontrol Central Data Bank. However tactical rerouting is common and an IKBS approach towards studying this aspect would examine the expertise necessary for this task. A natural longer term extension to ATFM would be to include the airfield aspects of Ground Movement Planning. This is largely rule-based and therefore possibly amenable to an Expert Systems approach. Ground Movement Control, which relies on knowledge of actual aircraft positions, would be a still longer term extension to this work as shown in Fig 7.

Conflict Resolution is already the subject of examination for IKBS application, as in the Mitre AIRPAC System [6], and is of interest. It is realised that the required knowledge base for this application would be large and complex.

Training is an expensive and time consuming function in ATC, taking place initially within a College and later under considerable experienced supervision in the operational environment. Application of Intelligent Computer Based Instruction techniques, initially within a College environment, could lead to an IKBS approach within the operational environment through the use of simulation.

Other areas, such as maintenance, have potential ATC applications but are common to a variety of users and are expected to be developed independently by them.

7. IKBS as an Example of the Introduction of a New Technology

The main aim of the CAA programme is to gain practical experience of IKBS applied to ATC. This experience could eventually provide information as a basis for cost-benefit analysis.

Ideally it should be possible to select IKBS application areas according to their suitability within an overall system framework. This has been described in control system terms, [2], and shown in Fig 8. This framework distinguishes the needs for human resources and for supporting technology, with the controller's function at the intersection of the respective control loops. Cycle times of several years for both loops are to be expected. The controller's function has been expanded in Fig 9 to indicate the knowledge categories required: rule-based, such as ATC procedural knowledge [12]; control and background experience.
In practice, however, when introducing a new technology to a large organisation, other aspects arise from the different perspectives of its components, eg operational, technology and research areas. Some guideline concepts emerge:

1. the selected programme should be within a research or simulation environment,

2. high visibility growth areas should be selected, if possible leading to a sequence of applications,

3. the programme should take into account current and planned development programmes,

4. the programme should consider the implications of system integrity.

Simulation has an important role in many areas of ATC, and this will continue to be the case with the introduction of newer systems such as IKBS. This is particularly so for applications close to the operational environment.

For successful implementation in the long term, it is important to select seed-point or growth application areas for investigation. These may fall within the description of 'on-line', related to operational control and operational support, or 'off-line', with no immediate effect on the operational system.

The difficulties currently being acknowledged of introducing a newer technology, [13], may become particularly acute in a large interacting system which is undergoing continuous, planned development and implementation programmes. It is then necessary to maintain an independent research study programme parallel to utilisation and implementation programmes as shown in Fig 10. Within this three track approach, the research programme should be relatively advanced, relaxed from constraints and ambitious with not all of its products expected to reach implementation. The utilisation programme draws on the opportunities and approaches as offered by research. It is therefore important to have operational staff not only identifying suitable ways of utilising research, but also taking an active role in the research and development stages of the system. With a central utilisation programme, the current and planned implementation programmes should be able to proceed in an evolutionary way.

System integrity and related fallback modes assume an important role in any system. With IKBS, the information available to the Air Traffic Controller must at all times be understood. Just as the reasons underlying any decision on the part of the IKBS must be clear, it is vital to have a clear explanation and situation description in any fallback or reversionary failure mode. Similarly with the use of IKBS in the wider context of a total Air Traffic Management system, with the use of IKBS in aircraft and in multiple ATC Centres it is vital to co-ordinate strategies towards resolving a common situation.

References

1. 'Future Applications of Intelligent Knowledge Based Systems in Air Traffic Control', Report Number 05.5051, Logica UK Limited, London, England, August 1985.

2. 'The Application of Intelligent Knowledge-Based Systems to Air Traffic Control from 1995', Report Reference C3247.41, Systems Designers plc, Camberley, England, July 1985.

3. Economics Systems, Forecasting and Surveys Branch, Civil Aviation Authority, London, England, April 1986.

4. 'London Area Runway Capacity and Passenger Demand', Report CAP 502, Civil Aviation Authority, London, England, January 1985.

5. 'Identification and Assessment of Artificial Intelligence Techniques in Air Traffic Control', G D Gosling, S L M Hockaday, Institute of Transportation Studies, Berkley, Research Report UCB-ITS-RR-84-14, September 1984.

6. 'AIRPAC: Advisor for Intelligent Resolution of Predicted Aircraft Conflicts', C A Shiveley and K B Schwamb, MITRE Corp, Project MTR-84W164, October 1984; also C A Shiveley, Mitre Report MP-85W13, July 1985.

7. Aviation Week and Space Technology, pp 79-81, February 17, 1986.

8. 'Scenarios for Evaluation of Air Traffic Control', R Wesson et al, Rand Corporation, Report R-2698-FAA, November 1981.

9. Wiener L "Beyond the Sterile Cockpit", Human Factors 1985 Vol 27, Part 1, pp 75-90.

10. V D Hopkin "Fitting Machines to People in Air Traffic Control Automation", Proc. Seminar on Informatics in Air Traffic Control, Capri, October 16-25 1985, In Press.

11. Horizon (BBC), February 1986, "The Wrong Stuff: Pilot Error and Automation on the Flight Deck".

12. 'Manual of Air Traffic Services', Civil Aviation Authority, London, 1974.

13. "Socio-tech: What is it (Why should we care)", Proc. CHI'86, Human Factors in Computing Systems, April 13-17 1986, Boston, Mass. pp129.

PRESSURES FOR CHANGE

TRAFFIC INCREASE

AIRPORT CAPACITY

AIRLINE OPERATORS

COST EFFECTIVENESS

SAFETY

Fig 1. *PRESSURES FOR CHANGE.*

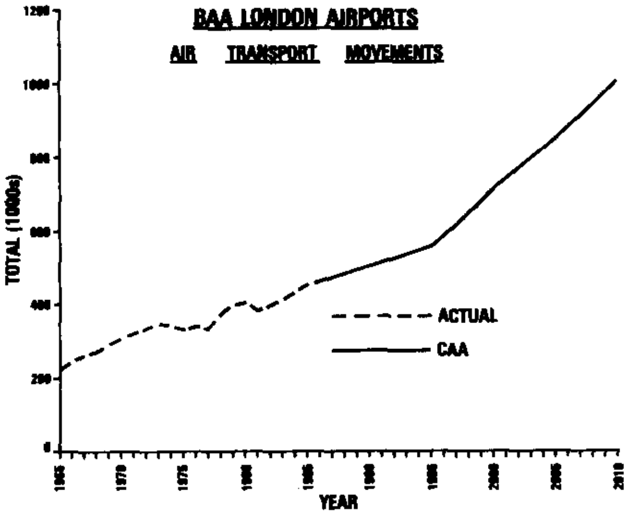

Fig 2. *BAA LONDON AIRPORTS*
AIR TRANSPORT MOVEMENTS.

CONSIDERATIONS WHEN INTRODUCING NEW TECHNOLOGY TO ATC

MAINTENANCE OF SAFETY

EFFICIENCY

GROUND - BASED ATC

SHARED CONTROL

COMPATIBILITY WITH
INTERNATIONAL DEVELOPMENTS

Fig 3. *CONSIDERATIONS WHEN INTRODUCING NEW TECHNOLOGY TO ATC.*

EXAMPLES OF COMPUTER ASSISTANCE TO ATC IN THE UK

	Facility	Function	Operational Since
1.	Flight Plan Processing System	Electronic data display and interactive update of flight data.	1972
2.	National Airspace System (9020D Computer Complex)	Integrated flight and radar data processing producing flight strips.	1976
3.	Code Callsign Database	Central source of SSR code to callsign pairings.	1975
4.	Radar Data Processing System	Synthetic radar display of plot data.	1979
5.	Online Data Interchange	Automatic interchange of activation and logical acknowledgement of messages with Maastricht.	1981
6.	Support Information Retrieval System	Colour display of aeronautical information, ATC procedures and maps as text and graphics.	1985

Fig 4. *EXAMPLES OF COMPUTER ASSISTANCE TO ATC IN THE UK.*

ATCO DATA INPUTS AND OUTPUTS

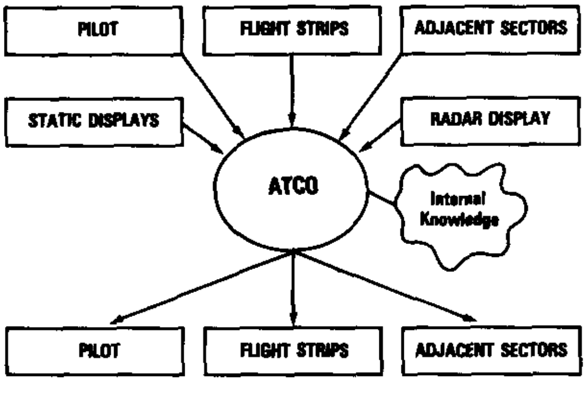

Fig 5. *ATCO DATA INPUTS AND OUTPUTS.*

EXAMPLE OF EXPERT SYSTEM RULES

CAN CLIMB (AIRCRAFT A) IF
    NOTHING ABOVE (AIRCRAFT A) AND
    NOT MAX ALTITUDE (AIRCRAFT A)
MAX ALTITUDE (BOEING 747) IF (RULES)
    CURRENT ALTITUDE (45000)
MAX ALTITUDE (BAC1-11) IF
    CURRENT ALTITUDE (35000)

NOTHING ABOVE (BOEING 747)
NOTHING ABOVE (BAC1-11) (FACTS)
CURRENT ALTITUDE (35000)

? - CAN CLIMB (BOEING 747) - YES (DIALOGUE)
? - CAN CLIMB (BAC1-11) - NO

Fig 6. *EXAMPLES OF EXPERT SYSTEM RULES.*

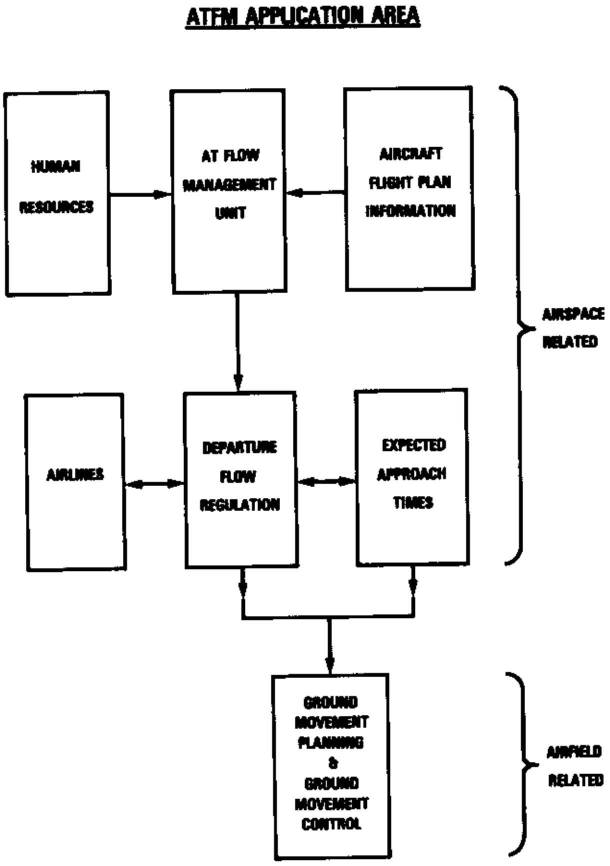

Fig 7. *ATFM APPLICATION AREA.*

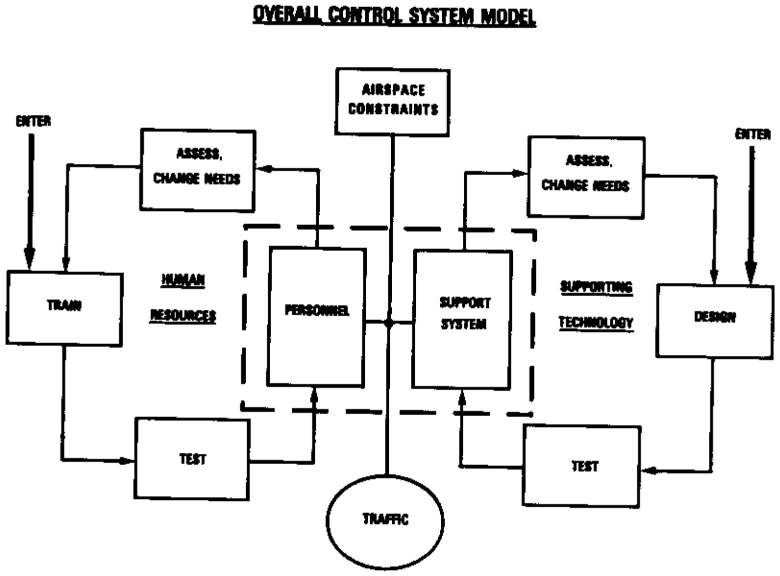

Fig 8. *OVERALL CONTROL SYSTEM MODEL.*

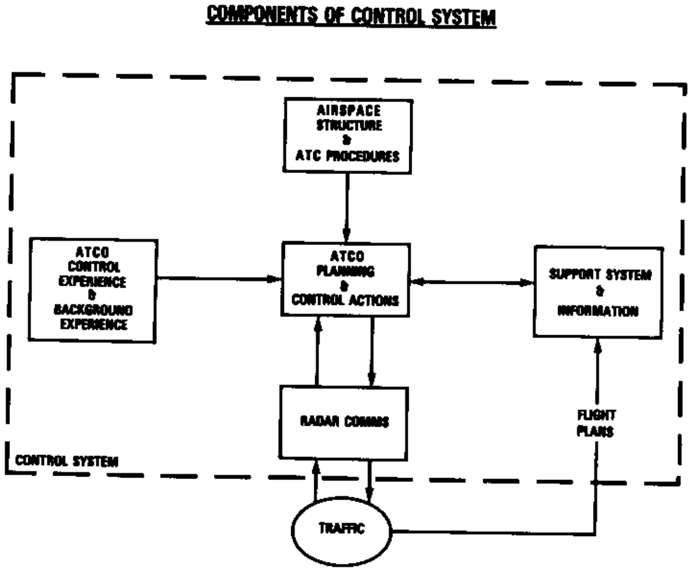

Fig 9. *COMPONENTS OF CONTROL SYSTEM.*

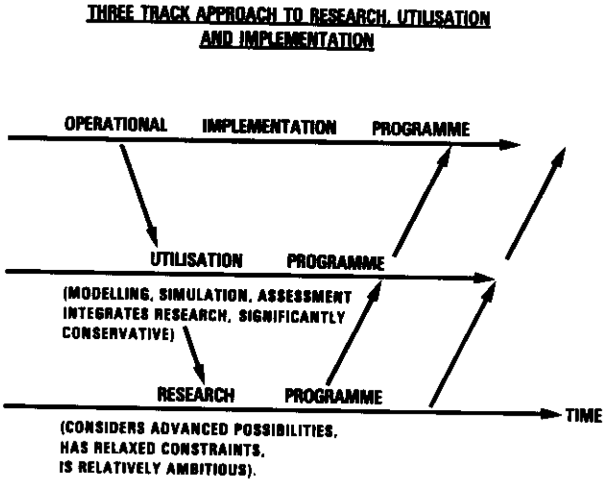

Fig 10. *THREE TRACK APPROACH TO RESEARCH, UTILISATION AND IMPLEMENTATION.*

ROUND-TABLE DISCUSSION

Moderated

by

André Benoît

Symposium Chairman
Guidance and Control Panel

At the end of a four-day Conference, we met for a final, pleasant and hopefully fruitful discussion, with the aim of drawing conclusions, calling the attention of the appropriate Authorities to specific options and possibly expressing implementation, development or study recommendations.

It would certainly have been too ambitious to review all the items presented during the Conference, since the programme covered a wide field of activities. The round-table discussion was accordingly limited to a few selected topics. Of course, these may not prove to be the most critical ones, but they at least, appear so today when seen against the background of our present knowledge.
On behalf of the Programme Committee, appreciation was expressed to all who attended. We thanked the delegates who contributed to this last session and, in particular, those who agreed to present their views on relevant issues.

Victor Vachiéry had already defined the broad lines of an air traffic services concept suitable for the year 2000 and beyond, but agreed to summarize the main characteristics of the system he had described.

Reference was made to various versions of the Flight Management System in the course of the Conference. A special session included several presentations on the subject. This constitutes a good example of an area in which it is highly desirable to strengthen co-operation between the air traffic services, the aircraft manufacturers and operators and avionics designers. Our experience indicates that the FMS could and should be used to optimize the en-route (cruise and descent) phase guided by speed and/or time directives from the ground. By contrast, in advanced extended terminal areas, it would probably be more advantageous to conduct the final phase in accordance with ground directives without using this facility unless, perhaps, it is properly configured for 4-D navigation.

When looking to the future during the first session, two authors, Olivier Carel and Sigbert Poritzky, had discussed the advent of future navigation systems, in particular the use of satellites for civil aviation. During the round-table discussion Olivier Carel commented further on the complementarity, compatibility and redundancy aspects of both the Mode S and the use of satellites development projects. Since this embraced the space-based multifunction radar sytems, Pasquale Murino also presented his views on the issue.

The promotion of automation in air traffic services has, for a long time, been received with mixed feelings. On the one hand, the engineers advocate its merits in terms of efficiency, productivity, economy and safety. While on the other, controllers are not necessarily convinced that automation will improve their professional situation, although, as with many aspects of life, there are indications that younger and older generations may have different attitudes on this issue. The philosophy of the Federal Aviation Administration (USA) on automation was explained at this meeting, as well as the status of progress. It was interesting to hear the comments expressed by Lee Holcombe and Bennett Flax, who were not directly associated with the presentations.

The on-line organization and subsequent control of flights inbound to a medium to high-density traffic terminal has been the subject of great interest for over 15 years. "Fuel Advisory Directives" as well as "Metering and Spacing" techniques introduced in the United States by the Federal Aviation Administration constituted preliminary attempts to reduce the economic penalty resulting from stacking procedures. The situation remains critical (in terms of delays, fuel consumption, economy and landing capacity), but the related problems have recently been approached in a systematic manner.

During the Conference, four papers were devoted to the subject, two originating from the United States (NASA Langley Research Center, Hampton, Virginia and NASA Arms Research Center, Moffet Field, California) and two from Europe (one from the DFVLR, Institut für Flugführung, Braunschweig, Germany, the other being presented jointly by EUROCONTROL and the Belgian Air Traffic Control Authorities). Each of these four contributions had something original to say. All the authors stressed the new role of the human controller in a system which automatically defines the best arrival landing sequence, but at that point ideas diverged. Dr. Winter (DFVLR, Braunschweig, FRG) felt strongly that the implementation of the landing plan should be maintained as an essential task of the controller. By contrast, the EUROCONTROL approach was intended to provide the human controller with accurate guidance directives for each individual aircraft from entry to touch down, the attention of the controller being kept throughout the flight. This last fuction was demonstrated during the Conference at Brussels National Airport (by EUROCONTROL staff, Belgian Air Traffic Controllers and SABENA crew) and those of you who attended the demonstration were able to observe the friendly relationship between the computer, the controller and the pilot.

Clearly, these developments will lead to an appreciable change in the role of the human controller, a change that will be for the best, we believe, although it is still perhaps too early to foresee all the implications.

During the Conference, Stewart Nicol had described in a lucid and lively manner the application of intelligent knowledge based systems to air traffic control. At first sight, it appeared that all the applications mentioned related to actions or functions located appreciably upstream when referred to the space/time jurisdiction of the controller. What was the potential of such techniques for solving on-line problems? Might this be, for instance, the definition of a 4-D conflict-free trajectory for each flight entering an extended area or in other words, the on-line automatic resolution of conflicts in a highly reliable manner? Stewart Nicol commented further on this and similar aspects at the round-table discussion. In relation to automation in general, Stan Ratcliffe considered the use of knowledge-based systems for keeping the software operational despite frequent ATC modifications.

In the history of aviation in general, and air traffic control in particular, many examples exist of research initiated by the military leading subsequently to products currently used, at times jointly, by both the military and the civilian communities. Air/ground/air digital communications and the Global Positioning System may fall into this category in the future. Throughout the Conference, the co-operation between the two communities was remarkable at all levels - preparation, logistics, participation, responsibilities - which we may hope was a reflection of the actual operational situation. Geoffrey Howell offered his views on military/civil coordination, with particular reference to military requirements. Subsequently, Jean Coupez described different ways of ensuring proper coordination between military and civilian ATC centres.

As was frequently clear during the course of the Conference, it is a difficult task to foresee the merits of a future component or of a new system. It is even more difficult to appreciate the advantages which should, could or might result from particular innovations, especially when quantitative benefit-to-cost ratio estimates are expected. Adequate tools are accordingly required to assess theoretical projections. Georges Maignan outlined his views on the necessary evolution of simulation if it was to provide efficient assistance to the Air Traffic Services authorities.

What will the role of the human controller be in the next generation of air traffic systems? This question was repeatedly asked explicitly, or implicitly throughout the Conference. David Hopkin who has devoted an appreciable part of his life to the man/machine relationship concluded the round table discussion on this human note.

Victor Vachiéry

Ancien élève de l'Ecole Polytechnique, Paris, France
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The future Air traffic Management system will offer an increase in capacity and minimum constraints on the economy of flight operations. It is mainly by augmenting the role of automated assistance in the decision-making process that this will be made feasible.

The ground system will require accurate input data and will have to provide the controller with efficient and acceptable automated functions.

Input data

The key to a significant improvement of ATM is the implementation of an Air/Ground/Air data link. This is the only way to benefit on the one hand from an accurate navigation system, and on the other from the ability of the aircraft to adhere strictly to a predefined 4-D profile.

Furthermore it will allow the ground to obtain actual information on the state vector of the aircraft and on other essential data such as the actual MET conditions. Finally, the data link will be the support for establishing the necessary dialogue between the air and the ground in order to select and follow the optimal flight profile.

Automated functions

The need to increase automated assistance in the decision making process raises immediate concern with regard to reliability, system integrity, system fault tolerance and man/machine relationship (human factors).

In addition, all individual functions must be considered and checked out in a system context. This points to the requirement for test facilities which constitute an adequate representation of the total system (Airborne and Ground sides).

It must also be borne in mind that ATM will have to face a mixed environment as far as airborne equipment capabilities are concerned.

It is obvious that future developments in the ATM field must entail close cooperation between aircraft and avionics manufacturers, aircraft operators, and the authorities responsible for Air Traffic Management.

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Two air ground data exchange systems are presently contemplated for air traffic control applications, the secondary radar Mode S and satellite communication systems. An ICAO meeting voted the Mode S format in September 1985. The United States Federal Aviation Administration passed a contract in 1984 for the procurement of 137 secondary radar stations capable of the new Mode S, with the first ones to be operational in 1988. Ground and airborne equipment prototypes are presently developed in Europe and will be tested by EUROCONTROL. The operational use of Mode S in Europe may begin in the early 90's. This relatively simple data link will exist. However, the SSR coverage will always be limited to some continental areas and the data flow of Mode S is limited. There is a corresponding need for a more universal system with worldwide coverage and data flows capable of all types of data exchange - ATC, but also airline services and, possibly, passenger private, communications. The aeronautical satellite communication system at 1559 MHz and 1646,5 MHz is the only universal solution. There may be a time when the two data links will coexist. The messages need to be standardized applying the ISO communication layer concept, so that the commonality of the two systems is optimized. This is presently the task of ICAO and a standard message structure is now developed by the ICAO SICASP Panel (SSR Improvement and Collision Avoidance System Panel).

Following a question asked about the future of satellite based surveillance of the civil aviation traffic, as far as I know, nobody in civil aviation is thinking of a satellite borne primary radar. Civil aviation surveillance is presently based on cooperative exchanges between the controlled aircraft and the air traffic services, either implementing voice position reports, or by secondary radar. Some years ago the concept of a geostationary satellite carrying a huge secondary radar (at 1030 MHz and 1090 MHz) was contemplated but does not seem to be studied any more. The ICAO Special Committee FANS believes that automatic position reports transferred through a satellite communication channel will be of a great importance in the future. Automatic Dependent Surveillance (ADS) using L-band civil aviation data communication by satellite is now the solution.

Pasquale Murino

Istituto di Aerodinamica "Umberto Nobile"
Facoltà di Ingegneria - Università degli Studi di Napoli, Italia

In this Conference, the great potential of satellite systems for both navigation and surveillance has been pointed out.

Concerning surveillance two concepts came out:

i) Automatic Dependent Surveillance (ADS) and

ii) Space Based Primary Radars and Secondary Radars (SBR/SBSR).

These two concepts are not competitive but complementary. Indeed, as Mr Poritzky reported, the FANS-2 Committee considered that an independent surveillance service based on satellites is likely to be needed. In my opinion a satellite navigation system, ADS and SBR/SBSR could form the overall Navigation-Surveillance System in the future, since this system meets the general requirements of accuracy, cross-check capabilities, redundancy and complete surveillance of the airspace.

The system should be developed as a whole but it could be realized in two phases: most likely the subsystem GPS-ADS (which is more mature) first, then, in 10-15 years, SBR/SBSR, which could replace some of the similar earth-based systems.

Lee Holcomb

Information Sciences and Human Factors
National Aeronautics and Space Administration, NASA, Washington DC, U.S.A.

The automation of Air Traffic Control (ATC) functions must be built based on a sound technical basis. The National Aeronautics and Space Administration (NASA) currently has over 100 efforts to apply knowledge-based systems to aerospace applications. To date only about three systems have become operationally useful. One successful system, called DEVISOR, was begun as a research program in 1980. After three years of research an initial knowledge-base was developed. Nearly three additional years were required to validate the knowledge-base. DEVISOR was used successfully as an offline planner for the voyager spacecraft encounter with Uranius in January 1980. The lesson learned was that validation of a knowledge-base requires several years.

Two technical issues have merged with the application of knowledge-based systems: (1) Man/machine interface, and (2) knowledge-base validation.

Man-Machine Interface

A key technical challenge is the ability to design an effective man-machine interface which will allow the system to transition between operator controlled and automated operation.
Overwhelming the operator with control options is of an acceptable solution. The user must be provided with sufficient information to effectively supervise the system in the event of unforeseen circumstances. User acceptance is essential if the automated system is to be effective. Human-machine interface must be built into the system from the start.

Validation

Finally, techniques to validate automated systems must be developed which will deal with system complexities associated with fault tolerant and artificial intelligent systems. Conventional aerospace software validation techniques, which strive to test every possible system state, are both infeasible und unaffordable.

The successful application of advanced automation to the ATC environment will be evolutionary - not revolutionary. NASA has begun a cooperation project with the Federal Aviation Administration (FAA) to demonstrate an Artificial Intelligence (AI) based "controller associate" in the Denver ATC center in 1988. This demonstration project is designed to be a first step in retiring the technical risks associated with the application of AI to the ATC environment.

Bennett Flax

Air Traffic Staff, Federal Aviation Administration
EUROPE, AFRICA AND MIDDLE EAST OFFICE, Brussels, Belgium.

The previous speaker briefly noted that the United States is switching to the mode S secondary radar system. That is true; but a few more details may help clarify the situation.

The FAA has ordered 137 mode S secondary radars. Deliveries are expected to begin in 1988. Each radar will interrogate both conventional (ATCRBS) transponders and mode S transponders.

All mode S transponders must be able to reply to mode A and mode C interrogations, as well as to mode S interrogations. Mode S transponders will therefore be detected by conventional SSRs.

The interoperability of both mode S radars and mode S transponders permits a gradual transition to the newer technology; and the FAA's rule on transponder installations takes advantage of this flexibility. The main feature of the rule is its requirement that transponders newly installed in U.S.-registered aircraft after January 1, 1992, meet the FAA's technical standard order for mode S transponders (TSO-C112).

There are over 200,000 U.S.-registered aircraft. The overwhelming majority of them already have ATCRBS transponders, and the rule does not require that they be replaced. Consequently, the transition is expected to be gradual. The FAA expects to induce owners to equip their aircraft with mode S transponders by offering various services that will use the mode S data link. Though the data link program is in a relatively early stage, and there have not yet been any decisions on the services to be implemented, it is generally expected that various kinds of weather information services would be useful and popular.

W. Stewart Nicol

Chief Scientist Division
Civil Aviation Authority, London, U.K.

It is important to gain early experience of the rapidly emerging technology of Intelligent Knowledge Based Systems (IKBS) within a research or rapid-prototype environment. In this respect both tactical and strategic conflict resolution offer suitable areas for examination. At present a large proportion of controller time is spent in situation assessment through monitoring the current airspace situation and in resolving potential conflicts.

An IKBS approach would be applied tactically to handle situation of potential conflict 10-30 minutes in advance of occurring. This would have the objective to maintain separation standards in the en-route phase of flight, incorporating rules and controller expertise. Knowledge required includes route structure within a defined region, separation standards, airspace restrictions, aircraft performance, flight profiles, aircraft intention, weather and surveillance information. Human factors would necessarily play an important part in the elicitation of controller expertise and in determining the role of IKBS in the man-machine interaction.

A natural extension to short term conflict resolution would be the strategic role of total trajectory planning or flow management, including aircraft intentions.

The Mitre AIRPAC (Advisor for the Intelligent Resolution of Predicted Aircraft Conflicts) has already used IKBS techniques to develop a rule based system for describing the resolution of the two-aircraft conflict situation. Systems such as AIRPAC offer the facility for gathering and assessing conflict resolution expertise.

Stanley Ratcliffe

Consultant
Civil Aviation Authority, London, U.K.

Earlier speakers have pointed out the difficulty of building and validating software that can suggest satisfactory solutions to ATC Problems, even under laboratory conditions, where the rules can be defined before the programmers begin work.

In the real world, ATC must deal with frequent changes in airspace geography and operating rules. In the UK, examination of NOTAMS shows that some change in ATC rules, large or small, would be needed about once per day. If software is to produce solutions consistent with these rules, and the rules concerned are embedded in, but distributed throughout, the software, the tasks of tracking down the software implications of each change, and of making appropriate modifications, is clearly prohibitive. A knowledge-based system offers a chance of effectively separating the problem - solving logic from a single explicit statement of the geographical constraints and other conditions that the solution must satisfy.

This offers, perhaps, hope of overcoming the difficulty.

Geoffrey C. Howell

Director of Research
Civil Aviation Authority, London, U.K.

Currently the requirements of expeditious flow and safety are mainly achieved by the separation of civil and military aircraft into their own airspaces. Civil airspace planning in Europe is based on this concept leading to controlled airspace for en-route sectors and Terminal Movement Areas.

Military peacetime training is requiring larger amounts of low level routes: this in turn leads to problems of Radar Surveillance. One area of particular concern is the North Sea where low level military aircraft wish to operate close to civil helicopters supporting North Sea oil and gas operations.

The short and longer term exploitation of RNAV and 4D Navigation inevitably leads to the desirability for the equipped civil aircraft to obtain direct routeings. Also advanced metering and spacing concepts call for control of flight paths 200 miles from major airports. The military are very unhappy about any increase in the volume of controlled airspace. The best solution to this problem would be to find a way for military and civil aircraft to share airspace. To do this, better co-ordination of plans is needed through accurate and up-to-date exchange of flight plans and progress.

Thus the strong conclusion to draw is that data bases for all levels of planning and control of military and civil aircraft should be better co-ordinated in the future and up-to-date information of military activity displayed clearly to the civil air traffic controllers and vice versa.

Jean J.E. Coupez

Lieutenant Colonel d'Aviation
Commandant du Centre de Contrôle du Traffic Aérien, Belgique

La coordination du trafic aérien civil et militaire peut s'effectuer de trois façons différentes :

a. Les contrôleurs du trafic aérien civils et militaires se trouvent côte à côte (elbow coordination) dans un même centre.

b. Les contrôleurs du trafic aérien civils et militaires se trouvent dans un même centre mais ils sont séparés physiquement. La coordination se fait par des moyens de télécommunication mais le dialogue personnel entre contrôleurs est aisé.

c. Les contrôleurs du trafic aérien civils et militaires se trouvent dans des centres séparés et la coordination s'effectue uniquement par des moyens de télécommunication.

Pour des raisons propres à chaque Etat, on rencontre ces trois types différents de coordination civile-militaire au sein de l'OTAN. Les différentes solutions sont à peu près équivalentes pour autant que dans le cas décrit sous c., la connaissance mutuelle des contrôleurs du trafic aérien soit réalisée au moyen d'échanges, visites, etc.

Georges Maignan

Directeur du Centre Expérimental, EUROCONTROL, Brétigny, France.

Evolution of Simulation Facilities to support Research Studies and Experiment of ATM Systems

- The EUROCONTROL Experimental Centre - Brétigny - is one of the 7 European Units working in the field of ATC Research, Studies and Experiments. Many of these units are represented at this Meeting.
- Our traditional job is ATC simulation. We have a relatively powerful real-time ATC simulator which is commonly used and commonly financed by the EUROCONTROL Member States.
- Our views and plans for upgrading this simulator in order to experiment in the area of Air Traffic Management Systems and of systems with closer air-ground coupling than today is as follows:

i) Improvement of the "Air" side

- To rewrite the traffic generation programmes (what we call the "Navigator"), mainly to have more realistic a/c performances, including performances of FMS-equipped aircraft.
- To add a few realistic aircraft (between 2 and 10), the flight decks of which are simulated by standard graphic displays (Multi-Cockpit Simulator).
- For these realistic aircraft to develop a "multi-aircraft" FMS.
- Possibly at a later stage, to connect the ATC simulator to an appropriate flight simulator somewhere in Europe.

ii) Improvement of the "Ground" side

- To add to the standard ATC positions, some advanced ATM positions with means of presentation more exotic than today's State of the Art. Currently we are working on projects such as 3-D type of display and knowledge-based expert systems to assist the planning controller.

iii) Programming Scenarios

The future ATC System is unknown. We have to experiment with various scenarios. Flexibility in programming these scenarios is necessary.

Currently we have started with:

- The most complicated one with a very advanced degree of automation. We have given it the name "ARC 2000".

Simulation of André Benoît's Zone of Convergence Concept with the "4-D descent advisor" presented by Sip Swierstra.

iv) Complementary experiments

Complementary experiments are contemplated for transmission of flight profiles and a/c state vectors via Mode-S data-link and by satellite. In the PRODAT ATC Programme a real-time simulation with actual use of the space segment in the simulator is foreseen.

The work to be done to achieve these goals is important and expensive. Discussions are in progress in the various EUROCONTROL Working Groups and Panels to specify their plan and to share the work between the various European ATC Research Units in order to avoid unnecessary duplication and expense.

V. David Hopkin

RAF Institute of Aviation Medicine, Farnborough, Hants, U.K.

MAN / MACHINE INTERRELATIONSHIP

Introduction

There seems to be general agreement that any automated air traffic control systems belong to the distant future and that, in the meantime, policies and plans should be made on the assumption that air traffic controllers will continue to have roles within the system. Over the years, evidence has accumulated that the human controller cannot fulfil passive roles well and that, in particular, his performance as a system monitor is poor if his role is to watch equipment functioning and to intervene rarely. Therefore any plans which envisage man primarily as a monitor imply serious human factors problems which can be difficult to resolve.

The presence of the controller often rests on arguments that he can be flexible and innovative, can compensate for system deficiencies or inadequacies, and can intervene effectively in emergencies to maintain the integrity, safety and efficiency of the functioning system. There are legal issues if he may retain responsibility for air traffic control functions even when using equipment which he cannot independently verify as accurate, reliable or trustworthy. It is important to recognise that human flexibility can be exercised only to the extent that the man-machine interface has been designed to permit flexible and innovative actions.

Attention

In the past, plans have tended to assume that the controller will be able to attend continuously to the content of his displays and will maintain an up-to-date picture of the air traffic control situation so that he can intervene effectively at any time, should the need arise. Yet practical experience, such as that gained by conference attendees listening to papers for a few days, demonstrates to each individual that it is not possible to sit passively and maintain attention, even to topics of acknowledged interest, without daydreaming and losing the thread of the speaker's remarks from time to time. Similarly, if a controller becomes a passive monitor of an actively functioning system, occasionally his attention will lapse. This is not a criticism of the professionalism of air traffic controllers but a statement about a fundamental human characteristic. Exhortations to try harder to maintain attention cannot resolve the problem which is not primarily a matter of motivation but of roles, functions, task designs and resultant levels of human activity and direct involvement.

An apparent consequence is that the system must be designed to remain safe when the man is not attending as well as when he is. This is quite a radical notion. It does not imply that attempts to engage and maintain human attention to the air traffic control situation should be abandoned, but it does imply that the safety of the system and of the aircraft under control should not be predicated on the assumption that these attempts will always be successful. Either human roles must remain active, or, if they can become passive, the controller will sometimes not be attending, and therefore be unable to intervene effectively and at once in a sudden emergency.

Role Definition

One way to tackle this problem is to assume that the man will be present, to define the roles which he must play, and to optimise his ability to fulfil them by means of selection, training, the provision of suitable equipment, and the design of appropriate tasks and procedures. This optimisation of human functioning could be done independently of the optimising of equipment functioning. Hitherto it has been axiomatic that if a function is performed by the machine it does not need to be performed also by the man, and should not be. Human roles have been determined in the past not so much by what the controller can do as by what the machine cannot do. This approach has led to many present difficulties. An alternative is to optimise human roles in their own right, regardless of whether this involves duplication of functions with the machine. This means that functions are not allocated to man or machine but the job of the man is designed as an entity to fulfil its objectives independently of those of the machine. Where this results in man and machine both performing certain functions in parallel this may sometimes be a potential extra source of safety. Normally the man would be performing the function at a much simpler level since he can handle much less data in a given time. It should often be possible to cross-check any major discrepancies between human and machine products. The discovery of such discrepancies may become an aid to safety.

Adaptability

Human efficiency ultimately depends on optimising human roles in their own right. In the future it will be possible for the machine rather than the man to do much of the adapting. In the past it has been assumed that man's great strength is adaptability, and roles and tasks have been designed on the presumption that he can adapt. Recently, adaptability has also become a characteristic of machines. It will, for example, become possible, if necessary, to design and conduct man-machine dialogues in which the machine adapts the level at which the dialogue is conducted to the most appropriate level according to the man's knowledge, skill and understanding, as revealed by his responses during the initial stages of the dialogue. This machine adaptation can be an iterative process throughout the dialogue. Such machine adaptability may also assist the optimisation of human roles.

Workload

One way in which machine adaptability may enhance human roles is by giving the controller greater influence over his own workload. Most people who can set their own workload choose to be busy rather than idle. This suggests that the air traffic controller should be able to do almost all the work himself when the traffic is light, and should allow the machine to do much of the work and confine his tasks to broader strategic responsibilities when traffic is heavy. This gives the man some control over his workload. Machine adaptability is necessary to achieve this but it has recently become a practical rather than an idealistic aim. It is difficult to reconcile the attempts of individuals who have control over their own workload to keep themselves fully occupied with the apparent crusade to reduce workload in air traffic control. In many countries a few air traffic control jobs and a few famous or infamous control sectors can generate high and burdensome workload and it is then necessary to check frequently that the high workload is neither unsafe nor inducing occupational health problems. Nevertheless such jobs are in the minority, and even in them the high workload does not generally apply all of the time. Therefore the need to reduce workload, often taken as self-evident during this conference, needs to be examined much more critically. It certainly seems dubious as a principle. The aim should be to enable the controller to influence or set his own workload rather than to reduce workload in all positions, times and circumstances. The reduction of workload does not necessarily resolve many existing problems, but may bring further problems in its train.

One of these is that people who are given more passive roles report that they feel less sure that they understand the situation which they are controlling, and they become anxious lest they lose their picture of the traffic. This effect seems to occur as aids are introduced. It occurs partly because of the passive role which these aids may engender and perhaps partly because of an incomplete understanding of how the various aids work. It is not possible to deduce from using the typical air traffic control problem solving, decision making or prediction aid how far it should be trusted, what it would look like if it failed, and which factors have been included in the decision, solution or prediction proposed.

The issue has to be more throughly addressed of what the controller needs to know about an aid in order to use it efficiently. The controller's necessary knowledge may take one of two forms: it may refer to training and experience in the sense that the knowledge is already possessed and reliance is placed on human memory to recall it when appropriate, or it may refer to the man-machine interface design if this interface must be used to retrieve the necessary knowledge from the system but reliance is still placed on human memory to recall what is available and how to retrieve it. The machine may be used to draw the controller's attention to necessary knowledge, but only in particular pre-defined conditions. If he is required to reject or accept a decision, solution or prediction, then some rationale is necessary to do this. The rationale depends on knowledge of which factors have already been incorporated in the automated proposal and which have not and could therefore form a basis for rejecting it.

Individual Differences

Attitudes to individual differences appear to be somewhat ambivalent. During selection it is assumed that individual differences are substantial and that it is possible to capitalise on them by selecting those individuals most suited to air traffic control because of the combination of abilities, skills and attributes which they possess or have potential to acquire. Thereafter individual differences tend to be seen as an encumbrance because individual controllers do not behave uniformly and cannot all achieve comparable levels of performance. However it may be possible to treat individual differences as an asset by measuring them more carefully and by using certain aspects of them as part of the basis for allocating controllers to future jobs.

One recent research topic with substantial individual differences is direct voice input, where those who are able to produce consistent results are now called 'sheep' and those whose performance is erratic and error prone are called 'goats'. This is seen as a nuisance, but suggests that performance in direct voice input tasks might be substantially enhanced by an appropriate selection procedure. Individual differences can be an asset which is not appreciated sufficiently in a systems context where the man is viewed primarily as a system component and variability between components which are nominally the same is frowned upon.

Manual Functions

As air traffic control systems evolve, existing manual functions tend to remain intact or be replaced by automated aids which substantially retain the manual form. This may not be the way to obtain the most efficient automated aids. It may be necessary to recast functions substantially rather than to automate existing human functions as they stand.

Teams

In air traffic control, as in other applications, most aids have been devised for individuals rather than for teams but air traffic control is largely a team activity. Replacing man-man interactions with man-machine interactions has major implications for team roles and team functioning. Traditional forms of supervision or assistance may no longer be practical, the sharing of tasks and responsibilities may no longer be feasible, and professional norms and standards may fail to develop because the evidence gleaned from the behaviour of one's colleagues, which forms the basis for their development, may not be present when tasks include few team activities and consist essentially of man-machine interactions.

Ultimately benefits are sought in terms of safety, efficiency or money. It therefore seems strange that many of the functions for which computer assistance has been tried are those at which the unaided controller already appears to be highly efficient, and in some cases approaches the theoretically maximum attainable performance, so that any benefits measured and expressed only in the above terms must remain marginal. A more logical approach may be to ask first what the controller does not do well and then ensure that he does not have to perform functions for which human beings are ill suited. High on the list of such functions would be monitoring. Evidence accumulates that the human being needs active roles in order to maintain his attention and knowledge of the system, to intervene in an emergency and to act flexibly with a full understanding of what he is doing and of the consequences of his actions. This also may be enhanced if the machine is adaptable. Perhaps it would be better to derive a hierarchy of functions in terms of those which lend themselves most to substantial improvement in quantifiable terms. Again the state of equipment development makes this a practical option where formerly it was not.

Acceptability

Controllers have developed skills. It is often remarked that one of the most important aspects of any aid is its acceptability. This is linked to the extent to which the controller can understand it and learn to trust it. Some aids do not sell themselves but have to be positively sold for their merits to be appreciated. Other aids, such as colour coding, sell themselves only too well and can lead to unrealistic expectations. Perhaps time should be spent on discovering the factors which determine the acceptability of the air traffic controller's work, tasks and equipment rather than simply its efficiency. A controller will tend to use equipment efficiently and safely if he accepts it. If he does not accept it, he may demonstrate how unhelpful it is, and its potential may never be fully realised. The need for acceptability should be addressed and the main determinants of the acceptability of new aids need to be identified.