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STATE OF THE ART SURVEY OF TECHNOLOGIES APPLICABLE TO NASA'S AERONAUTICS, AVIONICS AND CONTROLS PROGRAM

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FOREWORD

This report was prepared in support of the National Aeronautics and Space Administration, Office of Aeronautics and Space Technology, Avionics and Control Planning Team which consisted of

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This report was edited by Dr. R. K. Smyth of MILCO INTERNATIONAL, INC., with contributions from some sixty individuals in industry, Government, and the universities whose names and contributions are summarized in the next section under State of the Art Survey (SOAS) Contributors.

This effort was initiated by the request of Chairman Dr. Herman A. Rediess and was funded under NASA contract # NASW-2961 to ORI, INC., which issued subcontract #7Ø37 to MILCO INTERNATIONAL, INC. for the preparation of the Draft Report and for coordinating the contributions from the listed individuals.

The Editor sincerely appreciates the insight and material provided by the contributors who represent a truly significant body of knowledge relative to Avionics and Controls Technology State of the Art.

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The Editor gratefully acknowledges the support provided by Bill Mace and Duncan McIver of NASA Langley for reproducing the Draft Report and View Graphs for distribution to the attendees of the Avionics and Controls Workshop held on 27, 28 and 29 June 1978 at Hampton, Virginia.

Also, the editor acknowledges the loan of three COMPUTERM 32/63Ø word processors from the COMPUTERM CORPORATION which were used for typing, editing, and printing the final version of the report.

Finally the Editor acknowledges the review, assistance, and suggestions provided by Chairman Dr. Herman A. Rediess who provided the inspiration for the Avionics and Controls State of the Art Report.

THE STATE OF THE ART SURVEY OF TECHNOLOGIES APPLICABLE TO NASA'S AERONAUTICS, AVIONICS AND CONTROLS PROGRAMS

Abstract

The state of the art survey (SOAS) covers six technology areas including flight path management, aircraft control systems, crew station technology, interface & integration technology, military technology, and fundamental technology. The SOAS included contributions from over 70 individuals in industry, government, and the universities.

Flight path technology includes a description of the current navigation systems and air traffic control systems as well as a preview of the next generation systems including GPS, BCAS, DABS, and other planned ATC techniques.

Aircraft control system technology includes automatic flight control systems, digital fly by wire systems, fault tolerant systems, propulsion control systems, integrated flight/propulsion control, and active control systems.

Crew station technology includes a review of digital displays, flat surface display technologies, data entry and controls, and flight systems management.

Integration and interfacing technology includes avionics functional integration and architecture, microprocessor/memory technology, fiber optics, bussing concepts, and external interference effects.

Military avionics technology includes surveillance, detection and warning systems; IFF and ECM systems; JTIDS; weapons guidance and control.

Fundamental technology includes information and control theory, optimal control, Kalman filter and state estimation theory, direct digital synthesis, electronic device technology including silicon and gallium arsenide technology, low cost sensors, electro-mechanical devices, analog to digital and digital to analog conversion devices, fluidics, systems analysis, and system software including higher order language and structured programming.

Key Words

Navigation, Guidance, Automatic Flight Control, Air Traffic Control, Propulsion control, digital fly by wire, digital avionics, electronic displays, flat surface displays, flight management systems, avionics data bus, systems architecture, modern control theory, system analysis, systems integration, fluidics, electromechanical devices, actuators, electronic devices, silicon technology, gallium arsenide technology, microprocessors, digital memory, software, higher order languages, structured programming, direct digital synthesis.

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Dr. John E. Miller, Intermetrics	Software View Graphs
Mr. Al Norwood, Boeing	Collection of Papers on Flight Control, Avionics Displays, & Fiber Optics
Mr. Jack Reid, NASA Langley	Digital Operations (AIAA paper)
Dr. Al F. Schmitt & Mr. Donald W. Baake Teledyne Systems	LORAN C OMEGA Inertial Navigation NAVSTAR/GPS (Brochures & papers)
Mr. Leroy J. Singleton, Litton Aero Prod.	LED Displays & Controls (Brochures)
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GRAND TOTAL: Those who have made contributions to the effort:

70

TABLE OF CONTENTS

CONTENTS

CONTENTS

CONTENTS

CONTENTS

SURVEY OF THE STATE OF THE ART OF TECHNOLOGY APPLICABLE TO NASA'S AERONAUTICS, AVIONICS AND CONTROLS PROGRAMS

1.0 INTRODUCTION

This State of the Art Survey is in support of the NASA OAST planning committee for Aeronautics, Avionics, and Controls headed by Dr. Herman Rediess. NASA OAST sponsored a Workshop for Avionics and Controls held near NASA Langley Research Center 27-29 June 1978. This workshop included invitees from Industry, the Universities, various NASA Centers, FAA and other Government agencies. The workshop began with a plenary session during which the ground rules were outlined. A three hour oral summary of this SOAS Report was presented by the Editor. The workshop divided into committees which considered the issues of the six major sections of this SOAS Report including:

* FLIGHT PATH MANAGEMENT TECHNOLOGIES
* AIRCRAFT CONTROL SYSTEM TECHNOLOGY
* CREW STATION TECHNOLOGY
* INTEGRATION & INTERFACING TECHNOLOGIES
* MILITARY AVIONICS TECHNOLOGY
* FUNDAMENTAL TECHNOLOGIES

The principal objective of this State of the Art Survey (SOAS) Report is to identify the current State of the Art in each of these technology areas and to identify emerging trends which are important to the future development of these technologies. This SOAS Report will help the NASA OAST planning and study committee fulfill its charge to define just what NASA's role should be in these technologies during the next two decades.

The timing for this State of the Art Survey is particularly appropriate coming at the time when a virtual revolution in microprocessor technology is taking place which promises to have a profound impact upon the way avionics and control systems are implemented. There are a number of System technologies which are emerging which promise to contribute an even greater impact upon the way we structure the avionic and control system architecture of the next generation systems. These trends include:

NAVSTAR/GPS which promises to provide a common, accurate, worldwide navigation system, which may replace many of the current navigation systems. There are many painful trade-offs and transition decisions which must be made before such a change can occur. The complete system validation is still some seven years away.

AIR TRAFFIC CONTROL UPDATE which includes a Discrete Address Beacon System (DABS) with a data link capability, Beacon Collision Avoidance System (BCAS), Automatic Traffic Advisory and Resolution System (ATARS), and Microwave Landing System (MLS). These ATC improvements and others being considered will have a rippling effect on all aircraft avionics.

DIGITAL FLY BY WIRE SYSTEMS (DFBWS) are imposing new looks in fault tolerant hardware and software configurations which promise to reduce aircraft weight and cost without compromising flight safety or reliability.

THE ADVENT OF FULL AUTHORITY DIGITAL PROPULSION CONTROL SYSTEMS and their integration with digital automatic flight control suggests new economies and performance benefits to both propulsion and flight control systems.

THE INTEGRATION OF DIGITAL COMPUTERS with flat surface displays and integrated data control centers is producing a revolution in cockpit avionics. The crew station systems technology is providing control of more modes and functions in less panel space through the use of interactive display and control techniques. The introduction of human factors into crew station design at an early stage is simplifying the operational procedures from the crew's point of view.

THE TREND TOWARD MODULAR AVIONICS architecture with distributed microcomputers is accelerating and introducing new levels of flexibility to aircraft avionics. The digital multiplex bus concepts are making needed information accessible to all modular functional elements which makes for ease of system change and functional expansion.

THE INCREASING CAPACITY AND DECREASING COST of airborne information processing is having a dramatic impact upon the sophistication in avionics functions and capabilities even for low cost General Aviation aircraft which comprise the vast majority of all aircraft flying.

THE FEASIBILITY OF FIBER OPTICS for aircraft avionics interconnect and busses appears probable during the next decade. The replacement of copper wire bundles with fiber optics bundles will have a significant impact upon reducing avionics wiring weight and elimination of EMI and indirect lighting effects.

MILITARY AVIONICS TECHNOLOGY continues to provide system concepts and technology transfer elements to mission areas which fall within the responsibility of NASA OAST. For example, the military is on the leading edge of high speed digital processing applications used for such missions as hostile signal intercept, radar signal processing, and imaging guidance sensors. The high speed processing elements are already in the nanosec region and are progressing toward the picosecond region. Also the Military Avionics Technology is contributing to the State of the Art of high density electronics packaging which must survive a severe temperature, shock, and acceleration environment, such as the US Army Cannon Launched Guided Projectile (CLGP). These mass quantity programs such as CLGP must also result in designs which have a low unit cost.

MODERN CONTROL THEORY and Systems Analysis Techniques developed during the last quarter century are providing synergistic benefits to system design brought about by the low cost digital processing available through microprocessor technology, low cost memory, and new high speed mass memory technologies such as bubble memories and EBAM. Techniques which were at one time belived by practitioners of system design to be too complex (and not understandable) are now commonplace in current and emerging avionics and control systems. These modern control theory techniques include:

KALMAN FILTERS AND STATE ESTIMATION TECHNIQUES which provide filtering of data and accurate prediction of state variables made possible by analytical models of the vehicle and its controllers. These techniques have been applied to navigation, guidance and control systems and are becoming commonplace even on General Aviation avionics.

OPTIMAL CONTROLLERS which use cost functions to synthesize new system configurations to solve a wide array of complex control problems.

DIRECT DIGITAL SYNTHESIS is receiving renewed emphasis as real time digital control systems proliferate in the next generation avionics and controls designs. The challenge of multiloop, multi- sampling rate, multi variable, time varying, distributed systems provides for great potential payoff of new methods.

THE USE OF LARGE SCALE DIGITAL COMPUTERS to simulate complex real time digital-hybrid systems is, of course, commonplace. A trend toward using flexible, programmable breadboards of the actual system is emerging which relieves some problems of fidelity of simulation in distributed digital systems.

THE PROPORTION OF SOFTWARE costs to hardware costs is growing with each generation of new systems using low cost digital microprocessor/memory technology. As a result, widespread concern over the the growing costs of software has caused a large groundswell in the avionics industry aimed at curbing the escalating costs of software. This effort to reduce software costs has resulted in a collection of techniques referred to as 'Modern Software Programming Practices'(MSPP). MSPP has procuced the following trends in Avionics Software Design:

The use of Higher Order Languages for Avionics to replace the previous technique of using assembly language programming in the real time systems of avionics.

Top Down Software Development which defines the software as a hierarchy of levels.

Structured Programming which defines independent software modules with one entry and one exit.

Modular Software associated with distributed microcomputer archictectures.

THE DISPLAY RESEARCH AND DEVELOPMENT taking place to find a viable replacement for CRT displays in the cockpit is accelerating with a number of possible candidates on the horizon including Liquid Crystal Displays (LCD's), Light Emmitting Diodes (LED), Gas Plasma Displays as well as exotic new technologies such as electrochromic displays, electrophoretic displays, and electroluminescent displays. To date a clear winner in the candidate to replace CRT's has not emerged.

1.1 OBJECTIVES OF SOAS REPORT

The SOAS Report is intended to aid the NASA OAST Planning Committee for Avionics and Controls in making sound decisions relative to those programs and technology areas which should be supported by NASA during the next decade. The request for write-ups from the various contributors to this report suggested that the following viewpoints be considered in preparing the sections contributed to the report:

- Emphasize those aspects of the assigned technical areas which require more investment of R&D resources in order to reap the potential benefits through application to the US Aerospace programs.

- Identify emerging concepts which are likely to have a major impact on Aeronautics, Avionics, or Controls in the 1980's and beyond.

- Point out technologies which you feel are going to lose out to competing techniques as further R&D investments are made.

- Highlight the one or two most important developments or research required in your assigned areas which should be sponsored by NASA considering NASA's roles and missions.

- Identify any items which you belive NASA should not support because of roles and missions of other government agencies such as DoD, DoT/FAA, or because of the responsibilities of industry or the Universities.

- Suggest concepts of techniques developed by DoD which may be adapted to NASA's Aeronautics, Avionics, and Controls Programs.

One of the contributors, Mr. N. B. Hemsath, of Rockwell International - Collins Avionics, stated the NASA role in avionics in succinct terms which bears repeating:

'Industry addresses evolutionary, low risk, steady improvements to its designs with great attention to implementation details as it must live with its products amd meet the challenge of the marketplace. On the other hand, government R&D is better able to evaluate more radical, high risk approaches that potentially offer significant improvements over conventional approaches. However, even after potential benefits of new approaches have been demonstrated, industry must reduce the resultant technology to products that can achieve commercial success. Thus we believe that NASA should be supporting unconventional sensor development and new display media research but should minimize its efforts in evolutionary avionics systems work because industry is doing

1.2 SCOPE OF THE SURVEY

This Avionics and Controls State of the Art Survey (SOAS) Report addresses the six technologies listed on the first page of the Introduction. The Survey was conducted in a short time. However, the large cross section of Industry, Government, and Universities represented by the individual contributors provides a unique snapshot of avionics and controls technology in 1978. Equally important, however, since these more than 60 contributors are also working on the next generation avionics and control systems, their write-ups and viewpoints provide a preview of the future in these technologies.

The final version of this report was impacted by the deliberations and conclusions of the more than 100 participants at the NASA sponsored Avionics and Controls Workshop held at Hampton, Virginia, near NASA Langley on 27-29 June 1978. The working sessions of the workshop were organized into parallel groups which considered five of the six major technology areas (all except Military Avionics Technology) covered by this SOAS Report.

2.0 FLIGHT PATH MANAGEMENT TECHNOLOGIES

This technology area covers the navigation, guidance, communication, and air traffic control aspects of aircraft flight path management. This section also covers the means for avoiding hazardous weather conditions in flight. The civil aircraft considered by this technology include the broad spectrum from the simplest general aviation aircraft to the most modern wide body jet transport. The current state of the art of flight path technology is based upon a number of national navigation and air traffic control systems which will be changing during the next decade.

2.1 NAVIGATION AND POSITION FIXING

The backbone of civil aviation navigation is the visual omni range (VOR) and distance measuring equipment (DME) network which is now implemented world wide for over land navigation. The airlines widely utilize inertial navigation systems (INS) for transoceanic flights to supplement VOR/DME in areas of sparse coverage. Another selfcontained navigation system used on transoceanic flights is doppler radar which suffers from larger errors than INS. Both INS and doppler require position updates to bound the time increasing errors. For example, INS typical error rate is approximately 1 NM/hr for most of the widely employed civil units.

The primary navigation systems are being supplemented by other radio navigation aids and, to a limited extent, by non directional radio beacons whose primary use is for ILS acquisition. Omega is perhaps the most widely used of the other radio navigation aids, since it provides world wide coverage particularly when supplemented by the Navy's VLF communication stations. Seven of the eight Omega stations are operational with Australia's scheduled for operation in the near future.

Loran C is another long range radio navigation system which has found limited use in civil aviation primarily because of its limited geographical coverage to date. The principal use has been in the coastal waters and in the northern Atlantic and the Middle East.

The new satellite navigation system being developed by DoD, NAVSTAR Global Positioning System (GPS), promises to replace the existing navigation system in time and provide accurate, world navigation. The estimates for when NAVSTAR/GPS will replace VOR/DME range from 1985 to 1995. The GAO (ref 1) has recommended an early replacement of other navigation systems by NAVSTAR/GPS to stop the proliferation of overlapping navigation systems. However, other government agencies have challenged the feasibility of an early replacement primarily because of the early state of validation of GPS and the enormous effort required to change the navigation infrastructure.

Without entering the debate on the date of switch over, it does appear that before the end of the century it is highly probable that NAVSTAR/GPS will replace VOR/DME and the other radio navigation systems. The technology in receivers and digital processing are progressing at a rapid rate which should prove the most optimistic cost estimates for GPS receivers correct in the long run.

2.1.1 VOR/DME

VHF Omnidirectional Range (VOR)

The VOR transmitter sends out a radio signal which in effect shows 360 directions at one degree intervals. The VOR receivers pick up the part of the signal which corresponds to the direction to the transmitter. Like nondirectional beacons, signals from two VOR transmitters can be used to determine position on a map. An aircraft having a VOR receiver and distance measuring equipment (DME) can determine the direction and the distance of a single VOR, thereby enabling the user to position himself on a map when within range of only one transmitter.

NASA Ames' advanced avionics system program for general aviation has devised frequency switching methods coupled with Kalman filter processing which yield accurate position fixing with a single VOR or a single DME receiver.

VOR has a typical range of 200 miles, but its effective range is less for low-flying aircraft because the system uses line-of-sight radio signals. Aircraft at 26,000 feet of higher can receive VOR signals up to about 200 miles. On the other hand, an aircraft at 800 feet altitude can receive the signal only when within 35 miles of the VOR.

VOR has a typical navigation error of about 3-1/2 degrees in direction, which translates to 0.6 miles at 10 miles from the transmitter. At 75 miles from the transmitter the error could be as much as 4-1/2 miles. The distance measurement of the DME is accurate to 1/2 mile.

Many VOR transmitters are combined with the military TACAN system in what are called VORTAC transmitters. These provide both direction and distance to civil or military aircraft equipped with TACAN receivers.

FAA operates a nationwide system of 704 VORTAC transmitters, 203 VOR transmitters and 17 VOR/DME transmitters as the primary radionavigation system used by civil and military aircraft for overland flights. These transmitters are located between airfields for enroute navigation. In fact, they form the electronic airways which lace our country. Additionally, they are located at airfields to aid aircraft in approach and landings. FAA is required by international agreement to operate VOR and DME until January 1, 1985.

The military services operate VOR transmitters at many of their airfields for the same reasons that FAA provides them at civil airports. The Army has 17 VOR transmitters at airfields and plans to put in 15 more at other airfields. The Navy has 6 VOR transmitters. The Air Force has VOR transmitters at 14 airports.

USERS

VOR is used by an estimated 280,000 civilian aircraft and 13,000 military aircraft worldwide. Estimated US users include 8,000 military aircraft, 2,500 commercial airliners, and 130,000 private aircraft ranging from company-owned jets to single-engined, propeller-driven airplanes.

The Army currently has VOR receivers on 3,500 helicopters (40 % of all helicopters) and many of its 800 fixed wing aircraft. The Army uses VOR because VOR equipment costs less than TACAN and because Army helicopters can follow established airways in the United States and Europe. Current plans are to have VOR in 6,000 helicopters (70% of all helicopters) by the late 1980's.

The Navy has VOR receivers on most cargo, patrol and training aircraft. Some helicopters and other aircraft also have VOR.

The Air Force has VOR receivers in most bombers, cargo, and training aircraft and in some other aircraft.

Current Navy and Air Force plans call for the phaseout of VOR by 1990.

EQUIPMENT COSTS

A VOR transmitter typically costs about $45,000. The airborne VOR receiver costs from $1,000 for the lowest priced civilian receiver to $15,000 or more for a military receiver. Airborne DME costs from $2,000 for the lowest priced civilian equipment to $10,000 for equipment used by commercial airlines.

2.1.2 LORAN C/D

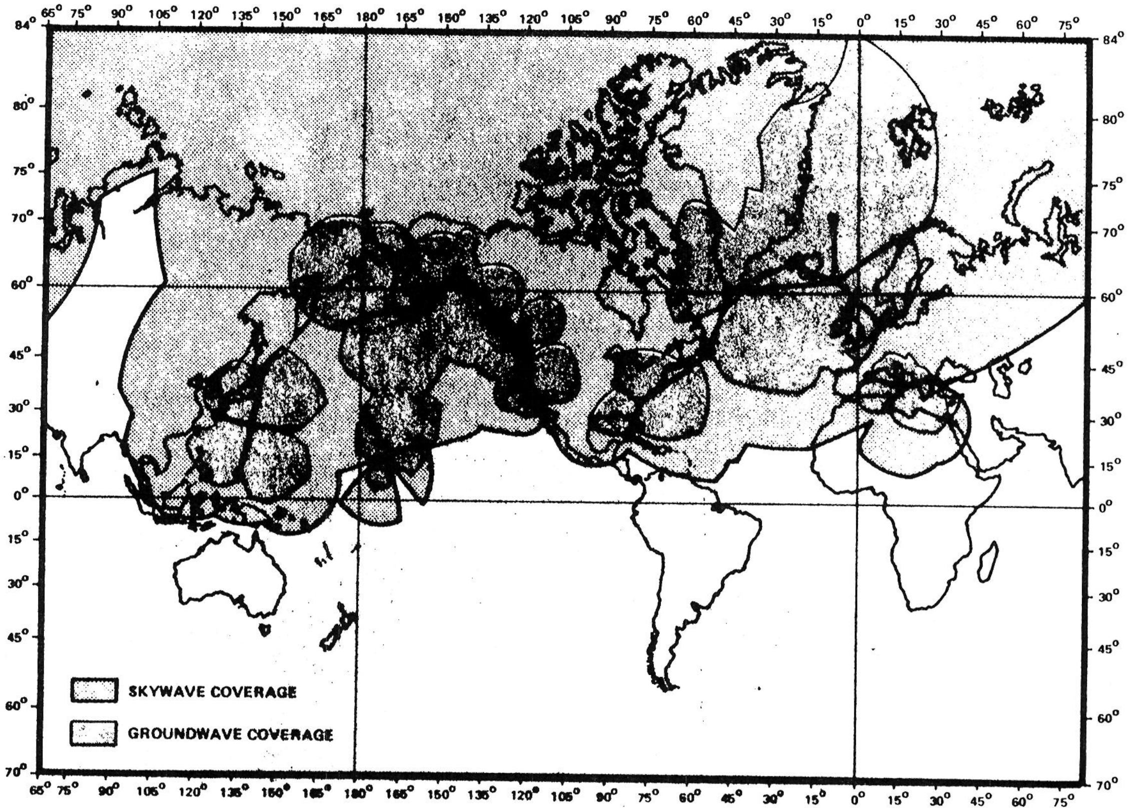
The Coast Guard's Loran C, first used in 1958, is set up in chains of three or more transmitting stations. Like Loran A, the Loran C receiver computes lines of position based upon time-of-arrival differences between signals from selected combinations of two transmitters of the same chain. One's position is where these lines of position cross. Although similar in operation, Loran A equipment cannot be interchanged with Loran C and Loran D equipment, because they use different frequency bands. The Air Force's Loran D system is a transportable version of Loran C, and the receiving equipment is interchangeable.

The Loran C ground wave signals provide a position error of three-tenths of a mile to as low as a few hundred feet. Loran D is more accurate primarily because of the proximity of receivers to the transmitters. Existing Loran C chains provide geographical coverage of 900 miles to 2,400 miles from the ground wave signal, but Loran D covers less than 500 miles. Loran C sky waves, which provide a position error of 2 miles, cover most of the Northern Hemisphere.

The current coverage is shown in figure 2.1.2-1 with a new US coverage planned for 1980 shown in figure 2.1.2-2.

The coast Guard operates seven Loran C chains, the East Coast chain, and six chains outside of the United States primarily to provide navigation for submarine operations. As discussed below, the Coast Guard is building other stations along US coastal areas for civilian use.

The Air force operates two Loran D chains in Germany to provide all-weather navigation during combat flight operations. The second



Source: Coast Guard

NOTE: The dark shaded areas receive groundwave signals giving a navigation accuracy of three-tenths of a mile to as low as a few hundred feet.
The light shaded areas receive skywave signals giving a typical accuracy of 2 miles.

FIGURE 2.1.2-1 LORAN C Coverage, World Wide

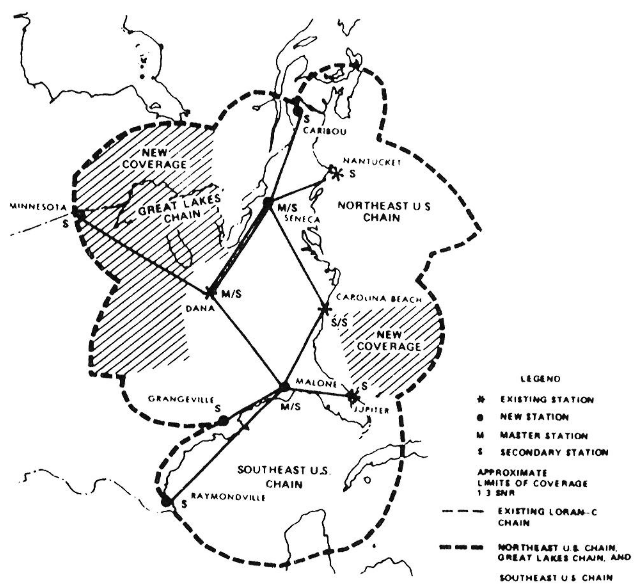


FIGURE 2.1.2-2 LORAN C Coverage, US New Coverage 1980

USERS

Loran C is currently used by an estimated 3,400 civilian maritime users, some US military aircraft, and some Navy submarines. Military aircraft carrying Loran C receivers include some Air Force and Navy cargo aircraft, some Air Force fighters, and some Navy patrol airplanes.

Except for the strategic submarines, the military will be phasing out their use of Loran C in the 1980's. However, the number of civilian users is expected to grow as Loran A receivers are replaced with Loran C receivers.

EQUIPMENT COSTS

A Loran C transmitting station currently costs $4 million, Loran C and Loran D receivers cost from $1,100 to $5,000 for civilian maritime receivers to as much as $20,000 for a military airborne receiver.

A typical Loran C receiver which displays aircraft position in latitude/longitude is shown in figure 2.1.2-3.

2.1.3 OMEGA

The Navy-developed Omega system will eventually consist of eight ground-based transmitters with each transmitter having a range of about 5,000 miles. Seven stations are at least partially working, and the last permanent station will be built in the near future, thus providing world-wide coverage.

The Omega transmitters send out coded and precisely timed signals to the Omega receiver which computes a line of position based on the time required for signals from two transmitters to reach the receiver. The receiver computes at least two lines of position to determine location, which is the point where the lines of position cross. The system currently provides an accuracy of 1 to 5 miles over most of the earth's surface and is expected to provide worldwide coverage with 1 to 2 miles accuracy.

Solar flares can cause temporary errors of 10-20 nautical miles.

Coast Guard personnel operate the two US stations, and the other nations operate the other five. The Navy expects to continue paying the operating cost of the US stations until the Coast Guard assumes full responsibility in 1980.

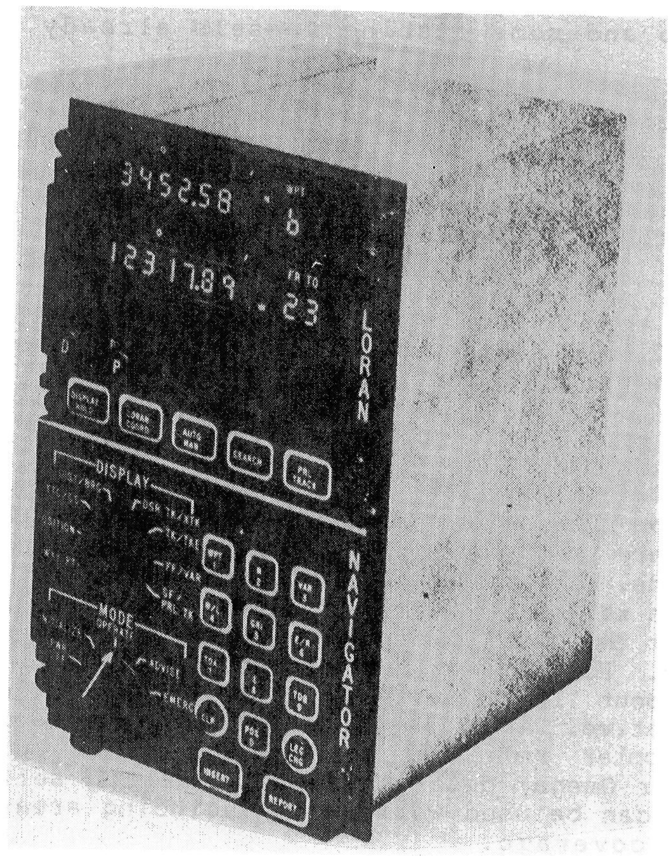


FIGURE 2.1.2-3 Teledyne TDL-424 LORAN NAVIGATOR

USERS

Omega provides navigation to airplanes on transoceanic flights and ships operating on the high seas. Although probably no more than 10,000 users now have Omega receivers, the number is expected to grow. The Navy is putting Omega receivers on surface ships and attack submarines and on some helicopters, patrol aircraft, and cargo aircraft. The Air Force is putting Omega on some cargo aircraft. The commercial airlines are experimenting with Omega for use on trans-oceanic flights, and commercial cargo and some fishing vessels already use Omega.

EQUIPMENT COSTS

Shipboard Omega receivers cost from $2,000 to $8,000. The Navy, however, recently paid $65,000 for receivers used on submarines. Airborne receivers cost from $10,000 to over $60,000. Each transmitting station costs $5.5 million to $8 million for installation and equipment.

The location of the VLF Communication stations and OMEGA stations are shown in figure 2.1.3-1. A typical OMEGA/VLF Navigation System the CCC ONTRAC III is shown in figure 2.1.3-2.

2.1.4 INERTIAL NAVIGATION

Inertial navigation systems depend upon gyroscopic principles for their operation. They are self-contained; that is they do not depend upon external radio aids. They calculate position by measuring acceleration or deceleration in relation to time and direction. Although they can be accurately set at the point of departure, inertial systems have drift errors over time. For example, systems commonly used by transoceanic aircraft drift about 1 mile for each hour of flight time. Hence, the errors are cumulative. Aircraft can correct for such drift either by self-contained doppler radar, or by using one of the radio navigation systems (Loran or Omega) described earlier. Being self-contained, inertial systems can be used world-wide including areas not having radionavigation coverage.

A significant trend toward strapdown inertial systems has developed which may yield simpler, lower cost systems. New technology gyros employing ring laser techniques are developing. One strapdown system uses electrostatically suspended gyros. The most common gyro employed in the current generation of INS is the tuned rotor gyro.

EQUIPMENT COSTS

Airborne inertial systems used by commercial airlines and the military services currently cost about $100,000 each and have a typical error of one nautical mile per flight hour.

Strapdown inertial systems costs are projected in the range from $35,000 to $65,000 for accuracies in the range of 0.7 to 1.0 NMi/hr.

A typical inertial navigation system is shown in figure 2.1.4-1 (the Litton LN-72). The block diagram for the LN-72 is shown in figure

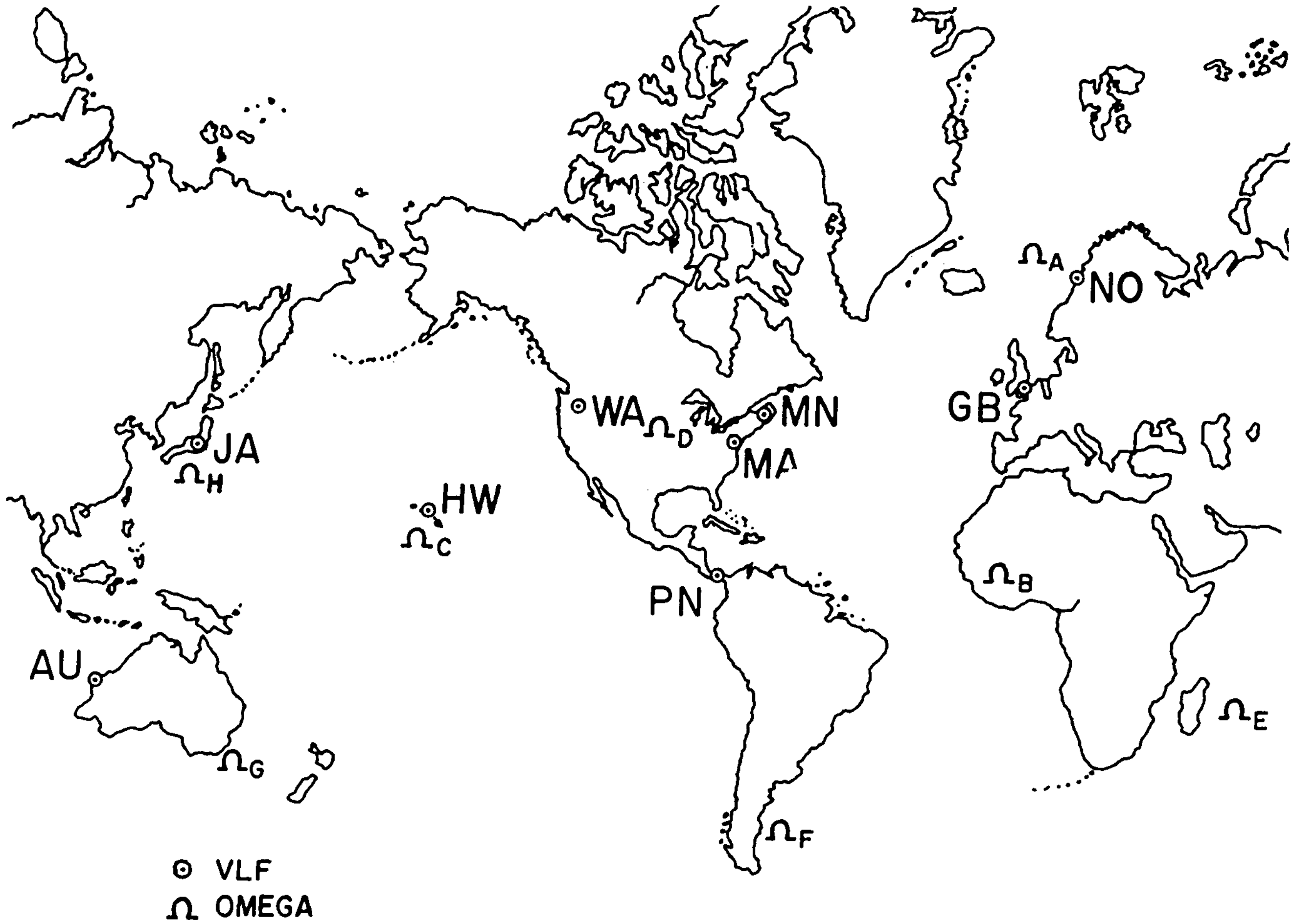


FIGURE 2.1.3-1 OMEGA/VLF Communication Station Locations

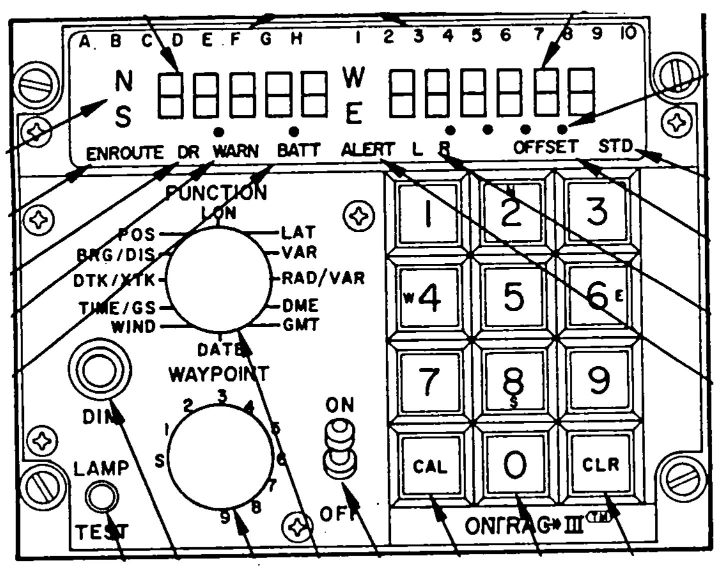


FIGURE 2.1.3-2 OMEGA/VLF Control and Display Unit

2.1.4-2. The LN-72 uses tuned rotor gyros.

Some 747 installations used for transoceanic flights utilize three INS's.

USERS

An estimated 4,000 military aircraft, some Navy ships, and virtually all Navy submarines carry inertial because unlike radionavigation systems, inertial is not subject to signal jamming or sabotage of the transmitters. Submarines also depend heavily upon inertial systems for navigation when submerged because signals from radionavigation systems cannot penetrate seawater to any appreciable depth. The commercial airlines are experimenting with a hybrid Omega/inertial system using one $100,000 inertial and one $20,000 Omega receiver rather than three $100,000 inertials. This hybrid system should give a maximum positioning error of 2 miles, the Omega system error, as long as the Omega system is operating.

2.1.5 NAVSTAR/GPS

2.1.5.1 Introduction

The Navstar/GPS is a space-based radio navigation aid which can be used by surface, airborne and space-borne vehicles. The precision of the GPS has been demonstrated to be less than 10 meters in three dimensions. With the 24 satellite constellation to be deployed starting in 1983, this precision will be available to all users on a world-wide common grid. This section describes the navigation concept prior to enumerating the critical technology areas, so that the reader will be better able to appreciate their functions.

2.1.5.2 Navigation Concept

The GPS navigation technique employs passive ranging to four selected satellites of the six to ten satellites of the total constellation in view. From a knowledge of the satellite positions, the user computes his instantaneous three dimensions of position and velocity, and time. This capability applies to both moving and stationary users, with user position and velocity measurements available, as often as the navigation set will allow. Ranging is accomplished by measuring the time of a correlation peak of the spread spectrum signal transmitted by the satellite, with respect to an internal crystal clock in each user equipment. The spread spectrum signal also contains a satellite data message containing updated precise ephemeris parameters, and corrections to its own on-board atomic standard clock. These corrections keep the satellite ephemeris parameters and clock contributions to the ranging error to less than several meters. The remaining causes of navigation error are user set noise pertubations encountered in the measurement of range. The characteristics of the satellite navigation signal are given in Table 2.1.5.2-1. The two-frequency transmission permits correction for ionospheric delay by direct measurement.

LTN-72 INERTIAL NAVIGATION SYSTEM

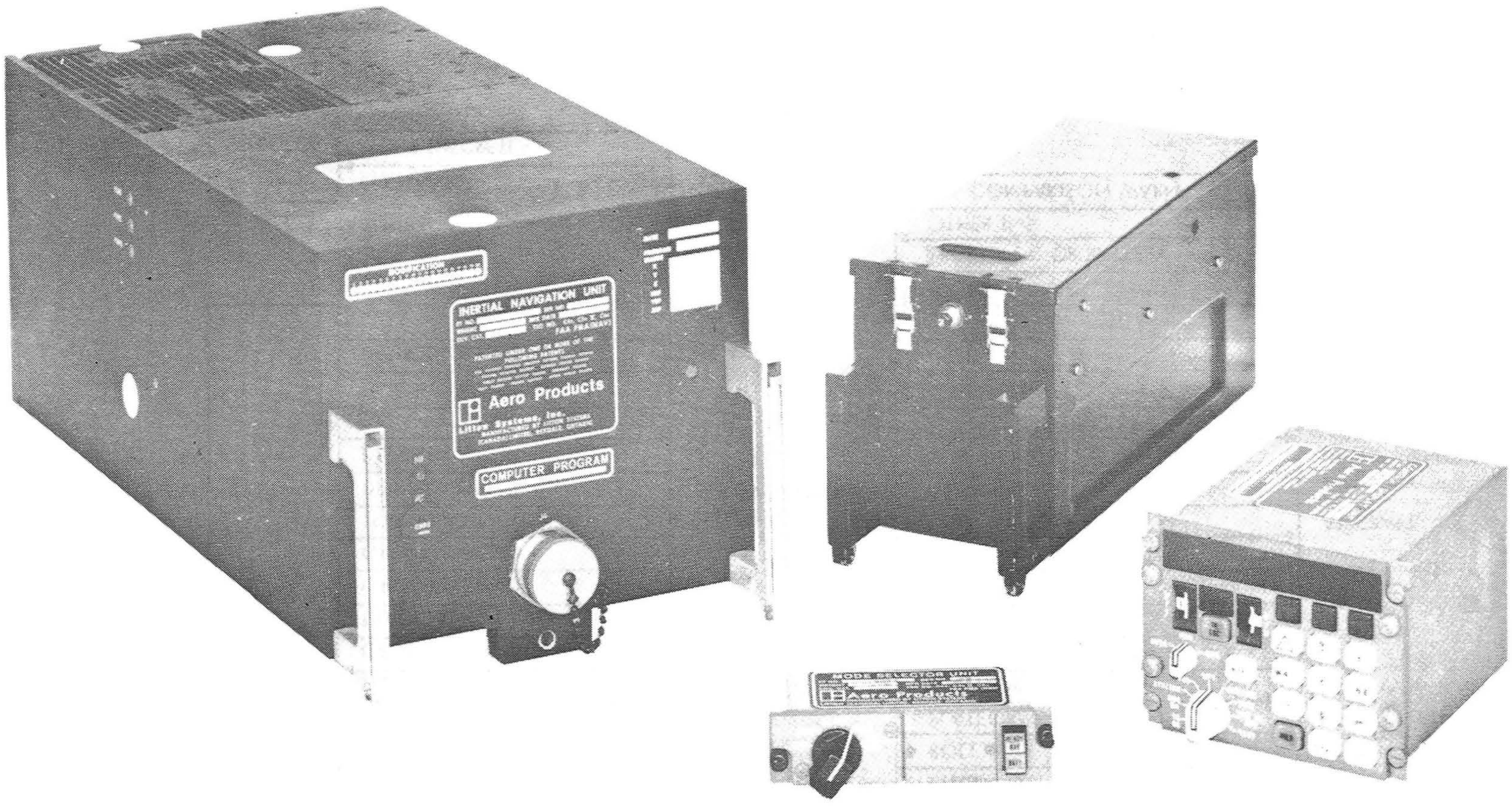


FIGURE 2.1.4-1 TYPICAL INS

LTN-72 BLOCK DIAGRAM

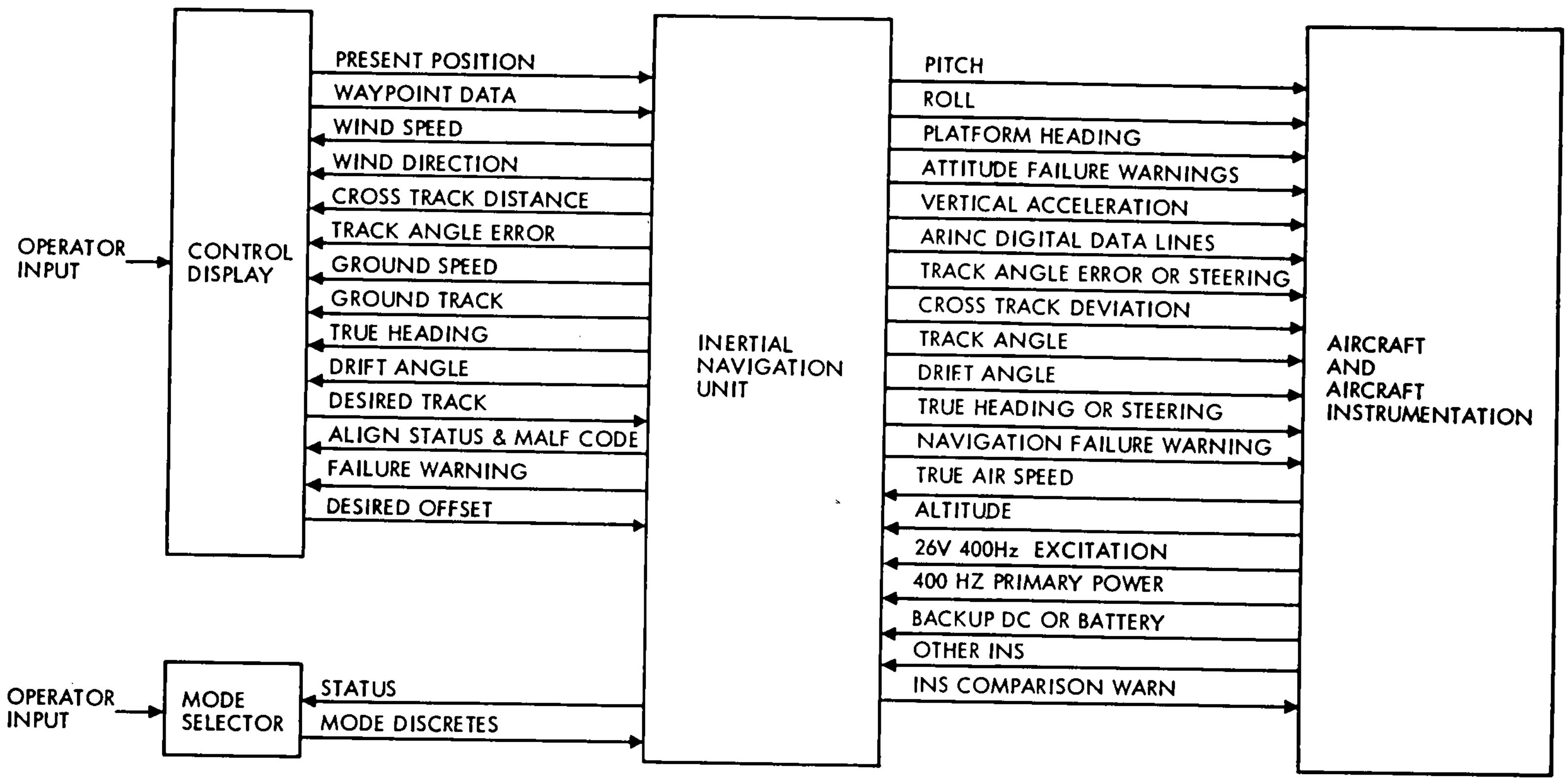


FIGURE 2.1.4-2 BLOCK DIAGRAM FOR TYPICAL INS

TABLE 2.1.5.2-1

GPS SIGNAL STRUCTURE

- L_1, L_2 CARRIERS — 1575.42 AND 1227.6 MHZ
- MODULATED WITH --
  - / P CODE:
    - 10.23 MBPS PSEUDO-RANDOM-NOISE (PRN)
    - LINEAR CODE
    - OVER 300 DAYS IN LENGTH
    - SHORT CYCLED TO 7 DAYS
    - REFERENCED TO SATURDAY MIDNIGHT GMT
  - / C/A CODE:
    - 1.023 MBPS PRN LINEAR CODE
    - 1 MS IN LENGTH
- P AND C/A CODES QUADRIPHASE MODULATED ON L_1 CARRIER
  - / P OR C/A CODE BI-PHASE MODULATED ON L_2 CARRIER
  - / P AND C/A MODULO-2 ADDED TO 50 BPS DATA MESSAGE
  - / MESSAGE IS 30 SECONDS LONG (1500 BITS)
    - SV CLOCK CORRECTION
    - EPHEMERIS CORRECTION
    - TELEMETRY/HANDOVER WORD (NUMBER OF 1.5 SEC EPOCHS SINCE BEGINNING OF WEEK AT BEGINNING OF NEXT MESSAGE)

2.1.5.3 User Equipment

2.1.5.3.1 Satellite Tracking

In order to obtain range and range rate from the satellite signals, each user set needs to contain four real or virtual code and carrier channels which can lock onto the code and carrier components of a selected satellite transmission. A block diagram of a GPS User Equipment is shown in Figure 2.1.5.3.1-1. Once the local coder phase has been aligned to that of an incoming signal, the bandwidth of the signal at IF2 signal is collapsed from twice the code rate (2Ø.46 MHz for P, 2.Ø46 MHz for C/A) to essentially a CW carrier. At this time, the code and carrier loops are closed so that carrier and code phase track are maintained. The phase of code loop during track determines range, while that of the carrier loop when differenced over a given interval is converted to range rate with respect to the given satellite.

High performance user equipment intended for rapidly maneuvering aircraft utilizes four code and carrier channels to maintain navigation accuracy. Lower cost sets can operate with as few as one channel, which sequences between the four necessary satellites. Typically, in the single channel case, two seconds per satellite provides adequate time to make the necessary measurements, so that each satellite is accessed once per eight seconds on the average.

2.1.5.3.2 Satellite Acquisition

After turn on, a set must be capable of selecting four satellites which provide the most accurate navigation solutions. Ideally, the best satellite geometry occurs when three satellites are equally spaced around the user, near the horizon, and the fourth is overhead. Knowing its own approximate position (input by the operator) and with an almanac for all the satellites (stored in a permanent memory), a user set can perform an intelligent search for the signals from the satellites in view, with the aforementioned geometry providing the best navigation performance. If an almanac is not available due to volatile memory, a 'search of the sky' operation is initiated which, due to the greater doppler uncertainty, takes longer than the intelligent search. In either case, the data from each of the four satellites must be read. Table 2.1.5.3.2-1 shows the data message format and content. TLM is a telemetry message of the satellite health, while the HOW word denotes the number of six second intervals since the beginning of the week. The total data message is 3Ø seconds long, so that after signal acquisition is accomplished 12Ø seconds is required to read all four satellites' data, if done sequentially. If read in parallel, only 3Ø seconds is required. Typically, the value is somewhere in between, since at some instant after the first SV signal is acquired and while its data is being read, the second signal may be nearly acquired, while the search proceeds for the third and fourth signals.

2.1.5.3.3 Navigation

After receiving pseudo-range and range rate from the channels tracking the satellites, the navigation data processor must perform the following calculations:

1. Compute the exact orbit of each of the four satellites for a short time before and after receipt of the satellite signal.
2. Compute the position of the satellite at the time of transmission.
3. Solve four simultaneous equations of range to four known satellite positions for three dimensions of user position and absolute GPS time.

Until the User Equipment's crystal clock is synchronized with absolute time, the range measurements have the User's clock bias incorporated, and thus are called pseudo-range measurements. As the carrier tracking loop makes adjustments in phase to compensate for satellite and user motion and maintain carrier lock, these adjustments are differenced every one tenth of a second. Satellite induced doppler is removed from each of the four measurements, leaving user range rate to each of the four satellites. Thus, once the user position is determined, multiplication of the direction cosines to each of the four satellites and the respective range rates, results in the three orthogonal components of velocity.

Each pseudo-range measurement and range rate measurement is sent to the navigation data processor, where it is incorporated into an N- state Kalman filter. N typically ranges from 6 to 11. In the latter case, the states include three dimensions each of position, velocity, and acceleration, and user clock offset and clock rate. Measurements are input to the Kalman filter at 10 per second, with navigation updates provided to the Cockpit Display Unit at that rate, also. The gains for each component of the Kalman filter are updated once each two to four seconds, depending on the number of states and the quality of each measurement.

2.1.5.4 Technical Areas Requiring R&D Development

2.1.5.4.1 Data Processing Technology

From the foregoing description of operation, it can be seen that a user set is required to perform numerous digital calculations, both for navigation, coordinate conversion, and for receiver control. For example in the Phase I development models, each navigation data processor requires over 30,000 lines of software code to implement its functions. In addition, these functions require 32,000 to 38,000 words of 16 bit memory, for storage of the navigation programs, of intermediate results, and longer term data (almanacs, waypoint data).

Receiver control functions which include the signal processing and the code and carrier loop control functions in Figure 2.1.5.3.1-1, are best implemented digitally in order to alleviate narrow band analog circuit drift with temperature. Such a digital implementation is usually not attempted due to cost and limitations in performance due to the throughput of such devices. Thus, while the GPS X and Y-sets (4 and 1 channel respectively) have digitally implemented code and carrier loops as well as AGC and carrier power measurements, none of the remaining

Phase I GPS sets (two manpack designs, the low cost Z-set, and the High Dynamic User Equipment) has extensively employed digital control and receiver signal processing.

There is, thus, a need for high speed (700K ops. per sec.) navigation and receiver control data processing technology. Moreover, to reduce installation and logistics costs, the size of the navigation data processor must be reduced from its present 3/4 ATR size (for the GPS X-set) to a unit with a volume on the order of 150 cu. in. Some of this technology has been advanced with the low cost Z-set (single channel, C/A only) implemented with LSI-11 architecture and instruction sets. More will be explored by the four Phase IIA contracts now underway, to be developed in Phase IIB, starting in mid-1979.

2.1.5.4.2 Spread Spectrum Correlators

Current GPS receivers perform a serial code search at the expected frequency (the exact frequency is modified by satellite and user motion induced doppler) of the satellite being sought after. If time is unknown to more than several milliseconds, the short C/A code is searched for first. A typical search rate is 100 steps per second, requiring about 20.5 seconds to look for all 1024 code phases of the C/A code at 1/2 code chip per step.

Filters matched to the various satellite C/A codes could perform this operation in under 10 milliseconds, reducing the four satellite acquisition time from 80 seconds to less than 1 second, for each frequency uncertainty step. Usually the doppler uncertainty (150 Hz) requires about three receiver dwells so that the real reduction in satellite acquisition made possible by matched filters, is from four minutes to less than one second.

While a four minute time to acquire four satellites and navigate, is not usually a burden, especially if conducted during preflight warmup, there are many instances when rapid satellite signal acquisition is needed. For example, during most aircraft turns, one of the satellites being tracked is usually lost due to antenna coverage limitations or wing masking. In this instance, the navigation filter has only three or less inputs, and the navigation solution rapidly diverges from truth. If another SV were capable of being acquired rapidly, this divergence would not occur. The initial navigation solutions using a new SV would depend on the accuracy in the almanac collected from Subframe 5 (see Table 2.1.5.3.2-1) for each of the satellites. After reading Subframes 1, 2 and 3 (18-30 sec.) of the newly acquired satellite, full accuracy would be achieved.

The technology for achieving matched filters of 1000 bit length potentially resides with either Charge Coupled Devices (CCD's) or Surface Acoustic Wave (SAW) devices. Neither of the above technologies is quite capable at this time of performing to the 1000 bit length requirement, and require further development. Military aircraft employing IMU's, as distinguished from the general aviation user, are not disturbed by signal losses, as described above, since the inertial units carry the navigation solution in such instances. For low cost general aviation use, rapid acquisition would be beneficial, or the use of an airspeed/heading dead reckoning may help.

2.1.5.4.3 Directional Antennas

The effective intercepted radiated power of the GPS constellation will be no more than about -153 dBw into an omni-antenna.

At -153 dBw, the signal power is about 17 dB above the thermal noise floor, in a high dynamic set having a 2Ø Hz Costas carrier loop bandwidth. In order to provide additional margin against ionospheric fading and potential tropospheric losses, a directional phased array antenna is needed, having five to ten dB of gain. This device could be made from a lesser number of elements and lower gain beams than the military set, since the latter's requirements for directivity against intentional jamming are much more stringent. The beamwidths of the civil phased array would be on the order of 4Ø deg., so that the pointing requirements are not stringent, and could be implemented by a single function microprocessor.

2.1.5.4.4 Hardened Semiconductors

The high speed semiconductor technology employed in GPS is, for the most part, NMOS. One contractor is using IIL, which has better radiation hardening characteristics, exclusively. However, due to its 3MHz present clock rate limitation, receiver signal processing functions are not digital, and the navigation processor has some throughput limitations. Since the radiation hardening problem is one which is being addressed by DoD, it need not receive further attention.

2.1.5.4.5 Low G-Sensitive Crystal Oscillators

The user clock is driven by a double oven crystal oscillator having a basic accuracy of one part in 1Ø exp. 9, and a sensitivity to vibration of 1 x 1Ø exp. -9 per G. This latter parameter limits the ultimate minimum bandwidth to which the Costas (carrier) loop can be reduced to about Ø.5 to 1 Hz. Further reduction in bandwidth may be desirable to improve the signal to noise ratio for precision approach guidance applications, if the phase noise in the satellite clocks would permit this. In military applications on aircraft having IMU's, the ultimate minimum bandwidth is also a function of the quality of the IMU.

Some diverse efforts are underway to reduce the vibration sensitivity of crystals, in order to permit the reduction of Costas bandwidth and to enhance the anti-jam capabilities of operational user equipment.

FIGURE 2.1.5.3.1-1 GPS USER EQUIPMENT FUNCTIONAL DIAGRAM

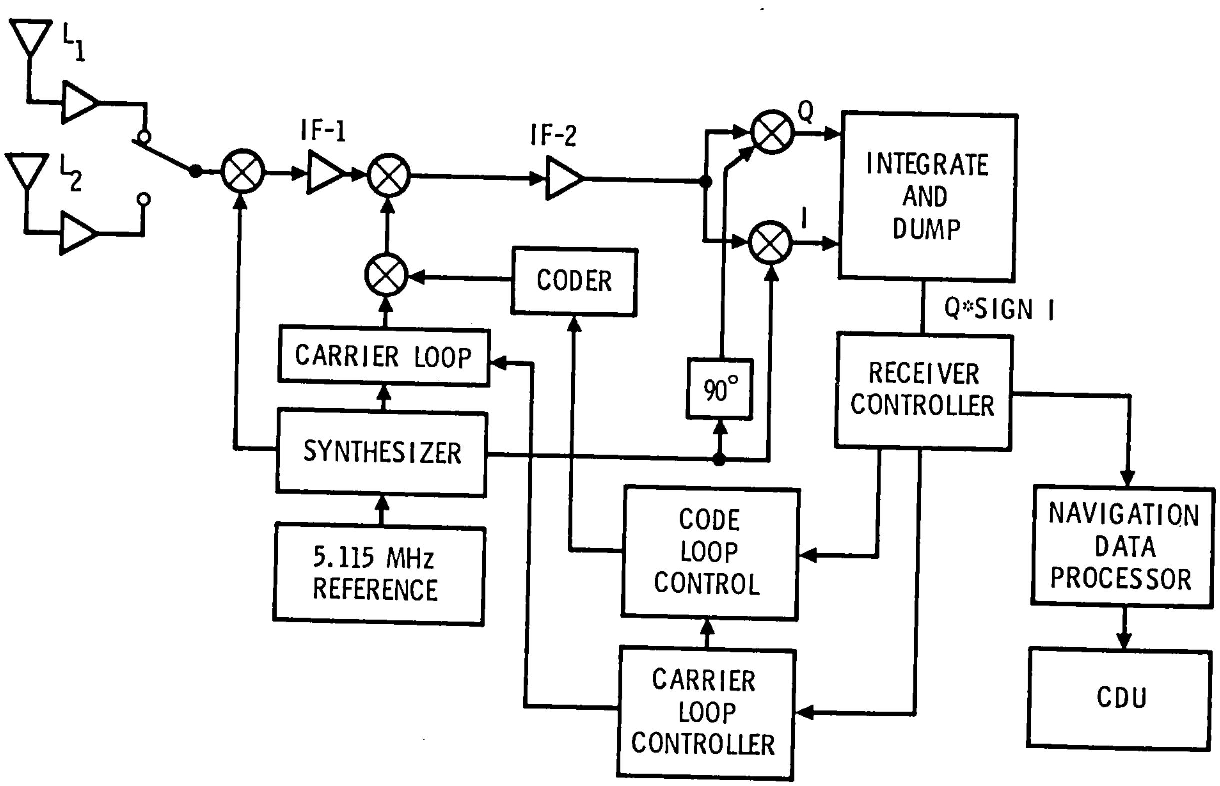
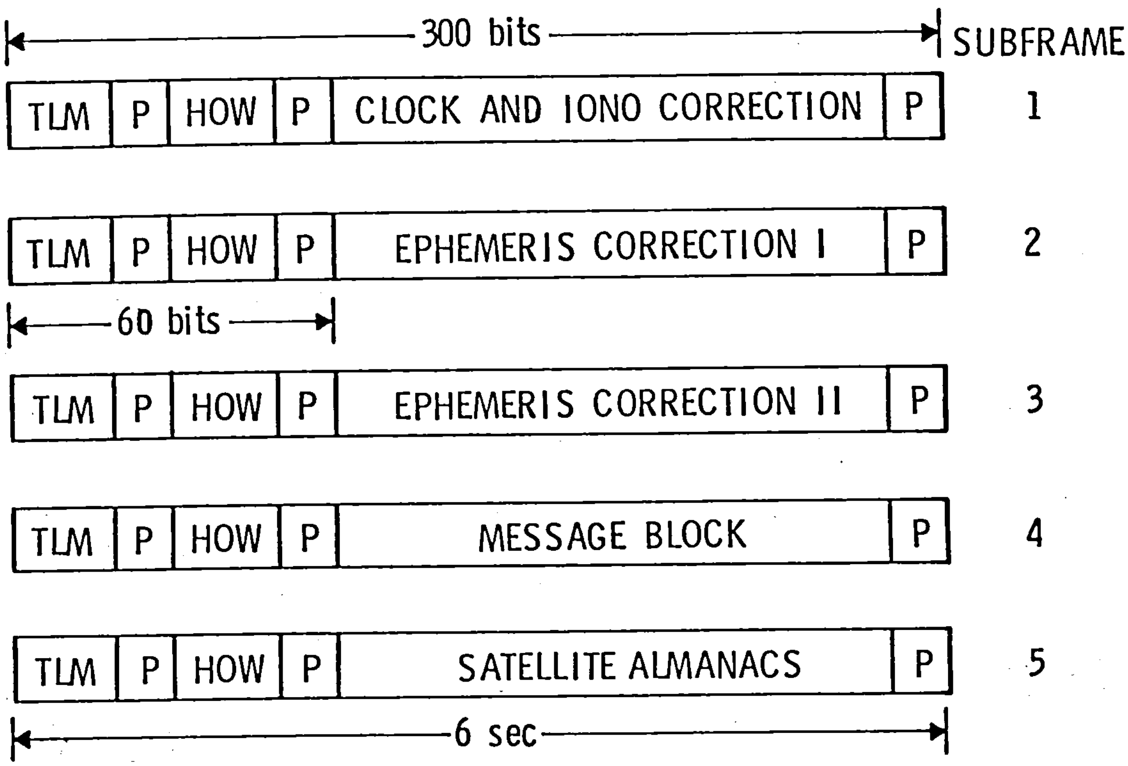


TABLE 2.1.5.3.2-1

DATA MESSAGE FORMAT



2.1.5.5 GPS for Civil Aviation

The operational requirements for civil aviation are significantly less demanding than those of military aviation. Some specific areas where these considerations apply are related to accuracy requirements, vehicle dynamics, jamming, environmental factors such as operating temperature and pressure range, shock and vibration. These reduced demands could result in simplifications in some of the areas of receiver design as shown in figure 2.1.5.5-1 which gives a detailed summary of proposed GPS equipment simplifications. It is most important to note that the most significant cost savings arise from the possibility of single channel multiplexed operation rather than four channel parallel operation of this receiver. Each of the other entries in Figure 2.1.5.5-1 impacts the receiver cost in a lesser way but the aggregate could be significant in reducing costs.

The combination of using a simple true airspeed/magnetic flux compass dead reckoning system to augment the low cost GPS receiver may prove an attractive system for general aviation users.

The broadcast of NAVSTAR satellite ephemeris data by FAA data link facilities may yield additional simplification to the low cost GPS receiver.

2.2 GUIDANCE

Comments on guidance section will be limited to outer loop control law aspects. Other aspects of guidance such as flight path definition, processor, and displey technology, and signals in space are covered in sections 4.3, 5.2.1, 4.1 and 7.5 and 2.1, respectively. As far as critical technology is concerned it is felt that flight path definition and control/display technology (amenable to ease of pilot/ATC controller and pilot/computer interaction) are the critical guicance technology areas.

RNAV and VNAV should be discussed in enroute, terminal and final approach areas, the latter being subdivided into narrow (ILS or low cost MLS) or wide angle (MLS) final approach guidance.

Lateral guidance techniques have approached a level of maturity where only fine tuning is required. Enroute and terminal area accuracies and ride qualities can be achieved from practically all recognized position fixing systems in single VOR/DME or multisensor configurations. (ref 2) Final approach guidance, even up to Category III, is not so much a problem of control law development as it is one of revisionary management leading all the way down to pilot awareness and takeover in the event of system failure. The major problems in the latter event are pilot factors and display technology. Acceptable means of transitioning from enroute/terminal navaids to final approach aids is also more a problem of providing acceptable means for the pilot to monitor progress than it is one of the control system providing performance. (ref 3) This is true whether the transition is to a wide angle or a narrow beam final approach guidance system. (ref 4) The procedures may vary somewhat but the control laws probably will not since the signals in space have approximately the same accuracy and stability characteristics. Aircraft 4D approach control has also been

FIGURE 2.1.5.5-1

Summary of Proposed GPS-Civil Aviation User Equipment Simplifications

PROPOSED EQUIPMENT SIMPLIFICATION	REASON
SINGLE CHANNEL MULTIPLEXED RECEIVER	• LOW VEHICLE DYNAMICS • 1000 FT CHIP • AIRSPEED AIDING
TRACK CLEAR ACQUISITION SIGNAL ONLY	• REDUCED ACCURACY REQUIRED • NO DELIBERATE JAMMING
TRACK SINGLE FREQUENCY	• REDUCED ACCURACY REQUIRED • ESTIMATE IONOSPHERIC MODEL
WIDE BAND TRACKING	• DELIBERATE JAMMING UNLIKELY • REDUCED VEHICLE DYNAMICS
NO INERTIAL AIDING	• NO DELIBERATE INTER-FERENCE • WIDE BAND TRACKING • AIRSPEED AIDING • REDUCED VEHICLE DYNAMICS
SERIAL BINARY DIGITAL CORRELATION	• NO INTENTIONAL PULSE JAMMING
TEMPERATURE COMPENSATED CLOCK	• REDUCED ENVIRON-MENTAL CRITERIA • REDUCED ACCURACY REQUIREMENT
SIMPLE SINGLE ELEMENT ANTENNA INSTALLATION	• NO DELIBERATE JAMMING • ANTENNA PATTERN NOT CRITICAL
AFC CARRIER TRACKING MAY BE POSSIBLE	• REDUCED VELOCITY ACCURACY REQUIRE-MENTS
USE GOOD COMMERCIAL ARINC PACKAGING	• REDUCED ENVIRON-MENTAL CRITERIA
INITIALIZATION FROM A MASTER SET	• COULD BE COST EFFEC-TIVE FOR CERTAIN LIMITED RANGE OPERATIONS

shown to be feasible for different complexities of ground and airborne equipment. (ref 5, 6) Incompatibility of procedures for aircraft equipped with sophisticated guidance systems and for those minimally equipped appears to be the major stumbling block inhibiting implementation of these techniques.

A similar situation exists for vertical guidance during final approach where a fixed flight path is defined. The control law technology exists to make close-in ILS captures from above or below the glideslope; closer aproaches require more RNAV aiding. (ref 5, 7) Curved approaches using digital autopilots have successfully demonstrated the performance capabilities of scanning beam MLS. (ref 8). In contrast, vertical guidance in enroute and transition areas has been poorly defined. Altitude changes are typically performed either by straight line segments (seldom) or by inner loop attitude hold/vertical speed hold procedures. Differing aircraft characteristics (which are weight and temperature sensitive) result in significant differences in flight profiles. Because of this, ATC has resorted to inefficient vertical procedures to ensure safe altitude crossings. By using modern airborne processors, these inefficiencies could be removed and the resulting flight profiles could be known a priori. Revised ATC procedures (discretionary descents for example) would become acceptable if it were improbable that aircraft would overshoot their endpoints. Whether such descents could continue to the final approach area or even to touchdown is highly debatable. NASA's experience with the Shuttle and the CV-88Ø demonstrator could be used as a basis for developing a full flight envelope energy management system. This is the primary area of guidance technology still to be resolved and an appropriate one for NASA to address.

2.2.1 RNAV

Area Navigation (RNAV) is currently implemented using the VOR/DME network with approved RNAV routes and waypoints. The current generation of RNAV systems also includes means for the pilot to establish waypoints which he defines. A number of RNAV systems have been marketed which use a combination of navigation sensors integrated through a control and display unit with a digital computer for solving the various navigation algorithms such as great circle route distance and heading computations between waypoints or from current position to any selected waypoint.

A typical RNAV system which uses VOR/DME and defines waypoints as range and bearing from a VOR station is shown in figure 2.2.1-1. This system also provides VNAV capability. This RNAV system also provides for waypoint entry via a preprinted data card.

Figure 2.2.1-2 shows a VOR/DME based RNAV system which utilizes waypoints defined by latitude and longitude. The computer automatically tunes to the proper VOR/DME stations based upon aircraft location. The unit stores the latitude and longitude of every VOR station in the world which it can access for RNAV computation. mputation.

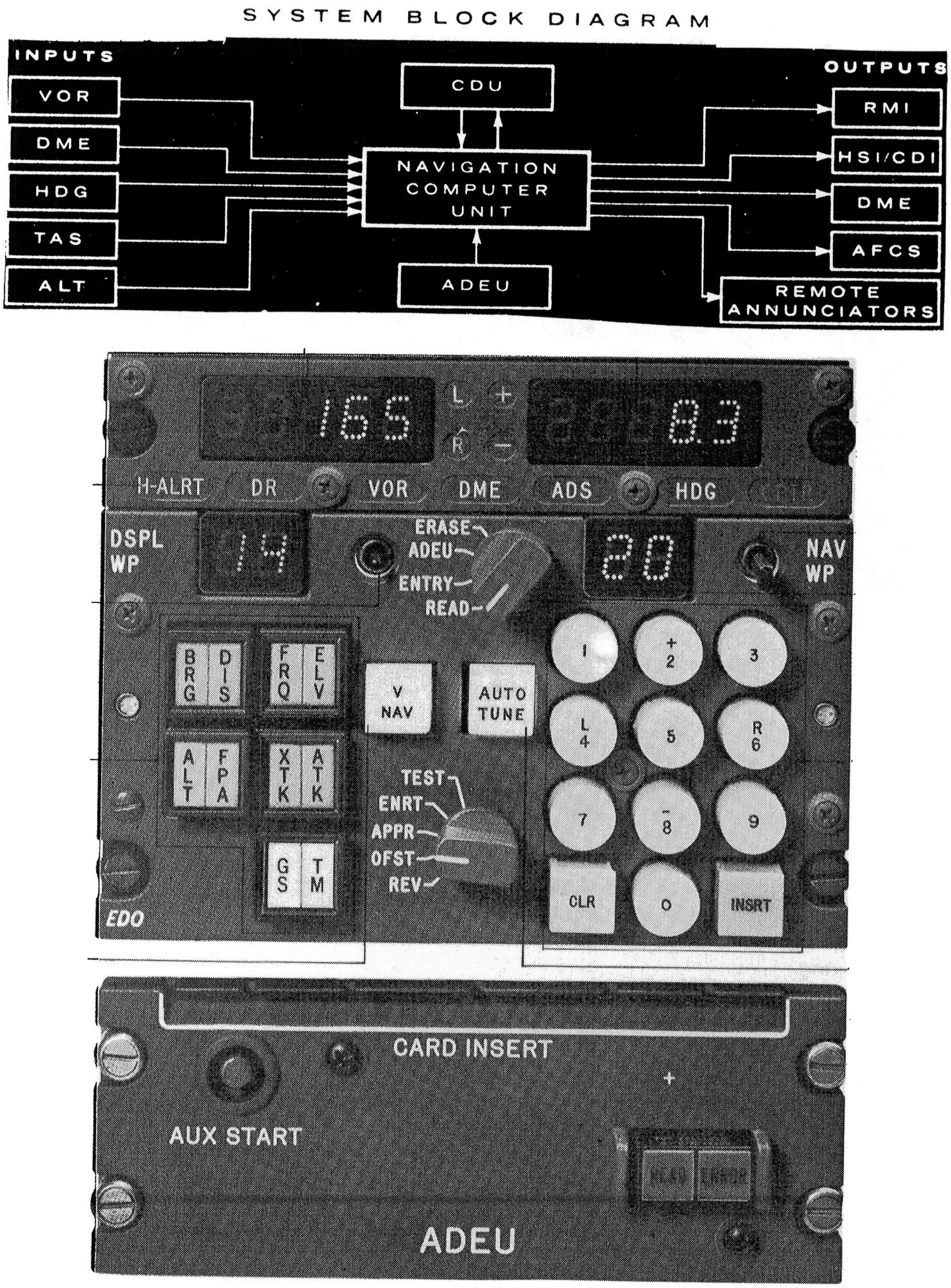


Figure 2.2.1-1 Typical R-NAV system using range/bearing definition of waypoints, 20 waypoint capability

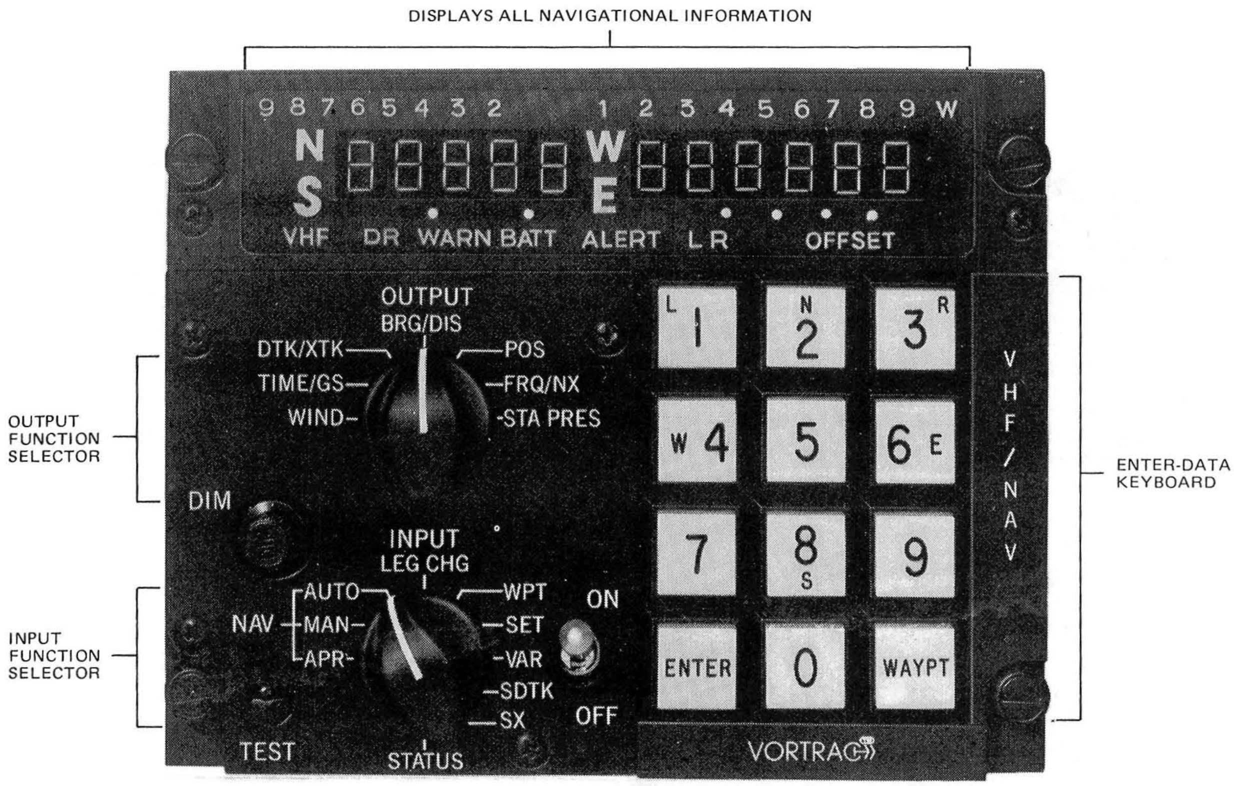


Figure 2.2.1-2 Typical VOR/DME R-NAV system utilizing LAT/LNG waypoint definition.

R-NAV FEATURES

- Great circle navigation
- Terminal area navigation, landing zone acquisition
- Position fixing
- Constant groundspeed indication
- Left/Right guidance
- Longitude/latitude, present position
- Bearing and distance to destinations (nine waypoints)
- Speed/time to waypoint
- Left/right track
- Wind direction/speed

NINE WAYPOINT CAPABILITY WITH NON VOLATILE WAYPOINT MEMORY

2.2.2 VNAV

The VNAV function provides for vertical steering to permit profile descents from one altitude at a given waypoint to a lower selected altitude at the next waypoint. The VNAV function utilizes altitude, speed, and RNAV distance in the computation. Some of the RNAV systems such as that shown in figure 2.2.1-1 also include the VNAV function.

2.2.3 TERMINAL AREA NAVIGATION

The most common mode of terminal area navigation at the present time is ATC issued radar vectors to the acquisition point for an ILS approach. However as terminal area traffic density increases the dependence of radar vectors on terminal area separation becomes less satisfactory. The RNAV systems equipped with multiple waypoints can be used in the terminal area. A strong trend has developed toward using 4D-navigation which includes adjusting time of arrival to an assigned time for traffic metering in the terminal area. Such 4D-navigation systems have been flight tested by NASA: for example, in the STOLAND program.

2.2.4 INSTRUMENT LANDING SYSTEM (ILS)

The most common landing approach aid used by civil aircraft is the VHF/UHF ILS system which has been in use for over thirty years. The ILS uses a VHF localizer for lateral guidance and a UHF glide slope for vertical guidance which is automatically channeled to the localizer receiver. Most VOR receivers include the localizer channels as part of the navigation set. A majority of aircraft including general aviation have localizer capability. Fewer general aviation aircraft have glide slope, although glide slope receivers are relatively inexpensive.

2.2.5 MICROWAVE LANDING SYSTEM

Purpose

The Microwave Landing System (MLS) is an electronic aid to aircraft navigation during the approach and landing at an airport runway. Its purpose is to provide a common civil/military approach and landing system with improved performance and more flexibility for implementation than existing systems.

In 1971, a joint development program was initiated by the Department of Transportation (DOT), the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) (ref. 9). This joint development was undertaken under FAA management to provide a National standard for a family of compatible landing system configurations which would be adaptable to the needs of a wide range of civil and military users. The system has also been designed to meet the international need for a new standard Non-Visual Approach and Landing Guidance System as a replacement for the existing ILS (ref. 10).

Development Status

The development program has progressed through three phases, which included (1) technical analysis and contract definition, (2) feasibility demonstration, and (3) prototype developments. Prototype development of a basic system configuration and a small community configuration have been completed, but prototypes for an expanded system configuration and military tactical configurations have not been completed.

System Configurations

The system has been designed so compatible system elements can be combined to meet the needs of a specific airport facility. The three major configurations were identified for prototype development. These are: (a) basic, (b) expanded, and (c) small community. Illustrations of these configurations are shown in Figure 2.2.5-1. (Ref. 11)

Basic System The basic configuration consists of the following functional sub-systems:

(1) Approach azimuth, nominally located on the runway centerline beyond the stop end.
(2) Approach elevation, nominally located beside the runway near touchdown.
(3) DME transponder, nominally located beside the azimuth equipment.

Expanded System
The expanded configuration consists of all the basic subsystems plus the missed-approach and flare subsystems, located beyond the approach end of the runway. The expanded configuration is designed with full redundancy to meet all the operational requirements of ICAO and all Category III requirements.

Small Community

The small comunity configuration meets the need for a minimum service system and consists of:

(1) Approach azimuth
(2) Approach elevation
(3) DME or ICAO standard marker beacons

This equipment is designed to meet Category I requirements in a cost-effective manner and does not have all the redundancy features needed for higher category all-weather operations.

System Description

The MLS is an air derived system in which ground based equipments transmit position information signals to a receiver in the aircraft. The position information is derived in the aircraft as angle coordinates and a range coordinate. The range information is provided by the Distance Measuring Equipment (DME) technique. The angle information is based on the Time Reference Scanning Beam (TRSB) technique and is derived by measuring the time difference between the successive passes of highly directive narrow fan shaped beams which scan through the coverage volume in alternate directions (TO and FRO). The 'TO' beam is scanned with uniform speed starting from one extremity of the coverage sector and moves to the other. The beam then scans back again to the starting point, thus producing the 'FRO' scan as shown in Figure 2.2.5-2 for azimuth. (ref 12) In every scanning cycle, two pulses are received by the aircraft. The time interval between the 'TO' and 'FRO' pulses is proportional to the angular position of the aircraft with respect to the runway. An important feature of the time reference encoded scanning beam system is the high data update rate, 13.5 Hz for azimuth and 40.5 Hz for elevation. These rates permit the integration of individual measurement samples to achieve guidance information having a very small noise content.

All angle and data functions are time-multiplexed so that a single receiver-processor channel may process all data. Since the functions are independent entities in the time-multiplexed function sequence, the receiver may decode them in any sequence. This is accomplished by providing each function with a preamble that, upon reception, sets the receiver for the function which follows. The function identification preamble is radiated as a stationary beam by a sector coverage antenna. The volumetric coverage of the scanning fan beam and the sector transmissions are illustrated in Figure 2.2.5-3. (ref 13) The coverage capabilities can provide data over a wide volume, bounded by +60 deg. or -60 deg. from the centerline for approach azimuth, 0 deg to 30 deg in approach elevation and 20 to 40 NMi in range.

Signal Format

The signal format is time-multiplexed. It provides information in sequence on a single carrier frequency for all the angle functions (azimuth, elevation, flare and missed approach azimuth). The format includes a time slot for 360 deg. azimuth guidance and other provisions for growth of additional functions if required. There are 200 channels provided for angle and range guidance. The angle guidance channels are provided in C-band between 5031 MHz and 5091 MHz.

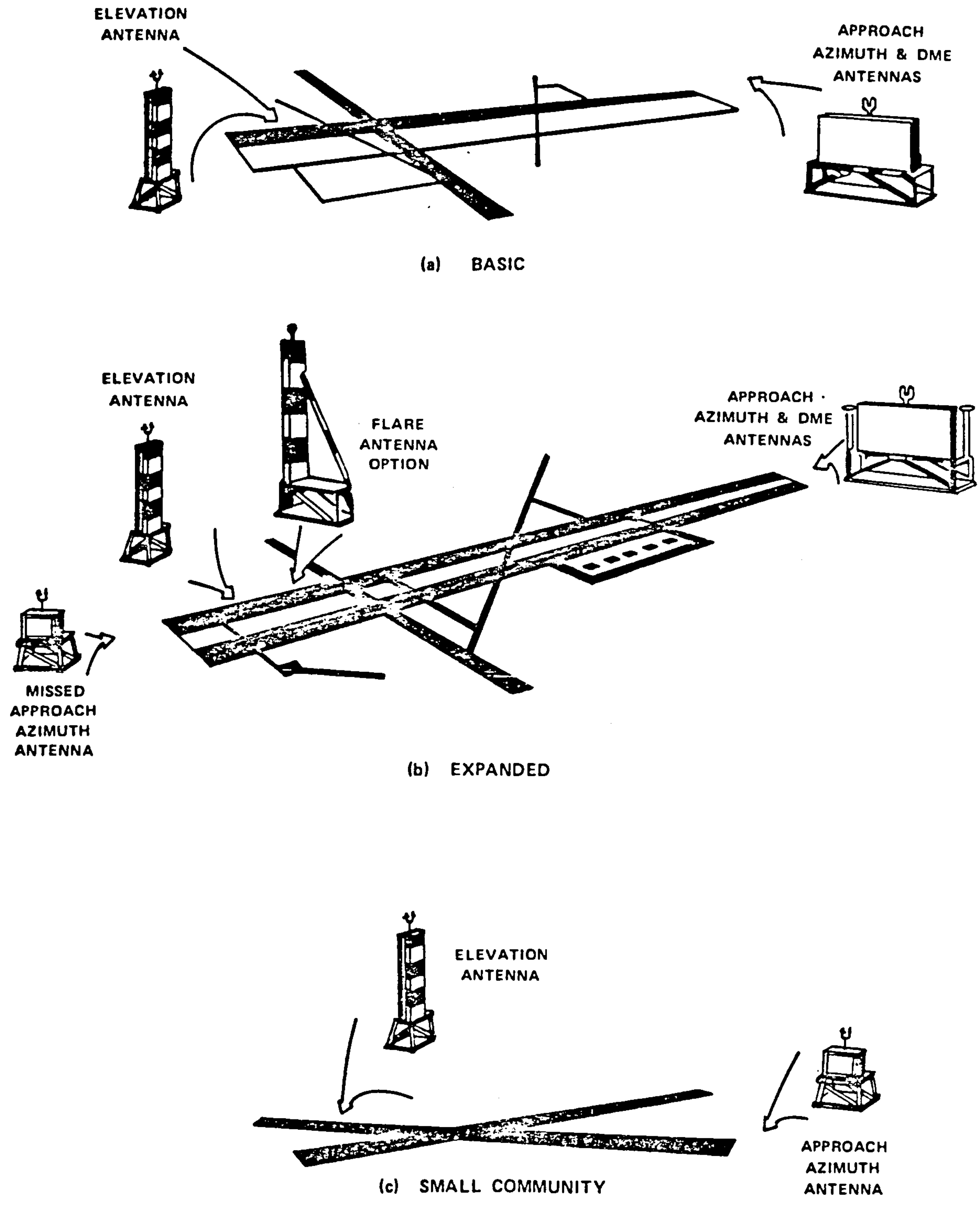


FIGURE 2.2.5-1 EXAMPLES OF TYPICAL GROUND CONFIGURATIONS

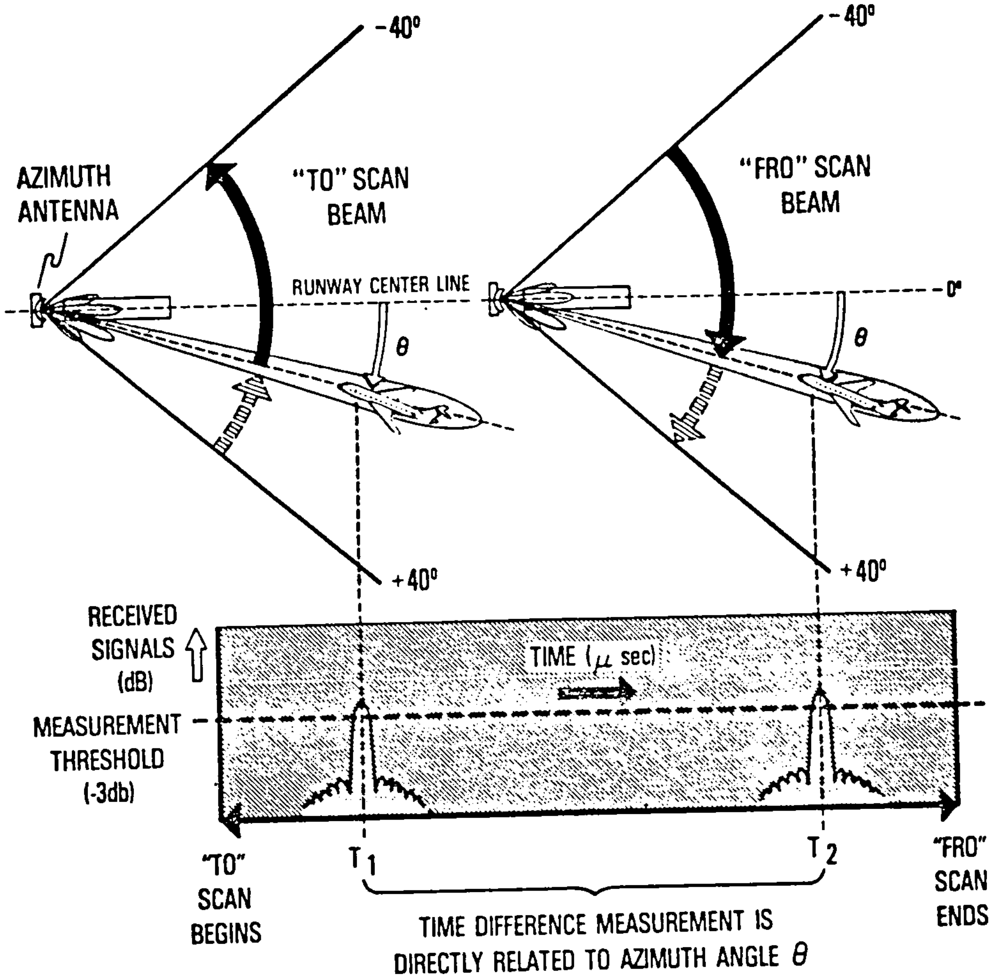


FIGURE 2.2.5-2 TIME DIFFERENCE MEASUREMENT

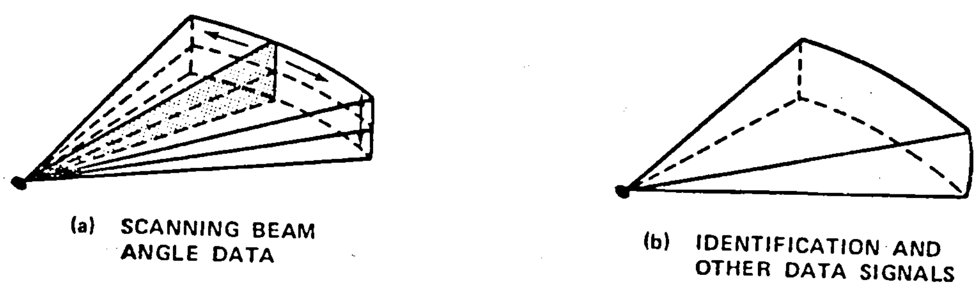


FIGURE 2.2.5-3 REPRESENTATIVE VOLUMETRIC RADIATION COVERAGE

2.3 AIR TRAFFIC CONTROL

Introduction

The Federal Aviation Administration (FAA) has primary responsibility for the development and application of technology for air traffic control in the domestic and contiguous oceanic airspace. The FAA conducts engineering and development programs to exploit current technology and examine future concepts to improve the National air traffic control (ATC) system (ref 14). These research and development efforts are aimed at keeping the current system operating safely with maximum efficiency and improving performance to meet capacity requirements of projected air traffic growth. To achieve these interrelated goals, major technical developments for near-term application (within 10 years) are being conducted by the FAA to provide new capabilities for aircraft separation assurance, surveillance of air traffic, reducing the constraints of aircraft wake vortex, and increasing the level of automation in flight service and control functions (ref 15). Developments in closely related areas, such as navigation, communications and weather information, are presented in other sections of this report.

Scope and Purpose

This section presents an overview of major developments for improving air traffic control and investigation of technology options that may have potential for future, longer-term (over 10 years) applications to air traffic control. The principal focus of this overview is on the functional rather than the technical aspects of the FAA developments. More detailed discussions of the technical aspects of selected programs are presented as subsections to this overview. Those subsections discuss Altitude Encoding Transponders (Section 2.3.1), the Beacon Collision Avoidance System (Section 2.3.2), the Discrete Address Beacon System (Section 2.3.3) and Time Division Multiple Access Data Link (Section 2.3.4).

The purpose of this overview of new technology applications in air traffic control is to identify emerging concepts which are likely to have major impacts on the National Airspace System (NAS) in the 1980's and beyond. Where applicable, potential areas will be identified where NASA technology efforts may best complement and support FAA E&D program initiatives in air traffic control.

Major Technical Developments (near-term)

Aircraft Separation Assurance

The FAA is engaged in three major development activities as backup safeguards against midair collisions. These are known as Conflict Alert, Beacon Collision Avoidance System (BCAS) and Automatic Traffic Advisory and Resolution Service (ATARS).

Conflict Alert.

The current software development program for the terminal and enroute computerized control systems includes new features to detect possible air traffic conflicts. These improvements in the processing of track information on aircraft with altitude reporting transponders alert the controller to possible traffic conflicts.

The Beacon Collision Avoidance System (BCAS)

all-weather airborne collision avoidance service by the FAA issuing a U.S. National Standard for BCAS avionics. The system is based upon use of airborne beacon transponders and is independent from the primary ATC system. Any aircraft operator desiring the BCAS service can install appropriate BCAS avionics when fully developed and receive warning of impending collision or near-miss threat from nearby aircraft carrying an altitude encoding transponder as the cooperating airborne element. The system will have an active mode for BCAS-equipped aircraft operations outside of ground-base ATC surveillance coverage and a fully passive mode for operation in high-density airspace. The BCAS-equipped aircraft can operate compatibly with the present Air Traffic Control Radar Beacon System (ATCRBS) transponders or future Discrete Address Beacon System (DABS) transponders.

Automatic Traffic Advisory and Resolution Service (ATARS)

This is a conflict alert and resolution service for use by pilots of ATARS-equipped aircraft. This capability is being developed concurrently with DABS and will use the DABS data link for transmission of ground-derived separation assurance information. If potential traffic conflicts are not resolved in a predetermined time frame by the basic ATC system or independent pilot actions, a ground based computer processing DABS data will be capable of issuing separation maneuvering commands directly to the aircraft involved.

NASA Technology Support

The widespread acceptance and use of cooperative airborne collision avoidance systems may require state-of-the-art applications in low-cost avionics technology and cockpit displays. The human factors aspects of integrating these new types of information displays into the cockpit environment are also important areas of supporting research.

Discrete Address Beacon System (DABS)

This is a ground based surveillance system with an integral data link being developed by the FAA to significantly improve the quality of ATC surveillance data. DABS is being designed as a compatible replacement for the present ATCRBS facilities. The new system will be able to discretely address aircraft equipped with DABS transponders to eliminate synchronous garble of beacon responses in high density areas. An integral two-way data link is being designed into the system for control messages and other air-ground communications.

NASA Technology Support

The capability to use the DABS data link for control messages will introduce a major new perspective into the cockpit. The impact and best approaches of using the data link for tactical control messages appear to be areas in which NASA could pursue supporting research.

Airport Surface Traffic Control

The Airport Surface Traffic Control (ASTC) program is two-phased to improve the surveillance and ground control of surface traffic at major airports. The first phase of the program is to replace existing tower radar equipment with new Airport Surface Detection Equipment (ASDE). The ASDE-3 now under development will increase system reliability and provide enhanced target detection and display capabilities to assist tower control of surface traffic in periods of reduced visibility.

The second phase of the program will develop a Tower Automated Ground Surveillance (TAGS) system for use under all-weather conditions at large airports. The TAGS system will utilize beacon transponder surveillance to provide controllers with aircraft identity and position information on surface traffic displays.

Wake Vortex Programs

A potentially hazardous condition can exist for aircraft departures and approaches to landing when encountering trailing vortices from other aircraft. Under certain atmospheric conditions and light winds, strong vortices generated by large jet aircraft dissipate rather slowly and can make aircraft encountering the vortices difficult to control. The potential existance of this hazard has required changes in aircraft separation standards and resulting reductions in airport capacity at jet airports.

The FAA and NASA are engaged in development activities to reduce the impact of trailing vortices on aircraft operations. The FAA has developed and placed in operation at the Chicago O'Hare Airport a Vortex Advisory System (VAS), which predicts the presence of potentially hazardous conditions for vortices at the airport. Development has also been initiated by the FAA on an automated Wake Vortex Avoidance System (WVAS), which detects vortices and alerts controllers and pilots of their presence.

NASA Technology Support

ultimately introduce design changes in jet aircraft to alleviate or minimize the generation of trailing vortices.

Flight Service Station Automation

to provide service facilities for airmen to obtain flight planning information and file flight plans. The FAA is engaged in a major program to automate many of the FSS functions and provide more efficient means for direct access by users to improve services and reduce system costs. This program involves the development of a new system configuration for automation, consolidation and collocation of FSS facilities.

Increased ATC Automation

new automation features in the enroute and terminal control systems. The bases for these programs are the NAS Stage A automation system and the ARTS III system. The NAS Stage A system is implemented at the 20 enroute control centers in the continental US (ref 16). It processes flight plan information and aircraft track information on all controlled aircraft. The ARTS III system is installed at 63 medium and high density terminal control centers serving major airports. Several new features are being developed to upgrade the capabilities of these automated control systems. An overview of these new features is presented below.

Enroute Control Automation

improve safety and productivity. Conflict alert has been implemented. An enroute minimum safe altitude warning system is being developed as a controller backup to aircraft systems. An enroute metering capability is being developed to provide efficient handoff of traffic to terminal area control. An Electronic Tabular Display (ETABS) is being developed as an aid to improving controller productivity. This automated display will eliminate the need for controllers to handle paper flight strips and improve the controller/machine interface (ref 17).

Terminal Control Automation

flight safety and increase capacity in the terminal areas (ref 18). Conflict alert is being developed to aid controllers in detecting and resolving potential traffic conflicts. Software development is being pursued to provide the controller with automated aids for metering and spacing (M&S) the traffic flow in high density areas to increase terminal area capacity. The Tower Information Processing System (TIPS) is being developed for more efficient use of computer-stored and processed data on flight information. This development effort will provide an electronic display of the flight information and traffic control data required by the controller.

2.3.1 Altitude Encoding Transponders/ATCRBS

Most Civil Aircraft are equipped with ATCRBS transponders. These transponders are required to include an altitude encoding feature for designated high density areas during IFR operation. All IFR operations will be required to have the altitude encoding feature in the near future.

The FAA ATC controller has the coded beacon return including altitude printout displayed on his sector CRT display as an aid to lateral and vertical separation of IFR air traffic.

The low cost 4096 code transponders for general aviation are about $600. The altitude encoding feature adds another $600 dollars cost.

2.3.2 BEACON COLLISION AVOIDANCE SYSTEM (BCAS)/ AIR TRAFFIC ADVISORY AND RESOLUTION SERVICE (ATARS)

2.3.2.1 BCAS

The objective of BCAS is to introduce a new ATC feature to reduce the threat of mid air collisions as the traffic density continues to increase. The BCAS is intended to be compatible with both the ATCRBS and the DABS altitude encoding transponders. The BCAS will provide supplemental separation assurance within the coverage of ATC radars and provide primary separation assurance in areas beyond the coverage of ATC radars.

The BCAS concept for an airborne collision avoidance system is based on the use of 1090 MHz replies transmitted by Air Traffic Control Radar Beacon System (ATCRBS) transponders or the future Discrete Address Beacon System (DABS) transponders. BCAS is also capable of transmitting 1030 MHz interrogations, using ATCRBS or DABS signal formats, and can receive and decode 1030 MHz interrogations transmitted by the ground based radar surveillance system.

Two basic modes of operation are contemplated, depending on the ground beacon environment. They are the active mode, for use in areas where no ground beacon coverage exists, and the passive mode, for use in high density areas with ground beacon coverage.

2.3.2.1.1 Active Mode

In the active mode the BCAS acts as an airborne interrogator, soliciting replies from other transponder equipped aircraft in communication range. The time between interrogation and reply is measured to determine aircraft range whereas altitude is determined by decoding the mode C transponder replies. Established tracks are used to provide vertical maneuvers in hazardous situations where other aircraft are in close proximity.

Since the Active mode uses an omnidirectional antenna, all ATCRBS transponder equipped aircraft in communications range reply to each interrogation. To reduce the number of replies, an adaptation of the side lobe suppression (currently used by ATCRBS transponders) called Whisper-Shout has been developed. Whisper- Shout is a means of grouping targets according to their detection capabilities which are principally determined by receiver sensitivity and antenna gain. Aircraft are first interrogated at a low power level, the whisper, picking up near and very sensitive receiver targets. Once these targets have replied they are suppressed. During this suppression period, nominally 35 micro sec., a second interrogation is transmitted at a high power level to pick up more targets. This procedure is repeared 5 to 7 more times with the last interrogation, the shout, at full power, insuring that all targets have been interrogated. This results in a smaller grouping of targets on each interrogation and should reduce synchronous garble.

In addition to the Whisper-Shout technique, phased-array antennas are being studied. Such antennas may further reduce synchronous garble through directional interrogate and receive functions which limit the processing load to relatively few aircraft. Other advantages accrue from the use of directional antennas. By using monopulse detection techniques, the relative bearing to other aircraft can be obtained to withih 10 degrees with the antenna now under consideration. Such bearing accuracy would enable the active mode to provide Proximity Warning Information (PWI). PWI will in some cases permit a pilot to visually acquire other aircraft during VFR weather but will, in any weather, provide an alert that other traffic is near.

The active mode DABS interrogations are based on the discrete address transmitted via "squitter" messages from DABS equipped aircraft within communications range. Squitter messages are spontaneous - occurring approximately once per second - and, in addition to making the DABS discrete address known to the BCAS interrogators, provide truncated altitude. BCAS uses the squitter altitude report to determine if the target aircraft poses a potential hazard and, if so, then uses the discrete address for the DABS interogation. No other aircraft reply to the interrogation thereby reducing fruit and garble.

The active mode will provide range, altitude, and, with a directional antenna, approximate bearing. Thus, the active mode can yield PWI or vertical maneuver data.

The active mode BCAS is a computer based system. The basic system components are shown in system block diagram, figure 2.3.2-1.

2.3.2.1.2 Passive Mode

In the passive mode, the BCAS "listens" to ground interrogations and the subsequent airborne replies. In addition BCAS obtains, as a minimum, the interrogation repetition frequency of the ATCRBS site and the bearing of the ATCRBS (DABS) relative to the heading of the BCAS aircraft. This information can be obtained by BCAS without any modification to an ATCRBS site using the BCAS unit's phased-array antenna. However, is is desirable that radar-based transponders (RBX's) be installed at the ATCRBS site to enable a BCAS aircraft to obtain more accurate ATCRBS site information, such as site main beam position, and to allow the BCAS aircraft to determine its range to the ATCRBS site.

In all BCAS passive modes, measurements of differential times of arrival between ATCRBS interrogations and aircraft replies are made by the BCAS equipped aircraft. The azimuth of the target relative to the interrogator is also measured and decoded from the target's replies. This set of measurements and decoded data is then sufficient to provide the target's three dimensional position.

A major feature associated with using an RBX is that a passive solution can be obtained with the use of a single RBX/ATCRBS site when the BCAS aircraft is within 20 nmi of it. In addition a two site passive solution can be obtained over a greater region of airspace when range to sites and ATCRBS interrogator main beam position are known (via RBX) than when only the main beam positons are known (i.e., via North reference pulse ATCRBS kits). The RBX presence also allows for a data link interface with ATC.

BCAS cannot always operate passively, even when there is some ground

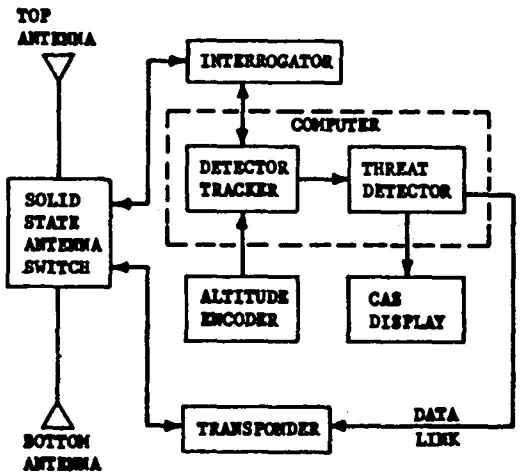


FIGURE 2.3.2-1 THE ACTIVE MODE BCAS SYSTEM BLOCK DIAGRAM

surveillance coverage. BCAS performance can vary dramatically as a function of the relative positions of the ground interrogators, the BCAS aircraft, and the target. Certain passive modes of operation have regions in which the positional errors tend to become unacceptably large. When such singularities occur or when the positional error in the passive mode solution is too large, then a semi-active mode of BCAS must be employed in order to provide acceptable BCAS performance.

Semi-active means use of data from both the Passive and Active modes of operation. Thus, BCAS will obtain data actively, passively, or semi-actively, depending on the environment. These data can be obtained in an ATCRBS or DABS environment with the total system performance improving as the ATCRBS undergoes a transition to DABS (fruit and garble levels are reduced).

Once potential conflicts have been detected, BCAS issues the appropriate warnings based on its tracking data. When both aircraft are BCAS equipped, the maneuvers are coordinated through the use of the DABS data link. Thus complementary maneuvers are assured. If the target aircraft is not BCAS equipped, maneuvers are based on the assumption that no change in his present course will occur. An appropriate display for providing the pilot with PWI and maneuver information is at issue.

BCAS development efforts also require consideration of performance and cost acceptability to all segments of the diverse airspace users. Recent advances in avionics technology, particularly in the availability of low cost digital microprocessors, have made airborne signal processing and data linking available on an economically acceptable basis. This technological advancement makes integration of the ATCRBS transponder into a Collision Avoidance System concept not only possible but especially attractive since wide-spread implementation of ATCRBS has already been achieved.

Several major tasks require solution before implementation of BCAS is possible. Of prime importance is the optimization of the threat evaluation and evasive maneuver selection logics from the standpoint of protection provided versus alarm rate. Undesirable or nuisance alarms from aircraft not posing actual danger should be eliminated to the greatest extent possible. Several aircraft configurations require study to resolve problems peculiar to them which cause these alarms.

Another important task is the integration of BCAS with the other elements of the FAA's aircraft separation assurance program. The interactions of BCAS, ATARS, and the conflict alert program must be defined and made compatible.

The BCAS program is divided into three phases:

Phase I	Feasibility Determination
Phase II	Engineering Model Development
Phase III	Prototype Development

Phase I has been completed. Feasibility models have been fabricated and tested. The program is currently in Phase II whose output will be a BCAS engineering model, completely flight tested, evaluated, and capable of being reduced to a prototype in Phase III which is scheduled to start in early 1982. The Phase III prototype equipment is intended to support the writing of rules, regulations, and as a final product in late 1983, a BCAS US National Standard.

2.3.2.2 ATARS

The Automatic Traffic Advisory and Resolution Service (ATARS) is a ground based collision avoidance system intended to improve safety by reducing the potential for near misses and mid air collisions which result from the increasong ineffectiveness of 'see and avoid' techniques as traffic density increases. The collision threat due to pilot error/aircraft deviations, ATC system errors and to ATC system hardware/software failures is also reduced by ATARS.

ATARS utilizes DABS for improved surveillance and utilizes the DABS data link for automatic traffic advisory service. ATARS is cost effective for general aviation aircraft which may not be able to afford the airborne BCAS equipment and is compatible with ATC procedures.

ATARS is based upon the earlier concept of intermittent positive control (IPC) and feasibility flight tests have already been conducted.

The Automatic Traffic Advisory and Resolution Service (ATARS) utilizes the DABS data-link for delivering conflict resolving advisories. ATARS is being developed to provide the pilots of equipped aircraft flying within airspace served by the Discrete Address Beacon System (DABS) with a comprehensive traffic advisory service and resolution service. For uncontrolled aircraft the traffic advisory service will enhance the pilot's 'see and avoid' capability while the resolution service will provide separation services not previously afforded by the ATC system. In the case of controlled aircraft, ATARS will serve as a back-up to the ATC system in the event of a pilot deviation, system error or ATC system failure.

For those equipped for ATARS service, protection is provided against all aircraft that are equipped with altitude reporting transponders (DABS or ATCRBS). To receive ATARS service, an aircraft must carry a DABS transponder which has altitude encoding capability and an ATARS display. The transponder, in addition to its beacon function, receives digital messages from the ground and relays them to the pilot on the ATARS display. The ground portion of the ATARS system consists of the DABS sensor, which provides surveillance information and acts as a communications link to the aircraft, a computer independent of the ATC computers, and interfaces to the ATC facilities serving the airspace covered by the DABS sensor.

Aircraft equipped for ATARS service will receive traffic advisories on aircraft that are determined by the algorithm to be proximate or a threat. In the case of a proximate aircraft information will be displayed to the pilot to alert him concerning the presence of the nearby aircraft and to aid him in visual acquisition. When an aircraft poses a threat, the traffic advisory service will declare it as a potential threat and display additional information to aid the pilot in threat assessment. The threat data should enable the pilot to avoid maneuvers which would aggravate the situation. If the aircraft continue to close relative to each other, one or both of the aircraft will receive a resolution advisory at a predetermined time before the estimated time of closest approach. These resolution advisories will be compatible with the threat data provided by the traffic advisory service.

Whenever a resolution advisory is issued to a controlled aircraft, an alert message will be issued to a controller of that aircraft at the same time. This resolution advisory alert would normaly follow the alert generated by the conflict alert program resident in the enroute and terminal computers.

The ATARS development program is being structured to provide for an orderly evolution in service beginning with a highly effective traffic advisory service and transitioning to a full capacity resolution service. Each phase of the program will result in a Technical Development Package for use by the FAA operating services in making implementation desisions.

The objective of the traffic advisory service is to reduce the probability for mid-air collisions and near miss encounters by providing data to assist the pilot in visual acquisition and threat assessment. The traffic advisory service will be a comprehensive yet flexible multi-level service that can be tailored, by means of a cockpit display unit, to meet the needs of various user groups. It is essential to the success of the program that the traffic advisory service be implementable using a low cost display in order to keep it within the reach of the VFR community. ATARS will utilize cockpit displays ranging from a simple display consisting of lights and numerics (LED's) to a sophisticated 'relative motion display.' During the test and evaluation program the traffic advisory service will be evaluated and demonstrated using two and preferably three levels of cockpit displays.

A general purpose microprocessor-based display will be developed as the basic vehicle for evaluating the display types selected. The most sophisticated display concept will be evaluated first since it represents the most complete set of information and therefore controls the design of the DABS data-link formats. Evaluation of subsequent display concepts will be accomplished by reprogramming the microprocessor and changing the display faceplate if necessary.

The resolution service will be developed to function compatibly with the traffic advisory service. The two services together comprise the complete ATARS service. It is anticipated that, in order to minimize pilot work load and ATC system interaction, controlled aircraft will rely more heavily on the resolution advisories rather than the traffic advisory service for resolving potential conflicts. In these cases the traffic advisory would serve as a means for alerting the pilot to the details of the potential conflict and would prepare the pilot for the possibility of an escape maneuver if the conflict situation persists or worsens.

The resolution service will consist of positive and negative resolution advisories such as turn left, don't turn left. Following development, the resolution service will be evaluated for compliance with the following performance goals:

1. ATARS resolution advisories must be safe
2. The resolution service must not disrupt routine air traffic control by frequently issuing unnecessary resolution advisories which force aircraft to depart from clearances issued by controllers.
3. The resolution service must be highly effective in preventing or resolving conflicts in all applicable regions of airspace.
4. Major changes must not be required in ATC procedures in order to make ATARS compatible with the ATC system.

Other resolution advisories such as turn to heading may also be investigated during this period.

A typical ATARS scenario which a pilot may incur is as follows:

1. When aircraft become proximate (as determined by system parameters), information such as relative bearing, altitude, range, etc. will be displayed to aid the pilot in visual acquisition. The extent of the information displayed will be determined during ATTRS development.
2. If the aircraft are projected to be in potential conflict, the corresponding aircraft indication symbol will begin to flash. At this point a threat advisory consisting of a more comprehensive set of intruder information will be forced on the display to aid the pilot in threat assessment. Information concerning the projected location of closest approach may be provided.
3. Should this encounter progress to a conflict situation, then the ATARS system will compute resolution advisories for all aircraft involved.

The ATARS development will investigate all aspects of the traffic advisory service thoroughly and evaluate the effectiveness of the resolution service. This test progran will be based on several sources of data, namely:

1. Extensive flight testing by MIT Lincoln Laboratory at DABSEF.
2. ATC simulations conducted at NAFEC with the Air Traffic Control Simulation Facility (ATCSF).
3. Monte Carlo Simulations of the 12 mid-air collisions provided by the National Transportation Safety Board (NTSB).

4. Analysis of ARTS III tapes for ATC interaction analysis.

These data sources along with the live flight testing done with the 3 DABS Engineering Models should provide an adequate data base for the ATARS development and evaluation.

There are a number of operational and interface issues to be resolved during the development, namely:

1. ATARS/BCAS (Beacon Collision Avoidance System) Interface - the protocol for ATARS and BCAS operating in the same environment must be investigated in order to prevent potential operational conflicts.
2. ATARS/ATC Interface - the operating procedures for controlled ATARS equipped aircraft must be defined so as to preclude any possible conflicts that may result between the two.

The above issues, although more procedural than technical in nature, will be addressed during the ATARS development program.

Upon completion of the ATARS development a complete Technical Development Package (TDP) will be handed over to the FAA operating services for implementation consideration. The TDP will cover single and multi-sensor operation in both the terminal and enroute airspace.

2.3.3 DISCRETE ADDRESS BEACON SYSTEM

2.3.3.1 Introduction

The Discrete Address Beacon System (DABS) will provide air traffic control surveillance and air to ground and ground to air data link capability needed to support automation of the FAA air traffic control (ATC) system of the 1980's and 1990's. Evolution from the present ATCRBS beacon system to the DABS system requires that present transponders be replaceable with DABS transponders at a cost acceptable to aircraft owners. Hence, a major concern of the DABS development program has been a data link design which permits simple, low cost implementation of DABS message and address processing and which will also allow a high degree of compatibility in transponder functions between ATCRBS and DABS transponders (ref 19).

The increase in the amount of information processed by the DABS transponders (as compared to the present ATCRBS transponders) and the requirement for a reliable communication link results in an increase in overall transponder cost. Major factors contributing to the cost of a DABS transponder are as follows:

- Possible requirement for diversity (i.e., two transmitters and receivers in each DABS transponder).
- Cost of RF and video processing components.
- Cost of maintaining the system.
- Cost of the logic required to perform DABS functions.
- Data interface.
- Packaging.

DABS is an advanced aircraft surveillance and data link system under development by the Federal Aviation Administration. It is designed to permit an evolutionary upgrading of the civil/military Air Traffic Control System utilizing advances in ATC automation and offering significant improvements in safety and communications.

Improved surveillance comes about by the use of a 24 bit permanently assigned discrete address code for each aircraft, allowing each aircraft to be interrogated individually by the ATC sensor. Only the addressed aircraft will reply and each reply is unmistakably associated with a single aircraft. This will provide the means for a flexible data link communications capability supporting a number of advanced ATC automation services.

The DABS system has been designed to be completely compatible with the existing Air Traffic Control Radar Beacon System (ATCRBS). It is intended to be introduced gradually and will not require significant operational or procedural changes.

In its role of providing improved surveillance for ATC facilities, DABS can operate with a colocated radar, providing correlated DABS/Radar data or it can operate independently, without radar. It is intended that the DABS sensors operate both as single site (no interconnect) sensors, or they can be interconnected to operate as an interactive network.

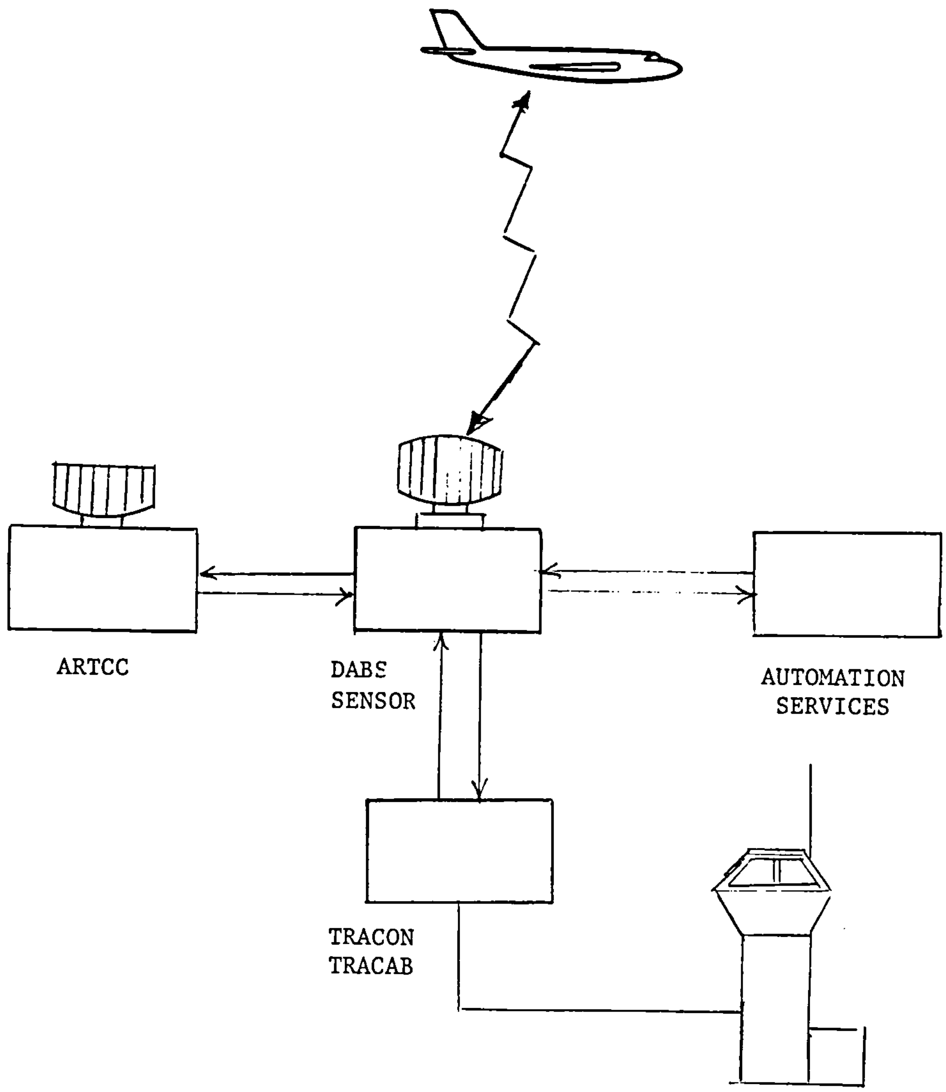


FIGURE 2.3.3 Discrete Address Beacon System (DABS)

The FAA has paid careful attention to the design of the supporting avionics so that the basic DABS installation will have minimal cost impact. Data link capability key and basic surveillance is handled by well defined interfaces. The basic transponder employs essentially the same RF sections as the mature ATCRBS transponder, with the majority of changes confined to the digital processing area where cost impact is minimized thanks to the component impetus provided by the 'Data Processing Revolution'. The avionics is discussed in sec. 2.4.2.

Development of the DABS system has been in progress for nearly a decade. MIT Lincoln Laboratories has provided support to the FAA in the area of systems engineering and has had a DABS ground station and DABS equipped aircraft employed in system test for about the past three years. In late 1978 the FAA will install a network of three ground sensors at NAFEC for more extensive testing. A DABS National Standard was published for comment in the spring of 1978 and the airline community has indicated that the next generation airline transponders will contain DABS capability. Considering all this, the program must be considered firm with direct impact on next generation avionics.

2.3.3.2 Diversity Transponders

Transponder diversity, one way of combatting the effect of aircraft antenna shielding to achieve high link reliability, results in a significant transponder cost increment. Although diversity is unlikely to be mandated for GA users, if it were it would particularly affect the acceptability of DABS to this class of user (ref 19). Two independent receivers and transmitters are required (one for a top-mounted antenna and one for the bottom antenna) for each diversity transponder, so that any new technology applied to reducing the costs of these RF sections (see below) would pay off doubly well. One particular implementation of diversity is based on the comparison of the signal strengths received on the two antennas. A major cost contributor in such a system is the requirement for log - IF amplifiers closely matched in gain over a 50 dB dynamic range. Such a matched IF amplifier configuration might be best realized as a single monolithic chip.

2.3.3.3 Transmitter

A promising area of research for cost reduction is solid-state high-power transmitters (300 watts peak at 1 GHZ). Transistor junction and other thermal problems arise due to the short-term high duty cycle required in DABS transmissions (50% duty cycle for 120 microsec with 1dB droop, but only .5% continuous duty cycle). The present cost of a suitable microwave power amplifier is prohibitive: a few thousand dollars per unit (ref 20). Recent developments in cooling and power combining (ref 21) may lower this cost, however. The advantages of a solid-state transmitter are longer life (hence decreased long-term maintenance costs), increased reliability, and reduced variation in power output with component age. Where diversity is required, it may prove economical to use one transmitter in conjunction with a high-power solid-state switch rather than to use two independent transmitters (although independent transmitters are desirable for reliability obtained through redundancy). Thus solid-state switches are another candidate for research.

2.3.3.4 Receiver Components

2.3.3.4.1 General

Due to rising labor costs, the costs of production and testing of RF components continue to rise. Automated production and testing techniques as applied to RF components are a potential means of reducing costs. As stated above, another means of reducing costs is in use of monolithic semiconductor linear devices.

2.3.3.4.2 Differential Phase-Shift Keying (DPSK) Demodulation

One approach to DPSK demodulation is to use a Surface Acoustic Wave (SAW) device in the DPSK demodulator. Although the present devices are expensive ($275 each), the prices should be reduced somewhat with increased production and investigation of different SAW materials(Ref. 22). Availability of an inexpensive, yet accurate, DPSK demodulator could mean savings elsewhere in the receiver section. Also, it could lead to a better diversity transponder where replies are transmitted on the top or bottom antenna on the basis of a valid DABS message being received on that antenna, rather than basing the decision on received relative amplitudes.

2.3.3.5 System Maintenance

Due to low cost of logic circuits, it will be possible to supply each transponder with built-in test circutry at a nominal cost. Such designs aid in performance testing and calibration and can reduce mean time to repair, thereby significantly reducing life cycle costs. Automated ground-based test equipment can be used to further reduce repair costs.

2.3.3.6 DABS Logic

The cost of logic has been reduced drastically in the past few years, and the use of custom LSI is becoming widespread in standard transponder designs (Ref. 23). It is possible to include sophisticated data processing capabilities in each DABS transponder at a nominal cost.

2.3.3.7 Data Interface

2.3.3.7.1 Optical Data Transmission

Recent advances in optical communication links (fiber optics) should make high-speed reliable communication aboard aircraft a reality. Advantages of optical communication between a transponder and its peripheral devices would be isolation and interface rejection, yet the transmission medium itself (the fiber) is as light-weight as wire and potentially cheaper.

2.3.3.7.2 Peripheral Devices

The problem of cost reduction of peripheral devices should not be overlooked. For example, new technology promises to reduce the cost of an encoding altimeter (Ref. 24).

2.3.3.8 Packaging

Some standard packaging concepts for transponders should be studied. Interchangability between manufacturers and ease of upgrading systems are important factors in user cost. In addition, new packaging methods (e.g., a transponder case which is of a 'molded' construction) should be investigated as a labor-saving means of cost reduction.

2.3.3.9 Summary

Specific items which could lead to future transponder cost reductions and enhanced performance are as follows:

- monolithic realization of video processing components
- automated production of RF components (it is not clear that funding of any form wil help solve the problem of automating RF component assembly. The problem will be solved by industry when mass production economics justify the required capital investment.)
- inexpensive means of DPSK demodulation
- built-in test circuitry and automated ground test equipment
- use of LSI in transponder design
- communication between transponder and peripheral devices
- the cost of the peripheral devices
- new packaging ideas

2.3.4 TDMA Data Link

Introduction

In order to analyze the state-of-the-art in a reasonable near time frame for TDMA, the following operational scenario is envisioned. A large communication network for data exchange and voice between the Air Traffic Control Center and en-route aircraft within predefined sectors is proposed. Within each sector aircraft position, movement, weather, route information, and voice can be exchanged. The availability and accuracy of GPS within this time frame indicates that GPS will probably be the most suitable system to support the requirements of the ATC system. The potential use of a series of ATC communications satellites to support the interchange of information between ATC and en-route air traffic appears the most sensible method to implement the ATC TDMA data link at this moment. Therefore, the postulated ATC TDMA data link major system elements would consist of (1) GPS, (2) ATC TDMA satellites, (3) ATC comm. center, and (4) aircraft data processing system.

The GPS system is necessary for the operation of the proposed ATC TDMA system as it provides the required accurate position, movements, and world wide synchronized time. A critical parameter for TDMA will be the accurate time of arrival of the large number of multiplexed remote data sources (i.e., the air traffic). Without a network synchronization time reference, data communications within the TDMA network would become impossible.

A major trade study will be necessary in order to establish a basic system to derive the critical parameters within the TDMA data and voice links. This study will include the operational, communication network, growth capability, and human engineering requirements in defining the communication network to support the projected traffic of the future. A state-of-the-art communication system will be needed to prevent the obsolescence of the communication system architecture.

State-of-the-Art Available

The techniques to handle the data traffic conceived by the ATC data link are available, but time to refine these techniques to insure reliable operation may be short. Due to the accuracy requirement of time corrections required both for GPS and ATC TDMA communications, intersystem software and procedural algorithms are required. The synchronous nature of these communications will also force design requirements on the elements of the entire communications system. These requirements will manifest themselves in increasing the complexity of the overall synchronization loops and procedures. A top down structure for the design of the communications system will be mandatory. Signal-to-noise ratios, timing jitter, frequency uncertainties will be of major importance. The reception of data onboard the aircraft (two-way data exchange) will require a symbol synchronizer. Symbol synchronizers have been designed to handle a multitude of specific problems, i.e., low signal-to-noise ratio, rapid acquisition, timing uncertainties, etc. The state-of-the-art is available once the requirements have been defined, but the low cost required by the program is not at hand. A state-of-the-art development is needed to package and develop the required symbol synchronizer.

Onboard parameter manipulation of specific required data within the composite ATC TDMA data voice link is necessary. General purpose time division demultiplex equipment is available but again not at the cost needed to make the communication equipment competitive. The advent of microprocessor technology is at hand to allow the development of a software compatible decommutation system that would be amenable to LSI implementatin yet allow ease of modifications either by upgrading of new requirements or dynamic reallocation by ground control.

The concept of TDMA communications is based on accurate timing and the maintenance of this timing. An accurate assessment of the vulnerability of the entire comm system to timing errors and loss of synchronization will be required. The methods of spread spectrum implementation and timing extraction along with symbol synchronizer parameters such as transition densities, timing errors, frequency uncertainties, etc., may require symbol stuffing of supervisory control of data to lessen the links' vulnerability to timing errors. A realistic analysis of the threat of intentional interferences to disrupt communications and ways to combat these effects should also be a mandatory requirement.

The efficient transmission of voice will require some method of digital encoding. Delta modulation of voice is one method of source encoding to lower the data rate but yet maintain voice intelligibility. The state-of-the-art has developed algorithms for reliable source encoding between 16-48 kb/sec. The selection of a good algorithm at a moderate rate implemented on a single LSI chip will be required.

Since the data rate of a single voice channel is many times higher than data, the impact of accomodating a number of voice channels is severe. Either a separate communication link to service en-route voice or its incorporation within the data link will be necessary. A reliability assessment of the two alternatives will be needed. A separate voice link could require an entirely different method of modulation and processing than the data link for efficient channel utilization.

The accuracies of timing thru use of GPS can resolve the timing acquisition associated with spread spectrum, but the time of arrival problem can complicate acquisition of a QPSK signal design. The frequency and phase uncertainties coupled with a rapid acquisition problem needs to be investigated to allow QPSK as a viable option.

Program Considerations

Development strategy should be based on a top down approach starting with FAA provided operational requirements for sizing ATC link rates, voice channels, sectoring, and phase out of existing systems. Initial studies should include critical analysis of techniques used in the GPS, DOD JTIDS and NASA Shuttle digital communication systems for application in the ATC design.

NASA's current Shuttle and relay satellite developments which include multiplexed digital voice/data systems, channel coding, spread spectrum and microprocessor based signal processing justify involvement in the ATC TDMA system conceptual design. A further role would be specific component developments in source and channel coding, digital signal processors, communication link synchronization, time division multiplexing, multiplexing using quadrature modulation and related areas.

Summary

In summary, much of the state-of-the-art technology is available, but uncertainties as to the technical approach exist in a number of areas. It is recommended that the following studies and developments be conducted:

(1) A data and voice link requirement trade study to size the basic system capability for entire communications system.

(2) A study of ATC digital data link synchronization for the overall communications system and the vulnerability to intentional interference and timing errors.

(3) A study of intersystem software and procedural alogrithms for

time of arrival problems between GPS and the ATC-TDMA data link.

(4) Development of a low cost design to maximize commonality among functional blocks within the communications system with an emphasis on increased use of LSI for voice channels and symbol synchronizers.

(5) Development of a microprocessor based parameter handler to allow dynamic allocation of data and voice channels and to interface with onboard displays.

(6) A study of the feasibility of rapid acquisition procedures of QPSK signals for increased bandwidth utilization.

2.4 COMMUNICATIONS

The current civil communications is based upon VHF voice communications using 72Ø channels in the spectrum between 118.Ø and 136.Ø MHz. In addition voice communications are available on HF in the frequency range from 2.8 to 26 MHz. At the present time data link is unavailable to civil aviation except on a commercial VHF channel operated by ARINC for airline operational data transfers.

The DABS system will provide a data link capability between aircraft and ATC which will have an effective baud rate of about 24ØØ for extended uplink and down link messages. The advent of DABS data link should reduce the amount of voice 'clutter' during ATC operations and provide for unambiguous display of ATC clearances and acknowledgements on cockpit and ground CRT (or flat surface) displays.

Section 2.3.4 discusses a Time Division Multiple Access (TDMA) data link which has some important potential for future ATC communications. It should be pointed out that FAA currently has no plans for implementation of a TDMA data link.

2.4.1 VHF/HF Communications

The VHF Aeronautical Band 1Ø8 to 136 MHz provides 72Ø Voice Communication channels for the General Aviation and Air Carrier Fleets. The band is assigned as follows:

1Ø8 - 118 MHz	Navigation
118 - 129 MHz	FAA ATC Communications
129 - 132 MHz	FCC (Operational Control)
132 - 136 Mhz	FAA ATC Communications

Prior to the recent introduction of a VHF data link by Aeronautical Radio, Inc. these frequencies have been used exclusively for Voice Communications (A3 emission).

Considerable experimentation was performed by Aeronautical Radio, Inc., supported by several airlines and avionics manufacturers, in the late 6Ø's and early 7Ø's resulting in the characterization of the 'ACARS' (Automatic Communication and Reporting System) that is now being introduced into service.

This system uses 'Minimum Shift Keying' Audio sub carrier modulation (A9 emission) to provide a 24ØØ bps data rate.

The system is controlled by the ARINC switching network and uses several frequencies in the ARINC band, operating in both demand and polled modes & providing a variety of services to ARINC users.

The system using 7 bit ASCII provides for 16 mode characters, 86 routing labels, and employs a 16 bit polynomial block check sequence for error detection. A single message may be a maximum of 22Ø text characters with the average message length now running at 8Ø characters. The most common messages are out-on-off-on times, fuel reports, voice circuit requests, & ETA reports.

It is important to recognize that although the technology has been available for over a decade, the system is only now being implemented. It was necessary for airline users to justify the expenditure on the basis of overall reduction of Air/Ground communication costs, brought about by the increased automation. The basic data link unit costs about $5,000 per aircraft and interfaces with existing VHF transceivers.

The general aviation segment can and does use ARINC services (largely the corporate fleet) and can be expected to use the ACARS data link now that it is available.

The impetus for using VHF data link for expanded flight services (ATC information, radar weather maps, etc.) would have to come from the FAA and there is no indication of this at this time. This is most likely due to the near term implementation plan for DABS which can also provide these expanded flight services. It might be expected that the VHF data link will remain an ARINC service available to all segments of aviation for automated air to ground and ground to air communications.

Frequency assignments and spectral constraints will likely keep this system from expanding beyond existing ARINC plans. The technology employed is straightforward and mature. It does not appear that this would be a likely area for NASA technology investment.

HF Communications

The HF aeronautical band accommodates voice communication for general aviation and air carier fleets within the frequency range of 2.850 to 26 MHz. The HF aeronautical band is principally used for air traffic and company communications in long distance transoceanic routes and routes over remote areas where VHF (line of sight) coverage is inadequate.

Worlwide HF communications is provided by various organizations such as ARINC (Aeronautical Radio, Inc.) and International Air Radio (British Organization). These service organizations operate HF ground stations in conjunction with ground communications networks to provide message handling for air traffic control and private applications. Frequency allocations are assigned by international agreement according to geographic locations and airways. Typically, four or five diverse frequencies are assigned to a particular geographic area in order to allow selection of the optimum frequency for a given time of day and atmospheric conditions.

In order to permit automatic channel monitoring by aircraft during long flight legs a system known as SELCAL (selective call) was developed. SELCAL permits the ground station to alert a particular aircraft of a ground inquiry through an audio tone code transmitted over the HF link. The code is typically assigned to each aircraft by air traffic control prior to transoceanic crossing.

At present, ARINC is coordinating two concurrent HF data communications programs. One is termed HF selective signaling system (form of digital SELCAL). The signal formats and modulation techniques are similar to the VHF ACARS. The system can provide data link and auto patch, air to near the end of 1978. The second program is a direct adaptation of ACARS to HF. Flight tests will be conducted in 1979 to transmit meteorological data over company operational control frequencies. It is anticipated that ICAO will become actively involved as development proceeds in HF data communications.

In the mid 1950's ARINC began working to develop a specification for single sideband SSB (A3J) modulation to replace the less efficient AM (A3H) mode. This specification was completed in 1960 and SSB was gradually implemented at ground stations throughout the world.

Although SSB provides a far more effective method of communications for a given amount of power, the HF signals are still subject to atmospheric conditions affected by storms, temperature, time of day, and the sun spot cycle. Even today there are certain conditions which can occur to prevent HF communications during portions of a commercial transatlantic flight.

One solution to this problem lies in the exploitation of communications satellites. Three synchronous satellites acting as repeaters could provide adequate worldwide coverage for the air carriers. The airlines have conducted extensive research in satellite communications with reliable results but to date have not been able to cost justify this approach.

It would appear therefore that a cost effective approach to Aeronautical satellite communications to replace HF would be a promising area warranting further technical development.

2.4.2 DABS Data Link

2.4.2.1 Background

Data link was offically initiated in 1947 when the Radio Technical Commission for Aeronautics (RTCA) established a special committee (SC-31) for a Universal Air-Ground Digital Communications System. During the 50's and 60's interest in data link vacillated between pro and con by providers of air traffic control services and the aviation community both nationally and internationally. In the early 1970 era FAA followed through with the Air Traffic Control Advisory Committee report to include data link as a system option in the upgraded third generation air traffic control system and, as a result of later (1976/77) study and experimental work at the Transportation Systems Center, MIT Lincoln Laboratory, MITRE and other in-house efforts, established the Discrete Address Beacon System (DABS) data link as the best technical approach for system implementation.

2.4.2.2 Introduction

The implementation of National Airspace System (NAS) En Route and Terminal Automation, Central Flow Contol, and National Flight Data Center automation has provided an enormous data base for considering sophisticated automatic air traffic control (ATC) techniques. The forthcoming Flight Service Station and Weather Automation programs will provide more current and accurate weather and other flight information to the pilot for the purpose of planning and executing the operation of his aircraft. Conversely, information regarding the environment in which and aircraft is operating and information about the actual performance of the aircraft is needed on the ground to improve the tracking and prediction of an aircraft's position and to aid in determining winds aloft and weather. All of the above improvements require much more information exchange between the ground and aircraft than is currently exchanged.

In order to exchange the amount of data suggested above, a digital data link capability between the ground and aircraft is required to enhance the voice communication currently used to exchange flight information and transmit ATC instructions. The Discrete Address Beacon Systen (DABS) provides a digital data link capable of satisfying the data communication needs expressed above. Initially, DABS data link will be used as a parallel link with voice communication to relieve frequency congestion and reduce pilot and controller workload. Ultimately, DABS data link is intended to replace most of the voice communication and increase the automation potential in the ATC system.

2.4.2.3 Development and Implementation Philosophy

Data link is the catalyst which may lead to total automation in the ATC system. As more automation capability is included in the cockpit of the aircraft and more ATC functions are automated in the NAS en route and terminal systems, possible extension of ATC automation is the delivery of ATC instructions via digital data link from the ground to the aircraft which directly affect the control surfaces of the aircraft. It remains to be seen if and when this kind of ATC automation will ever be implemented. In the meantime, there are real and immediate benefits to be expected from data link when DABS is implemented. These benefits fit in the categories of NAS near term (pre 1985), NAS far term (post 1985), and next generation advanced systems development (post 1990).

An overall objective of the FAA development and implementation philosophy is to provide ATC and flight information digital data link services to a wide range of users (airlines, general aviation, military, etc.) equipped with a variety of input/output devices (cathode ray tube (CRT), light emitting diode (LED), printers, electronic displays, keyboards and touch techniques) associated with a DABS transponder. FAA intends to implement near term data link products when the first DABS sensors are installed.

2.4.2.4 Near Term (Pre 1985)

The NAS near term data link benefits coincide with the DABS implementation plans begining in the 1982-84 era. The initial data link implementation philosophy is to exchange information between the pilot and controller to enhance safety and efficiency of the current method of air traffic control and flight operations with little or no involvement on the part of the pilot or controller. The type of information to be exchanged during this period is that which is currently contained in the existing data base and that which is in the process of being added to NAS. It is information which has been chosen by the ATC and aviation community users, which is needed, will reduce the amount of voice communication between the controller and pilot, and will promote DABS avionics equippage. Specific examples of services to be provided are:

1. Assigned Altitude Confirmation
2. Minimum Safe Altitude Warning
3. Runway Surface Winds
4. Runway Visual Range
5. Takeoff Clearance confirmation
6. Automated Terminal Information Services (ATIS)
7. Selected Weather Data

These services will be technically demonstrated at the Lincoln Laboratory DABS Experimental Facility (DABSEF) at Hanscomb Field, Massachusetts, in the fall of 1978, and will be functionally tested and evaluated in a more realistic operational environment at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, in late fall 1979 with the Texas Instruments DABS system.

Figure 2.4.2.4-1 is a pictorial example of the method to obtain routine weather data and other pilot self-briefing information via DABS data link.

In addition to testing and evaluating the above stated services at NAFEC in fall 1979, the Texas Instruments DABS sensor and data link will be used to test an air traffic advisory and resolution service (ATAR/IFRS) primarily for VFR air traffic and as a backup to the ATC system for IFR traffic.

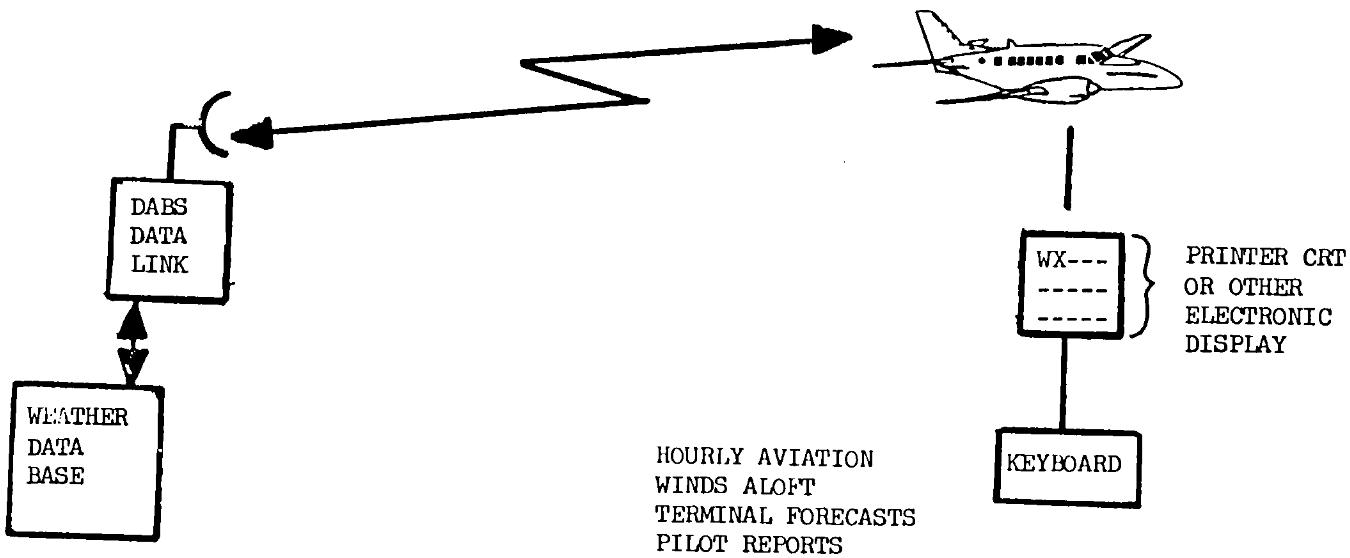
2.4.2.5 Far Term (Post 1985)

The current ATC automation system does not provide any tactical control support to the pilot and controller. The information contained in the existing system is used for strategic planning and as a monitor of the performance of aircraft movement. The current plans for enhancement to the existing en route and terminal automation programs is the inclusion of automatically generated conflict free ATC instructions. During the post 1985 era, the ATC automation systems will generate at least the following ATC instructions:

1. Conflict Alert and Resolution Instructions
2. Holding Instructions
3. Approach and Departure Clearance
4. Metering and Spacing
    - Heading
    - Altitude
    - Speed
    - Time to Execute ATC Instructiion

These ATC instructions will be relayed via DABS data link for those aircraft which are equipped, otherwise, the instructions will be relayed via voice. There are also plans to provide a situation display to aircraft equipped with CRT or electronic displays requiring a digital data link to transmit the appropriate information to the cockpit. The pilot will observe his situation with regard to traffic of his concern and monitor his own performance in the execution of ATC

FIGURE 2.4.2.4-1 - ROUTINE WEATHER (WX) DATA ON REQUEST (PILOT SELF-BRIEFING WHILE AIRBORNE)



instructions received via data link.

In addition to receiving ATC instructions via data link, the pilot will receive other flight information services such as weather, notices to airmen (NOTAMS), airport terminal information (ATIS), wake vortex and wind shear information, and terminal information processing system (TIPS) data (flight plan, beacon code, active R/W, standard taxi route, standard instrument departure and arrival, etc.). This information combined with the automatic generation of ATC instructions will certainly require a digital data link and well engineered man-machine interfaces for initiation, receipt display and acknowledgement of information exchanged over the data link.

The development and functional testing of this phase of ATC system improvement will be accomplished primarily at NAFEC. Related activity, particularly in the cockpit area, is being accomplished at NASA within the scope of a joint FAA/NASA Cockpit Displayed Traffic Information (CDTI) program. FAA also has a contract with ARINC Research Corporation and United Airlines to evaluate pilot performance and commercial aircraft operation when operating with aircraft seperation assurance avionics.

2.4.2.6 Advanced Systems Development (Post 1990)

Planning for this era of ATC system development begins to incorporate a philosophy of using very advanced automation technology in the air and on the ground, and voice communication will be used only when necessary or when serving non-DABS equipped aircraft. The existing en route and terminal automation hardware will have been replaced or at least under consideration for replacement. Digital data link will have been implemented, the cockpit of aircraft will have been improved with better displays and flight control systems, and a beginning form of distributed air traffic control for pilot self-spacing in the terminal area, and for pilot arrival merging will have been initiated. ATC communications at this point will be designed between the aircraft and ATC ground system with controller and pilot in monitoring roles. The initial implementation of this design will involve the controller and pilot as active observers initiating and acknowledging computer generated ATC and flight control instructions. The system will eventually evolve to passive monitoring by the pilot and controller for the purpose of manual takeover in the event of system failure.

All the functions identified in the pre and post 1985 eras will be included in the advanced system of post 1990. Questions regarding the concept of distributed air traffic control will have been further addressed and functional definition and distribution of controller and pilot ATC responsibilities will be tested and defined during this period. FAA and NASA are currently planning simulation and live testing of distributed air traffic control (CDTI). Three ATC secnarios are being developed for 1985, 1990, and 1995, respectively. Simulation and testing of these scenarios will be completed in the spring of 1980.

This is very timely since test and evaluation of the near term (pre 1985) ATC and flight information data link functions will have been completed and the output of the FAA/NASA simulation of CDTI will form the basis of a test plan for subsequent test and evaluation of data link applications.

NAFEC will be the test facility for the experimentation and evaluation of the advanced concepts determined for this time period. The enroute and terminal automation systems will have been functionally expanded and the data processing and display technology currently used in NAS will be replaced during the 1990 era. DABS will be expanded beyond the single site concept where problems of multiple DABS sensor coverage and netting of the sensors will be solved.

2.4.2.7 Design Development and Scheduling Constraints

Data link is keyed to the development and implementation plans for DABS. Single site DABS will be implemented in the 1982-84 era with multi-netted sites to follow shortly thereafter. Ground to ground communications of data link applications processors is necessary for some near term applications of data link. The National Airspace Data Interchange Network (NADIN) may be used to link the applications processors until the multiple DABS sensors are implemented and netted.

Another pacing item in the data link program is the development of cockpit display and associated input equipment for data link. The airlines and aircraft manufacturers are working together with the help of FAA/NASA to select an electronic display for the cockpit of the next generation air carrier aircraft (1985).

FAA is working with the industry to determine the availability of inexpensive input/output equipment to be used with a DABS transponder for general aviation. Initial data link application tests will be designed to provide data link information to a complete range of devices including cockpit printers, light emitting diodes (LED), CRT and other electronic displays. The Bendix BX 2000 color CRT and an inexpensive cockpit printer will be tested during the initial data link tests at Lincoln Labs in late 1978. An improved display (includes graphical input/output) will be tested 1979 at NAFEC. FAA is working together with NASA to test other electronic display concepts for more advanced functions involving data link such as CDTI, metering and spacing, and conflict resolution.

Finally, the NAS en route and terminal automation enhancement plans impact the advancement of data link. The next generation of automation enhancements incorporate computer generated ATC instructions for the controller and pilot to exchange. The current NAS automation system has capacity limitations and there are plans to expand the present computer hardware and software where it is possible, to off-load the current system using mini-computer subsystems, and finally, to replace the existing NAS automation hardware and software completely. FAA DABS data link plans are to implement data link applications in the near term (pre 1985) era which will not have significant impact on the limitations of the NAS route and terminal computers, and for far term data link applications (post 1985) to coordinate a system architecture design with the NAS en route and terminal system which will allow the addition of data link functions while supporting the effort to redesign the NAS system for ultimate replacement of the enroute and terminal computers.

2.4.2.8 DABS Data Link as a Data Modem

The DABS role in the ATC environment is discussed in general terms above. This section will briefly discuss the characteristics and capacity of the avionics as a data modem.

As an evolutionary system, the DABS format is constrained by the need to perform in the ATCRBS environment in a completely compatible fashion, and to perform all ATCRBS functions as well as the DABS function. A primary constraint on message length is the need to operate within the suppression period (35 +/- 10 microsec) of the existing transponders.

The DABS interrogations may be divided into ATCRBS/DABS and DABS. The ATCRBS/DABS interrogations consist of the normal ATCRBS signals with an additional pulse following P sub 3. This interrogation would elicit a normal response from an ATCRBS transponder, however the DABS transponder would reply with a DABS message indicating DABS capability and address permitting acquisition and 'enrolment' by the DABS ground computer. Once enrolled, surveillance is maintained with the DABS interrogation of Figure 2.4.2.8-1.

The transmitted DABS interrogation has a message block that is differential phase shift keyed (DPSK). Notice that a P sub 2 pulse is included as part of the standard DABS message. This will supress the ATCRBS transponders while the DABS message is transmitted. Contained within the interrogation in the parity/address field is a binary code that corresponds to the permanent identity code (address) of the desired aircraft. Other aircraft will also receive the interrogation. However their transponders will 'recognize' that the interrogation was for another aircraft and not respond. This illustrates the concept of 'discrete' aircraft interrogations.

The DABS only interrogation may be further divided into long, 112 data bits, and short, 56 data bits. The short interrogations would consist of two types of Discrete addressed interrogations and an ALL-CALL. The ALL-CALL interrogation would trigger a response from any receiving DABS transponder not already enrolled. This is accomplished by using an all '0's address in the parity/address field of the interrogation. The discrete interrogation would use the 24 bit binary address of the aircraft in the parity/address field. The three different types of long interrogations are all discrete. The difference is in the kind of data sent to the aircraft.

The DABS downlink message is shown in figure 2.4.2.8-2. It was designed to minimize the avionics requirements and to operate in a heavy ATCRBS interference environment. It is a 1M bit pulse position modulation waveform.

The two data formats are shown in figure 2.4.2.8-3.

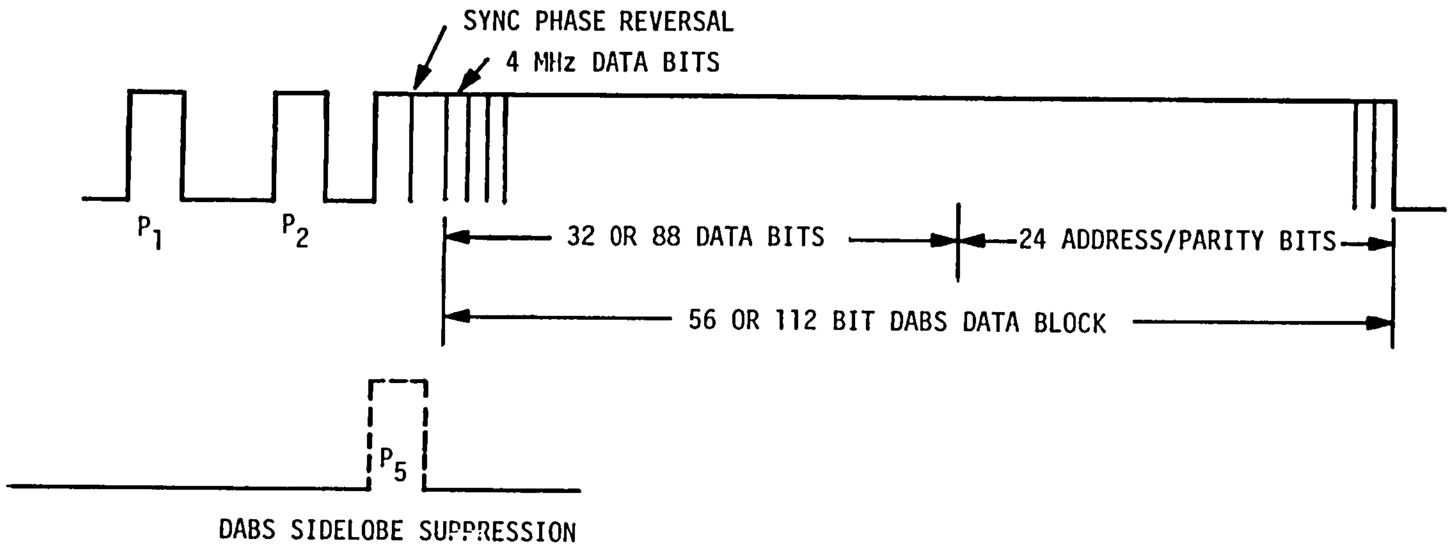
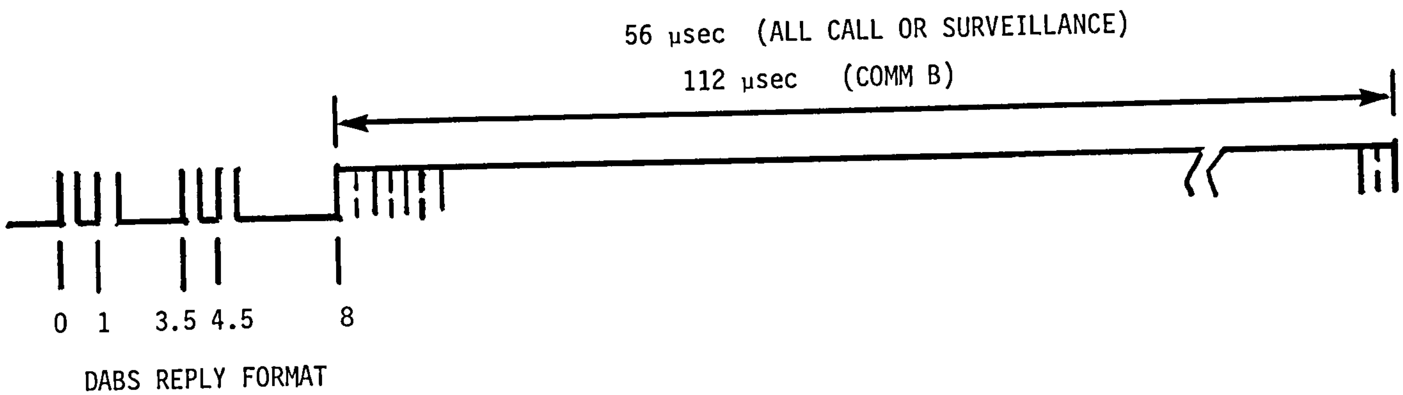


FIGURE 2.4.2.8-1 DABS INTERROGATION



DOWNLINK REPLY FORMATS

FIGURE 2.4.2.8-2

LINK CONTROL FIELD 16 BITS	SURVEILLANCE DATA FIELD 16 BITS	STANDARD MESSAGE FIELD 56 BITS	ADDRESS/PARITY FIELD 24 BITS

a) Normal

LINK CONTROL FIELD 8 BITS	EXTENDED LENGTH MESSAGE FIELD 80 BITS	ADDRESS/PARITY FIELD 24 BITS

b) Extended Length

DABS Data Block Formats.

FIGURE 2.4.2.8-3

The DABS transponder, of course, performs all the basic Beacon surveillance functions, but additionally can act as a modem which has the capability of interfacing with a variety of display and input devices.

The majority of DABS transmissions will use the standard message format, providing a 56 bit message field in addition to the lockout control and surveillance fields. The ELM - Extended Length Message - field is provided for the most efficient transmission of longer messages. With ELM, sixteen 80 bit messages can be transmitted in sequence air to ground or ground to air with a single acknowledgement.

The transponder must accomodate 30 normal messages (56 data bits) per 25 msec beam dwells or 4 sixteen segment (80 data bits per segment) ELMs. In low to moderate trafic densities this would determine the data link capacity per airplane. At higher densities, capacity would be determined by the range azimuth mix of targets and mix of message types. Details on link capacity may be found in ref. 25.

At this time there is not a great deal of definitive information on the use of the capability, other than surveillance, beyond recognition that an automated separation assurance function will be provided. Obviously though, when the link becomes available a considerable portion of the ATC routine can be automated.

The hardware implementation of the avionics is quite straightforward. RF sections are quite similar to the mature ATCRBS transponder with the DABS functions largely confined to the logic area. The straightforward well designed DABS processing lends itself nicely to custom LSI where the technology is still moving toward lower cost and increased performance. Normal industry evolution and competition should provide DABS transponders for both general aviation and airlines at a price of 20 to 30% above current ATCRBS avionics. The higher number would be called for if diversity transmission and reception (upper and lower antennas) was required by link reliability for the separation assurance functions. This would likely affect only the airline hardware.

The avionics have been demonstrated to be straightforward and relatively inexpensive.

Basic technology improvements in solid state power generation at L-band would be the most cost effective area for NASA 'seeding'. Digital processing will nicely take care of itself due to competitive pressures from the data processing and consumer markets.

There might be considerable opportunity for technical investigation as the operational use of the DABS function becomes better defined, i.e., general aviation display technology, input devices, etc.

2.4.2.9 Conclusion

It has taken more than three decades to satisfy all the basic needs to provide a digital data link system. The voice link has become congested for ATC company communication and flight information services. Traffic is and will continue to grow tending to aggravate the voice link congestion problem. More ATC, company communication, and flight information services are needed as airports and airways become more congested. And finally, technology is rapidly advancing to the point where costs for improved avionics are within reach of the many varied users of the system to receive the additional services which can be provided.

DABS in itself strictly as an improvement to the ATC surveillance system can be questioned on a cost benefit basis; however, when ATARS and data link are considered as an integral part of DABS providing combined services of improved surveillance, aircraft separation assurance and all the services made available by digital data link; e.g., weather, ATC, and flight information services, the total system of DABS/Data Link/ATARS is salable.

2.5 WEATHER AVOIDANCE

2.5.1 INTRODUCTION

The Federal Aviation Administration has primary responsibility for providing those weather advisory services having immediate application to aircraft operations. The Aviation Weather Research, Engineering and development (R,E&D) activity of the FAA is closely coordinated with the Department of Defense , National Oceanographic and Atmospheric Administration (NOAA) and NASA to ensure that individual responsibilities are respected and combined obligations carried out efficiently. As an operating agency with statutory responsibility for the development and operation of a common civil-military system for air traffic control and navigation, primary emphasis is placed on research and development problems which would adversely impact the safe and efficient utilization of the airspace and the National Aviation System (NAS). The objective is to improve the air traffic control system and to increase progressively its efficiency and capability to meet the air traffic demands of the future. The effort to increase air traffic capacity is based on exploiting the established technology base by the development and integration of new equipment into the total system.

Weather represents the major uncontrollable variable affecting the operation of the air traffic control (ATC) system. It is the largest single causal factor in the delays encountered in the National Airspace System (NAS), and is a major contributor to aviation accidents. Even with planned improvements in ATC system capacity, costs attributable to operating delays may reach $1 billion in the next several years. The safety of flight as well as operating efficiency is highly dependent on the terminal area ATC system, both in the air and on the ground. The ATC system improvement and automation programs will include weather data for use by traffic controllers and for transmittal to pilots.

General aviation is expected to lead growth in aviation activities over the next decade, the fleet increasing by about 70%. The existing Flight

Service Station (FSS) system is made up of about 290 facilities and is now a technologically obsolete, labor-intensive system. The demand for these services is forecast to more than double by 1990, with a required staffing level increase from about 5,000 to 11,000 positions, if no relief is provided. Development of a national plan for automation of weather aeronautical data collection, processing and dissemination will help assure a major saving in system resources with a low capital investment and reduced operating costs.

2.5.2 SCOPE AND OBJECTIVES

To minimize of avoid the impact of weather factors on aircraft operations requires the capability to predict or forecast weather conditions for both short-term and long-term periods. It also requires the availability of sensors and supporting systems to acquire, process, transmit and display weather data relevant to aviation needs, especially as related to severe weather phenomena. To achieve these capabilities, the Weather Avoidance programs have been divided into three general categories: wind shear, automation of weather observation, and weather data processing and distribution. These are funded under the Research, Engineering and Development appropriation request, along with related air traffic control, navigation, and aviation medicine engineering and development programs. Each of the programs is structured into a number of subprogram areas and is conducted by FAA personnel, other Government agencies by means of interagency agreements, or through contracts with qualified organizations. These programs are described in the following sections.

2.5.2.1 Wind Shear

Overcoming the hazards to aircraft posed by wind shear during terminal area operations has been one of the FAA's top priority programs. Its objective is to minimize the dangers of wind shear on aircraft flight path control during takeoff and landing operations and to incorporate a wind shear hazard warning system into the NAS. The program is structured into three areas, each conducted cooperatively with DOD, NASA, NOAA and the airlines.

2.5.2.2 Airborne System

The flight control response capability required to counter wind shear occurrences has been investigated using both manned and unmanned flight simulators and in flight under actual operational conditions. Wind shear related avionics subsystems installed as part of the aircraft cockpit instrumentation were successfully flight tested for effectiveness to assist the pilot in wind shear detection during actual wind shear conditions. These flight systems involved integrated ground speed and wind differential displays prototyped for operational test and evaluation. An Advance Notice of Proposed Rulemaking (ANPRM) has been issued to obtain reaction to a proposed requirement that certain airline transport aircraft have installed an airborne system or device to assist pilots in coping with wind shear during approach and landing. Standardized wind shear profiles were developed for use in certificating flight control and on-board flight advisory systems. The results of a comprehensive accident/incident analysis in which low-level wind shear was a contributing factor were published.

2.5.2.3 Ground-based Equipment

A dual acoustic doppler and pulsed doppler radar system and a Continuous Wave Laser Sensor system were field tested for operational suitability. The range capability of an advanced pulsed laser was evaluated, to provide full landing approach zone wind shear measurements. In addition two gust front (thunderstorm shear zone) pressure-jump sensors were evaluated for suitability as gust-front warning devices. Feasibility studies of using an advanced wind-shear detection system capable of monitoring airport arrival/departure corridors and directed toward providing complete wind shear detection capability were completed, and prototype development of the system is scheduled. Full inclusion of the low level wind shear alert system into the NAS is scheduled for FY 1981.

2.5.2.4 Improved Wind Shear Prediction

A data base of low-level wind shear incidents, categorized by meteorological cause, severity and frequency has been instituted at NAFEC for use by interested organizations. As the result of FAA funded research, the National Weather Service implemented improved techniques for forecasting low-level wind shear in the terminal area on a nationwide basis. As a follow-on effort, FAA is supporting additional work on low-level wind shear prediction for shears associated with violent thunderstorms.

2.5.2.5 Automation of Weather Observations

This subprogram is directed at providing weather observations automatically as close as possible to that provided by a human observer, at lowest possible cost and automatically recorded for transmission to users. A user evaluation of an automatic aviation weather observation station (AV-AWOS) was completed sucessfully and demonstrated the capability to provide weather observation service at airports where no FAA personnel are available. Development work is continuing to obtain improved sensors having greater sensitivity and increased reliability.

A simple, low-cost, automated weather observation system is being developed by FAA jointly with the National Weather Service (NWS). This will provide minimum acceptable weather observations at low cost for more than 900 airports that have instrument approach procedures but no weather observations at present. Engineering tests of models at user airports should provide data for design of systems suitable for demonstration to general aviation user groups, which requested this effort.

Semi-automated weather reporting capability for limited aviation weather reporting stations (LAWRS) is under development by FAA jointly with the National Weather Service. A developmental model has been procured for operational test and evaluation. This system, intended to be used when NWS personnel are not available, provides more up-to-date weather information and better data transmission than otherwise available, and allows the FAA controller more time for his ATC function.

2.5.2.6 Weather Data Processing and Distribution

An effort was undertaken to provide very short-range thunderstorm forecasts to the terminal controller and the pilots, with sufficient warning and accuracy to avoid the extreme weather hazard. This should help minimize aircraft operating delays and result in increased safety of terminal area operations. Near-term modifications to ATC radars should permit 0-30 minute forecasts for thunderstorms and severe weather activity using the past history of the cell, location, size and intensity and without requiring a weather forecaster's input. In the future, the application of MTD/pulse doppler techniques will be evaluated (these MTD/pulse doppler techniques involve advanced signal processing methods for aircraft detection and would be used to modify FAA radars for tracking and forecasting movement of individual thunderstorm cells). This evaluation may lead to the possibility of a nation-wide doppler weather radar network.

Under FAA sponsorship the National Weather Service (NWS) has undertaken a program to improve forecasting techniques to provide better forecasts from 0 to 4 hours ahead. Initial activity will improve thunderstorm forecasts for the 0 to 2 hour time period with forecasts every 10 min. for the 0-30 minute period. Major end products will be a short-range 0-4 hours aviation weather forecast plan and implementation of 2 hour thunderstorm forecasts by NWS.

3.0 AUTOMATIC CONTROL SYSTEM TECHNOLOGY

Automatic control system technology is undergoing a significant rate of technology turnover which at first seems surprising for such a mature technology. The technology turnover is caused by several factors which include:

- A strong trend toward digital mechanizations of control systems brought about by the rapidly decreasing cost and increasing computational power made possible by micro-processor technology and other very large scale integration (VLSI) circuits.

- A trend toward increasing the functions of flight control systems to include such active control modes as flutter control, gust alleviation, and ride quality enhancement.

- The trend to fly by wire systems to reduce aircraft weight is requiring the development of fault tolerant computer hardware and software to retain the same levels of safety and reliability as for the mechanical systems being replaced.

- Digital electronic controls are now being applied to propulsion controls in order to achieve additional performance and economy benefits not possible with the mature hydromechanical technology.
- The integration of propulsion and flight control is a natural consequence of the digital implementations of these control loops.

The above cited factors contributing to a high rate of technology turnover in an area considered mature are applicable to the more complex aircraft such as airline transports and the emerging V/STOL aircraft.

An equal rate of technology turnover is made possible in general aviation aircraft flight control by the availability of low cost microprocessors. However, this trend has not yet surfaced in terms of digital general aviation autopilots. Possibly the reasons for the static technology situation in general aviation control are (1) relatively low performance requirements for general aviation autopilots and (2) the fact that GA autopilots are not flight critical.

The emphasis in general aviation flight control has been the digitization of the outer loop or guidance modes. Also, NASA has been supporting some important research directed toward providing an ultra low cost 'wing leveler' type general aviation autopilot using fluidic and electro-fluidic elements. This ultra low cost autopilot, which has analog inner loops,is compatible with digital outer loop control provided by R-NAV systems.

3.1 AUTOMATIC FLIGHT CONTROL SYSTEM

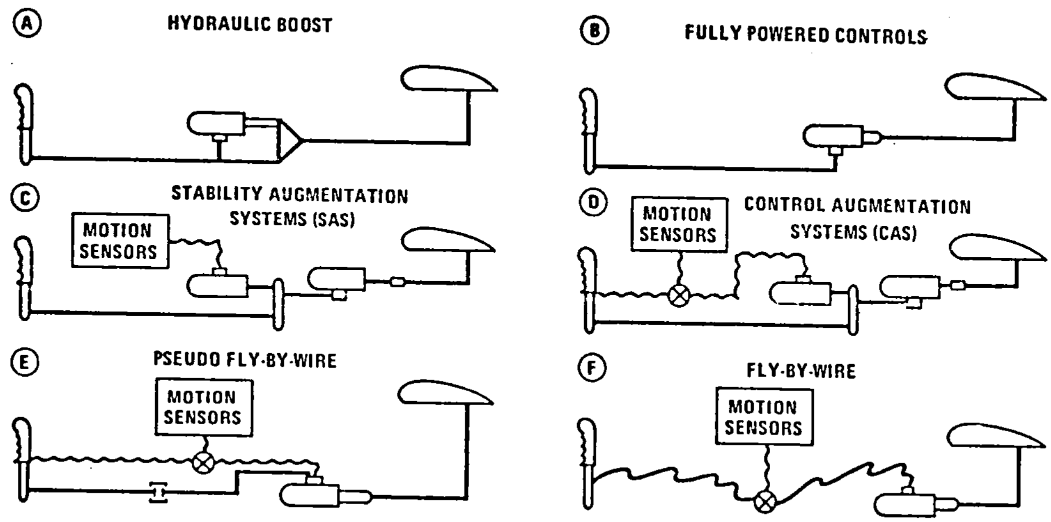
Primary flight control systems for aircraft have evolved from simple mechanical linkages between the pilot's controllers and control surfaces to electronic (Fly-by-Wire) flight control systems with fully powered control surfaces. Aircraft flight envelope expansion and increased response requirements have given impetus to this evolution. Improvements in reliability and miniaturization of electronics, coupled with technical advances in hydraulic actuation, have made it possible to incorporate flight control systems which can provide significant aircraft performance improvements. The evolution of flight control systems is depicted in Figure 3.1-1. Each of the flight control system types illustrated in Figure 3.1-1 is presently in use or being designed for use in future aircraft.

Fly-by-Wire (FBW) controls were initially developed and flight tested on the MCAIR F-4 Survivable Flight Control System (SFCS) program funded by AFFDL and subsequently implemented in production by General Dynamics on the F-16 aircraft. Sperry supplied the redundant analog system. FBW technology makes possible the implementation of the active control capabilities in a more cost effective manner. Digital mechanization of FBW avionics provides the flexibility and computational capacity to implement these capabilities in a more cost effective manner. Digital avionics were flown on the LTV A-7 aircraft in an AFFDL funded program to Honeywell. The mechanical controls in the A-7 aircraft were retained. NASA is currently developing a triplex digital FBW with an analog FBW backup for an LTV F-8 aircraft. In addition Boeing is developing a triplex digital control system with a mechanical backup for the AMST using Marconi Elliott flight control electronics. The first production digital system is being developed for the Navy F-18 fighter/attacker aircraft built by the MCAIR and the Northrop team with flight control avionics supplied by G.E. The F-18 incorporates a minimal mechanical backup system.

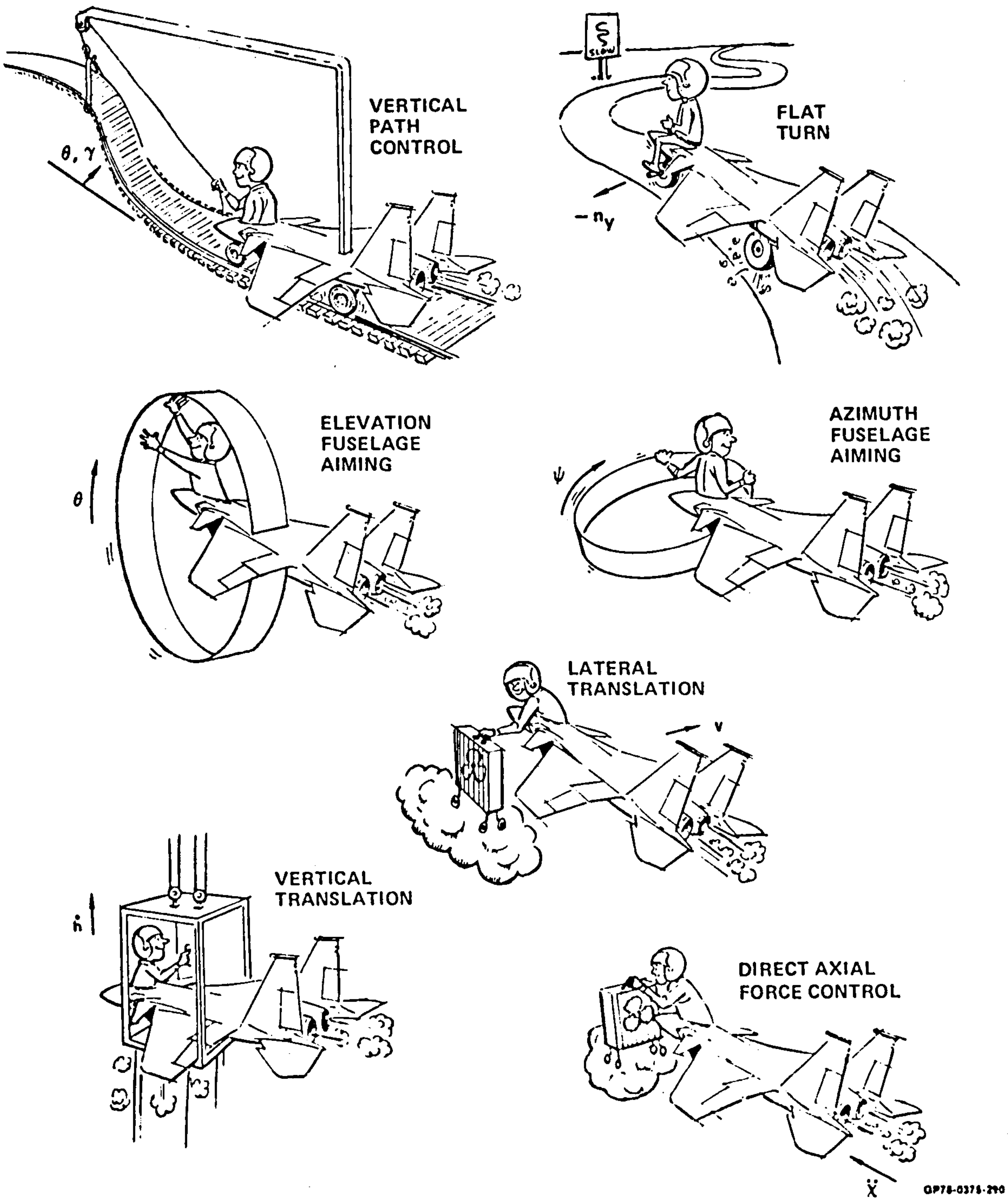
Customized flight control modes can designed and implemented effectively in a digital FBW flight control system to provide enhanced tactical effectiveness. Modes that optimize velocity vector control for delivery of ballistic free-fall air-to- ground weapons and optimize attitude control for gun aiming in aerial combat missions are primary examples. Coupling of the digital FBW system to the fire control system can provide significant improvements in weapon delivery accuracy and aircraft survivability for both aerial combat and air-to- ground attacks. Utilization of an aircraft configuration with direct force control in conjunction with the digital FBW technology enables the improvement of maneuvering performance through relaxed static stability, flat turning, vertical path control, fuselage aiming and vertical/lateral translation. These direct force capabilities are illustrated in Figure 3.1-2.

FIGURE 3.1-1

HOW FLY-BY-WIRE EVOLVED



(FROM J. P. SUTHERLAND AND R. C. HENDRICK, "ELECTRONIC FLIGHT CONTROL IS GETTING SET TO TAKE OFF", ELECTRONICS, NOVEMBER 9, 1970, PP 87-92)



MANUAL DIRECT FORCE FEATURES - PILOT'S VIEWPOINT

FIGURE 3.1-2

3.1.1 FUNCTIONAL REQUIREMENTS

The Automatic Flight Control System (AFCS) is generally configured to operate in a number of modes of control. These control modes are designed to provide stability augmentation, pilot work load reduction, and aircraft/weapon system improvement. Active control technology can provide improved aircraft performance through the application of new or advanced technologies in three general areas; inner loop control, outer loop control and pilot control steering. The flight envelope can be expanded using active control technologies. Aircraft stability is maintained or achieved using inner loop control. Additional control capabilities can be added for increased performance through both inner and outer loop control. The pilot and vehicle interface can be improved to reduce workload and improve performance.

The inner loops of the AFCS include the pertinent rate and accleration feedback loops to achieve stable, highly responsive, and well-damped aircraft dynamic characteristics. Conventional outer loop modes are provided through the AFCS to assist the pilot during peak work load activity or during extended mission segments for relief of fatigue. Examples of these modes are attitude hold, altitude hold, ground track/heading hold, and automatic carrier landing using approach power compensation to automatically control the throttles during landing. Special control modes that have been implemented in current AFCS designs include direct lift control, stall warning, and precise stable weapon platform control for air-to-air and air-to-ground weapon delivery.

With the emergence of fly-by-wire and direct force maneuvering concepts, the utility of the AFCS has increased. Implementing these technologies will enable multi-mode control, relaxed static stability, direct force control, maneuver load control, ride qualities improvement, and active flutter suppression through use of active feedback control. These emerging technologies require further development, flight validation, and the establishment of design criteria for application to future vehicle designs.

3.1.1.1 INNER LOOP STABILITY AUGMENTATION

The development of advanced control concepts for conventional high performance attack fighters differ from those developed for V/STOL aircraft due to the unique control and sensors required for the V/STOL in the very low speed, low altitude and flight regime. Therefore, conventional fighters and V/STOL aircraft are addressed separately.

I. CONVENTIONAL HIGH PERFORMANCE ATTACK/FIGHTER AIRCRAFT

The inner loop control laws for high performance and short takeoff and landing aircraft have evolved from basic surface command systems with stability augmentation (F-4, F-14) to high authority maneuver command systems (F-15, F-16, F-18). Several key design philosophies are currently evolving that can provide significant aircraft performance inprovements through the inner control loops. These include configurations with relaxed static stability margins, high angle of attack maneuvering capabilities, ride quality improvement, and active flutter suppression.

a) Future research and development needs.

aircraft maneuvering envelope to fully exploit the high angle of attack capabilities of their aircraft. Configurations are being developed to provide controllability and satisfactory handling qualities in angle of attack regime. New aircraft may feature improved maneuver capability provided by relaxed or negative static stability. Control systems have been designed and already flown in R&D programs on aircraft configurations with relaxed and negative stability margins (F-16, F-4 (PACT)). However, to date, these aircraft with relaxed static stability have required either angle of attack limiters or placards to prevent loss of control due to stall induced departures. Criteria such as C sub n beta dynamic, Lateral Control Departure Parameter, and Weissman criteria have been developed for predicting aircraft departure susceptibility. The impact of using active feedback control on augmented aircraft designs to improve aircraft stability and controllability in these departure regions should be determined.

In general, aircraft flying in the low altitude, high speed environment are very sensitive to gust and turbulence disturbances with resultant ride qualities that can reduce mission efffectiveness because of degradation in pilot performance. Mission effectiveness can be enhanced, particularly in those mission segments requiring low altitude, high speed flight, by designing the vehicle and flight control system to provide ride qualities which are significantly improved over those of current fighter aircraft.

Current design guidelines as stated in MIL-F-9490D for achieving satisfactory ride qualities in the low altitude, high speed regime are inadequate and need to be upgraded. Programs for developing suitable gust alleviation systems for aircraft configurations with low wing-loading and flexible bodies have been undertaken with various degrees of success. However, a comprehensive design approach encompassing aerodynamics, structures, and controls features is lacking. Therefore R&D should be directed to develop ride qualities design criteria, and analysis techniques for improved ride qualities in new aircraft. The use of integrated redundant sensor assemblies with high accuracy capability may eventually supersede the use of individual sensor sensitivity to gust disturbances.

Flight control design should consider the multiple control capability now possible with the inherent flexibiliy of digital fly-by-wire control systems. Pilot performance for tasks demanding accurate control of the velocity vector or accurate attitude control may be significantly improved by multimode implementations. R&D is needed to establish meaningful design criteria for multi-mode control system design.

b) Emerging Concepts.

Active flutter suppression is an emerging concept that offers significant potential for aircraft weight saving and performance improvement. This technology requires development and flight validation to ensure aircraft safety when flying at supercritical speeds. Further R&D analysis and refinement are required in the area of estimating the dynamic charateristics of control effectiveness derivatives. Aerodynamic derivatives are generally developed for static deflections;

however, the control effectiveness derivatives need to be defined for the control frequencies used for active flutter control systems. Electronic implementation of fail safe control implementation for flutter suppression applications is a significant challenge.

c) Superseded technologies.
The development of highly reliable digital air data systems may eliminate the need for complex self-adaptive gain changing. Developing the digital flight control system with highly reliable air data gain scheduling may provide a flight control system more nearly optimized over the flight envelope that can be achieved with the use of rather complex self-adaptive gain changers.

d) Recommended research.
It is necessary that R&D be directed toward better definition of high angle of attack aerodynamic characteristics and control systems to provide post-stall control and to prevent high angle of attack departures.

II. V/STOL AIRCRAFT

The current trend in the design of some high performance aircraft is toward the integration of aircraft control and stability functions such that aircraft stability becomes totally dependent on the flight control systems. This is particularly true in V/STOL applications where the basic aircraft has no inherent stability for at least a portion of its flight regime regardless of its aerodynamic configuration. Such total dependence on the flight control system for aircraft stability demands a variety of motion sensors with a high degree of reliability.

a) Future Research and Development Needs.
Sophisticated V/STOL flight control systems in the past were on the traditional angular rate and attitude feedbacks required for stability and control augmentation functions. Availability of three-axis inertial velocity information, low airspeed magnitude and direction, and side force control capability in future V/STOL aircraft will enable formulation of new concepts in flight control to enhance V/STOL control precision and flight safety. R&D effort should be directed towards development of these sensor concepts and the associated control laws. Sensor technology requirements, levels of redundancy, and signal quality should be identified, and criteria for design established.

b) Emerging Concepts.
Skewed sensors have received much recent attention because better reliability can be realized using fewer sensor elements than normally required with more convential sensors. Arranging rate sensore in a skewed configuration, and using a digital computer to resolve the measured rates into aircraft body rates about the orthogonal axes, reduces the number of sensor elements required. For example, a set of five skewed rate gyros can provide the necessary rate information to a triplex computer configuration that would otherwise require nine gyros in a more conventional orthogonal arrangement. Integration of inertial and air data information capability into this sensor package can provide the quantity and quality of sensor signals required for the full V/STOL flight envelope from hover to maximum speed.

R&D effort is currently being expended to develop accurate and reliable low airspeed sensors for applications in V/STOL aircraft, with some promising concepts reaching the flight test stage. The major problem, however, is with installation of such equipment on an aircraft which at low speeds is usually enveloped in propulsion generated or induced airflows. The need for further R&D in this area is readily evident.

c) Superseded technologies.
The use of integrated redundant sensor assemblies with high accuracy capability may eventually supersede the use of individual sensor elements throughout the aircraft, and, thereby, diminish problems associated with installation and interelement communications.

d) Recommended Research for NASA Sponsorship.
R&D for integrated redundant inertial velocity and low air-speed sensors and their implementation in V/STOL aircraft flight control systems is required to provide all weather operational capability. Implementation of propulsion side force control will further enhance control precision during the difficult task of a vertical landing in small space areas in the presence of crosswinds and air turbulence. V/STOL control concepts based on using these sensors and side force control are well suited for piloted evaluations using six-degrees-of-freedom motion base simulators. R&D on criteria for V/STOL aircraft control power requirements is needed because of the impact of these requirements on airframe weight, size and cost.

3.1.1.2 OUTER LOOP CONTROL

The development of outer loop control laws differs for conventional high performance attack/fighters and V/STOL aircraft, again due to the low speed, low altitude flight characteristics of the V/STOL aircraft. Therefore, the outer loop control discussions are also separated for this reason.

I. CONVENTIONAL HIGH PERFORMANCE ATTACK/FIGHTER AIRCRAFT

Outer loop control implementations have been developed for current fighter aircraft varying from relatively simple relief modes to highly sophisticated command modes. Typical relief modes include altitude, attitude, heading and ground track hold. More sophisticated modes such as terrain avoidance and terrain following, autoland, and precision course direction enable improved aircraft system performance. Additional outer loop control capabilities can be generated by direct force control derived from non-conventional control surfaces such as horizontal canards, vertical canards and variable incidence wings.

Digital fly-by-wire technology enables integration of flight control systems with other primary systems such as the fire control systems and propulsion systems. Integrated flight and propulsion concepts are discussed in Section 3.3.

a) Future Research and Development Needs.
Limited wind tunnel, simulation, and flight test experimental studies have demonstrated benefits of using non-conventional control surfaces to generate direct force control capabilities such as drag modulation, flat turning, maneuver enhancement, fuselage aiming, and vertical and lateral translation control. These capabilities can be used to substantially improve and increase firing opportunities and weapon delivery accuracy.

b) Emerging Concepts.
Four dimensional navigation control can potentially provide the capability of controlling the air vehicle flight path to enable aircraft arrival at the desired location (X, Y, Z) at the time required (t). This capability provides positive control of the aircraft and should result in (1) more firing opportunities when used on interceptor missions, (2) reduced pilot workload and increased effectiveness when used on attack aircraft, and (3) increased safety when used with instrument approaches. Flight development of a four dimensional navigation control system and establishment of design criteria are necessary.

c) Recommended Research.
The development of automatic four dimensional navigation modes for application on interceptor and attack aircraft should be pursued.

d) Other Research.
Terrain following and avoidance, autoland, and precision course direction modes have ben developed for specific configurations. Any further development in these areas is configuration sensitive and mission critical and therefore, should be sponsored by the specific user. Integrated flight and fire control provides significant improvements in weapon delivery accuracy and aircraft survivability. This development requires detailed understanding of fire control and is currently sponsored and should continue to be sponsored by the Air Force Avionics Labs and the Air Force Flight Dynamics Labs.

II. V/STOL AIRCRAFT

The V/STOL crew is equipped with a control stick, rudder pedals, power lever (in place of the throttles) and one additional control required to vector the thrust for transition. The transition lever is generally used less frequently than other controls, and is usually located at the pilot's left hand. Nevertheless, this additional control further divides the pilot's attention thereby increasing pilot workload in transition, particularly as required for precise tracking on approach.

Tracking of a localizer signal can be performed by banking the aircraft in the conventional manner. Tracking a conventional glide path signal, however, is more difficult because the power lever, transition lever, and pitch control stick inputs all affect the flight path of the aircraft. In performance of steep or curved path approaches to a vertical landing, the landing approach is also the transition maneuver. To track a glide path, particularly under IFR conditions, deceleration on approach must be performed using the transition lever with certain precision, which is a difficult task without suitable command guidance.

a) Future Research and Development Needs.

Outer loop control is necessary to provide guidance functions and pilot assistance to reduce workload to within acceptable levels. R&D is needed in the area of range and range rate sensors, flight director control laws, command display functions, display formats and display devices. Development of various levels of outer loop automatic control designed to function reliably with available equipment aboard the aircraft and on the ground is also required.

In designing for all-weather landing capability, the ground installation of landing aids, the automatic landing modes, the primary flight control systems, and the cockpit displays must be considered as parts of the overall systems. One of the most important considerations in the design of the system is the division and coordination of the control and display functions between pilot, flight control system, and cockpit displays. This division of functions can range from a fully automatic landing to one with the pilot as a link in the outer control loops. The integration of automatic and manual functions into the design, consistent with the specific landing site requirements, necessitates a development program which makes extensive use of pilot participation through pilot-in-the-loop simulation programs.

b) Emerging Concepts.

The steep glide path or curved path approach to a vertical landing is the planned concept for the future V/STOL operations. The advantages of V/STOL capability are best realized when the duration of flight in the powered lift flight regime is minimized to reduced fuel consumption, noise, and exposure to ground fire.

c) Recommended Research.

Development of piloting techniques, flight director command functions, display methods and formats, and a definition of automatic pilot assistance are all required for the performance of the V/STOL all weather approach and landing task. Design criteria for sensor accuracy, tracking precision, and overall system performance requirements need to be established. These research and development tasks can be effectively accomplished using piloted six-degree-of-freedom flight simulation programs.

d) Other Research.

The Navy's NAVTOLAND program is an approach for solving many of the problems associated with V/STOL outer loop control. However, the technology field associated with the takeoff and landing segments of V/STOL all-weather operation is so broad that the extensive research will be required for many years. NASA can assist in promoting the R&D by funding pertinent studies and and analyses. Flight demonstration of promising concepts should be pursued.

3.1.1.3 PILOT CONTROL STEERING

Control stick steering systems for generating a pilot input into outer loop attitude control have been in use on numerous aircraft. The signals are generated from force transducers at the base of the stick grip. Other mechanizations such as position transducers on the control linkages have been used successfully. As control augmentation systems were developed, these transducers were used to provide the required maneuver command signals. The stick transducer was used to generate roll rate command signals for roll control, and it was used to command blended load factor and pitch rate command signals for pitch control. These signals were either a linear or nonlinear function of force or displacement. These transducers have evolved into redundant transducers used for generating commands for the multiple channel FBW control systems.

The center stick has been the primary flight controller on all operational fighter aircraft. Side stick controllers are currently being implemented on FBW control systems. The work on side stick controller development was initiated for the X-15 rocket plane (by NASA) on a F-101 aircraft. This was a generic study investigating pivot location, force vs. displacement, and grip configurations. This study was followed by further NASA sponsored work for the Mercury, Gemini, Apollo, and Apollo Lunar Excursion Module. The first successful aircraft fighter development of a side stick controller was accomplished for the F-4 (SFCS). The first production side stick controller application is on the F-16.

a) Future Research and Development Areas.
Additional R&D is required to identify how control tasks affect critical controller parameters such as controller location, force vs. displacement, grip and pivot location. Current side stick controller implementations have significant deficiencies which appear to vary among individual pilots and control tasks. High gain tasks such as tracking and landing are particularly troublesome with the side stick controller configurations.

b) Recommended Research.
A generic controller evaluation similar to the early NASA F-101 study should be performed using a modern high performance fighter test vehicle. Controller configurations should be evaluated for a variety of tasks. Evaluation pilots should include a range of sizes from the fifth to ninety-fifth percentile.

3.1.3 FAULT TOLERANT SYSTEMS

The development of fault tolerant systems is one of the most important efforts in adapting advanced technology to aeronautical applications. Recent developments, particularly in micro-electronic technology, give the potential for much more capable and cost effective avionics systems than the ones currently in use. These systems promise to provide significant increases in the effectiveness of aircraft operations and basic aircraft design. Operations can be improved by the increased use of automated functions including the routine use of low visibility automatic landing and by automated monitoring of all aircraft systems which can provide more reliable operations. The basic aerodynamic and structural design of the aircraft can be made more efficient by the use of active control technology as will be discussed in Section 3.4.

Basic electronic components, however, do not have the inherent reliability of many traditional mechanical devices and the basic aircraft structure. In order to give electronic systems the function reliability needed for new flight critical functions, they must be designed to be tolerant of inherent failures. In this area of fault tolerance , aeronautical equipment has a much greater requirement than the great majority of other applications of electronic technology. Thus much of the development of fault tolerant systems must be done specifically for aeronautical applications without being able to fully depend on other more generally supported developments.

Fault tolerant systems are made up of several sub-elements each of which has to have a comparable degree of fault protection for the total system requirements to be met. One basic element in a fault tolerant system is a fault tolerant computer complex. The computer complex must be supplied with data from fault tolerant sensor systems and command inputs and be able to apply outputs to fault tolerant actuators and displays. These computers, sensors, and effectors must be integrated together into a total system by a fault tolerant data communications system. This entire system must be supported by fault tolerant sources of electrical power and possibly hydraulic power. An assessment of current technology and needs for further development will be discussed for each of these sub-elements.

3.1.3.1 FAULT TOLERANT COMPUTERS

A basic requirement for most fault tolerant systems is one or more fault tolerant computers. Fault tolerant computers are necessary to assure the reliable computation of the flight control commands. In many fault tolerant system designs, a fault tolerant computer complex can have an even more important function than its direct involvement in the control loop. This function is the management of the total fault tolerant system.

Once a high degree of confidence has been established in the reliable operation of a computer, its inherent capability can be used to maintain the fault tolerance of the rest of the system including the computer itself. The capability of the computer can be used to assist in detecting faults in system elements and reconfiguring the system to assure that the elements that survive are combined into a coherent system that is able to perform all vital functions.

There has been a number of development efforts for fault tolerant computers using several different concepts. There are at least three different approaches that can be identified. One approach uses fault tolerant hardware techniques within the computer design. These techniques such as redundant circuits and error detecting codes would usually have to be applied at the component level. The continued increase in the number of components on a chip with LSI and VLSI technology means that these techniques would be applied within a chip. This means that special purpose chips would have to be developed. This could prevent taking advantage of the lower cost and extensive support facilities available from chips developed for mass markets. Moreover, this would violate important assumptions of fault independence. The low cost of mass produced components, however, makes possible alternate approaches to fault tolerance, which replicate entire computers to form a fault tolerant computer complex. Two of these approaches unite redundant sets of basic computers into fault tolerant systems. In one approach, the fault tolerance is implemented largely by software. In the other approach, judicious use of some special hardware is used to achieve an efficient balance of hardware and software techniques.

Prominent examples of these two approaches are the Software Implemented Fault Tolerance (SIFT) development by SRI International and the Fault Tolerant Multiprocessor (FTMP) development by the Charles Stark Draper Laboratory. Each of these will be discussed briefly and the need for further development will be emphasized.

Software Implemented Fault Tolerance.

The major units of a SIFT system are shown in Figure 3.1.3-1. The system consists of a number of central processing units with associated memories and input/output processors and their associated memories. These processors and memories are connected by a number of redundant buses. The numbers of processors, I/O processors, and buses are variable and depend on both the reliability required and the size of the computational task.

High reliability is achieved by having critical tasks performed in more than one processor. The number of different processors used for each task can be variable as a function of the criticality of the particular task. The input for the critical task is obtained by the intermodule buses from redundant sensor data contained in central processor memories or the results of previous tasks contained in central processor memories. These intermodule buses are unidirectional in the sense that they can only read from other memories and not write into them. This restriction keeps a faulty module from unduly affecting other good modules. The redundant input data is noted in each processor and any discrepancy is noted. A global executive program reads the reports of errors written by the different modules and initiates a diagnostic program that identifies the faulty module. The global executive performs any change in task schedules that must be made because of the failed module and saves the data necessary for the maintenance action to replace the module. The global executive is also replicated and its reconfiguration commands are noted as is any other program.

Fault Tolerant Multiprocessor.

A diagram of the FTMP is shown in Figure 3.1.3-2. This system also consists of a number of processor modules, memory modules and I/O access modules connected by a number of buses. Again the number of modules and buses is variable and depends on the reliability and capacity requirements. In this system a memory unit is not associated with a particular processor.

High reliability is accomplished by forming processors and memories into computer and memory triads connected by a triad of busses. In a typical installation there will be a number of triads performing as a multiprocessor. Each member of a single triad executes identical programs in synchronism with the other two members. By noting all the results that appear on the buses,the triad can mask any failure and quickly detect the faulty module. If there is a spare module available, it replaces the faulty one. If there are no spare modules available one triad in the operating set is lost, but two new spares are created. The multiprocessor is designed with sufficient capacity that critical tasks can be performed with the remaining triads.

The FTMP is also designed to minimize the effects of any latent failure. Spare modules are not allowed to remain unused. The system is continually reconfigured so that spare units are including in operating triads causing other units to become spares. Tests are also performed using intentionally generated 'bad' data to test the operation of error detection circuits.

The functional reliability of the FTMP is further enhanced by the use of submodules called Bus Guardian Units. These submodules are contained in each unit and govern the power-on status, connection of the unit to the active bus triad and certain self-test configuration selections. Redundant bus guardians are used to bias failures in a safe direction as either power-off or disconnected from the buses. The design assures that the probability is extremely low that any module can fail in such a way as to disrupt the operation of the computer complex.

An experimental multiprocessor has been constructed at the Draper Laboratory that demonstrates most of the basic features of the FTMP. It has been used to simulate a digital autopilot in a Boeing 707 simulator. Both the FTMP and the SIFT are scheduled to be constructed in prototype form by avionics equipment manufacturers under NASA sponsorship. It is recommended that these programs be continued and expanded.

These current protype programs emphasize the computer complex itself. It is very important that these development programs continue to allow expansion into an entire avionic system. It is essential that the discipline of being integrated with a complete system be imposed on the computers to assure that there are no gaps in the requirements and that the computer design is truly compatible with the most efficient overall system design. This integrated development is also valuable for the design of the other elements in the systems. It is important that the design of the total system reflect the advantages offered by fault tolerant computers. The capability of the computers can make possible new concepts in redundant sensor configurations, equipment self-test philosophies, etc. This integrated system development should result in flight to provide operational demonstration of the concepts. This system demonstration is necessary to prove the usefulness of the concepts and provide the confidence necessary for the aviation industry to apply the results.

3.1.3.2 FAULT TOLERANT SENSOR AND EFFECTORS

For many of the flight critical active control functions being proposed, the availability of sensor information will have to have as high a reliability as the computer complex. In most cases it is unlikely that the individual sensors will have the inherent reliability needed to meet system requirements. It is necessary that the sensor system also be made fault tolerant.

Concepts must be developed to determine how to most efficiently achieve this fault tolerance. Questions which must be answered are how many sensors are needed, how should they they be arranged, how are failures to be detected and how should the system be configured after a failure.

The most straightforward approach is to replicate each critical sensor and use triple angular rate and acceleration sensors in each required axis for a fail-operational flight control system. These sensors are in addition to redundant heading and attitude sensors. More effective sensor configurations are now being developed. The Air Force is developing a Multifunctional Inertial Reference Assembly which provides unified inertial data for flight control, heading, attitude and navigation. Another concept to achieve a more efficient redundant configuration for inertial sensors is to arrange the sensors in a skew configuration with respect to each other. It has been shown, for example, that six skewed single axis sensors have a greater functional reliability than three independent systems containing a total of nine sensors. Demonstration systems have been built and tested in aircraft. Skewed sensors are being used in the guidance system for the Interim Upper Stage being developed by Boeing for the Air Force for use as an upper stage for Titan III and the Space Shuttle. Continued development and demonstration, however, is necessary to evolve similar concepts for the other types of sensors such as air data and radio navigation.

Another concept under development which can result in more efficient configurations for fault tolerant sensors is analytic redundancy.Analytic redundancy uses a combination of dissimilar sensor data combined analytically to provide a redundant measure of the performance of a sensor. For example, inertial data can be used to detect errors in air data sensors and a combination of inertial data can assist in determining which of two disagreeing radar altimeters is at fault. One program for developing these analytical redundancy concepts is a part of the NASA Advanced Flight Control Program. It is planned to flight test some of these concepts in the Digital Fly-By-Wire system in a F-8 aircraft.

Considerably more development is necessary to perfect these techniques for use in commercial aircraft applications. Research is needed to determine what kinds of sensor data can be analytically converted to forms which provide redundant information for other non-similar sensors. Even more effort will be required to determine what accuracy requirements these techniques place on the sensors involved. These techniques will have to be demonstrated in an operational enviroment before commitments can be expected for their use in production systems.

Development efforts are also needed for fault tolerant actuators and displays. Much of the current technology for redundant actuators can be used in more advanced fault tolerant systems. However, even more efficient configurations are possible using techniques similar to analytic redundancy for sensors. The power of the fault tolerant computer can be used to detect failures in actuators and then reconfigure the control commands to the other available actuators to compensate for the failed actuator. Considerable new effort is required in this area to determine what constraints should be placed on the design of the actuators and control surfaces to allow the most efficient application of such techniques.

3.1.3.3 FAULT TOLERANT POWER SUPPLIES

A system will be no more tolerant than the supply of power to the system. The development of the necessary power systems has not received as much attention as computers, sensors and data communications systems. Future applications of avionics systems, however, will require a reliability of power that is greater than is available from current systems. Research will be necessary to develop the requirements for redundant power sources and a fault tolerant network to supply this power to the various components of the system.

The power supplied for most currently envisioned systems is both electrical and hydraulic. The establishment and maintenance of two power systems where the complete failure of either one would cause a complete system failure may not be the most effective approach. Work is being done by the Air Force and others on electrically operated actuators. If these actuators can be developed to the point that they are competitive with hydraulic actuators, then only one fault tolerant power system will be needed.

Research is needed to establish the most effective form for electrical power for aircraft. The current dual system of 28 volts DC and 115 volts 400 Hz may not continue to be the most effective with the new requirements being imposed by advanced systems. There is interest in using high voltage DC. Considerable development would be necessary to compare alternative approaches and specify the characteristics of the system. Any new approach would have to be fully demonstrated to have significant advantages before the aircraft industry is likely to change from their current standard.

3.1.3.4 FAULT TOLERANT DATA COMMUNICATION SYSTEM

One of the most important requirements of a fault tolerant system is a fault tolerant organizational structure and data communications system that allows the entire system to be reliably integrated. Fault tolerant computers and fault tolerant sensors and effectors are of no value if there is a failure to get the necessary data from one unit to the other.

There are several approaches to the problem of interchanging data reliably. The approach taken by the Airline Electronic Engineering Committee for the generation of digital avionics systems that are currently being developed for commercial aircraft is independent broadcast buses. Each unit provides its data on one or more dedicated buses. Other units have a receiver for each bus from which they need data. Isolated buses are used to keep nonflight critical users from causing a failure on the bus supplying data to flight critical users. This approach allows considerable isolation and fault tolerance to any common mode failures. However, as future systems become more complex and more units are integrated with each other, this organization can become very cumbersome and inefficient. The most effective design will probably require units to be interfaced with almost every other unit on the aircraft which will require an unreasonably large number of interface circuits and wires.

Multiplex data buses are another approach to data communication which are now being developed particularly by the Air Force. Multiplex buses can be made fault tolerant by using redundant buses, by having redundant controllers for the buses and providing isolation between the bus and the terminals. Redundant buses are discussed further in Section 5.3.2.

Another approach that is being developed to achieve reliable data communications is a fault and damage tolerant network. Communication within the system is achieved by chaining together a set of links which connect system nodes as shown in Figure 3.1.3-3. Each node is connected to two or three other nodes by fully duplex serial data links. Each node is associated with one or a small number of units which make up the system. A fault tolerant processor is associated with one of the nodes and is responsible for establishing and maintaining the communications network that allows data to go to all serviceable nodes in the system and for data from these nodes to be transmitted back to the processor. Software programs within the processor 'grow' the network by sending messages to the nodes which close switches connecting selected links of the network until paths are established to all functioning nodes as shown by the solid lines in Figure 3.1.3-3.

The network achieves its very high level level of tolerance to faults and damage by the large number of alternate paths that can be established which bypass a failed node or link. The fault tolerance is maintained by programs which continually modify the network to exercise all links to assure that there have been no latent failures. This network approach has been demonstrated in breadboard form with a limited number of nodes. More effort is needed to apply this concept to an operational system and demonstrate its characteristics as a candidate for further systems applications.

The development of the overall systems structure and data communications technique may be the most important effort needed to achieve practical fault tolerant systems for aeronautical applications. Many of the components of fault tolerant systems already exist. It is necessary, however, for these components to be tied together into a total system organization. A well planned development and demonstration program for avionics system organization structure could also provide an excellent framework for the development recommended for the other elements of a fault tolerant system including the computers, sensors, effectors and power supplies.

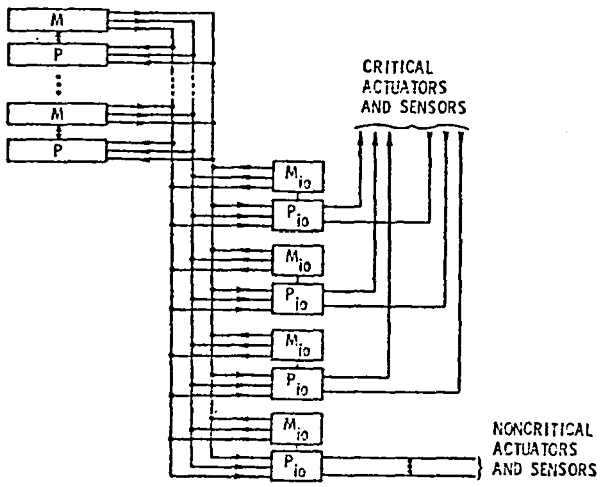


Figure 3.1.3-1 SIFT Configuration

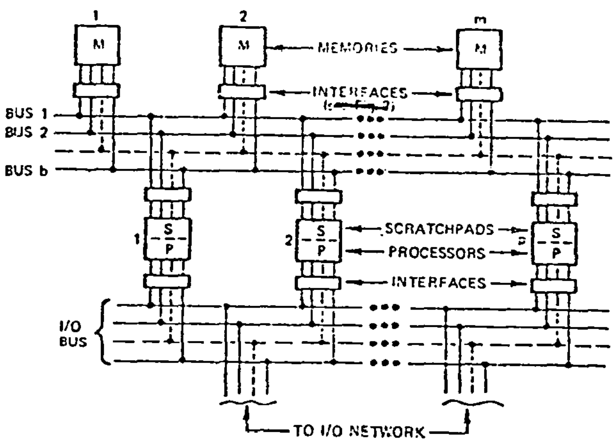


Figure 3.1.3-2 FTMP Configuration

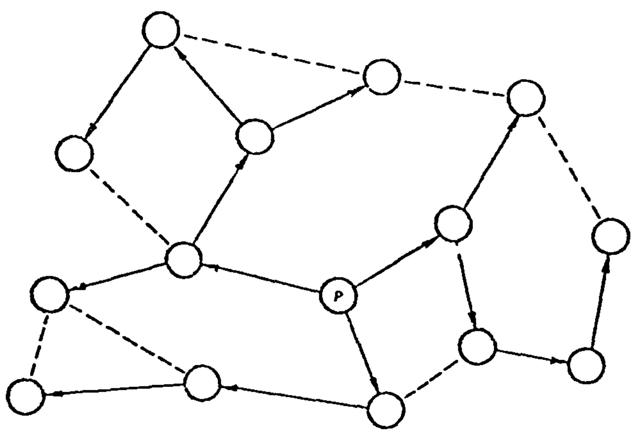


Figure 3.1.3-3 Example of an I/O Network

3.1.4 DIGITAL FLIGHT CONTROL

The implementation of a primary fly-by-wire flight control system employing digital technology is becoming an increasingly attractive concept due to the repeatability, flexibility and versatility of the digital computer. This concept is a logical extension of the analog fly-by-wire flight control systems which have been flight tested for fighter aircraft application in the last few years. Several of the major advantages found for a predominantly digital flight control system are:

- Capability for implementing multimode control laws and mode related displays for increased weapon system effectiveness and reduced pilot workload,
- Reduced redundancy requirements and increased failure monitoring capability due to the high degree of self-test, and
- Integration of flight control with related avionics functions such as navigation and fire control.

Multimode control laws which provide significant improvements in handling qualities and mission effectiveness can be designed. These control laws permit design for specific mission requirements and avoid compromise in system performance. Stability and control can be peaked for the application area of the flight envelope. Specific mission maneuvers can be defined and the desired transient response provided. Coordinating these control laws with the displayed data simplifies the pilot's tasks and enhances performance. Digital flight control provides the means for cost effective implementation of multimode control systems with advanced displays.

Redundant or multiple channels of control are necessary in fly-by-wire systems to achieve the essential low probabilities of failure, namely 2 x 10exp.-7 failures per flight hour or less. Analog fly-by-wire systems usually require quadruplex redundancy, i.e., four sensor sets, four computers and four actuator channels, to achieve the necessary level of safety. Digital flight control systems are expected to achieve the necessary level of safety using a triplex implementation. This concept uses the failure monitoring capabilities of the digital computer. Control system weight, necessary maintenance effort, and life cycle cost will be reduced using the triplex digital implementation. Interfacing of a digital flight control system with a state-of-the-art digital avionic system can be readily accomplished. Standardization of multiplex bus protocol and interfacing hardware, presently being developed in the Digital Avionics Integration System (DAIS) program, will significantly simplify these interfaces.

a) Future Research and Development Needs.
More investment of R&D resources is needed to reap the potential benefits of digital flight control.

Flight test of a digital fly-by-wire control system to validate triplex redundancy management techniques for production application is essential. Such a flight test program is presently planned as part of the Advanced Fighter Technology Development and Integration (AFT) program being conducted by the USAF.

The use of direct force maneuvering features to enhance the multimode capabilities is potentially rewarding. Research into aircraft configurations with control surfaces and/or thrust vectoring nozzles to achieve direct maneuvering forces, i.e., direct lift, direct side force, and direct axial force should be accomplished.

Integrated flight and propulsion control could be used to enhance independent control of the six degrees of maneuvering freedom. This capability could be used to reduce runway length needed for landing, improve speed control in vertical plane maneuvers, and increase turn rate.

b) Emerging Concepts.
Aerodynamic configurations with close aerodynamic coupling between horizontal canards and wings offer the potential for significant drag reduction particularly during maneuvers. Direct force capabilities enabled by simultaneous deflection of multiple aerodynamic surfaces in each axis of control can provide unique maneuvering features with such configuration.

Digital technology applied to flight control will enable simpler control system designs. Flight control software (control laws) will tend to be different in each application, but the hardware can be similar for a wide variety of aircraft. Interfacing of the flight control system with other avionics will be greatly simplified through multiplex bus interface standardization.

c) Superseded Technologies.
Mechanical control systems with associated high authority control augmentation systems will probably be replaced by digital fly-by-wire in high performance aircraft. Weight, cost and maintainability of mechanical control systems will be difficult to justify after digital fly-by-wire systems have been demonstrated. Analog fly-by-wire implementations which must currently use quadruplex implementations to achieve necessary flight safety are also expected to be replaced for similar reasons.

d) Recommended Research.
New concepts should be developed that can provide direct lift and direct side force capability and will give the designer some choice for practical integration of this capability into the aircraft and control system. Configuration development should be extended to obtain features at high angles of attack that will give confidence that the configuration will not have departure tendencies and will be recoverable from spins.

e) Other Research.
Research into the military application of multimode flight control laws is presently being conducted by DOD and should not be duplicated by NASA.

3.1.5 REDUNDANT FLIGHT CONTROLS

In discussing redundant flight controls, we will concentrate on digital fly-by-wire (FBW) systems for basically two reasons: (1) the digital FBW control system is the particular type of redundant flight control system in which interest is currently centered throughout the aerospace industry; (2) the principles and algorithms used in redundant digital FBW systems have wide applications to any system in which redundancy management is used to achieve higher reliability. In fact, some of the redundancy management techniques involved (computer self-test, for example) have application to nonredundant systems as well (e.g., terrain following, or integrated flight/fire control).

The advantages of FBW control systems (lower weight and cost, increased survivability, etc.) over mechanical systems have been much discussed in the literature. The advantages of digital mechanizations over analog have also been cited: lower weight, size, power and cost when the system is a complex one; increased flexibility with changes introduced by software.

The discussion deals with that important aspect of digital FBW systems that must be developed to a high level of maturity if such systems are ever to achieve their potential through wide acceptance and usage: redundancy management. A common thread running throughout the discussion is the importance of coverage, i.e. the probability of detecting, isolating and recovering from a failure. Coverage is the prime figure-of-merit in determining the efficacy of redundancy management. It impacts all phases of redundancy management; in fact, the design of redundancy management strategy is largely directed at improving coverage. As coverage is improved, the potential exists that a given system reliability can be achieved with a reduced redundancy level, with an attendant improvement in maintainability and reduction in size, weight, complexity and cost.

Redundancy management is a process designed into a redundant system whereby:

- System elements are monitored for failure,
- Detected failed elements are isolated from system operation,

and

- The remaining good elements are reconfigured.

The purpose of redundancy management is to make the FBW systems fault-tolerant to the degree necessary to yield the required system reliability.

Techniques for monitoring to detect failures can be broadly classified as:

- Cross-channel monitoring, and
- In-line monitoring.

Cross-channel monitoring means that signals from two or more channels are used to detect failures. A voting mechanism employing signals from three or more channels is an example of a cross-channel monitoring technique. In-line monitoring generally implies that elements within a channel are monitored without reference to other channels. Data reasonableness check, the use of sensor tracer signals, and the execution of computer self-test routines are examples of in-line monitoring techniques. Cross-channel and in-line monitoring techniques can be implemented in hardware, software or both. They are physically and functionally distributed throughout the FBW system. They may operate continuously (compute memory parity) or only on special call (rate gyro torquing signal).

Failed elements are isolated from system operation in various ways. In the simplest case, a failed element is merely ignored. A rate signal from a failed rate gyro, for example, can simply not be used in calculations (e.g., control laws) in which the signal is normally employed. In other cases, more elaborate action is required. To isolate failed hydraulic actuator, for example, usually requires that hydraulic power to the actuator be removed.

Reconfiguring the system frequently involves the same steps as isolating a failed element: ignoring the signal from a failed sensor or removing hydraulic power to a failed actuator. Other more elaborate reconfiguration schemes are possible: substituting computed data from a secondary data source for a failed prime source (analytical redundancy); reloading a permanently altered memory with data from a good computer, are but two examples.

a) Future Research and Development Needs

The potential of digital FBW systems is widely acknowledged. However, if such systems are to achieve their potential through wide acceptance and usage, redundancy management must be brought to a high level of development. Coverage must be raised with better cross-channel and in-line monitoring techniques and these techniques demonstrated with a high level of confidence. In particular, better in-line monitoring techniques must be devised so as to reduce the redundancy level, with an attendant improvement in maintainability and reduction in weight and cost. More consideration needs to be given to this inclusion of in-line monitoring hardware and algorithms in the design of sensors, computer and actuators. With today's micro- processors, the potential exists for sophisticated self-test algorithms that can be embedded with sensors and actuators.

Two important aspects of analytical redundancy techniques have been largely ignored and need to be addressed: (1) what are the actual cost savings achieved by replacing redundant sensors with computer implemented modeling techniques, and (2) what coverage is provided by these techniques?

The trend to distribute control systems employing digital bus structures for each control channel in many ways complicates the redundancy management problem. The redundancy management implications of such distributed systems need to be addressed.

b) Emerging Concepts

Digital FBW is a technology which is having, and will continue to have, a major impact on aeronautics and controls. Because redundancy management is the key to digital FBW and because the concepts and techniques are generic and have wide application to any control system in which redundancy is used to achieve higher reliability (and in nonredundant systems to achieve higher safety), it is not difficult to foresee redundancy management emerging as a separate discipline.

c) Superseded Technologies.

Contemporary operational FBW systems, whether analog or digital, are predominantly quadruplex. As redundancy management techniques are improved, these systems will be superseded by fail-op triplex systems, and in some cases, by fail-op duplex systems.

d) Recommended Research.

It is recommended that NASA: (1) take the lead in developing self- test techniques for the various control system elements, (2) extend the F-8 triplex digital FBW system to a dual fail-op capability without analog reversion, and (3) demonstrate failure coverage and probability of loss of control, to establish a sound baseline for future FBW designs.

3.2 PROPULSION SYSTEM CONTROLS

3.2.1 BACKGROUND

Most present aircraft turbine engines are controlled by rugged, highly reliable, hydromechanical devices. These mechanical devices consist of cams, linkages, hydraulic servos, etc. They have, over the years, developed a high level of maturity. In fact, the mean-time-to-failure for typical units on civilian aircraft engines is between 20000-30000 hrs. Most of today's commercial engines, however, are relatively simple aero-thermodynamic devices. Fuel metering and possibly some compressor variable geometry are the variables which must be properly manipulated by the controls. On military engines, where supersonic applications are typical, the number of inputs to the engine increases. In fact, on future engines where the design emphasizes high performance for minimum weight, the number of inputs to be controller becomes quite large (5-7).

Experience with the multiplicity of inputs on today's military engines has shown the design of a complete hydromechanical controller to be a difficult, if not nearly impossible task. The computational task to be accomplished accurately and repeatedly by the controller is the reason for the inadequacies of hyrdomechanical components. As a result, one of the more modern military engines, the P&WA F-100 afterburning turbofan, uses a digital electronic computer as a trim control for a rather complex primary hydromechanical controller. Only with the intelligence of the digital trim control can the F-100 achieve full-rated performance.

Thus, there is at this time a great deal of attention being paid by the aircraft propulsion control industry to determining the technology needs for a more universal applicability of digital electronic turbine engine control.

The current generation of high bypass ratio turbofan engines requires relatively complex systems for internal engine control and protection. Consequently, a proliferation of system components has occurred to earlier engine models. For example, the JT9D employs approximately twice as many control components as does the JT8D. The retention of conventional hydromechanical control methods was a major factor in this trend. Notably, the newly proposed JT10D and CFM56 engines employ hybrid electronic hydromechanical methods.

Several recent programs have successfully addressed the application of electronic controls to both the airframe and engine parts of the propulsion system (Figure 3.2-1). However, only one program has progressed to a flight evaluation and then only on a single engine of a two engine military aircraft. Further hardware developments are needed to establish the technology base necessary for commercial aircraft application. In particular, a flight test evaluation should be conducted on a multi-engined aircraft.

These programs and other previously conducted studies have produced many affirmative conclusions as to the advantages of electronics in propulsion control systems. Some of the prominent benefits are:

PREVIOUS RELATED PROGRAMS

- o JT8D-ELECTRONIC PROPULSION CONTROL SYSTEM

  JT8D GROUND DEMONSTRATION OF FULL AUTHORITY DUAL CHANNEL DIGITAL CONTROL

- o IPCS-INTEGRATED PROPULSION CONTROL SYSTEM

  F-111/TF30 FLIGHT DEMONSTRATION OF FULL AUTHORITY INLET/ENGINE/AFTERBURNER/NOZZLE INTEGRATED DIGITAL CONTROL (ONE ENGINE

- o QCSEE-QUIET CLEAN STOL EXPERIMENTAL ENGINE

  FULL AUTHORITY DIGITAL CONTROL PRESENTLY BEING EVALUATED ON GROUND TEST ENGINE

- o F100-MULTIVARIABLE CONTROL SYSTEM PROGRAM

  F100 GROUND DEMONSTRATION OF AN ADVANCED MULTI-VARIABLE ENGINE CONTROLLER BASED ON LINEAR-QUADRATIC REGULATOR DESIGN TECHNIQUES AND IMPLEMENTED WITH A MICRO PROCESSOR

FIGURE 3.2-1

- Increased engine life
- Reduced pilot workload (through improved speed-path controllability)
- Reduced fuel consumption
- Improvement in on-time departures, reduction in unscheduled removals and aborted flights
- Improved stability and failure protection

All the above described benefits are of an economic nature and, therefore, of high interest to the airlines.

These benefits are enhanced for powered-lift aircraft because of the increased interaction between the engines and flight controls. In addition, these configurations often involve extensive and variable use of engine bleed and variable geometry exhaust systems. The associated engine management and protection functions lead to a significant increase in control complexity and pilot workload, which can be avoided with proper application of Electronic Propulsion Control System (EPCS) technology.

Several programs which have helped add to the technology base needed for a digital engine control capable of full-authority control of a turbine engine have been either completed or are in progress. Briefly, these are:

1) F-111-IPCS (Integrated Propulsion Control System) program which evaluated in flight a full-authority digital electronic control for one propulsion system of the F-111 E A/C (1975).

2) EPCS - Electronic Propulsion Control System which was an industry sponsored effort to develop and evaluate an engine mounted -full-authority controller for an operational civilian aircraft engine. System was demonstrated at sea level.(1975)

3) FADEC - Full-Authority Digital Electronic Control is a NAVY sponsored effort to develop an engine control using the very latest state-of-the-art electronic technology. System will be engine mounted and a sea level evaluation and possibly a flight evaluation will be performed. (1978)

The major hurdle for the acceptance of a full-authority digital electronic engine controller is that of reliability. For technical as well as warranty reasons, the engine manufacturers insist that the electronic controlling mechanisms be mounted directly on the engine. Technical reasons are the weight penalty of the wiring encountered when connecting the control remotely as well as the cable's susceptibility to noise pick-up. The warranty reason should be obvious. With a control some distance from the aircraft who will be responsible for a control induced failure?

Installation anywhere on the side of an aircraft turbine engine imposes a severe environmental problem upon the digital electronic controller. Elevated temperature, temperature shock as well as vibration are the major problems. For electronic technology to operate long term in such an adverse environment requires certain technology advancements. The absence of the needed advanced technology is slowing the incorporation of full-authority digital electronic propulsion control into new systems.

3.2.1.1 FLIGHT TEST DEMONSTRATION

The basic lack of flight test experience has delayed the application of electronic digital control system techniques in new engine developments because of the risk involved. The application of electronic propulsion control systems is seriously affected due to the constraints of a production program. Prototype design and test phases of EPCS development would reduce the technical risk of applying digital controls to propulsion controls.

A program which utilizes the YC-14 AMST prototype as a test bench for the EPCS research would be one possible means for implementing EPCS testing. This activity could be a part of the Quiet Propulsion Lift Technology (QPLT) program. The YC-14 EPCS should include a direct electrical link between the pilot and an electronic fuel controller. The EPCS should perform the folling functions:

- Thrust Rating Command
- Engine limiting
- Multi-Engine Management
- Engine Health Monitoring

The YC-14 is a good EPCS test bed for several reasons:

- It's a multi-engine airplane with current technology engines (CF6-50D). Because the CF6 and its derivatives will see many more years of transport application, the results of this research should be of general interest.
- The YC-14 is well suited for flight control system-propulsion system integration. The airplane has a triplex digital control system and dual auto throttle system.
- The YC-14's operational envelope (Mach No, Ve, altitude) is representative of current transport requirements.

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3.2.1.2 TECHNOLOGY NEEDS

The specific areas of technology which should be pursued for digital electronic engine control will be briefly stated below. Each of these is presently being pursued to some extent by either industry or the government.

1) Sensors for the aero-thermodynamic process which have electrical outputs suitable for a digital system.

2) Actuators which will be electrically actuated.

3) Reliable controller software.

4) Control algorithms which will accomodate sensor actuator failures.

5) Hardware/software computing systems as fault-tolerant controllers.

6) Better definition of the integration needs between the flight control and propulsion system.

7) Control methodologies for multivariable nonlinear systems.

8) Electronic circuit configurations designed for operation in extremely severe enviroments.

As each of the above technologies gains maturity, the potential reliability of engine-mounted controls will increase. It is only a higher level of reliability which will enable digital controls to take on the critical task of complete control (full-authority) of aircraft turbine engines.

3.2.1.3 ENGINE SENSORS AND ACTUATORS

Sensor and actuator technologies associated with advanced turbofan engines (both low-pass and hi-pass configurations) need further R&D. AFAPL is developing comprehensive methodologies for controls and data processing technologies which can be used effectively for future engines such as variable cycle engines. These control methodologies will be limited only by the availabity of appropriate hardware.

3.2.1.4 INLET/AUGMENTOR REGULATION

Advanced control methodologies for integrated inlet and/or augmentor regulation also need further R&D. NASA Lewis is primarily responsible for pursuing this research now.

3.2.1.5 MICROPROCESSOR TECHNOLOGY

The U.S. Navy and U.S. Air Force are currently supporting developments for applying microprocessor technology to engine controls. The use of GaAs technology discussed in Section 7 is a promising technology for engine controls because of its high temperature characteristics. GaAs continues to operate at temperatures in the regime of 300-400 degrees C. Si technology is limited to 100 degrees C or more. Sample quantities of GaAs MSI and LSI IC's are projected to be available in the next two to three years.

3.2.2 FULL AUTHORITY DIGITAL PROPULSION CONTROL

Increased system requirements and functional integration with the aircraft have placed an increased demand on control system capability and reliability. To provide these at an affordable cost and weight and because of the rapid advances in electronic technology, hydromechanical systems are being phased out in favor of digital electronic systems. The transition is expected to be orderly from electronic trimming of hydromechanical controls to full authority digital electronic control.

Future propulsion system controls will be highly reliable full authority digital electronics with selected component and circuit redundancy to provide the required safety and reliability. Redundancy may include a complete backup control of a different technology for single engine applications. The propulsion control will be required to communicate rapidly with the various flight and fire control avionics as part of an integrated control concept.

Development of the technology for advanced control systems will continue to evolve in the on-going progression from hydromechanical controls to prime reliable digital electronic control systems for advanced aircraft in the late 1980s and 1990s. Part of this technology progression has already taken place with programs supported by government and industry. Two such programs have been the Full Authority Digital Electronic Control (FADEC) program and the Integrated Propulsion Control System (IPCS) program. The FADEC program will engine test advanced technology control hardware. The IPCS program has developed and tested an integrated inlet/engine/nozzle integration concept in the F-111 aircraft.A planned NASA program, Propulsion Flight Integration Technology, will develop a dedicated F-15 flight test vehicle for integrated aircraft/propulsion control research.

An early step at P&WA was the use of a limited authority supervisory digital electronic control and a full function hydromechanical control unit for the F100 engine. This combination allowed the realization of some of the benefits of digital electronic controls while maintaining the proven reliability of the hydromechanical control. This same kind of supervisory system is currently being developed for our advanced JT9D and JT10D commercial engines. A full function hydromechanical unit is included in these control systems to provide the confidence necessary to introduce digital electronic controls into commercial service.

Several research and development programs are being conducted at P&WA to evaluate the reliability of full authority digital electronic systems when subjected to the environment of JT8D and JT9D engines. For mid term transport applications, a dual channel approach is being evaluated to provide acceptable system failure accomodation. A single channel full authority digital electronic control in combination with a limited capability hydromechanical backup control is being developed for advanced F100 engines. A full authority digital electronic control was also tested for an integrated inlet/engine/nozzle system in an F-111 aircraft under the Integrated Propulsion Control System (IPCS) program.

Further development of electronic control technology is being conducted under the Navy Full Authority Digital Electronic Control (FADEC) program. The P&WA FADEC design features two processors in one box, selected redundancy, parameter synthesis, and built-in-test to provide a high degree of fault tolerance. Advanced component technology used in the P&WA FADEC design is based upon projections for production of a control system in the mid-1980 time frame. For example, both central processors will be implemented with three very large scale integration (VSLI), silicon-on-sapphire (SOS) complementary metal-oxide semiconductor (CMOS) devices. This design will represent a significant technology improvement over an existing 11 chip LSI CMOS processor design, and indicates the rapid trend toward greater packaging density, higher reliability, and improved computational capability. Further advances are required to accomplish the transition to a full authority digital electronic control system in a single channel configuration without the need of a backup control for multi-engine aircraft. Presently at P&WA, a conceptual control study is being conducted under NASA's Energy Efficient Engine (EEE) program for a single channel system. This program will identify control technology areas requiring development. It would be beneficial to the advancement of propulsion system control technology for NASA to support programs in these areas.

It is important to continue technology development for all components of the complete propulsion control system to make possible the optimization of performance, weight, cost, reliability, maintainability and other operating benefits. Important hardware considerations include the advanced output interfaces, advanced sensors, control system environment, integration, and electronic and component reliability. Some hardware examples of technology areas that need to be pursued follow.

Further research is required on advanced output interface devices which can be incorporated into actuation systems to provide interfaces that are more compatible with digital computers. An example of such an interface is the pulse-width modulated solenoid, developed for a fuel metering valve under the NASA Digital Output Interface (DOI) program. New sensing devices for propulsion system parameters should be developed that are compatible with digital controls and will reduce the input interface hardware requirements.

Optical communication has been proven feasible and cost effective for aircraft use by the ALOFT study and demonstration program. Presuming that immunity from electromagnetic interference is necessary, optical data links that are suitable for use in the engine environment must be developed. Also, alternate interface configurations such as multiplexing of feedback signals to the control unit and locating power switching elements away from the computer control unit need to be pursued.

Electronic component reliability is adversely affected by increasing temperatures. Therefore, it is necessary to provide cooling to the digital electronic control unit. For engine mounted control systems, this cooling may be provided by flowing fuel through passageways in the control unit. This approach may not be adequate at the elevated ambient and fuel temperatures encountered during supersonic flight. Therefore, research into alternate cooling approaches could be conducted. Also the use of GaAs technology may alleviate the electronic temperature problem.

System integration of the propulsion and airframe would benefit from cooperative programs in which airframe and engine manufacturers consider:

1) Supplying data from the aircraft central air data computer to the propulsion system controls;
2) Supplying electrical and hydraulic power with acceptable characteristics from the aircraft power systems to the propulsion system controls;
3) Configuring the control system and intersystem communication links to accomodate such problems as lightning strikes, EMI, and common mode failures; and
4) Design of the control system to minimize damage resulting from engine fires.

A single channel digital control with selective component and circuit redundancy will result in a system of minimum cost and complexity, but requires considerable substantiation to ensure that acceptable reliability levels will be obtained without the use of a dual channel or backup control configuration. Technology advances are therefore required in the area of digital electronic components to provide continuing improvement in system reliability. Design studies are also required to determine how to utilize advanced technology components and features such as selective redundancy and fault tolerance logic to optimize the control systems reliability.

Software development areas include propulsion and flight controls integration and the application of advanced control methods. Because of the flexibility and logic programming capability of full authority digital electronic controls, a number of sophisticated control functions can be incorporated which will promote efficient propulsion system operation, and reduce fuel consumption. For advanced supersonic transport and fighter aircraft applications, further technology development is required in the area of integrated aircraft/inlet/engine/nozzle control modes. More sophisticated control algorithms should be investigated to improve logic capability of a digital control instead of just implementing control algorithns developed from classical control theory. Technology development would also be desirable for performance seeking controls and integration with Engine Condition Monitoring functions. Performance seeking logic can be implemented on-line to provide improvements in propulsion system and aircraft system performance through optimization of control variable settings. The software capability of the propulsion control can be used to provide data to an engine condition monitor which analyzes the mechanical health and component efficiency of the engine to provide early identification and prevention of problems, thereby reducing operating and maintenance costs.

3.2.3 TURBINE INLET GAS TEMPERATURE CONTROL

Advanced propulsion systems operate at, or near, design limits with tight control of speed, pressure, temperature, and airflow to achieve maximum performance while maintaining engine durability. An accurate and reliable control system is required to ensure needed engine performance and operational stability throughout the flight envelope. The control system must sense pilot commands, airframe inputs, and critical engine parameters. It must then compute the necessary actions and actuate system variables for total engine control over the full range of criteria. Although these criteria differ for different propulsion systems, engine protection is usually on top of the list, and temperature is on the top of the protection list. The actual temperatures that must be maintained within the limits to protect the engine are compressor discharge temperature and turbine inlet temperature. These limits are based on maximum allowable metal temperatures and the fact that turbine cooling effectiveness decreases rapidly at high Mach numbers.

Current controls generally limit turbine inlet gas temperature indirectly by measuring a nearby temperature and utilizing other measurable parameters to synthesize turbine inlet gas temperature. These methods tend to be slower and less accurate than desired for both protection and performance considerations.

Several techniques are being explored for more direct measurement. These include many technologies from improved thermocouples to digital optical pyrometry. Even with a wide range of possibilities, no clear-cut selection has emerged.

In addition to better sensing techniques, improved synthesis techniques should be developed. These techniques need to be rapid, even predictive. Temperature control could also be utilized by performance seeking control modes in future systems.

3.2.4 INLET BUZZ SUPPRESSION

Inlet buzz is a violent propulsion transient that results in large unbalancing external aerodynamic forces and almost always causes engine stall and/or flame-out. Its severity increases with increasing supersonic speed. Fundamentally buzz is caused by a breakdown in the aerodynamic compression process of the inlet which results in an unstable characteristic direct for the flow. The consequence is a violent and cyclic emptying and filling process for the duct. The development of a technology to suppress or prevent inlet buzz (with 100% reliability) would be a particularly important contribution to the safety of supersonic transports and would result in weight reductions for all supersonic aircraft by eliminating structural and other design requirements that must be incorporated to withstand buzz.

Research is needed to improve the basic aerodynamic stability of supersonic inlets. However, it is felt that to completely suppress buzz will require the development of an aerodynamic device such as a 'super shock trap' possibly combined with special inlet control provisions.

Suppression of inlet buzz will be a challenging research program that will involve extensive supersonic wind tunnel tests supported by 'inventive' analyses. It is recommended that the research be directed to the development of a basic technology that is, in general, applicable to all inlets. It is likely that a buzz suppression research program would also contribute to the technology for preventing 'unstarts' for internal compression inlets that provides best performance at speeds above about mach 2.0.

3.2.5 SMOOTH AFTERBURNER TRANSIENTS

Relatively large fan stability margins must be maintained to minimize fan stalls instigated by pressure discontinuities that can occur during augmentor modulation. New fuel management control systems need to be developed to provide smooth augmentor transients. Programs need to be directed toward a wide range of technologies. These include pumps. metering, actuation, sensing, quickfill, injection and distribution.

3.3 INTEGRATED FLIGHT CONTROLS/PROPULSION CONTROLS

Flight Propulsion Control Coupling (FPCC) is part of the trend in advanced aircraft design technology toward more complete interaction and integration of the propulsion system and aircraft controls (Figure 3.3-1) to obtain increased performance. Preliminary studies have been conducted to explore the benefits and design considerations of coupling airframe and propulsion system force producers. From these activities, it was shown that in the design of an advanced aircraft, control of the force production, distribution and management must be addressed collectively, in order to establish the overall weapon system benefits and risks.

In addition to the performance implications of FPCC, there are significant design considerations dealing with the harmonization of the flight control and propulsion (inlet,engine and nozzle) control systems. A FPCC system uses both conventional and nonconventional force producers which are blended to provide the pilot with a manual and/or automatic flight path control capability. Implementation of FPCC approach using fly-by-wire technology appears to be the most practical means for achieving an effective design.

3.3.1 AIRCRAFT CONTROL

Integration of controls for propulsion and flight is expected to significantly reduce pilot workload and enhance flight safety. Coordinated response of both flight and propulsion controls to a single pilot command is desirable for increasing control effectiveness in more demanding flight enviroments. Such blending of flight and propulsion control has potential payoff in several areas, and is an area for R&D.

a) Future Research and Development Areas.

Thrust reversers have been developed for commercial aircraft to reduce landing distance. R&D is required to apply this technology to advanced fighter configurations and to expand this capability to include in-flight operation. In-flight operation will enhance deceleration and acceleration capabilities which, in turn, will improve operational effectiveness.

b) Emerging Concepts.

The entire field of flight and propulsion control coupling is an emerging technology. Preliminary studies indicate several related technologies that offer significant performance payoffs. They are:

- Adjusting engine stall margins as a function of flight regime, to improve engine efficiencies in non-maneuvering steady state flight modes.
- Using engine thrust to augment lift or aerodynamic control moments for extending the aircraft flight envelope and improving performance.
- Using modern digital computers to optimize flight path and

thrust levels for efficient energy management in various mission elements such as climb, cruise, descent and loiter.

c) Recommended Research.

All of these integrated flight and propulsion control technologies require further R&D development. Control laws (analysis and simulation), equipment selection and sizing, aircraft design modification, and ground and flight testing must evolve in an orderly manner to insure realization of projected payoffs and to provide the most efficient transfer of experience to the design of new weapon systems.

NASA's prime objective for integrated propulsion and flight control should be to sponsor concept demonstration programs. Theoretically, the concepts of energy management for aircraft should be significantly enhanced by such control integration. Similarly, landing and take-off functions may be optimized by integrated controls. It should be noted that the payoff for commercial aircraft (transport class) has not yet been identified, except on the DC-10. Here, the fact that a DC-10 may be controlled by the engines (in differential modes) has prevented at least one major aircraft loss, when conventional controls were inoperable. Extensive trade-offs in this area would be of immense value to the FAA, for example.

Two topics of flight/propulsion controls integration recommended for evaluation are speed-path control for minimum fuel burn and configuration management for powered-lift aircraft.

- Speed-Path Control for Minimum Fuel Burn: NASA should investigate the application of speed/path control laws for cruising flight on the backside of the power required curve. This flight condition, which minimizes fuel consumption, is a high pilot workload situation. Control laws designed for STOL landings could be applied to the cruise flight task. This study could be sponsored by either the TCV or EET programs at Langley.

- Configuration Management for Powered-Lift Aircraft: Automatic configuration management (aerodynamic and propulsive control) is probably required for a powered-lift aircraft to reduce the pilot's workload and to preserve performance margins during transition flight maneuvers. Transitioning flight is more difficult for powered-lift vehicles because the pilot has a variety of control devices for changing energy states. The Ames Research Center should be interested in flight management system applications for both the QSRA and XV-15 aircraft.

Weapon system delivery may be enhanced by integrated propulsion and flight controls in two distinct areas. These are (1) bombing, and (2) missile deployment. The A-10 already has such bombing capability for subsonic aircraft. Extensive results for supersonic air-to-ground operation could improve survivability for future aircraft.

The integration of flight controls with propulsion controls should be a principal objective of the AFTI program at Dryden. Unfortunately, the J-85 engine of that aircraft does limit the engine flexibility, but some progress on thrust level/airframe stability and control could be attained.

3.3.2 ENGINE CONTROL

The design of propulsion systems has traditionally been based on the primary objective of maximizing steady state perfomance of the total vehicle. New aircraft designs and technology advancements are giving designers a great range of aerodynamic and propulsive capabilities for interactive/integrated force controls. This requires that the force configuration be visualized in terms of concepts such as force production, force distribution and force management. Force production incorporates aerodynamic propulsive interactive force systems such as in-flight vectored thrust, in-flight reversed thrust, jet flaps and external blow flaps. Force distribution includes advanced concepts such as relaxed static stability, canards and maneuver flaps. Force management includes features such as flight propulsion control, coupling systems, maneuver load control, direct lift control, direct side force control, energy management and energy maneuverability.

The next generation of aircraft should reflect requirements to dynamically blend the control functions of the weapon system for military aircraft. An example would couple flight control, propulsion control and laser tracker control to the weapon fire control with the object being to maximize aiming precision or target range. Performance seeking control actions could be supervised by the mission control system. Algorithms could be selected to maximize range, minimize time to target or maximize flight time. Contributing systems (flight, propulsion, navigation) could optimize performance while simultaneously observing subsystem limits.

Research to define these blended control modes will require cooperative 'team' studies to assure that each subsystem is properly represented and modeled with adequate fidelity. The studies should derive data transmission rates that support the control performance objectives, and will probably indicate that optical data communication is desired for speed and noise immunity.

3.4 ACTIVE CONTROL SYSTEMS

The term active system has been used to describe systems performing a wide variety of control functions. It will be used here to describe only those systems, utilizing force and moment controls, which are not intended to directly influence the flight path of the vehicle. Active control systems, specifically, are those feedback control systems which sense aircraft motion or structural responses and tend to diminish or limit some variable by introducing counteracting control forces or moments. The functions performed by active controls include the augmentation of the inherent aircraft stability, limiting of maneuver loads, alleviation of gust load, augmentation of the stability of flutter or other elastic modes, modification of load spectra to improve fatigue life, and alleviation of flight station and/or cabin motions to improve ride quality. A related term 'control configured vehicles' has been coined to describe aircraft for which the basic configuration is derived to include the use of active control systems. Weight and drag savings resulting from the use of active controls will unquestionably be greater if the compounding and synergistic effects which can be realized in a new design are achieved, compared with the use of an active control system as a 'fix' after the original design is frozen.

Active control systems are not new. In an article on the first 100 years of automatic flight controls, Howard (ref. 26) describes an 1873 experiment in which an unmanned multi-wing glider was fitted with a pair of rotatable 'steering' wings operated differentially by a transverse pendulum to provide stability in the roll axis. In the test of this decaplane, the stabilizing wings appeared to operate as expected, but they were unable to counteract the powerful lateral instability inherent in the aircraft design.

About 26 years ago, a beautifully simple load alleviation and ride quality control system was developed for a DC-3 by Douglas under an Air Force program. A cable, fixed to the wing root, was run out each wing and located off the elastic axis. The far end of these cables moved relative to the local structure to provide deflections proportional to wing bending. These deflections were summed with the pilot's inputs to move the ailerons. As the wing deflected in response to positive maneuver or gust loads, the resulting upward motion of the ailerons reduced the outer wing lift. Flight test results showed significant reductions in loads and improved ride qualities, but with relatively low gains to avoid instability.

NASA's symposium on Advanced Control Technology and Its Potential for Future Transport Aircraft (ref. 27) , in July 1974, included a number of papers on active control systems which covered the state of the art to that point in time. Production applications were described of a ride quality control on the 747, a wing load alleviation system on the C-5A, and a relaxed stability system on the F-16. Numerous other applications on test aircraft, including flutter mode controls, were also covered. Authors of several of the papers addressed technical areas where advancements were needed to facilitate future active control applications but very few considered the economics. Since the use of active controls is in most cases simply an alternative to larger stabilizing surfaces, additional structural weight or higher fuel consumption, their use should be selected on the basis of value exceeding cost. However, the difference between value and cost will generally vary as a function of the degree to which the active control is used, e.g., the degree to which stability is relaxed or the degree to which the flutter speed is reduced below 1.15V sub D. For example, if the active control is not flight critical, the level (and cost) of redundancy may be low, and the cost of dispatch delays may not enter the picture. If the active control is flight-critical, the cost of providing operational and dispatch reliability, in terms of equipment and maintenance, may be relatively high.

A sample of questions which should be addressed in considering the use of an active control system is given in Figure 3.4-1. The answers to a number of these questions are strongly configuration dependent while others are generic; some depend upon whether the aircraft is military or civil; and they all require a measure of sound engineering judgement. The set of plots of values and costs versus the degree to which the active control might be designed, shown in Figure 3.4-2, is intended to depict the answers to these questions for an application of relaxed/augmented stability to a hypothetical configuration. (The ordinate - the degree of relaxed stability - in each of the nine small plots is the CG location.) The net plot at the bottom of this figure indicates that the degree of relaxed stability which should be chosen in this case is somewhat less than the 'limit' shown. The design with this degree of relaxed stability would involve a fail operative/fail safe system wherein the flight envelope might be restricted after the first failure.

The plots of value versus degree will typically be configuration dependent. On the other hand, the cost versus degree plots for data and modeling/analytical techniques are basically generic. Synthesis of the concept and the inflections in the design/verification plots are also generic in the sense that previously developed and validated concept alternatives, particularly concepts or mechanizations which have differing failure rates, can significantly influence these costs or change the degree at which the inflection points occur.

This scenario of the decision process for ACT applications brings into focus those areas where R&D resources can most profitably be invested to reap the potential benefits. In all cases, the R&D effort should have the long-range goal of increasing the ratio of value to cost while achieving the required level of safety. Those areas which are configuration dependent should generally be covered by Independent Research and Development funding by the company involved or by design studies sponsored by the customer, e.g., the Air Force or Navy. Generic areas, with some emphasis on those related to civil application, are candidates for sponsorship by the National Aeronautics and Space Administration. A tabulation of the apparent need and importance of a number of generic areas for various ACT applications is given in Figure 3.4-3. Comments and observations for each of the five listed active control functions are given in the following subsections for the technical areas shown.

3.4.1 RELAXED STABILITY

Flying or handling qualities criteria generally do not recognize that stability or control augmentation systems may be 'full time' and flight-critical or that future aircraft may use back-up controls that include purposely introduced dynamics and not just direct links between the pilot and the control force or moment sources. In such cases, stick-fixed characteristics are meaningless and of no use in setting performance criteria, even for failure conditions. New handling criteria are needed. Criteria are also needed for the effects of turbulence and for failure effects, both with regard to failure rates and allowable degradation after failures. Total failure rates will unquestionably be very low. Economical validation methods, for software as well as hardware performance and failure characteristics, are required.

The data base for relaxed-stability aircraft and stability augmenting systems is generally available for conventional designs. However, even for conventional aircraft, data for large-angle excursions and other nonlinear cases need to be expanded. Stability characteristics and control surface effectiveness associated with laminar flow control, winglets, advanced airfoils, flight in ground effects, and other configuration factors should be added to the data base.

Math modeling and analysis and synthesis techniques are generally well in hand, but the opportunity for developing new concepts for augmenting aircraft stability or control still exists. Simple, highly reliable, and low-cost concept and mechanization developments deserve support. Advancements in maintenance methods are also important to reduce life-cycle costs.

3.4.2 MANEUVER/GUST LOAD ALLEVIATION

Performance criteria are needed by the designer for any particular application but should be developed on an 'ad hoc' basis, not as industry or government standards. Failure criteria, however, should be standardized and would logically include performance limits in their definition. Economical validation methods are required, especially for the low failure rates of flight-critical applications.

The data base for computation of loads and the dynamic effectiveness of aerodynamic controls should be expanded, especially in the transonic range . Static and dynamic control effectiveness for advanced airfoils, laminar flow control, and propulsive lift designs should be added to the data base. Data on the potentials and limitations on 'molding' bending and torsion strengths in composite structures is also needed so the optimum integration of strength and loads , including load control systems, may be achieved.

Modeling techniques and computer programs for the analysis/synthesis of the combined aerodynamic-structure-control system need to be expanded to include more accurate results in the higher frequency dynamic ranges. There is a special need for techniques and programs to handle the problem of synthesizing the structural characteristics of a composite wing in conjunction with synthesizing the load alleviation system.

Considerably more effort is appropriate in developing maneuver and gust load alleviation systems to minimize their cost. With the cost of digital computers going down while their reliability is going up, distributed load alleviation systems, located at the various control surfaces used for alleviation, should be seriously considered. However, alternate concepts and mechanizations, either as the prime system or a highly reliable back-up, should also be supported. The DC-3 system, previously discussed, shows how simple a concept can be if the ultimate in performance is not demanded. Maximum value per dollar is generally the goal, not maximum performance.

3.4.3 FLUTTER MODE CONTROL

As for load alleviation, flutter mode control performance criteria needed by the designer should be the purview of those involved with the specific application. Failure criteria, however, should be standardized. Economical methods, including the possibility of wind tunnel testing of the complete system as used for load alleviation systems (ref. 28), are needed for perfomance validation. Validation techniques are aso needed to prove compliance with failure criteria.

It should not be assumed that flutter mode controls will necessarily be flight-critical. It is likely that the first production applications will be to reduce flutter speeds only to the dive speed, with envelope restrictions being imposed after failures. However, even these applications will require a data base of unsteady aerodynamic, and most likely transonic unsteady aerodynamics, which is not currently available. (It should be noted that the unsteady aerodynamics needed are not simply steady-state oscillatory data unless it can be verified that superposition applies.) Unsteady aerodynamics data are required for advanced airfoils, wings with laminar flow control, or other advanced concepts, since these may be included in the aircraft under consideration.

Modeling techniques for the aerodynamics-structure-control system for flutter mode control applications need to be developed and refined together with analysis/synthesis computer programs. Unfortunately, it is probable that the analysis/synthesis techniques and the concept developments will leap-frog one another for some time. Concepts which use conventional trailing-or leading-edge control surfaces, or combinations of these, may yield to concepts using spoilers, blowing or other techniques, especially when the flutter frequency involved is considerably higher than the low frequencies for which flutter controls have already been demonstrated. Certainly the development of promising concepts should be supported.

3.4.4 FATIGUE LIFE IMPROVEMENT

As indicated by the 'need' and 'Importance' values assigned to this ACT function in Figure 3.4-3, the data base is the prime technology area identified as insufficient.Again, this requirement is primarily affected by the need for data defining the system performance for configurations using advanced aerodynamic and structural technologies. There is also a need to achieve unanimity in criteria.

3.4.5 RIDE QUALITY CONTROL

The value or motivation in applying a ride control system is difficult to define, except in cases where the mission might be jeopardized, such as terrain following. Both performance and failure criteria are needed for ride quality controls, as well as economical means for validating the systems. Data-base needs are similar to those previously mentioned and could extend to relatively high frequencies. It is likely that dedicated surfaces for this ACT function, as used in several prototype and test programs, will continue to be used.

3.4.6 SUMMARY

Active control system use on future aircraft promises to expand. However, the aircraft manufacturers must show these applications to be cost-effective. The availability of sound criteria, economical validation techniques, the necessary data base, appropriate modeling and analysis/synthesis techniques and a variety of sound design concepts from which to choose will reduce the cost of these systems. NASA can contribute significantly to a realization of the benefits of ACT applications by investing R&D resources in these technology areas.

The techology area where the need is greatest is the data base with unsteady aerodynamics and the control effectiveness for advanced airfoils or other drag minimizing concepts deserving prime consideration. In the concept and mechanization area, the normally experienced cycle from simple to complex to less complex could be shortened through NASA's support of the development of generic concepts which are potentially less costly and more reliable.

1. What is the value of applying this ACT system as a function of the degree to which it is used?

2. What is the cost of providing the ACT system, as a function of the degree to which it is used:

From question #1 comes the following subset questions:

A. How much drag can be avoided; what is the value?

B. How much weight can be avoided; what is the value?

C. What are the synergestic values?

From question #2:

A. What data base is needed; what is available; what will it cost to obtain; is there time to obtain it; what are the risks of going with less than "needed"?

B. Are adequate math modeling techniques and computation methods (programs) available; what will it cost to obtain them; is there time to obtain them?

C. Is there otherwise a commitment to fly-by-wire or some other ACT function; if so, what is the added cost of developing the concept for this function; if not, what is the cost of developing the concept; would its use make some additional ACT function economical?

D. What is the cost of producing the detail design, including any software; what is the cost of purchased equipment; what is the manufacturing and installation cost; what are the validation costs?

E. What are the other costs, including maintenance, and dispatch reliability degradation?

Comparing the value from question #1 to the cost from question #2:

To what degree should the subject ACT function be used? Are there any overriding non-technical considerations?

FIGURE 3.4-1 QUESTIONS TO BE ANSWERED WHEN CONSIDERING ACT APPLICATIONS

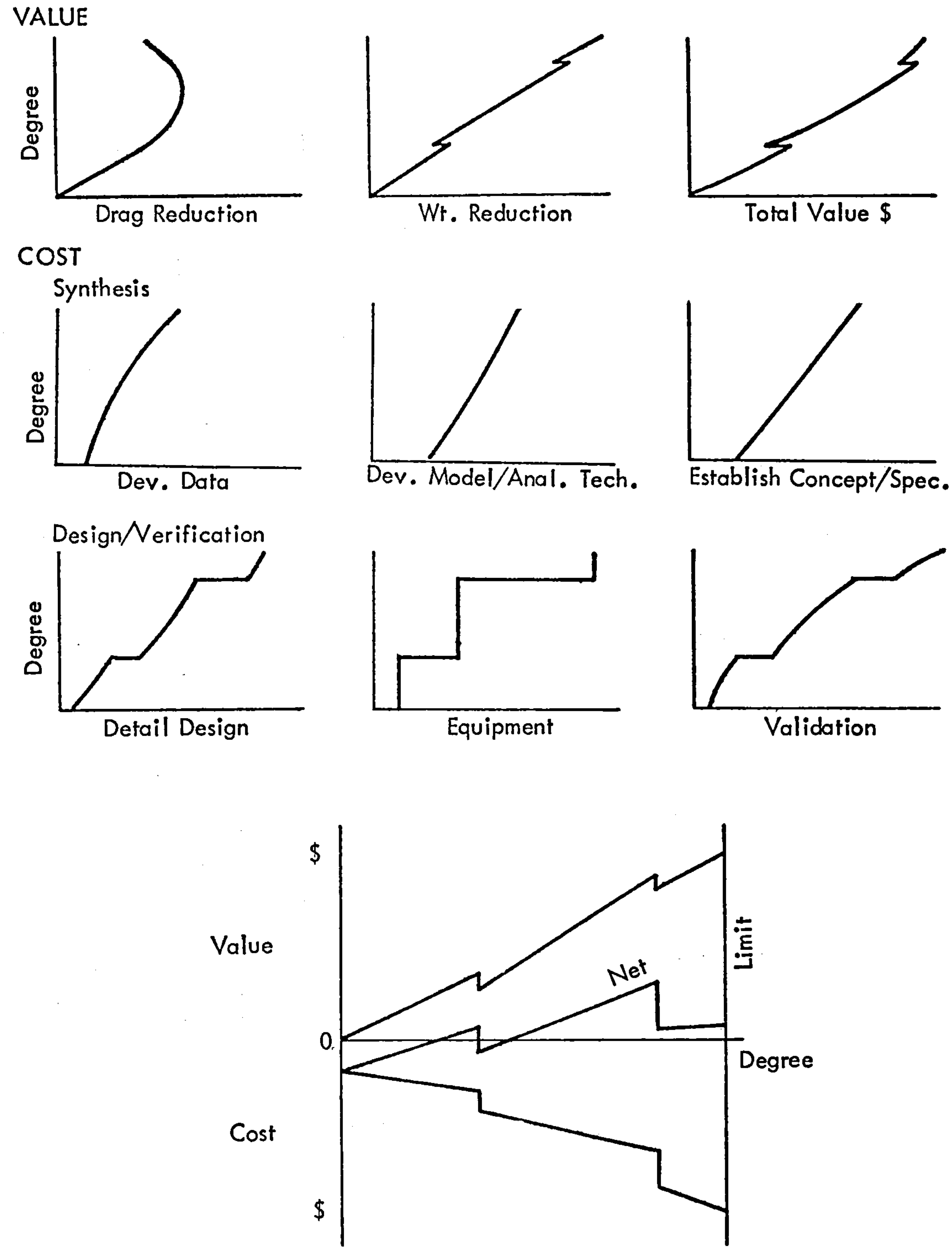


FIGURE 3.4-2 VALUE AND COST VERSUS DEGREE OF APPLICATION

Technology Areas	Relaxed Stability	Maneuver/Gust Load Alleviation	Flutter Mode Control	Fatigue Life Improvement	Ride Quality Control
Criteria	* 2/3	3/3	3/3	2/2	2/1
Validation Techniques	3/3	3/3	3/3	2/2	2/2
Data Base	2/3	3/3	3/3	3/2	2/2
Modeling and Analysis/Synthesis Techniques	1/3	2/3	3/3	2/2	2/2
Concepts and Mechanizations	2/3	2/3	3/3	1/1	2/1

ACTIVE CONTROL FUNCTIONS

* Need/Importance 1 - slight 2 - moderate 3 - great

FIGURE 3.4-3 NEED AND IMPORTANCE OF ACT TECHNOLOGY AREAS

4.0 CREW STATION TECHNOLOGY

The cockpit displays and controls are undergoing a dramatic change as digital avionics bring more functions and modes, but the control panel remains limited. A strong trend is emerging in crew station technology which is pushing toward multi-function, interactive displays to accomodate the increased functions in the limited panel area.

The increased functional load and attendant multitude of modes are causing a potential problem of learning how to operate the systems in an already overly complex cockpit environment. The most promising system solution to the management of cockpit complexity is the introduction of hierarchical, prompting menu selections for the many functions and modes which must be controlled from the limited panel area. This system technology has been studied and refined by many investigators in the field, but requires considerable additional refinement to assure acceptable operation in a busy IFR environment.

A new generation of aircraft will be entering the civil air transportation system in the last decade of the century - new in concept to satisfy stringent noise regulations, to optimize fuel efficiency, and to operate under more severe weather minima. The aircraft will be highly automated, with integrated flight controls, and operate in an advanced air traffic management system (ATMS) in which they will be precisely controlled in space and time, to accomodate the increased air traffic expected. (Ref. 29)

Within the cockpit the pilot's role will expand to include monitoring and managing as well as controlling a more highly automated aircraft, and a more effecient flow of information about the status of the aircraft and its position in space will be needed. A new cockpit interface will be required (Figure 4.0-1), with the necessary controls and displays to allow the pilot to operate efficiently in his expanded role, and to provide the redundancy to manually back up automated flight.

A number of aviation experts recently stressed the need for a new cockpit in testimony before the House subcommittee on transportation, aviation, and weather chaired by Congressman Dale Milford. The purpose of the hearing was to review 'Future needs and Opportunities in the ACT System.'

James E. Gorham, testifying for the AIAA, identified the need for someone, NASA or FAA, to undertake the complete redesign of cockpit displays, integrating as many systems as possible to reduce complexity and save weight. James J. Kramer, Associated Administrator of NASA's Office of Aeronautics and Space Technology, stressed the necessary inclusion of human-factors engineering in the design of the cockpit and proposed the incorporation of advanced electronics to simplify the pilot's task and to improve safety.

The dramatic advances in electronics technology over the past few years that Kramer referred to, coupled with an improved understanding of human factors, provide us with the opportunity to improve greatly the functional range and performance of these future man/machine systems. Further, these advances can provide the basis for designing future cockpit avionics to be more efficient in space, weight, and information and more reliable and economical to own. The field needs a plan, however, to accelerate, coordinate and integrate the proper related technologies.

This section examines the requirements for a new cockpit for the 1990-2000 period, reviews emerging related technology,and describes the benefits of a conceptual cockpit based on projections of this technology. Finally, we believe that a national program is required for the timely development of the design tools for the new cockpit, and we describe such a program.

Cockpit Requirements:

The new cockpit (Figure 4.0-1) should be designed with careful consideration of the requirements placed on the pilot in terms of monitoring complex aircraft systems and in managing aircraft operations. Conventional cockpit design using a large number of electromechanical indicators, switches, and warning devices is simply not adequate. Essential will be a fresh approach using multifunction displays and controls, an intelligent integration of information, and simple and convenient methods for the management of the system. The following are some requirements that the new cockpit needs to satisfy:

- Reduced pilot workload through information integration and greater display flexibility.
- Higher reliability through functional redundancy and more reliable parts.
- Easier pilot interface with aircraft and air-to-traffic-management systems.
- Modular design to increase commonality and to reduce required spare and system down-time.
- System flexibility to accomodate changes efficiently.

The heavy pilot workload in GA aircraft during instrument flight rules (IFR) could also be reduced by improvements in the cockpit; and an initial GA effort is underway in NASA. In addition, new cockpit systems could assist the pilot during such high-workload maneuvers as crop dusting.

Several technology areas will have a major impact on the design of the 1990-2000 cockpit: digital avionics and electronic display devices, already being used effectively in DOD and civil aircraft; simulation and flight experimental studies providing human-factors data; and initial advanced-configuration studies.

Cockpit Subsystem Developments:

Digital avionics have made dramatic progress in recent years, increasingly being applied in aircraft systems. If these trends continue, the 1990- 2000 aircraft will incorporate an 'all digital'

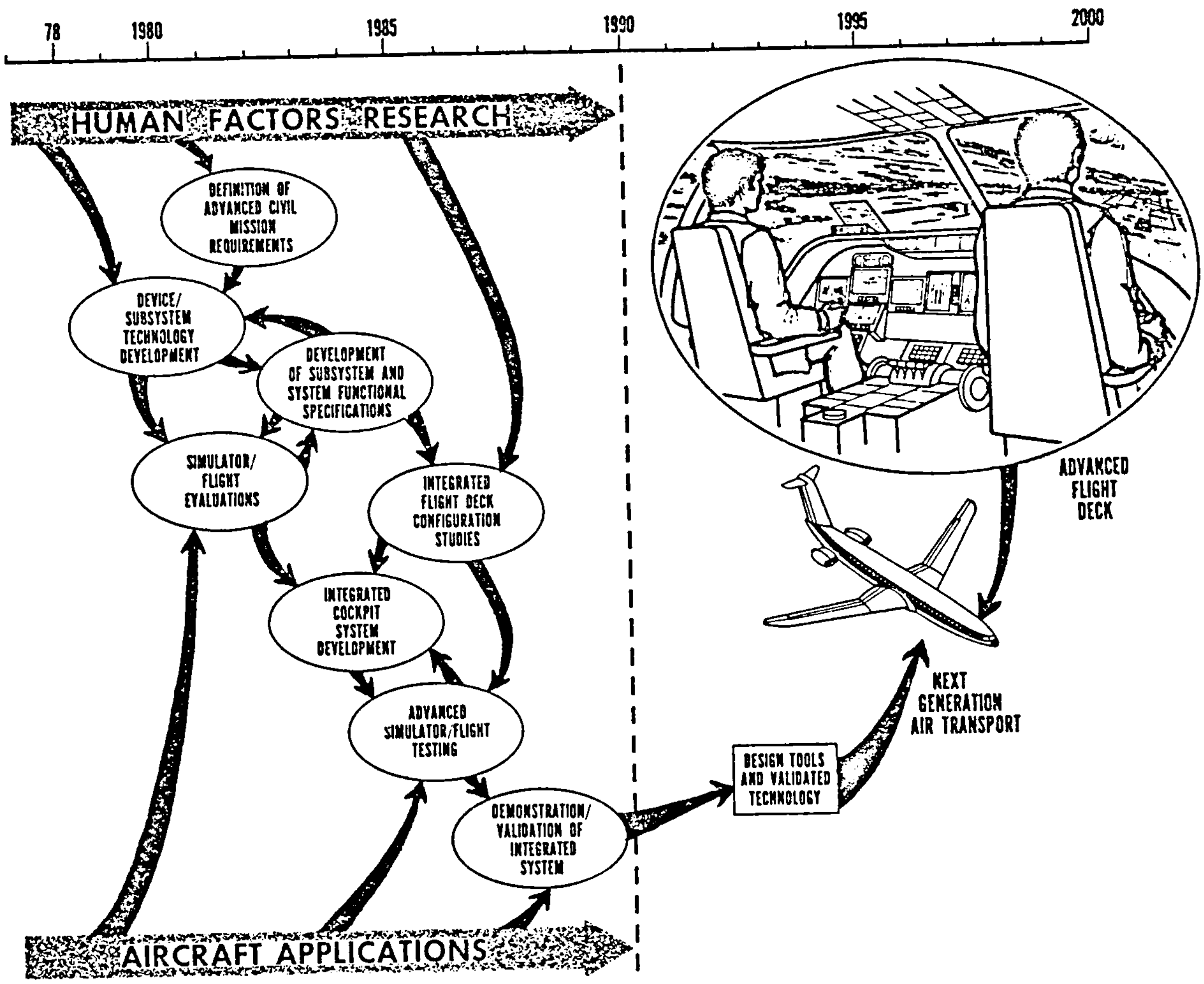


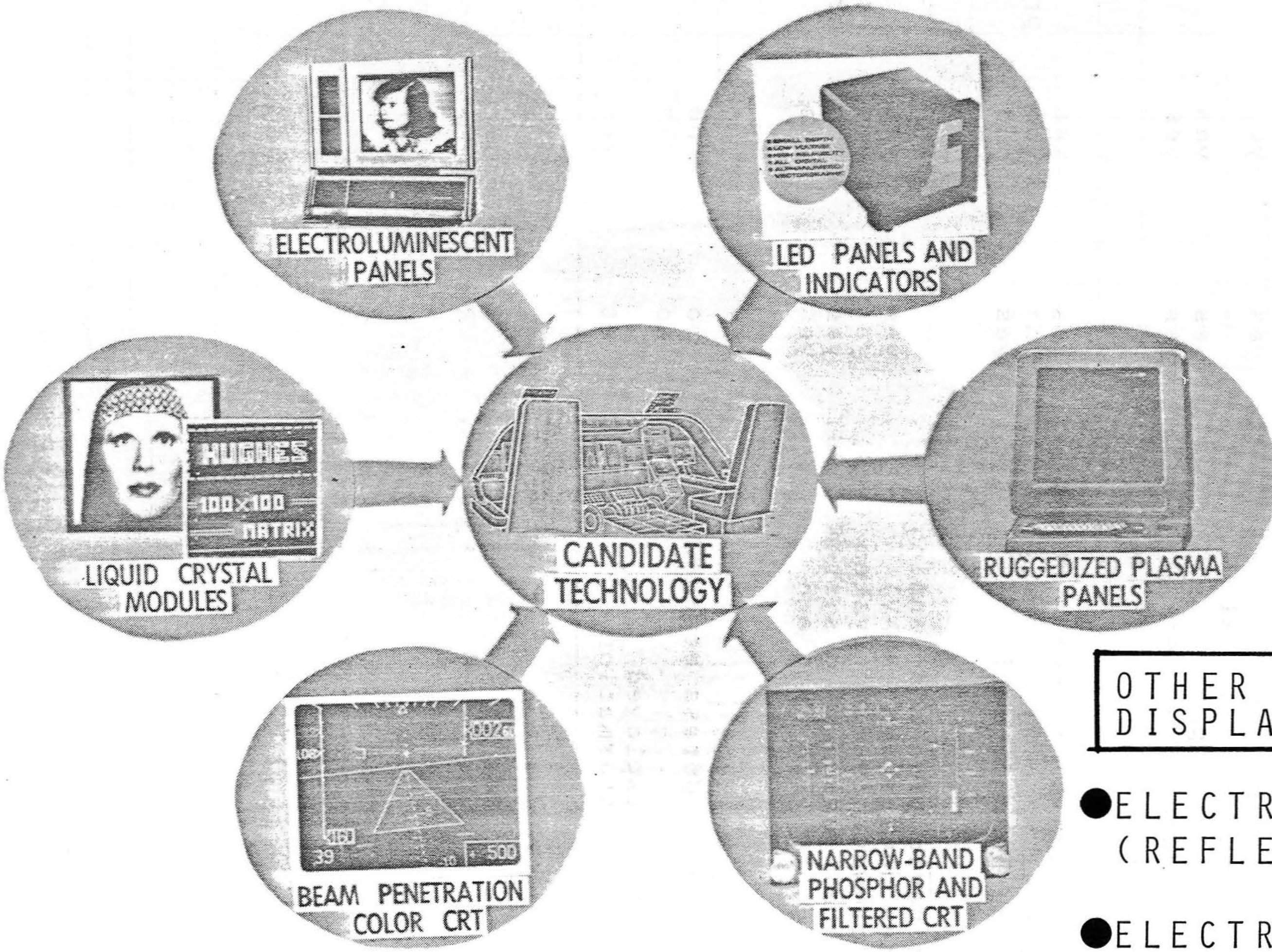
FIGURE 4.0-1 COCKPIT AVIONICS PROGRAM

avionics system making extensive use of large-scale integration electronics and based on a highly reliable, fault-tolerant computer architecture which features distributed microprocessors. The system will use the latest in electrical or electro-optical data bus technology for rapid and flexible communication between subsystems. Figure 4.0-2 shows one possible arrangement of this system. (Also, see the article in this issue on integrated controls.) One study has shown that many of the electronic systems proposed for the ATMS require additional computation, controls, and displays in the cockpit (Table 4.0-1). It was concluded that efficient use of a central computer and common (or integrated) electronic displays may be appropiate. The report stressed that the airlines and government should be very conscious of cost versus benefit in adopting new systems.

Although the basic information requirements in the cockpit are the same for all classes of aircraft, there are differences related to the complexity of the aircraft and its operation. In addition, there are economic considerations, such as initial cost and cost of ownership, that are especially important to the general-aviation fleet.

NASA has several research programs directed at providing new technology for the civil air transport fleet; they are closely coupled to the airlines industry and the FAA and include the Terminal Configured Vehicle (TCV), Aircraft Energy Efficiency (ACEE), STOLAND, and work on helicopters and general aviation (GA) aircraft. Each program is producing requirements for new cockpit design. The clear thrust of the TCV program, for example, is to develop procedures and airborne systems for more efficient terminal-area operations, and a significant part of this program will develop new display formats using an advanced cockpit. Already it provides important early experience with electronic primary flight-control displays and an excellent experimental facility for developing requirements for future cockpit displays.

CANDIDATE DISPLAY TECHNOLOGIES



OTHER EMERGING DISPLAY TECHNOLOGIES

- ELECTROCHROMIC (REFLECTIVE)
- ELECTROPHORETIC
- PLZT (Pb, La, Zr, Ti)

FIGURE 4.0-2

TABLE 4.Ø-1 IMPACT OF FUTURE ELECTRONICS SYSTEMS ON THE COCKPIT

Candidate systems	Significant airborne computation needed?	New cockpit controls needed?	New cockpit display needed?
For better a/c mgmt:			
Electronic attitude-director indicator	yes	yes	yes
Electronic horizontal situation display	yes	yes	yes
Performance computer	yes	yes	yes
For safety:			
Collision-avoidance system	yes	yes	yes
Central warning system	no	no	probably
Wind-shear detection	yes	no	yes
For navigation and landing:			
Area navigation (RNAV)	yes	yes	yes
Microwave landing system (MLS)	yes	yes	maybe
Global positioning system (GPS)	yes	yes	probably
Category IIIA autoland	yes	yes	yes
For better ATC:			
Discrete-address beacon system	no	no	no
Data link	no	yes	yes
Cockpit-displayed traffic information	yes	yes	yes

4.1 DISPLAYS

Progress is being made in many areas of displays technology which can have significant impact on the design, configuration, and performance of civil crew stations of the future. This display technology has the potential to help declutter the cockpit, reduce pilot workload, enhance flight management, and, thereby, improve operational safety and efficiency. In addition, it has the potential to help reduce the size, weight, and life-cycle cost of cockpit avionics through improved display flexibility, reliability, and maintainability. The basic thrust of many efforts in the crew station technology area is to develop the capabilities for computer-based (or microprocessor-based) electronic displays to replace cluttered arrays of electromechanical instruments. Crew station display concepts which are emerging can be categorized as follows:

- Programmable Electronic Multimode Displays

Electronic display systems, used as primary flight indicators, navigational indicators, engine indicators, and systems status and/or warning indicators. These systems can: (1) present information in pictorial and/or abstract formats which can be more readily interpreted by the pilot; (2) time-share the precious display panel space using multimode presentations; and (3) be reprogramed with new formats when aircraft are assigned new missions or as new sensor and data link information becomes available.

- Automated Data Presentation Management

Computer-based displays which present data automatically to the pilot on an as needed (management by exception) basis as determined by mission phases and/or equipment malfunction(s) and yet allow the pilot full access to flight and systems data for control, monitoring, and planning purposes.

- Advanced Input/Output Techniques

Advanced display media, used in a multifunctional switching capacity, or, in the form of voice synthesis and recognition (VSAR) devices, to reduce the number of single-function switches and, consequently, pilot scan pattern and entry errors.

- Display Data Busing Techniques

Electronic and electro-optical techniques appropriate to multiplexing data between the cockpit equipment bay (display generators) and the cockpit instument panel (electronic displays) which can reduce the clutter, size, weight, and number of avionics cables, while at the same time implementing methods for display redundancy management.

- Display-Based Automatic Checkout Concepts

Advanced display media and electronics systems which facilitate cockpit avionics systems checkout and maintenance through compatibility with built-in test equipment (BITE), thus increasing the safety of operation.

- Display Modularity and Redundancy

Modular electronic displays which can be physically and electronically interchanged, with formats being determined through display generator programing or selection from a multiplexed data bus. These devices can provide extensive reversionary capability (in the event of display failure) and greatly reduce the spares complement required for maintenance purposes.

The emerging display technology base, which will be necessary for implementation of the above concepts in future civil crew stations, is a mixture of military, civil, industrial, and commercial technology developments. Specific technology developments include the following areas: (1) electronic display media,such as the CRT and flat-panel matrix-addressed displays; (2) electronic display generation techniques based on microcircuit/ microprocessor and/or host microcomputer technology; (3) integrated display format and device developments, such as the electronic attitude director indicator (EADI) and electronic/electro-optical navigation map indicators; (4) analytical and experimental tools for measurement and prediction of pilot's control/display performance and scanning behaviour; (5) display avionics systems and cockpit display configuration studies. In the sections which follow, these interrelated areas of emerging technology are discussed with regard to the impact that they are presently having and are likely to have on future crew station technologies. In addition, those areas are pointed out in which existing programs (including NASA programs) should be accelerated and in which new NASA programs are needed.

4.1.1 ELECTRONIC DISPLAYS MEDIA

4.1.1.1 CRT TECHNOLOGY

The CRT has dominated the flat surface display for aircraft cockpits to date. There is a strong push to find a flat surface technology to replace the high voltage technology of CRT's with a technology more compatible with low voltage VLSI technology which is being used to drive the displays. The flat surface display technology which is desired to replace the CRT must, of course, compete with the desirable qualities of the CRT display.

The cathode ray tube (CRT) dominates the technology, not only in aeronautical applications, but in industrial and commercial applications. This is because it represents a competent, cost-effective, mature technology (ref. 30). The CRT's origins date back from 1895 to 1910 with landmark discoveries of Wehneit and Braun, and 1935 to 1940 with the first electrostatically deflected CRT's, invented for oscilloscopes and television (ref. 31). Technological progress from 1940 through the early 1960's made possible more sophisticated tubes for oscilloscopes, radar, display consoles, and led to the introduction of shadow-mask tubes for color television. Continued progress through the present has led to the development of: (1) high-resolution shadow-mask color CRT's for industrial applications, (2) high-resolution, high-brightness,ruggedized, monochrome CRT's for aeronautical applications, and (3) high-resolution beam penetration color CRT's for industrial and aeronautical applications.

The CRT has found application as primary display devices in many military aircraft and, to a much lesser extent, in civil aircraft. This device offers a flexible, software reconfigurable unit that can replace most of the electro-mechanical displays currently used in the cockpit. The CRT has a number of advantages over currently competing electronic display media such as (ref. 32):

- Addressability
- Resolution
- Brilliance
- Dynamic Response
- Flexibility
- Accuracy
- Environmental Resistance

The above advantages, in conjunction with the wide application of the CRT in military programs, would indicate that the CRT is the primary candidate for integrated display in crew stations for the 1980's.

The CRT, however, does have certain disadvantages that are leading to research on and development of flat-panel display media for its replacement. These disadvantages are listed in Figure 4.1-1, which also lists some of the advantages of electronic display media, in general, and some of the specific problem areas or disadvantages with present-day flat-panel display media technology. The disadvantages of the CRT include its high voltage requirement, form factor (depth), implosion risk, and (possibly) reliability or mean time between failure (MTBF). This latter area has been the subject of hot debate. Proponents of the CRT point out that it has achieved MTBFs of between 10,000 and 15,000 hours in well designed airborne display systems--14,960 hours MTBF for the CRT type shown in Figure 4.1-1 and used in the DC-10 area navigation system (ref.33)--and that this exceeds the 700 to 800 hours MTBF presently being experienced by electromechanical ADI and HSI instruments by quite a margin. Detractors of the CRT point out that certain military programs have experienced CRT MTBFs of as low as 17 hours and that often CRTs must be replaced long before failure because of the reduction of phosphor brightness as a result of having to drive the tubes at high brightness levels in the high-ambient light environment (as great as 10,000 to 20,000 ft. Candles) encountered in the cockpit. A realistic MTBF for a present-day ruggedized CRT used in an airborne high-ambient light environment is in the 3,000 to 5,000 hours range.

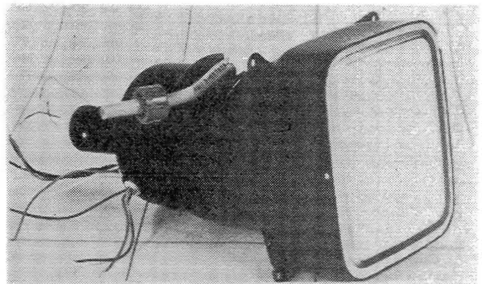
CREW STATION TECHNOLOGIES

Figure 4.1-1 - MOTIVATION FOR DISPLAY MEDIA R and D

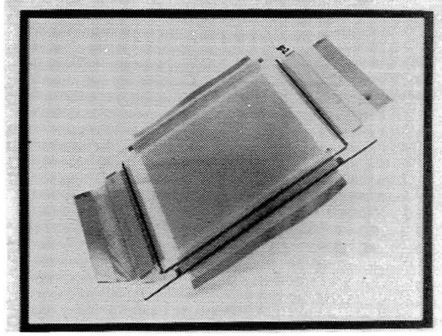
- ELECTRONIC DISPLAY MEDIA SHOWS PROMISE FOR DECLUTTERING
  - INTEGRATION OF CONTROL/DISPLAY INFORMATION
  - MULTIMODE DISPLAY PRESENTATIONS
  - REDUCTION OF PILOT EYE SCAN
  - INTERACTIVE CAPABILITY

- DISADVANTAGES OF PRESENT-DAY ELECTRONIC MEDIA
  - CATHODE RAY TUBE
    - O HIGH VOLTAGE
    - O FORM FACTOR
    - O IMPLOSION RISK
    - O MTBF
  - FLAT PANEL TECHNOLOGIES
    - O LUMINOUS EFFICIENCY
    - O MATRIX ADDRESSING
    - O DUTY CYCLE
    - O UNIFORMITY
    - O COST
    - O COLOR

DC-10 CRT



EL PANEL



- EXTENSIVE R&D NEEDED IN THIS LONG-LEAD-TIME AREA

4.1.1.2 OTHER FLAT PANEL DISPLAY TECHNOLOGIES

Flat-panel technology problems at present include (see Figure 4.1-1): luminous efficiency, matrix addressing complexity, duty cycle driving problems, uniformity, cost, and a lack of color capability (Ref. 34). The first problem area is summarized by Figure 4.1-2 (updated data from Ref. 35), which compares the luminance and luminous efficiency performance of various flat panel display media with that of cathodoluminescent phosphors used for the CRT. The low luminous efficiency indicated leads to problems in the area of display element addressing and duty cycle. For example, in order to increase duty cycle, and thereby brightness of the flat-panel display, it is common practice to address the display a line-at-a-time as opposed to one picture element at a time as is done with the CRT. The major problem in addressing flat-panel vectorgraphic and video displays is addressing the hundreds of thousands of pixels required for a high-resolution presentation. Taking commercial television (TV) as an example, a matrix can be set up of 480 rows by 500 columns. To address any given pixel, a specific row and column must be energized. Thus, the number of addressing lines must be 980 (as compared to 3 for the CRT).

Since flat-panel display technology is in its infancy, the techniques used in their production combined with the small quantities produced have led to costs significantly higher than the CRT. Also, no flat panel display technology (except for the plasma panel using ultra-violet plasmas to in turn excite CRT- type colored phosphors) has demonstrated a color display to date.

The leaders in flat-panel concepts are liquid crystals, electroluminescence, light emitting diodes, and plasma (gas-discharge) panels (see Figure 4.1-3). Of these, only the plasma panel (now available as a military airborne display) has emerged as a product and is being widely used (Ref. 35). Present panel technology has several inherent problems at present that will limit its application in the cockpit: (1) it has a large mask area surrounding the actual display surface; (2) it lacks gray scale capability; and (3) the panel's upper altitude limit is 20,000 ft. above sea level. Thin film electroluminescent panel technology is showing a great deal of promise with defect-free area video and alphanumeric displays having been produced and the latter being available commercially as engineering evaluation units.

While flat-panel matrix-addressed display technology has been developing, CRT technology has not been standing still (see Figure 4.1-3). Recent developments include narrow band phosphors, such as P43 and P44 (Ref. 31) coupled with both a matched bandwidth restrictive filter and two-way attenuation filter to achieve high contrast ratios (10-to-1) under high ambient light conditions (10,000 ft. Candles). Another important development is that of the beam penetration color CRT which uses two phosphor layers (normally red and green) in conjunction with programmed, fast-switching accelerator voltages to produce color-coded displays having 3 to 4 distinct colors, yet with the high-resolution characteristics of a monochrome display. Still another development is that of the high-resolution shadow mask tube color display having approximately 80 phosphor-dot triad/inch, thereby doubling resolution capability.

CREW STATION TECHNOLOGIES

Figure 4.1-2 LUMINANCE AND LUMINOUS EFFICIENCY OF DISPLAY MEDIA

	CHARACTERISTICS		
DISPLAY MEDIA	PEAK LUMINANCE (FOOT LAMBERTS)	MAXIMUM AVERAGE LUMINANCE & 1/500 DUTY CYCLE (FOOT LAMBERTS)	EFFICIENCY (LUMENS/WATT)
PLASMA	7,500	10-15	.05-.5
AC EL	10,000	40	2-3
DC EL	3000-5,000	25-50	0.5-1.0
LED	5,000	5-10	0.5
CATHODO-LUMINESCENT PHOSPHORS (CRT)	>100,000	>500	20

CREW STATION TECHNOLOGIES

Figure 4.1-3 RECENT ADVANCES IN DISPLAY MEDIA TECHNOLOGY

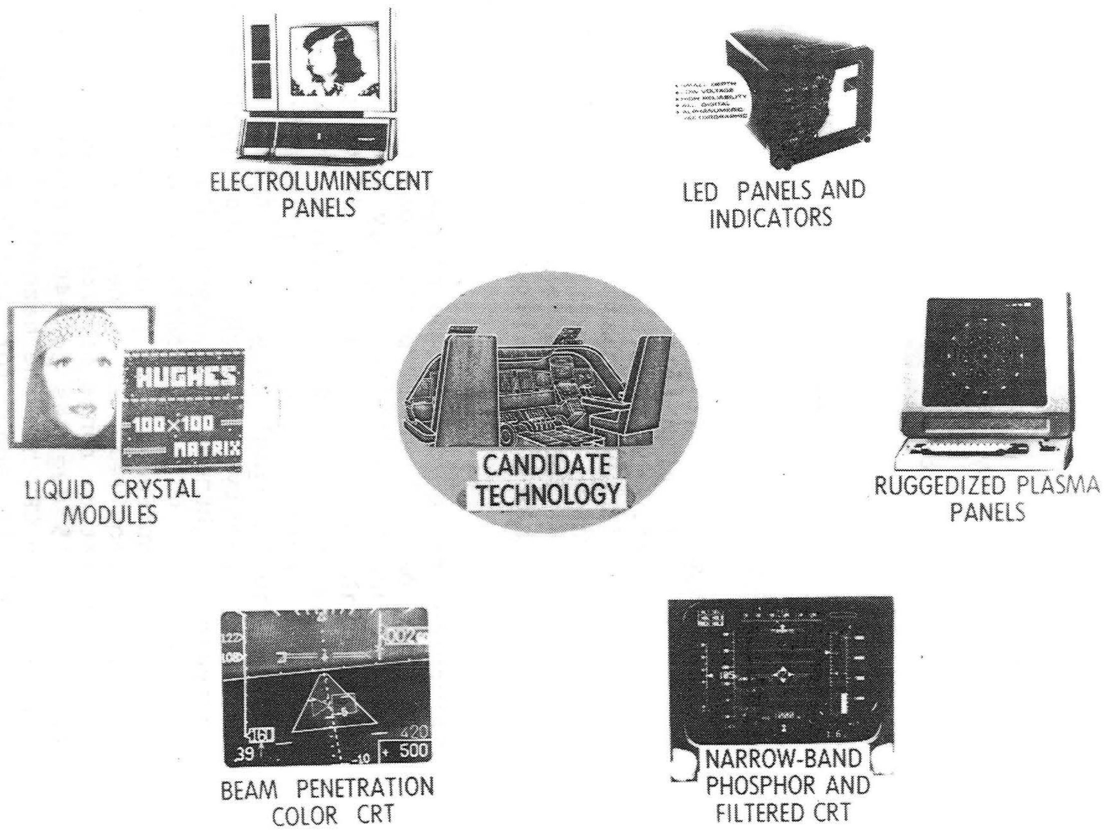


Figure 4.1-4 shows a more detailed comparison of leading display media. Included are the CRT and the two technology areas most likely to replace the CRT, the thin film A.C. electroluminescent (EL) panel and the liquid crystal (LC) panel. The relative strengths and weaknesses of these technologies are identified in the figure. As can be seen, a strong point for both the EL and LC panels is the shallow depth of the panel as compared with the 10-12 in. of depth required for a 10 in. diagonal CRT display. The EL panel is implemented using vacuum deposition technology. Thus, the present panel is not limited by technology but rather by facilities. EL has the potential for relatively inexpensive and uniform production. One approach to LC panel implementation is based on MOS addressing technology being used in the implementation of small display modules which can be interconnected to form large-area displays. The largest module that this technology has produced to date is a 1 3/4 in. module (Ref. 36), but the largest defect-free module that has been produced is a 1 in. module (Ref. 37). NASA has put very limited funding into this approach (interconnect technology R&D) in conjunction with more significant Air Force funding (Air Force Avionics Laboratory). Figure 4.1-5 shows a summary of progress to date on this liquid crystal display effort and Figure 4.1-6 summarizes the basic advantages of liquid-crystal matrix displays. Figure 4.1-7 illustrates the MOS LC display addressing technique. The Air Force Avionics Laboratory is continuing development of this technology with the goal of applying it to airborne head-up display (HUD) (Ref. 38). (See also Figure 4.1-19).

Another approach to implementation of a large-area LC display panel is that of thin film transistor addressing of dynamic scattering LC material (Ref. 39). See also Figure 4.1-19. Here, thin-film transistor addressing is used to overcome the multiplexing limitation of LC material. This effort, supported by the Navy and the Army, has produced a 6 in. x 6 in. alphanumeric/video panel, but the technology at present has a yield problem and has not produced a defect-free panel.

Returning to a discussion of the relative strengths and weaknesses of CRT, EL panels, and LC panels, one can see from Figure 4.1-4 that both the CRT and LC panel technology are strong in the area of contrast under high ambient conditions. (Data provided is for ambient light conditions of 10,000 ft. Candles). The LC technology achieves this high contrast ratio through dynamic scattering rather than emitting of light. The EL panel is weak in this area, but has the potential to improve greatly through appropriate research and development to increase brightness and contrast. In the area of highest operating voltage, the CRT is clearly the poorest in this category with as high as 25 KV required and LC panel technology is clearly the best with only 35 volts required. EL panels have already demonstrated an extremely wide temperature range of from -40 degrees to +100 degrees C as opposed to only +15 degrees to +40 degrees C for LC panels. As indicated earlier, the CRT has the hazards of high voltage and possible implosion as opposed to none for the EL and LC panel technology. Both the CRT and EL panel displays can be viewed from within a cone of vision which is quite wide relative to the perpendicular to the screen. The liquid crystal display viewing angle, however, can be quite small (about 15 degrees in Ref. 37). Although power requirements are not a pressing issue in airborne displays, it can be seen that the EL and LC panels

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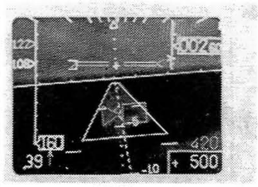
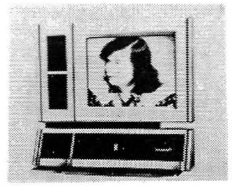
Figure 4.1-4 COMPARISON OF LEADING DISPLAY MEDIA

LEGEND
PROBLEM AREA X
STRENGTH ✓





CHARACTERISTIC	CRT	EL PANEL	LC PANEL
1. SIZE (PIX. DIAG.)	5-10"	6"	X 1"
2. DEPTH	X 10-12" MIN.	✓ ¼"	✓ 3/4"
3. RESOLUTION	100 LINES/"	50 LINES/"	100-500 LINES/"
4. CONTRAST	10:1	X 2:1	✓ 30:1
5. HIGHEST VOLT.	X 25 KV	230V	✓ 35 V
6. TEMP. RANGE	-20°C TO +70°C	✓ -40° TO +100°C	X ±15°C TO +40°C
7. HAZARDS	X HIGH V; IMPLOSION	NONE	NONE
8. SHOCK, VIB.	RUGGEDIZATION REQD.	INHERENTLY RUGGED	INHERENTLY RUGGED
9. VIEWING ANGLE	± 80° ⊥	✓ ± 90° ⊥	X ±15° ⊥
10. POWER REQTS.	5 WATTS/SQ."	0.8 WATT/SQ."	✓ 0.1 WATT/SQ."
11. ADDRESSING	✓ ELECTRON BEAM; B CONNECTIONS	X EL X-Y MATRIX; N+M CONNECTIONS	X X-Y MATRIX; N+M CONNECTIONS
12. ELEMENT SWITCHING	✓ BEAM BOMBARDMENT	✓ THRESHOLD CHARACTERISTICS OF EL	X TFT SWITCHING & THRESHOLD CHARACTERISTICS OF LQ
13. MTBF	3,000 -15,000 HRS.	10,000 HRS. +	10,000 HRS. +

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Figure 4.1-5 PROGRESS IN LIQUID CRYSTAL DISPLAY TECHNOLOGY

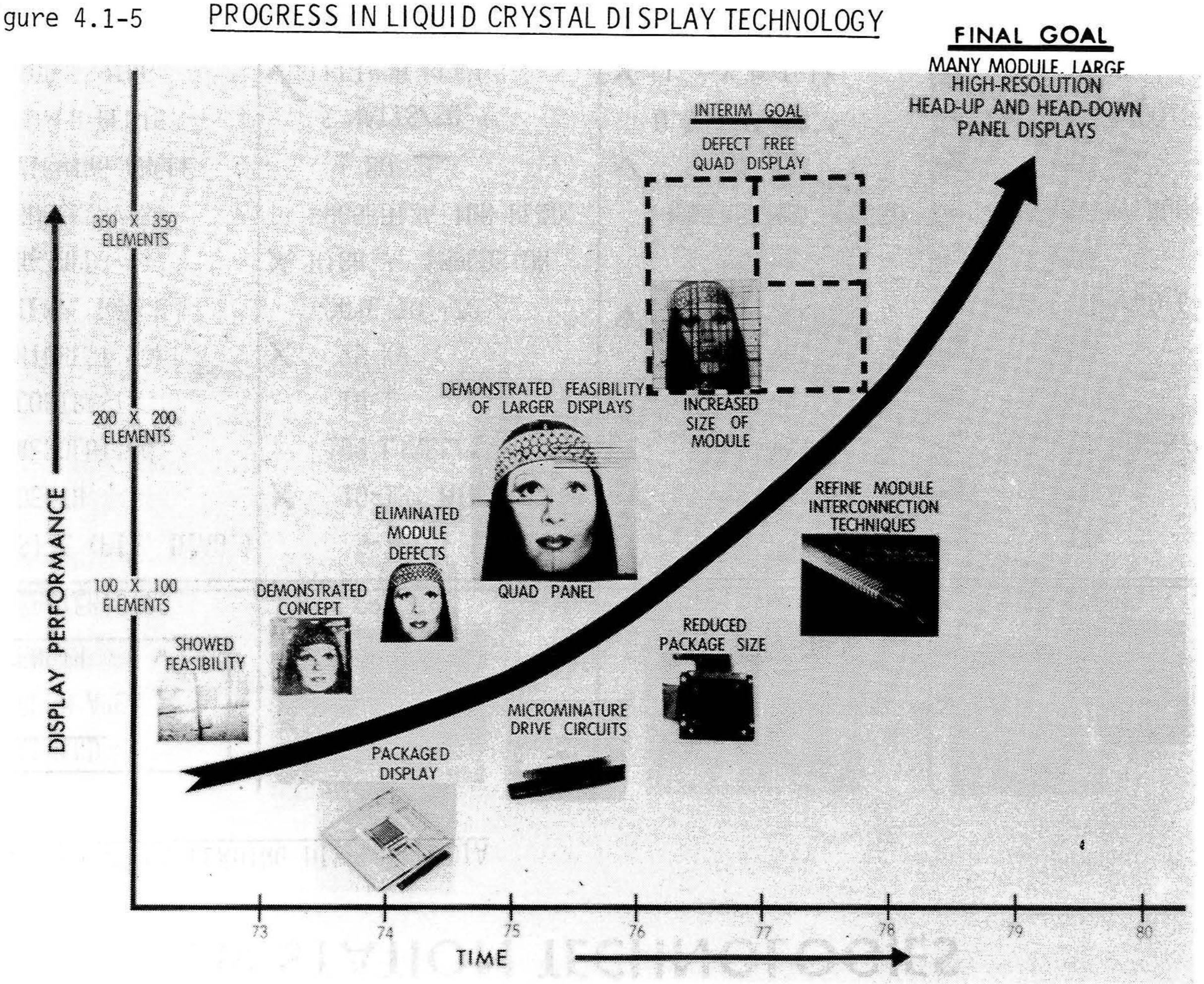
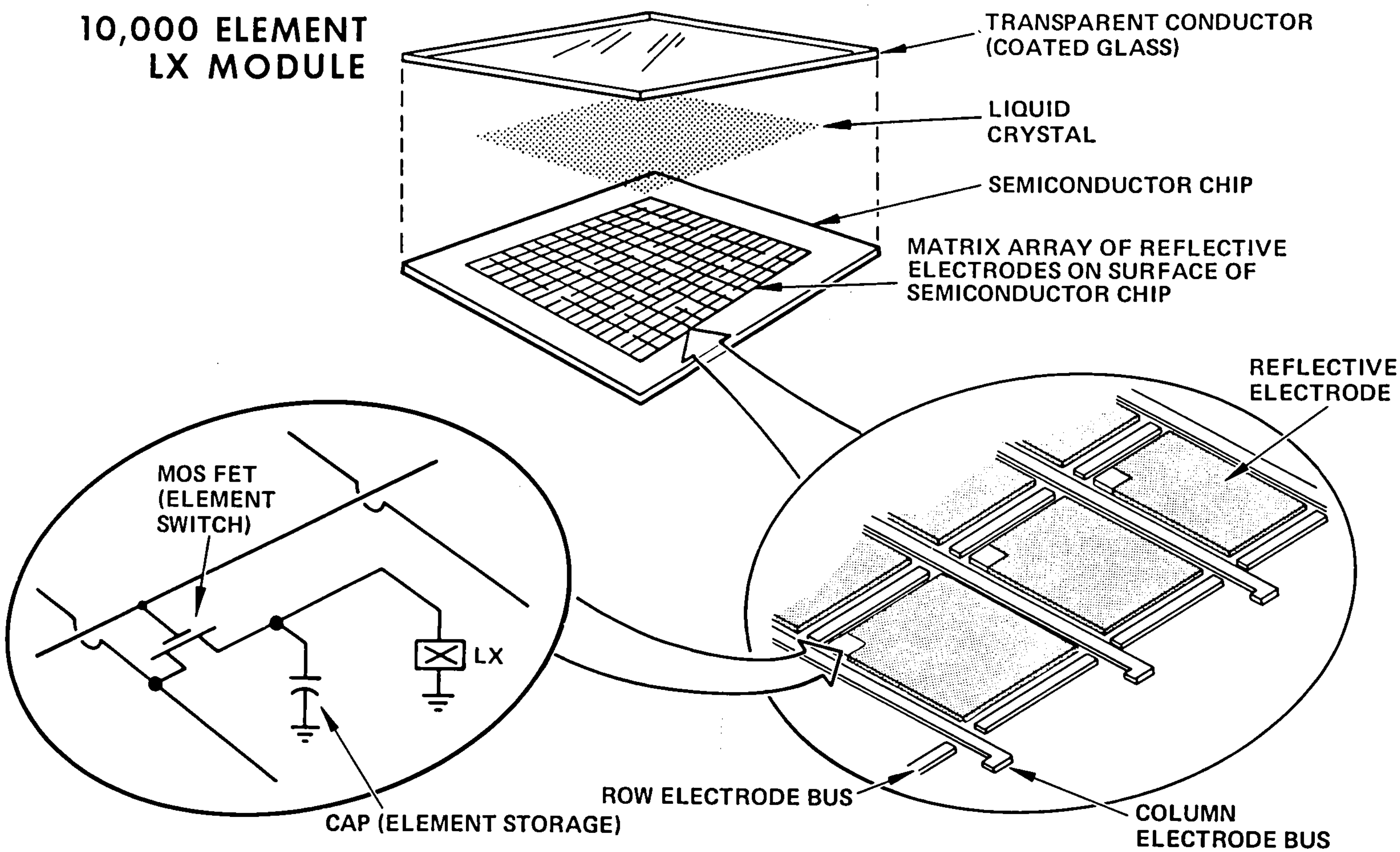


Figure 4.1-6 Summary of Liquid Crystal Display Potential.

CHARACTERISTIC	POTENTIAL PERFORMANCE
CONTRAST	• CONTRAST RATIO OF 40:1 IN DIRECT SUNLIGHT • HIGH CONTRAST IN LARGE AND SMALL AREAS
RESOLUTION	• 100 PIXELS/INCH FOR PANEL DISPLAY • 600 PIXELS/INCH FOR HUD • MECHANICAL REGISTRATION WITH A/C DATUM LINE • UNIFORM FOCUS OVER ENTIRE SCREEN
GREY SCALE	• 8-10 SHADES OF GREY IN DIRECT SUNLIGHT
COLOR	• FUTURE COLOR CAPABILITY USING: - TRICOLORED DOTS OR STRIPES WITH BROADBAND LIGHT - OPTICAL COMBINATION OF SEPARATE R-G-B DISPLAYS - FIELD SEQUENTIAL R-G-B ILLUMINATION
HIGHEST OPERATING VOLTAGE	• NO HIGH VOLTAGE POWER OR DEFLECTION CIRCUITS • 35 VOLTS IS THE HIGHEST VOLTAGE
POWER	• 0.1 WATT/10,000 PIXELS FOR DISPLAY SYSTEM • 0.3 WATT/SQUARE INCH FOR ILLUMINATION
ELECTRICAL INTERFACE	• RASTER SCAN GRAPHIC AND TV COMPATIBLE • MULTIPLE LOW-BANDWIDTH CHANNEL DRIVE CAPABILITY
RELIABILITY	• 20,000 HOURS MTBF ANTICIPATED
WEIGHT, VOLUME	• 0.2 POUND/SQUARE INCH FOR PACKAGED DISPLAY • LESS THAN 3/4-INCH PANEL DEPTH

CREW STATION TECHNOLOGIES

Figure 4.1-7 HUGHES LIQUID CRYSTAL DISPLAY MODULE CONSTRUCTION



are more power efficient. The addressing advantage of the CRT, as well as the addressing disadvantages of flat panels, have been covered previously. In actually turning a display element 'on' to emit or scatter light, several processes are utilized. In the case of the CRT, simple electron beam bombardment is used causing the phosphor light emitting process known as cathodoluminescence to occur. In the case of the EL panel, the most efficient process known is that of applying a variable AC voltage across the thin-film EL cell and utilizing the nonlinear or threshold characteristic of the EL cell to control whether a cell is 'on' or 'off'. Also, the AC EL panel technology provides for control of 'gray scale' or light emission levels using either applied voltage levels or pulse width modulation. Element switching within the LC technology area usually has required thin-film resistor or MOS FET switching in conjunction with capacitor voltage level storage associated with each display element. An example of this type of circuitry is shown in Figure 4.1-7 along with details of construction of a LC display module. The requirement to include an active switch associated with each resolution element of an LC display has led to yield problems in both the thin-film transisand the MOS-FET approach to addressing. One approach, that uses the nonlinearity of threshold characteristic of twisted nematic LC mater(Ref. 40), has led to an essentially defect-free large area display (6 in. Diagonal), however, the response time of the twisted nematic material is several times too slow for dynamic displays.

A comparison summary of most major candidate media for use in airborne displays is shown in Figure 4.1-8. Promising candidates which are not incuded are (1) electrochromic displays; (2) electrophoretic displays; (3) PLZT displays; and (4) flat CRT displays. Of the first three candidates ('solid-state' devices), the most promising technology is electrochromics since they have demonstrated the capability for electronically-controlled color coding and image storage (Ref. 41) and matrix addressing (Ref. 42). Item 4 above, the flat CRT utilizes an area cathode to emit multiple electron beams with scanning controlled by a switching stack. It has made excellent progress and a 6 in. x 8 in. color display was recently demonstrated(Ref. 43). The only problem with technology advances in this area is that they solve only one of the CRT's disadvantages (form factor) and at the expense of requiring hundreds of addressing leads for the digitally addressed switching stack.

As can be seen from the above discussion, the electronic display media area is filled with many promising and exciting candidates for use in future cockpits. It should be realized, however, that the forcing functions for major developments in these areas are the industrial and commercial applications, such as a flat-panel display that can be wall-hung for display. of commercial TV. Sales volumes for these applications can run in the hundreds of thousands or millions of displays. Unfortunately, this is not the case for aircraft applications, where sales volumes are much smaller. It is this factor, combined with the facts that display media R&D is a long-lead-time high-risk technology area and that airborne displays have uniquee requirements, that dictate that NASA should support R&D in this area and should support it strongly. (At present, NASA has a minimal effort in this area). The aspect of the research and development which NASA should support is the orientation and adaptation of display media

Figure 4.1-8 A Comparison of the CRT with Matrix-Addressed Media

ADVANCED DISPLAY MEDIA					
CHARACTER-ISTICS	CRT	PLASMA PANEL	LIQUID CRYSTAL	ELECTRO-LUMINE-SCENCE	LED
Resolution (Lines/Inch)	60-200	60-83	100		
Brightness (Foot Lamberts)	1000-2000	75 (360 W/ Uv Gas/Phos.)	N/A (Reflect.)	60	200-300
Grey Scale (@ 10,000 Ft. Candles Ambient Illumination)	6-8	2	8-10	2	4-6
Conrtast Ratio (@ 10,000 Ft. Candles Ambient Illumination)	12-to-1	1.6-to-1	32-to-1	1.5-to-1	6-to-1
Type Medium	Non-storage	Storage	Non-storage	Non-storage	Non-storage
Highest Oper. Voltage	20-30KV	100v	35V		
Power Consumed (Per Square In. of Pix. Area)	5	2.4	<0.1		>350
Temp. Range (Degrees Cent.)	-20 to +70	0 to +50	+14 to +40		
Color Potential Status	Yes-Beam Pene-tration & Shadow Msk	Yes-Lab. Demo. of Tri-Color Disp	Yes-No Devel. to Date	Yes-Full Color Spectrum Difficult	Yes-
Basic Status of Development	Full Mil Spec., Oper. for 15 Yrs.	Full Mil. Spec., Oper for 2 Yrs.	Under Dev., Feas. of 1"X1" Module Demo.		

advances to the cockpit environment, which includes: (1) viewability under high-ambient lighting conditions of 10,000 to 20,000 ft. Candles; (2) resolution adequate for viewing at 28-30 in. ; (3) gray scale sufficient for intensity encoding; (4) high-speed update and refresh capability; (5) reduction in size, weight, and volume; and (6) color coding capability. To meet these requirements, performance goals as follows should be utilized:

CONTRAST RATIO	:	15-40 to 1
GRAY SHADES	:	8-16
RESOLUTION	:	65-100 lines/inch
UPDATE RATE	:	20-30 frames/sec.
REFRESH RATE	:	60-100 fields/sec.
COLOR CODING	:	5-8 colors

Since it appears that CRT's have been basically adequately developed for use in flight decks of the 1980's, it appears that NASA should put it's major emphasis in the area of flat-panel display technology for the 1990's and beyond.

Since the major investment in flat-panel display media R&D is presently oriented to industrial and consumer applications, this is an area in which NASA should greatly increase R&D investment in order to reorient a portion of the effort toward potential benefits in U.S. aerospace programs. Since civil and military requirements in the area of display media are similar and since the military already has significant R&D efforts going in these areas, NASA should strongly consider joint programs with the military in this fundamental technology area.

4.1.2 ELECTRONIC DISPLAY GENERATION TECHNIQUES

Display generation techniques have evolved over the years in conjunction with CRT technology and, only recently, in conjunction with flat-panel matrix-addressed display media. The function of display generators is to receive parametric and mode information from other aircraft systems, to process this information as required to generate the symbology for displays formats, and to convert the information into addressing and intensity information for use by display units. Two basic display generation techniques have evolved for use in conjunction with CRT media:

- Calligraphic (Stroke Drawing)

This technique evolved from oscilloscope technology. Addressing consists of random-access deflection of the electron beam along the vertical and horizontal CRT screen axes in the exact shape of the symbol to be displayed. Addressing signals consist of two wideband deflection signals and are generated in synchronism with one wide intensity (unblank) signal.

- Raster Scan Graphic

This technique evolved from television technology. The electron beam traces a predetermined pattern (raster),typically, from left-to-right (horizontally) and from top-to-bottom (vertically) on the CRT screen. Symbology is generated by forcing predetermined intensity (video) levels at appropriate horizontal - vertical positions during the raster scan. Addressing and intensity control can therefore be combined into one composite wideband video signal which includes synchronization information to insure that the symbol generator and the display unit operate in synchronism.

Stroke-drawn, raster-scan, and combination graphic display generation techniques, have been and are being used in airborne display applications (refs. 44,45 & 47); however, each has its own advantages and disadvantages. Displays produced by stroke-drawing techniques: (1) are primarily skeletal in nature, (2) have more esthetic symbols than raster-scan techniques (especially for rotated symbology), (3) are difficult to prioritize from an overlapping symbology standpoint, (4) are difficult to mix with raster images, requiring scan conversion or vertical-retrace drawing, (5) can be generated using simpler circuitry than raster-scan techniques, and (6) require power-consuming wideband non-resonant deflection circuitry in the display unit. Stroke-drawn displays are especially suited to HUD applications, since their skeletal characteristics allow the pilot to look 'through' the display at the real-world visual scene. Displays produced by raster-scan techniques: (1) can be of a continuous-tone-photographic nature employing large- and small-area shading and 8 or more shades of gray, (2) have a bolder symbol quality than stroke-drawn techniques, (3) are easiliy prioritized from an overlapping symbology standpoint, (4) are easy to mix with other raster imagery (such as low-light-level TV), (5) require more complex circuitry than stroke-drawing techniques, and (6) use low-power resonant deflection circuitry in the display unit. Raster-scan graphic display techniques are especially suited for head-down vertical situation displays (VSDs) and electronic attitude director indicators (EADIs), since their capability can include sky/ground shading, prioritizing of bolder symbology, and mixing of the symbology with image sensors. Many advanced CRT display systems combine the capability of stroke-drawing and raster-scan graphic generators into systems which can service two CRTs simultaneously (an EADI and an electronic horizontal situation indicator (EHSI)) and in which one of the two CRTs (the EADI) uses both stroke-drawing and raster-scan graphic capability (refs. 44, 45 & 47). The advantages and disadvantages of stroke-drawing and raster-scan graphic techniques are summarized in Figure 4.1-9.

Rapidly advancing microcircuit/microprocessor technology is impacting the area of display generation techniques greatly. The technology is making raster-scan graphics more attractive, even though more complex circuitry is required than with stroke-drawing techniques. This is because the size and cost of the circuitry, including display refresh memory has been dropping rapidly. Many of the advantages of raster-scan graphics for use with the CRT have already been mentioned. Additional advantages are: (1) that this technology has demonstrated the ability to generate extremely realistic synthetic visual scenes (ref. 48); and this may prove very important in the generation of displays for low visibility landing (already such technology is being used for training simulator visual scene displays) (ref. 49); and (2) it provides for ease of mixing display symbology with the outputs of imaging sensors such as radar, low-light-level TV (LLLTV) and forward-looking IR (FLIR), which are candidate sensors for aiding in low-visibility and/or nighttime landing situations.

Raster-scan graphics are also showing advantages for use with some flat-panel display media. They offer an organized method for addressing flat-panel displays in the line-at-a-time method required for adequate brightness and one which is suitable for driving the panel through one multiplexed coax cable. Display generation methods other than raster-scan and stroke-drawn (random addressing) graphics may be more suitable for driving flat-panel display media and should be the subject of further research.

Again, in the field of display generation techniques, the majority of the recent advancements have been in the area of displays for industrial and commercial applications. Flexibility and programmability in symbology and display format have been achieved through microprocessor-based and/or minicomputer-based display generation techniques. Extensive use of LSI circuitry has been incorporated in symbol generators, especially for the mass consumer market area of TV (raster-scan) gains for the commercial or home market and for the industrial raster-scan display market (ref. 50) of displays for process control, business computation, and information display such as airline schedule listing.

Display generation developments for the commercial and industrial markets generally lack two characteristics necessary for cockpit application - high-speed update rate and high-resolution capability. Yet, unfortunately for aerospace applications, commercial applications constitute the lion's share of recent developments. Notable exceptions to this are display generator advancements such as those by Sperry Flight Systems, Hughes Aircraft Company, and Bendix Thompson CSF.

gure 4.1-9 A Comparison of Stroke-Drawn and Raster-Scan Graphic Techniques

ADVANTAGES AND DISADVANTAGES FOR DISPLAY GENERATION				
CHARACTER-ISTICS	STROKE-DRAWN		RASTER-SCAN	
	Advantages	Disadvantages	Advantages	Disadvantages
Display Format	Skeletal- Good for HUD Applications	Can Become Cluttered	Shaded or Skel-etal- Good for VSD Application	Stairstep of Near-Horiz./ Vert. Lines
Display Grey Scale	None	Limited to Sev-eral Intensity Levels	Large- & Small-Area Shading; 8 or More Shades Grey	Not Good for HUD Applications
Symbol Clarity	More Esthetic Appearance on Rotated Symbols	Large Symbols Not Bold	Boldness of Symbology	Lack of Clarity on Rotated Symbols
Symbol Priority	None	Difficult to Prioritize Overlaping Symbology	Symbols Easy to Prioritize and Grey-Scale-Encode	None
Display Color	Compatible With Beam Penetration CRTs	Colors Limited-Red, Yellow, Orange, & Green	Full Color; Compatible With Dot-Matrix & Vert.-Grill CRT	Resolution and Environ-mental Capa-bility of CRT
Image Sensor Mixing	None	Reqs. Scan Conversion or Vertical-Retr. Drawing	Simple Video Mixing With Raster-Image Displays	Small-Area Flicker Unless High Frame Rates Used
Generator Complexity	Reqs. Less Complex Circuitry	Analog and D-to-A Circuitry Reqd.	Circuitry Being Implemented in LSI	Reqs. More Complex Circuitry
Display Hardware Character-istics		Wideband Non-resonant De-flection Cir-cuits Reqd. (Higher Power Higher Cost)	Resonant De-flection Cir-cuits Reqd. (Less Power, Less Cost)	
Output Signal Character-istics		3 Wideband Signals Reqd.; Not Easily Multiplexed	1 Wideband Signal Reqd.; Easily Multiplexed	
Flat Panel Adapt-ability	Compat. With Random Addressing	Scan Conversion Reqd. for Ele-memt or Line Seq. Addressing	Suitable for Element or Line Seq. Addressing	Not Compat. With Random Addressing

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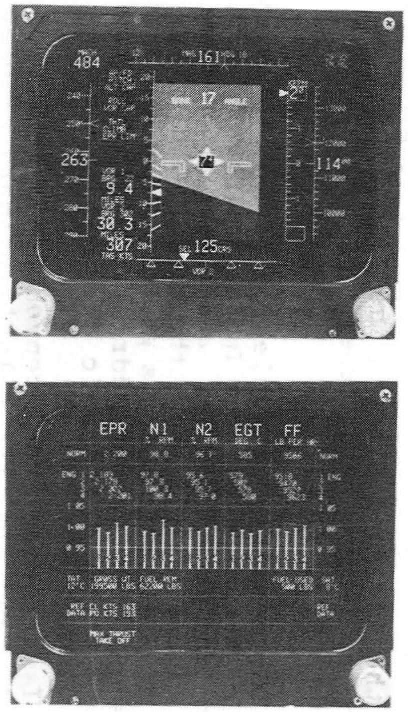
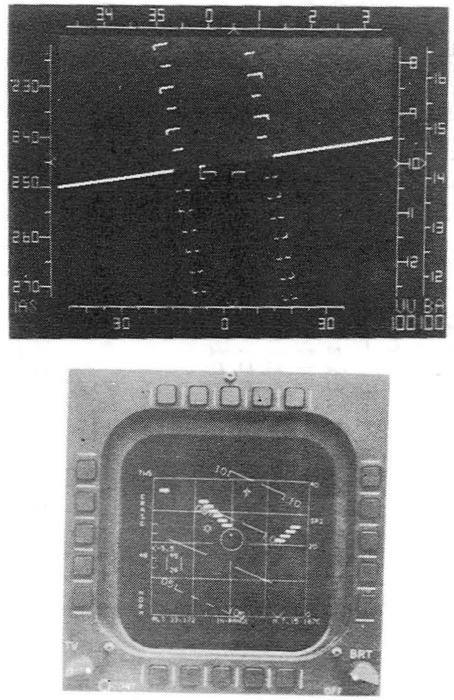
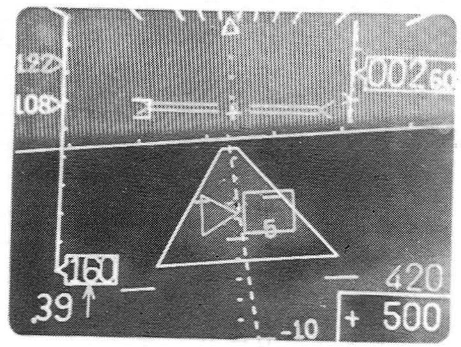
Figure 4.1-10 ADVANCED FLIGHT DISPLAY GENERATION CAPABILITY



SPERRY - RASTER / STROKE



HUGHES - RASTER / STROKE



THOMPSON CSF / BENDIX - STROKE

Displays produced by these programmable symbol generators are shown in figure 4.1-10. All of these display generators are programmable and are based on microprocessors for stored program control and display generation. The Sperry system is a simulator display system and is unique in its approach to raster-scan graphic display generation in that it requires a minimum of display refresh memory and utilizes high-speed update and refresh rates that result in a display that is completely flicker-free, both from a small-area and a large-area basis. The Hughes and Bendix/Thompson CSF systems are both airborne quality systems. The former is based on the AN/UKY 30 military microprocesser and is being used in the Air Force Digital Avionics Information Systems (DAIS) program (to be discussed later). The latter is used in the generation of stroke-drawn beam penetration color displays, but to date has not been incorporated in major research programs in the U.S.

It is recommended that NASA should support R&D in the display generation technology area so that techniques which are matched to evolving advanced display media, such as flat-panel displays, can be developed and so that rapidly developing microcircuit/microprocessor technology can be incorporated to the fullest extent to meet unique aerospace display requirements including generation of flight displays with the following characteristics: (1) high-speed update and refresh rates for flicker-free displays to be viewed in the high-ambient light environment; (2) resolution commensurate with viewing at 28-30 in. ; (3) 2-D and 3-D pictorial and abstract formats including large-area shading, symbology prioritizing, and color coding as necessary to reduce display clutter; (4) multimode and interactive display capability as necessary to time-share display panel space; and (5) reduction of volume, weight, cost, and power while increasing the reliability and maintainability of display symbology generators.

4.1.3 INTEGRATED DISPLAY FORMAT ADD DEVICE DEVELOPMENT

A number of government and industry research programs are examining the effectiveness of different display devices and formats. One of the more significant in the civil sector, the NASA Terminal Configured Vehicle (TCV) program, uses a Boeing 737 equipped with an experimental flight deck located in the passenger compartment. A feature of this aft flight deck is the Advanced Electronics Display System, ADEDS, originally developed by Boeing and General Electric as part of the DOT/FAA SST technology program,

The ADEDS, a highly flexible research display system, includes an Electronic Attitude Director Indicator (EADI), an Electronic Horizontal Situation Indicator (EHSI), and a Navigation Control and Display Unit (NCDU). Figure 4.1-11 shows the three CRT displays control input units in the TCV aircraft pilot's position. The ADEDS uses a combination of raster-scan and random addressing (stroke-drawn) graphics in the creation of its electronic display formats.

The EADI replaces the conventional electromechanical attitude indicator, and is the pilot's primary display of pitch and roll attitude for instrument flight. Symbology for velocity vector, flight path acceleration, vertical guidance, speed error, and thrust command

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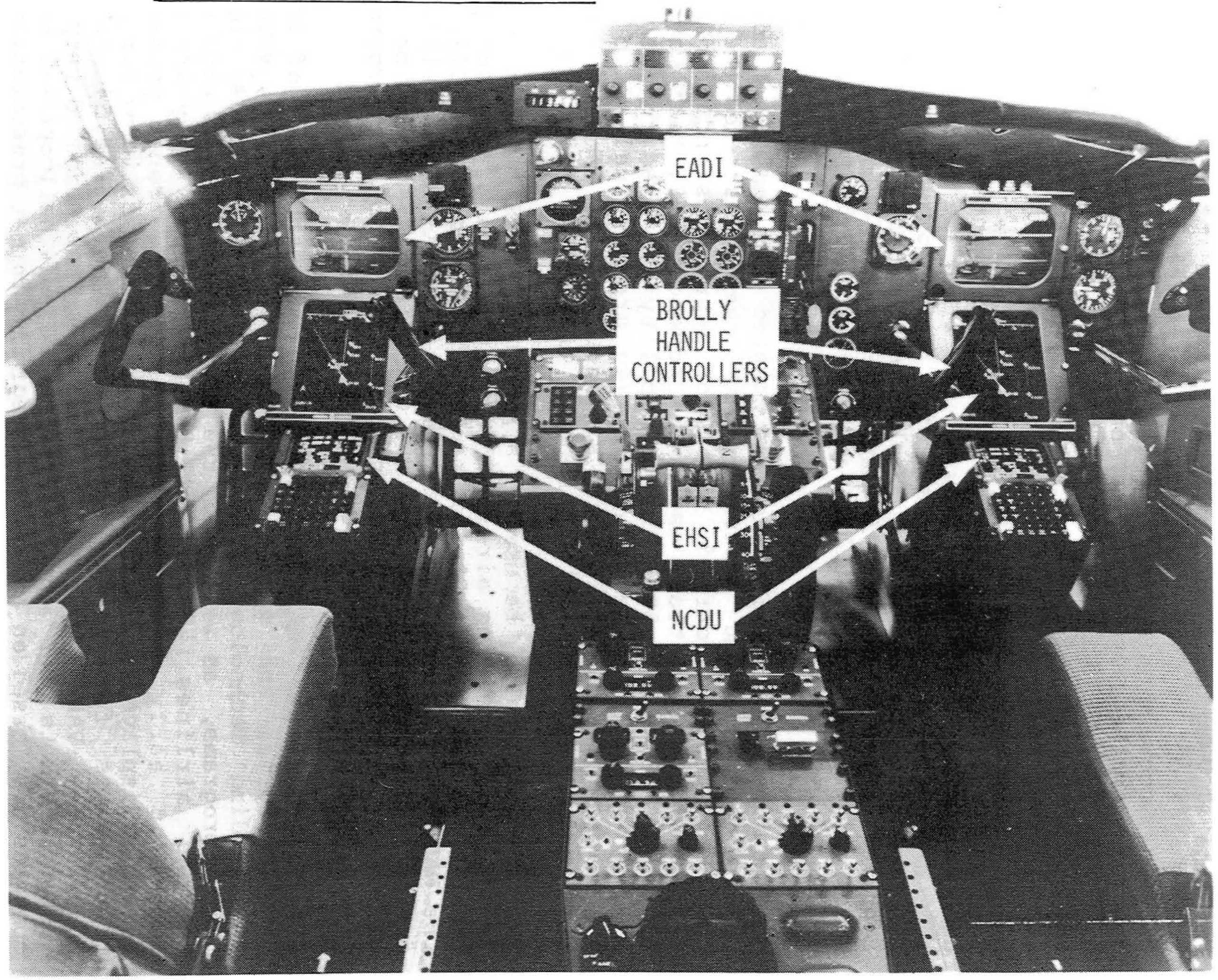
Figure 4.1-11 TERMINAL CONFIGURED VEHICLE(TCV) RESEARCH COCKPIT SHOWING THREE CRT DISPLAYS AND CONTROL INPUTS



are integrated into the display format. At the pilot's option, the EADI symbology can be superimposed on the picture from a forward-looking LLLTV camera. The EHSI, a pictorial navigation display, gives the pilot a plan view of points of interest such as airfields and VORTACS, and displays the desired horizontal flight path by a solid line connecting points. A curved trend vector can be added to display the predicted path over the ground. Figure 4.1-12 shows details of some of the EADI symbology.

For the TCV program there is a ground-based replica of the aft flight deck in which display concepts can be developed before flight. The aft-deck cockpit simulator is a highly efficient research tool. When coupled to the computer, it not only will simulate the flight dynamics of the TCV B-737 aircraft, but also all onboard systems and a computer-generated terminal area with a realistic aircraft mix, thus permitting very realistic experiments.

One study using this unique pair of experimental cockpits involved adding runway symbology (figure 4.1.-12) to the TCV baseline EADI for the approach and landing tasks (ref.51). It showed that the addition of a perspective runway image and relative track information significantly improved pilot performance (Figure 4.1-12) . In October 1977 one of the research pilots sucessfully landed the TCV aircraft from the aft deck using this display.

The combined use of ADEDS formats coupled with the use of advanced TCV onboard guidance and control systems have demonstrated the capability to fly strongly curved, precision approaches and landings under simulated IFR conditions using the advanced U.S. Microwave Landing System (MLS) (ref.52). This capability can lead to many benefits including: (1) noise reduction, (2) greater fuel efficiency, (3) operations during low minima (schedule reliability); (4) reduction in terminal area congestion; and (5) improved safety (ref.53).

The TCV will also be used in a planned FAA/NASA program to study the benefits of providing air-traffic information in the cockpit. This program called Cockpit Display of Traffic Information (CDTI), would use the NASA-Langley-Wallops, NASA-Ames, and FAA-NAFEC facilities; and during flight tests at Wallops the CTDI information would be displayed on the TCV aircraft EHSI. The initial phases of this program will be run primarily on ground-based simulators.

Other significant NASA programs from the standpoint of integrated display format and device development are the STOLAND, VTOL Approach and Landing Technology (VALT), and general aviation (GA) programs. In these programs, as well as in the TCV program, NASA is coupled closely to the airlines industry and the FAA. Already they are providing important early flight experience with electronic primary flight control displays and excellent experimental facilities for developing requirements for future cockpit displays (ref.44,54 and 55). The NASA-Langley VALT program, for example, has produced very promising display formats for approach-to-landing of helicopters. Each of the concepts is based on a two-CRT integrated format presentation in which vertical situation and command/predictive information is presented on an upper CRT while horizontal situation and command/predictive information is presented on a lower CRT. The first concept is shown in

Figure 4.1-12 DETAILED VIEW OF TCV'S ELECTRONIC ATTITUDE DIRECTOR INDICATOR (EADI) WITH PERSPECTIVE RUNWAY AND SUPERIMPOSED TELEVISION SCENE

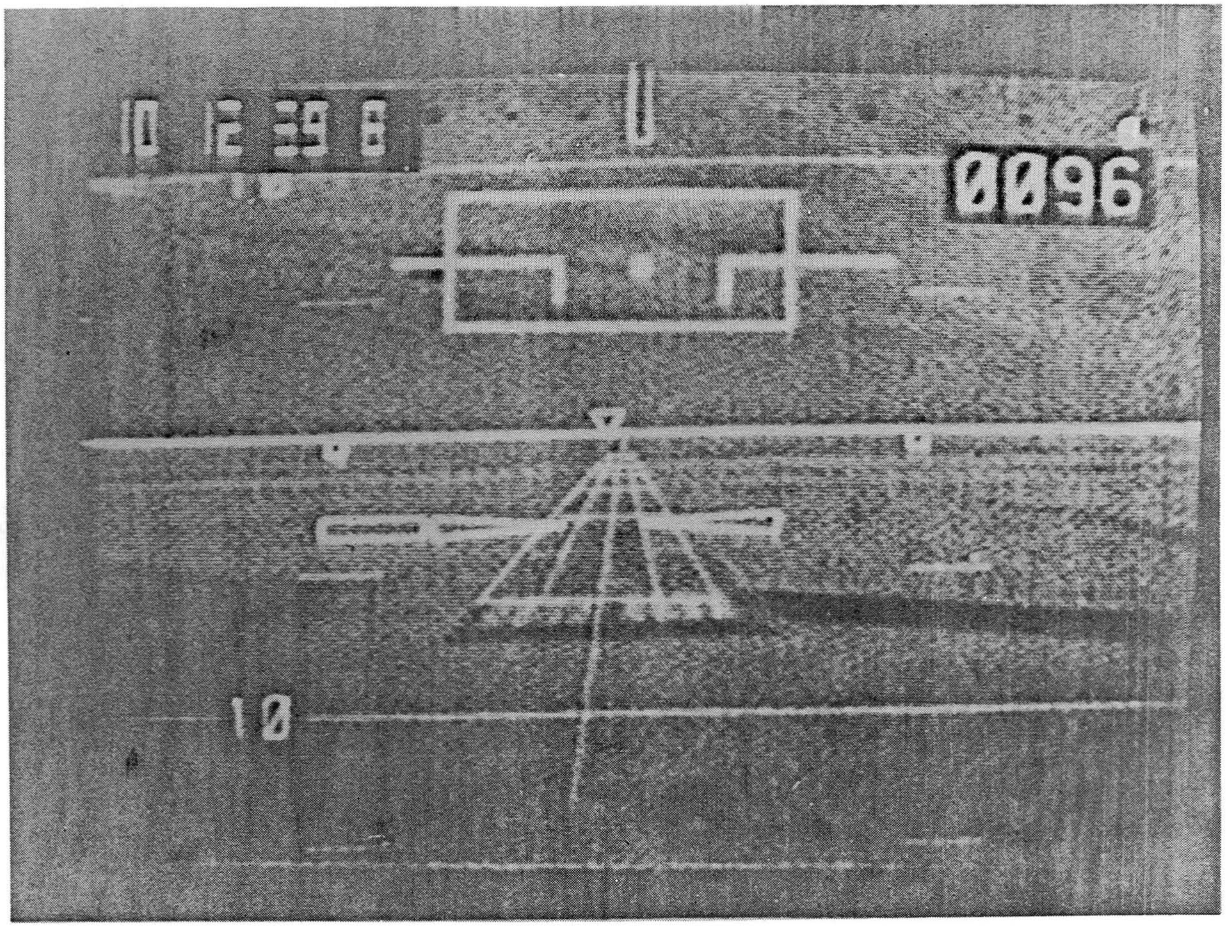
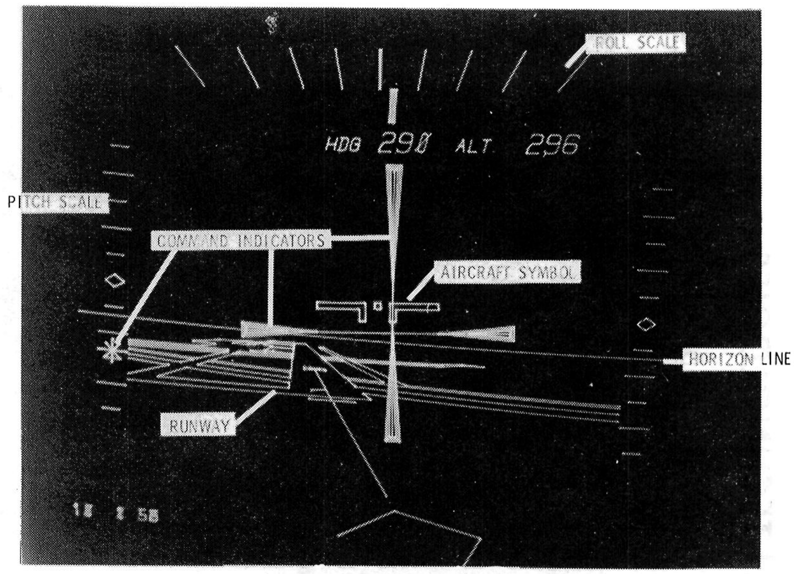
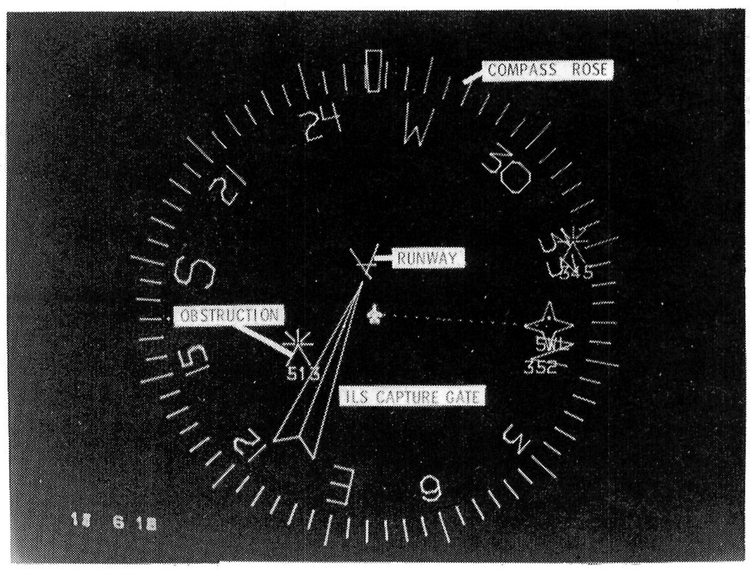


Figure 4.1-13 INTEGRATED DISPLAY FORMATS FOR HELICOPTER APPROACH, HOVER, AND LANDING UNDER IFR CONDITIONS



VERTICAL SITUATION DISPLAY

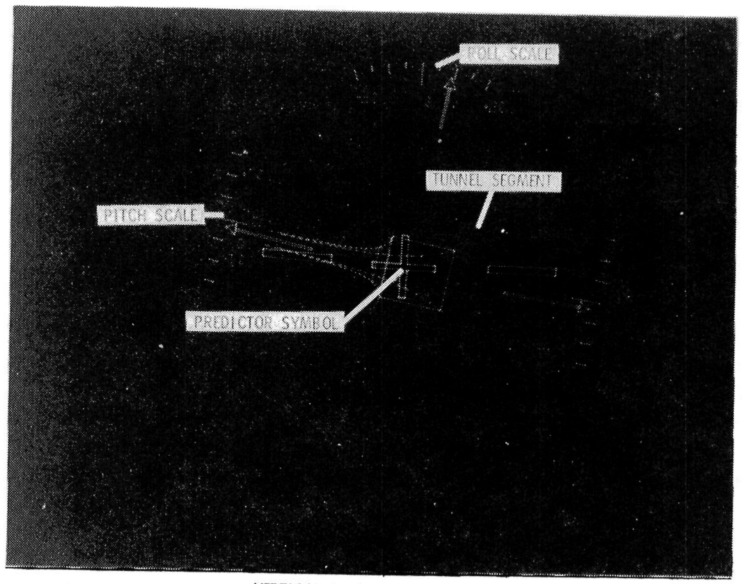
NASA
L-77-3988



HORIZONTAL SITUATION DISPLAY

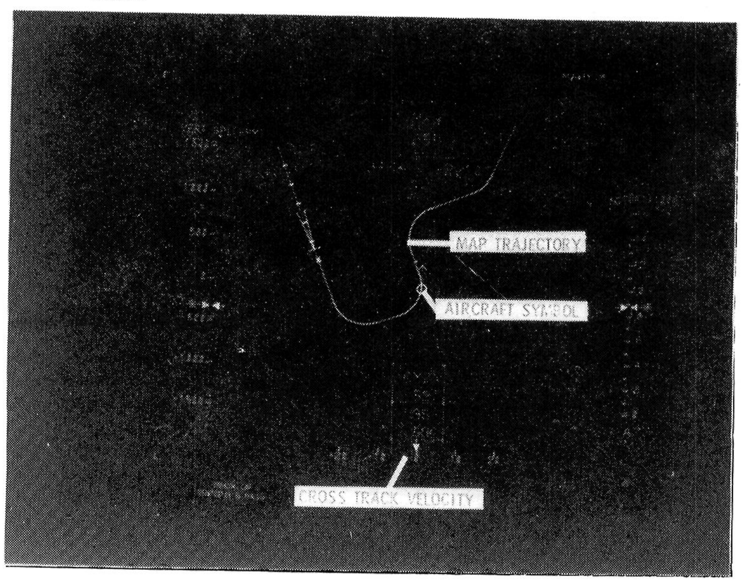
Figure 4.1-14 INTEGRATED DISPLAY FORMATS FOR STRONGLY CURVED HELICOPTER APPROACH UNDER IFR CONDITIONS

NASA
L-78-3921



VERTICAL SITUATION DISPLAY

NASA
L-78-3919



HORIZONTAL SITUATION DISPLAY

Figure 4.1-13 and was developed in Langley's Flight Research Division. The second concept is shown in Figure 4.1-14 and was developed in Langley's Flight Electronics Division. These concepts are presently under evaluation and will be completed prior to the transfer of the VALT program from Langley to Ames in October of 1978. Many elements of these advanced concepts may be applicable to future transport and GA aircraft.

Many military programs are also developing display formats and devices. For the most part, however, these developments may be applicable to the unique military environment. Some of the reasons for this are that: (1) military information display requirements are unique, including national security; (2) cost is not as paramount as in the civilian sector; (3) the aircraft performance envelope is much broader than in the civilian sector; (4) unique control/display requirements are necessitated by weapons systems management and the aircraft performance envelope; (5) military displays often must be compatible with a wide variety of exotic imaging sensors; and (6) the resulting hardware/software sophistication often exceeds civil requirements. Military programs should be monitored, however, to determine if spin-offs from their programs in the area of display formats and devices could aid civil cockpit technology.

An especially important area of military technology to monitor is that of head-up display (HUD) formats and devices. The military has had extensive experience in this area (Refs. 38 & 56), compared to limited experience in the civil area. One important program in the civil area is a joint FAA-NASA (Ames) program to investigate human factors and display format requirements for a civil HUD.

It is recommended that the present NASA programs in the area of display format and device development be continued at or above their present levels, but that they be broadened to perform display format and device development in the context of interdisciplinary technology development needed for advanced whole-flight-deck systems. For example, NASA Langley's TCV program should be broadened to include engine instrument and systems displays as well as the primary flight control and navigation displays presently being studied. Further, the program should be enriched with more advanced display device and avionics systems technology.

4.1.4 ANALYTICAL AND EXPERIMENTAL TOOLS (HUMAN ENGINEERING CONSIDERATIONS)

Questions of display and control configuration in the cockpit and how the crew interacts with the system must be addressed in human-engineering terms. A number of important research efforts in this area are underway in this country. Several NASA programs have produced significant analytical and experimental tools for measurement and prediction of pilot's control/display performance and scanning behavior.

NASA- Ames has an extensive effort focused on the role of the flight crew, and it makes effective use of simulators (see figure 4.1-15). NASA-Langley has an important effort tied to the TCV program, and it has developed a unique research instrument, the oculometer, (ref.57) which permits nonintrusively finding out where a pilot is looking. The device has been used in an airline's training simulator and in flight experiments. Figure 4.1-16 shows the Langley oculometer as integrated into a conventional cockpit and an advanced model of the oculometer presently under development within NASA.

In other NASA studies, the display information and format requirements have been studied using an analytical (optimal control) model of the pilot and aircraft to predict pilot/vehicle performance with various displays and control system sophistication (refs. 58 & 59). The results of these studies were verified in simulation and/or flight tests. Figure 4.1-17, for example, shows the predicted performance for a piloted CH-47 helicopter in the hover mode using two different levels of control sophistication. Still other NASA studies in conjunction with Boeing (ref. 60) have utilized a time-line mission analysis approach for the determination of control display requirements and piloting workload. The time-line mission analysis tool is currently being used to develop workload profiles in NASA-Langley's single-pilot IFR program and will be used in the future evaluation of cockpit display of traffic information (CDTI) using the Langley TCV aircraft and simulation facilities. These analytical and experimental tools mark an important step forward in developing a systematic approach to cockpit design.

FAA human-factors studies have treated optimization of crew effectiveness in future cockpit designs (ref.61) and assessment of alert and warning devices to develop criteria for cockpit design (ref. 61). The latter area is important because of the alarming increase in the number of audio and visual alert signals in the cockpit over the years.

As mentioned in an earlier section, the use of the HUD in civil transport aircraft is also being studied in a joint NASA-FAA program. Head-up versus head-down is a continuing controversy; but the technology appears to be at hand, and has been used succesfully by the military in this country and in category IIIa civil operations in Europe. NASA-Langley is furnishing NASA-Ames with one of its development oculometers for use in programs such as the HUD program.

Programs in human-factors engineering, such as the ones described above, must be continued and intensified by NASA as investments in other aspects of cockpit display technology grow in the future. It is

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Figure 4.1-15 AMES RESEARCH CENTER FUNCTIONAL AREA NAVIGATION REQUIREMENTS SIMULATION SHOWING CHART AND MULTIFUNCTION SWITCHING DISPLAY.

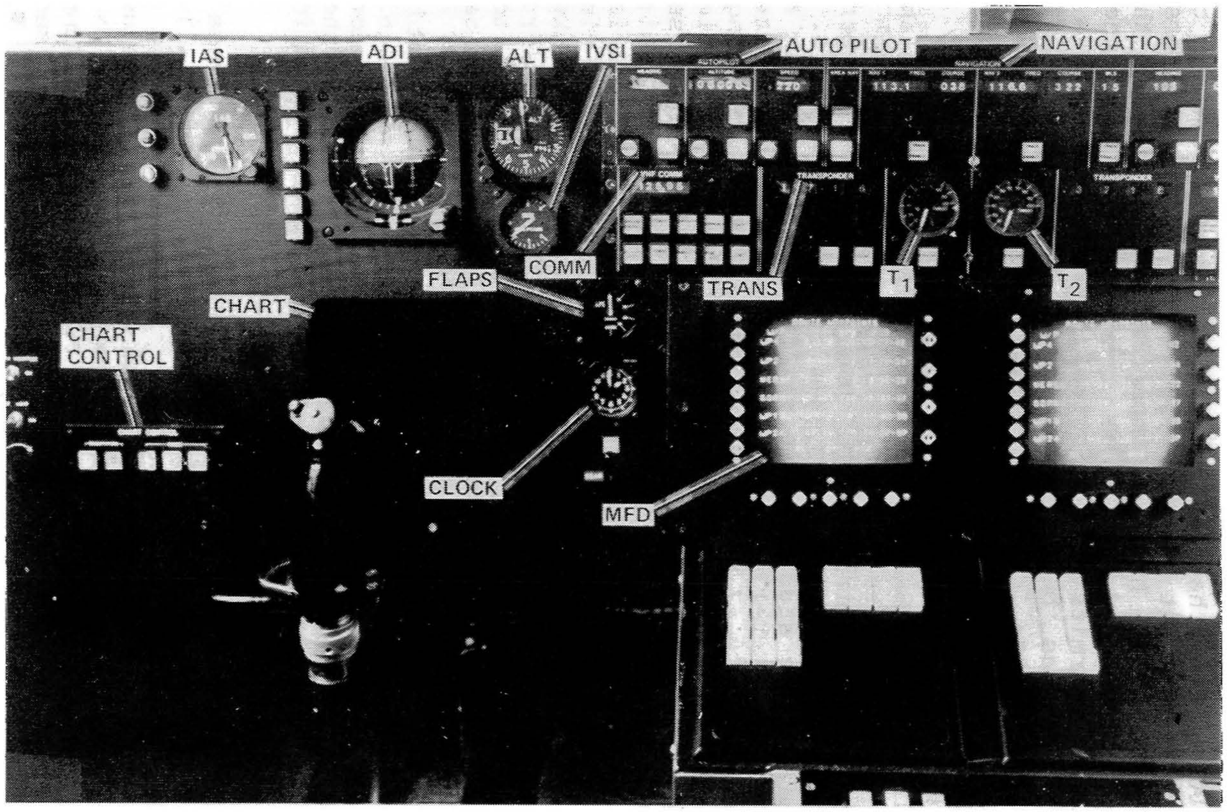

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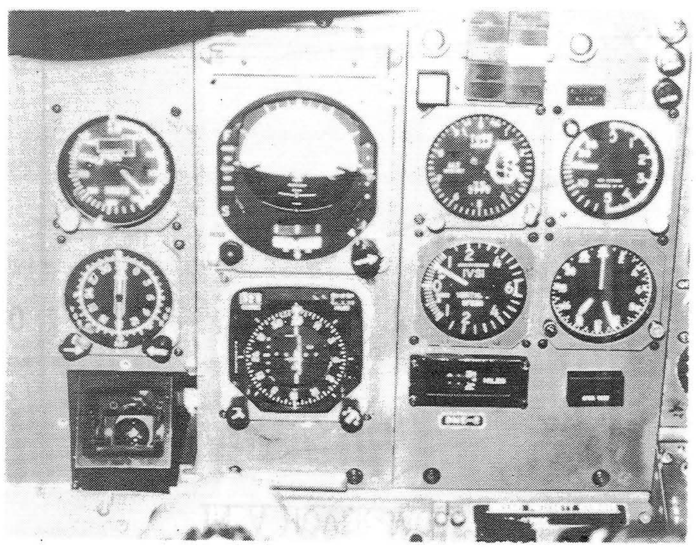
Figure 4.1-16 - NASA-LANGLEY OCULOMETER TECHNOLOGY SHOWING BASELINE OCULOMETER AS INSTALLED IN A CONVENTIONAL INSTRUMENT COCKPIT AND AN ADVANCED PROTOTYPE OCULOMETER BEING DEVELOPED IN-HOUSE



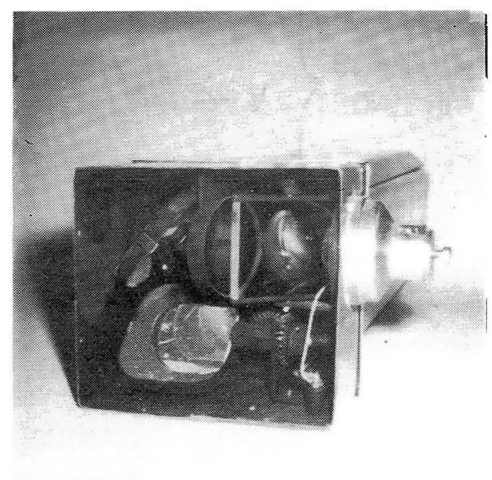


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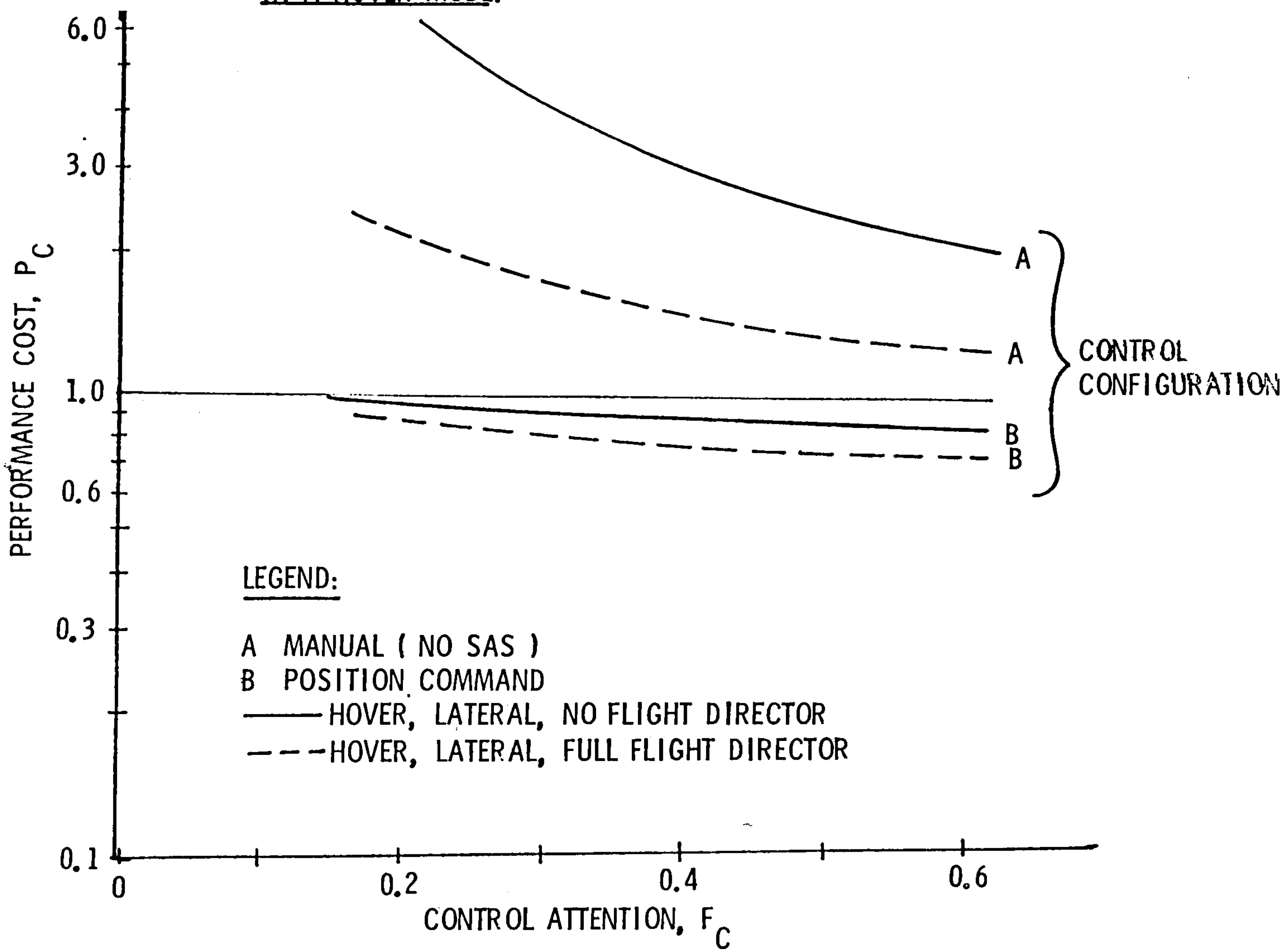
Figure 4.1-17 ANALYTICAL PILOT/VEHICLE MODELING RESULTS FOR THE CH-47 HELICOPTER IN A HOVER MODE.



important that flight deck technology, including display technology, be developed in the context of an interdisciplinary effort involving: (1) human factors engineering; (2) flight operations and procedures; (3) instrumentation and avionics engineering; and (4) systems engineering.

4.1.5 DISPLAY AVIONICS SYSTEMS AND COCKPIT CONFIGURATION STUDIES

A number of studies are underway in industry and government to develop display avionics systems and to decide how the cockpit should be configured. The most dramatic technological advances in the civil sector are appearing in general aviation avionics, which has assumed the role of innovator formerly held by airline avionics (ref.63). Examples of this innovation are: (1) the new Bendix Avionics Division BX 2000 line of communications/navigation/identification equipment which uses plasma discharge displays to replace conventional electro-mechanical indicators and microprocessors and 30 large-array micro-circuits for system computation and control (ref. 63) and (2) the new Bendix and RCA Avionics color digital weather radar displays (refs. 65 and 66) with ancillary area navigation and checklist display modes, (ref. 64). The major reason for this role reversal is that economy-conscious airline managements are reluctant to purchase new types of avionics because of their heavy investment in older generation hardware and their concern over commonality (ref. 63). Recent advances in general aviation cockpit technology and some of the reasons why GA has assumed the role of innovator are shown in Figure 4.1-18.

One important activity, a NASA-Ames effort with industry, will develop an avionics package to demonstrate concepts for low-cost advanced GA systems for the 1980's and beyond (ref. 67). Display ideas include an electronic map display with a touch-sensitive overlay to permit graphic entry of waypoints. Other concepts include voice feedback which would have a voice synthesizer verbally repeat keyboard entries. Early design studies pointed to two different bus-based configurations, one in which a pair of multipurpose flat-panel displays replace all instrumentation and the second in which all IFR-critical instruments are retained and an electronic map display and integrated control/display center using CRT technology is added. Cost will be a major driver in the eventual application of these concepts; they must be affordable.

The design and architecture of cockpit subsystems will be influenced strongly by emerging electronics technology. Traditionally, military programs have led the way in development of cockpit avionics. An example is that of the F-18 fighter aircraft (ref. 56). This developing aircraft uses three ruggedized head-down CRT displays, a head-up display (HUD) as a primary flight display, integrated multi-function switching for communication, navigation and identification, data multiplexing throughout, and subsystems with built-in-test-equipment (BITE).

Other examples of advanced military avionics programs are the Air Force Digital Avionics Information System (DAIS) program (ref. 68) and the Navy Advanced Integrated Display System (AIDS), formerly (AIMIS), program (refs. 69 & 70). These programs aim mainly at developing the necessary digital computation, data-busing, display generation, display media, and input/output technology for advanced military flight-deck

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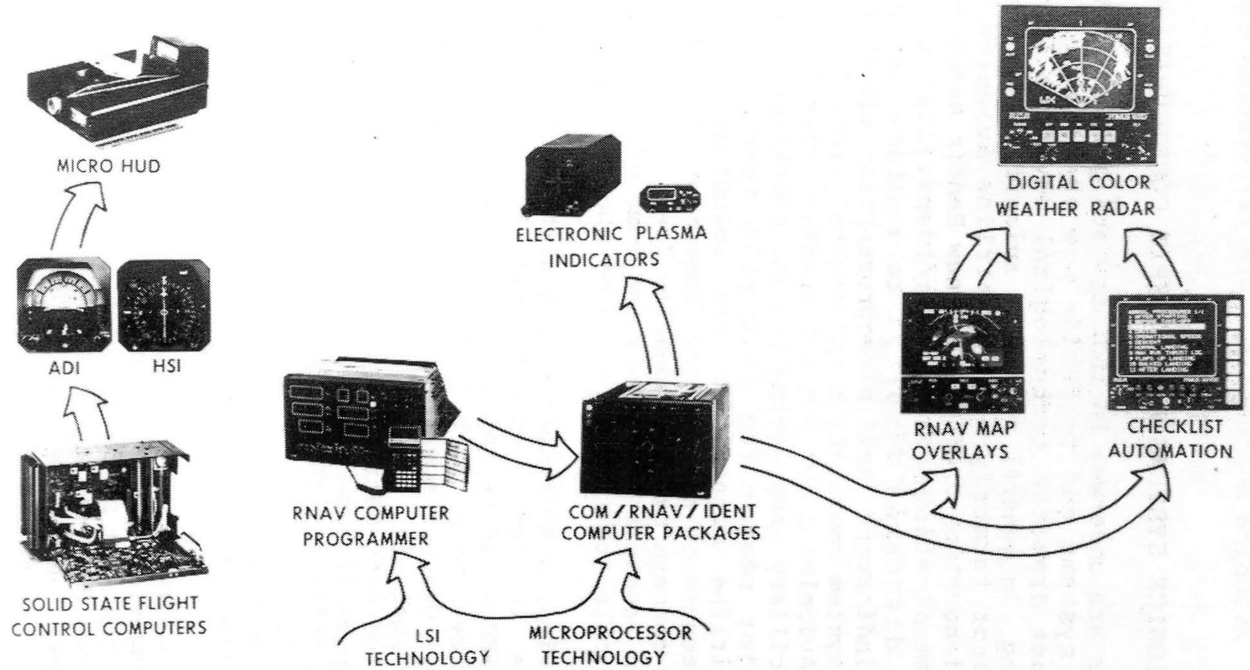
Figure 4.1-18 RECENT ADVANCES IN GENERAL AVIATION COCKPIT TECHNOLOGY



- GA HAS ASSUMED ROLE OF INNOVATOR IN U.S. CIVIL COCKPIT TECHNOLOGY
  - — HEAVY AIRLINE INVESTMENT IN OLDER GENERATION HARDWARE
  - — CONCERN OVER EQUIPMENT COMMONALITY
  - — RECENT AIRLINE PROFIT PICTURE
  - — NEAR - TERM MARKET APPEARS TO BE DERIVATIVE A / C USING EXISTING TECHNOLOGY

systems. Expected improvements in capability and reliability reflect modern computer-based data processing and display-generation techniques in conjunction with electronic display media to replace electro-mechanical switches and indicators with programmable multimode electronic controls and displays. The fast moving technology of microcircuit/microprocessor electronics and the evolving area of electronic displays represent keys to these efforts. The military developments in the area of display avionics systems and cockpit configuration studies are almost too numerous to discuss in depth in a report of this type. Major configuration studies have been described above. Perhaps the best way to summarize is with a figure. Figure 4.1-19 summarizes major military programs with possible civil cockpit technology spin-offs.

In the civil transport technology sector, on-going efforts appear to be more fragmented than in the military and are oriented toward the near-term derivative aircraft. The next aircraft that appears on the world market in the 1980's to replace aircraft that are aging or that cannot meet noise regulations will be derivatives with extensive use of digital systems (Refs. 71 & 72). Airlines, airframes, and avionics suppliers are working through the Airlines Electronic Enigeering Committee to define these digital systems. One approach partitions functions among several computers with some levels of redundancy. A Flight Management Computer will be responsible for navigation calculations, generation of guidance signals, and map display. A Flight Control Computer would automatically control the aircraft.

At present, control and display standardization is more difficult to define. It appears that a general purpose alphanumeric input control panel and an integrated frequency-management control panel are being considered. For the near term, the displays will probably be conventional electromechanical multiport instruments with separate inputs for each data source; this is considered a logical step toward future use of CRTs or other advanced flat-panel displays. The lack of a certifiable integrated CRT display for the flight control station prevents early application. It appears at the moment that the first extensive use of CRT or flat-panel displays will be in the flight engineer's station.

Lockheed has proposed a new flight-engineer's station for the L-1011; information formerly on 28 panels will be presented on three multimode CRT displays. Touch matrix techniques would permit switch closure by touching the face of the CRT. Benefits expected include a saving of over 90,000 ft. of wire and over 200 lb., and a reduction in the flight engineer's workload.

Recently, Lockheed certified a flight management system that integrates performance management with automatic navigation and automatically controls the airplane's throttles to provide fuel savings of 3-6%. Control-display units are located on either side of a CRT area-navigation display. The system is being installed in all Saudia Arabian L-1011's and is planned for the L-1011-500.

McDonnell Douglas included several CRTs in the modern cockpit of the DC-10 and they performed successfully in airline operations. These were not in primary-flight-control applications, but the company's

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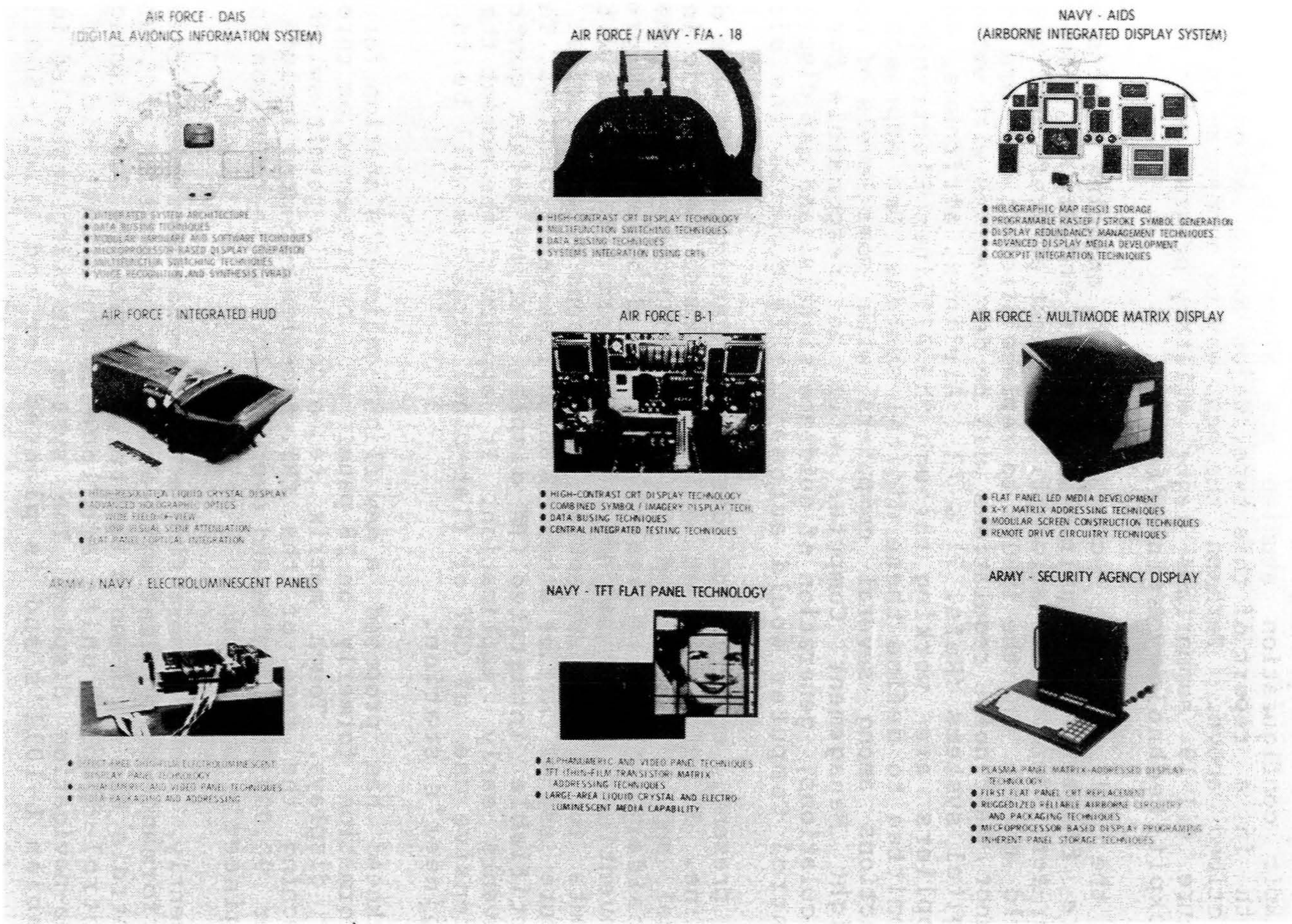
Figure 4.1-19 MILITARY PROGRAMS WITH POSSIBLE CIVIL COCKPIT TECHNOLOGY SPINOFFS



advanced systems engineers are studying the potential of wider use of flat-panel displays in the cockpit.

Boeing has gained valuable experience in electronic displays from development of the TCV aft flight deck, and has completed a number of important studies related to future cockpit configurations, including an advanced systems monitor using multifunction CRT displays (ref. 62).

As the airline industry evaluates new cockpit systems and considers more advanced ones, they always underscore the importance of economics. New systems, such as integrated flat-panel flight control-displays, will have to be cost-effective before they will be considered for introduction in the fleet.

The former FAA Administrator, John I. McLucas, has recommended to Congress an additional annual funding of $15-25 million for an intensified joint FAA/NASA research and development program on cockpit displays and controls to bring this technology into use much earlier than would otherwise be the case (Ref. 73). The Air Transportation Association (ATA) also expressed concern, recently, that the next generation of commercial transport aircraft will be implemented without incorporation of advanced avionics concepts, such as programmable multimode CRT displays. The 1990-2000 time frame will see the addition of still newer transport aircraft with requirements for even more advanced technology. In addition, the general aviation portion of the civil aeronautics spectrum, which is presently booming (ref. 74), is expected to have continued requirements for advanced low-cost-of-ownership cockpit avionics.

The major problem with civil transport flight deck display technology R&D within the U.S. is that the efforts toward development of a certifiable integrated electronic display system for cockpits of the 1980's are fragmented and are coming along too late to be incorporated in the early derivative aircraft of the 1980's. Such is not the case for civil flight deck system R&D in Europe. British Aerospace (BA) Inc. is investigating how much of the information and control functions on a whole-flight-deck basis could be handled by computer-based electronic flight displays (refs. 75,76,77 &78). This program is the only civil program in the world, to this writer's knowledge, that is attacking the civil flight deck display problem on a whole-system/whole flight-deck basis. The BA effort is focused on certifiable CRT display system technology for the 1980's. It is an interdisciplinary effort that has invested $2.5 million to date. The effort has interested American Airlines and ARINC and is causing enthusiasm that could eventually sway airline purchases (derivative-type aircraft) from Europe.

There is no program within the U.S. comparable to the BA flight deck program. The closest effort is the NASA TCV program. However, the TCV program is emphasizing primary flight control and navigation display (format) development only, with a minimum of display avionics systems development. To compete with the BA program, the TCV program would have to be expanded significantly and to incorporate greater involvement of the airframe and avionics industry.

The BA program is now developing an A-300 simulator and performing engineering studies on avionics components and systems architecture.

Three vendors have done detailed studies and one will be selected momentarily to develop a flight system. The BA future program includes cost effectiveness studies; analysis of cost, weight, and reliability; cost-of-ownership studies, installation studies; and investigation of alternate technologies such as color displays. The benefits which the BA program is now projecting from the use of computer-based electronic flight dareplay is shown in figure 4.1-20.

The 7 to 9 CRT VC-10 flight deck which the BA program has developed is shown in figure 4.1-21 along with some other European technology from Thompson CSF of France. The Thompson CSF program is a joint effort with Bendix and is aimed at the application of penetration color CRT technology to integrated cockpit systems. This program has developed flight quality head-down color CRT display systems and monochrome HUD systems. The HUD systems have been used in category IIIa operations in Europe.

As the above discussion indicates, civil efforts within the U.S. on display avionics systems and cockpit configuration studies are: (1) somewhat fragmented and don't deal with the entire flight deck; (2) limited in research and development expenditures; (3) focused on near-term pay-offs; and (4) minimal on longer-range, higher-risk technology areas. Thus, it is felt that it is important for NASA to develop a strong program with major investments to develop display avionics and advanced flight deck concepts and technologies for the 1990's and beyond. Such a program is described by ref. 29. It is felt the role that NASA should play is as follows: (1) R&D in basic long range, high-risk technology areas (e.g., flat-panel display media); (2) development, test, and evaluation of advanced concept technology; (3) integrated systems development for civil sector using military developments where appropriate; (4) development of a cooperative program with the FAA and industry to evolve viable, certifiable technology.

The benefits which such a flight deck development program could achieve could be far in excess of those projected by the British Aerospace Program (figure 4.1-20). To accomplish additional benefits the technology will have to be based on flat-panel, solid-state displays and extensive use of microprocessor/microcircuit LSI technology to implement advanced integrated control/display systems. Benefits which can be projected at the component and subsystem level are: (1) improved control/display integration; (2) improved modularity/commonality; (3) reduced spares complement; (4) improved maintainability (MTTR); (5) higher reliability (MTBF); (6) number of indicators reduced by up to 70 %; (7) number of switches reduced by up to 50%; (8) weight and volume reduced by up to 30%; and (9) cockpit wiring reduced by up to 80%. Benefits which can be projected at the cockpit systems level are: (1) reduced pilot workload; (2) improved performance; (3) reduced life-cycle cost; (4) greater cockpit flexibility; (5) improved backup capability; (6) improved safety; (7) easier pilot training; and (8) automation optimization.

Figure 4.1-22 shows an advanced civil air transport cockpit configuration conceived at NASA-Langley Research Center, that could lead to many of the benefits projected above. This cockpit and the program leading to its development are described in Reference 29.

Figure 4.1-20

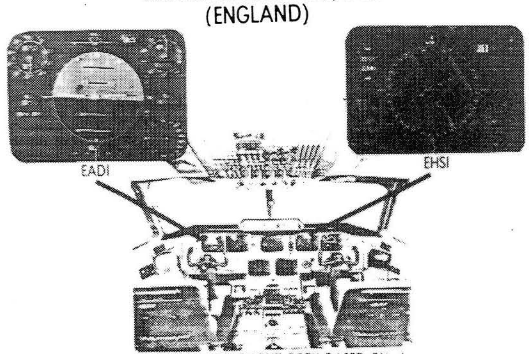
BRITISH AEROSPACE BENEFIT PROJECTION
CONVENTIONAL VS. ELECTRONIC (CRT) FLIGHT DECK

CHARACTERISTICS	CONVENTIONAL	ELECTRONIC
DISPLAY AREA	2,000 Sq. Inches	420 Sq. Inches
NO. OF INDICATORS	110	7 to 9 (+ Backup Indicators)
WEIGHT	250 Pounds	200 Pounds
RELIABILITY	ADI/HSI; MTBF 700 Hours	CRT Display; MTBF 2,000 Hours
REVERSIONARY CAPABILITY	Limited	Extensive
COST	$200,000	$150,000
NO. OF MANUFACTURERS	50	Several
DISPLAY FLEXIBILITY	Single-Purpose Indicators	Multimode Displays

CREW STATION TECHNOLOGIES

Figure 4.1-21 IMPORTANT CIVIL PROGRAMS FROM EUROPE

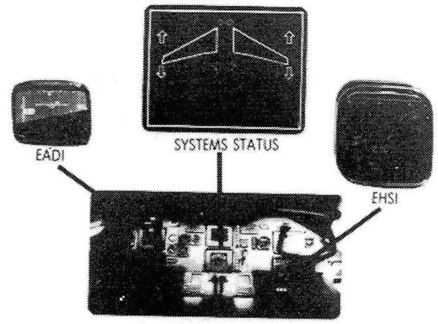
BRITISH AEROSPACE, INC. (ENGLAND)



INTEGRATED FLIGHT DECK BASED ON MONOCHROME CRT TECHNOLOGY

- PROGRAM AIMED AT INTEGRATING ENTIRE FLIGHT DECK
- EFFORT FOCUSED ON CERTIFIABLE 1980'S TECHNOLOGY
- PROGRAM COMBINES HUMAN FACTORS, FLIGHT OPS. AVIONICS & SYSTEMS ENGINEERING DISIPLINES
- 2.5 M INVESTED TO DATE
- EFFORT HAS INTERESTED AMERICAN AIRLINES & ARINC
- EFFORT COULD SWAY AIRLINE PURCHASES TO EUROPE
- THERE IS NO COMPARABLE U.S. PROGRAM

THOMPSON CSF, INC. (FRANCE)

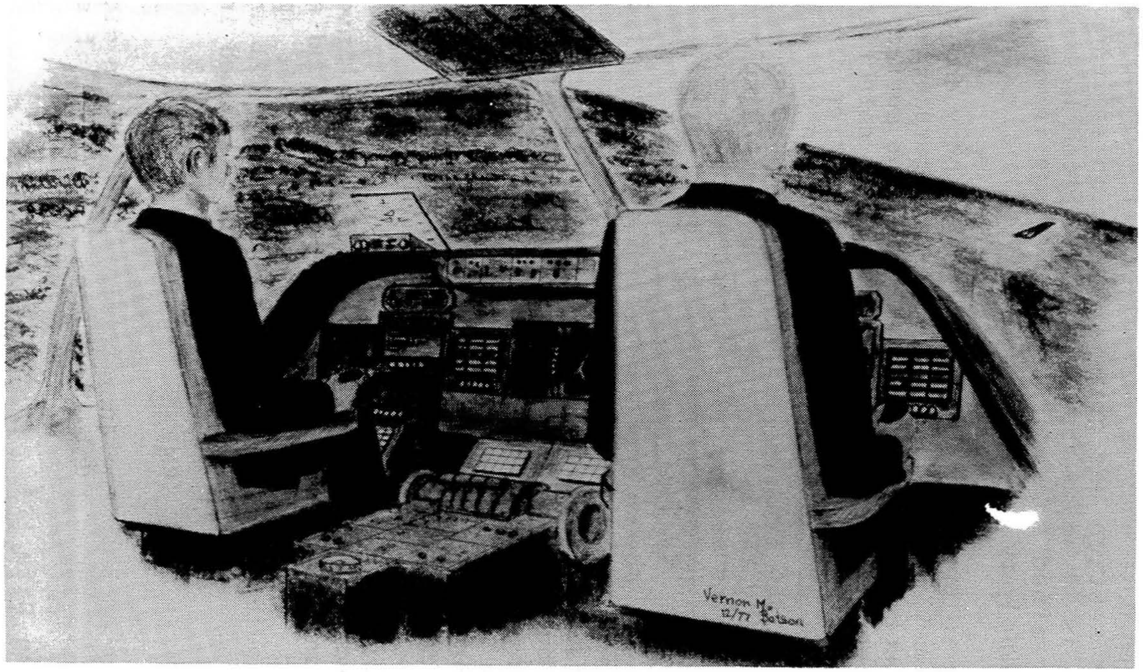


INTEGRATED COCKPIT SYSTEMS BASED ON (PENETRATION) COLOR CRT TECHNOLOGY

- EFFORT AIMED AT PRIMARY & SYSTEMS DISPLAYS
- COMBINED PROGRAM WITH BENDIX (U.S.)
- STATE - OF - THE ART STROKE SYMBOL GENERATION & COLOR CRT DISPLAYS DEVELOPED
- COLOR HEAD-DOWN CRT & MONOCHROME HUD SYSTEMS HAVE BEEN FLIGHT TESTED
- ONLY COMPANY IN THE WORLD OFFERING FLIGHT QUALIFIED COLOR DISPLAYS

CREW STATION TECHNOLOGIES

Figure 4.1-22 ADVANCED CIVIL AIR TRANSPORT COCKPIT CONCEIVED AT LANGLEY RESEARCH CENTER



- **COCKPIT CONFIGURATION**
  - REDUCED CREW WORKLOAD
  - IMPROVED SAFETY
  - REDUCED LIFE - CYCLE COSTS
  - IMPROVED PERFORMANCE AND FLEXIBILITY

4.2 PILOT CONTROLLERS AND DATA ENTRY

Pilot controllers and data entry methods have been a slowly changing part of crew station technology; however, the increase in digital avionics functions implemented in civil aircraft is forcing a change in the traditional approach to controllers and data entry. The traditional approach has been to use dedicated controls and data entry means for each function. As the number of functions and modes proliferate and the amount of cockpit area remains largely fixed, it becomes necessary to devise means to select many functions and modes from an integrated data entry & control center (IDECC). As pointed out in the previous section the general aviation segment of the civil aviation market is leading the way in innovation in this area because it is less constrained by standards and large investments in older generation technology equipments than the airline segment.

The first step to providing integrated data entry and controls from a single control and display instrument (see figure 4.1-15, right side) utilizes a computer driven CRT (or other flat surface display) with switches along each side of the CRT. Function selection switches are provided along the bottom. When a given function is selected, the corresponding mode or options for that function are displayed on the screen adjacent to the switches. The pilot selects the desired mode or option by depressing the switch nearest the mode displayed on the CRT. This approach retains mechanical switches of the traditional approach, but defines the meaning of the switches by computer generated displays.

A variation to the above approach which eliminates the mechanical switches along side the flat surface display is the use of a touch panel on the face of the display as shown in figure 4.2-1. The touch panel surface consists of embedded layers of wires that contact for a 'switch' closure when touched by the pilot's finger. In order to compensate for a lack of tactile feedback, an audio tone is issued when the closure is made. The modes and numerical keyboard are displayed on the flat surface display.under computer control.

Another approach which provides even more flexibility in function and mode/option selection utilizes a simple keyboard with numbers keys and a few special function keys. This approach was studied by Systems Technology, Inc. and Milco International, Inc. for application to NASA's general aviation avionics programs. (ref. 121 and 122). This approach is based upon an interactive menu described in section 4.3.

4.3 FLIGHT SYSTEM MANAGEMENT

Flight management is becoming an important function in digital avionics systems. Flight management includes a number of subfunctions:

- Flight Plan Data Entry
- Avionics Function/Mode Selection
- Data Entry and Display
- Flight System Warning Displays and Annunciators
- Data Base Management
- Aircraft Performance
- Checklists and Other Handbook Data

VHF-FM MENU

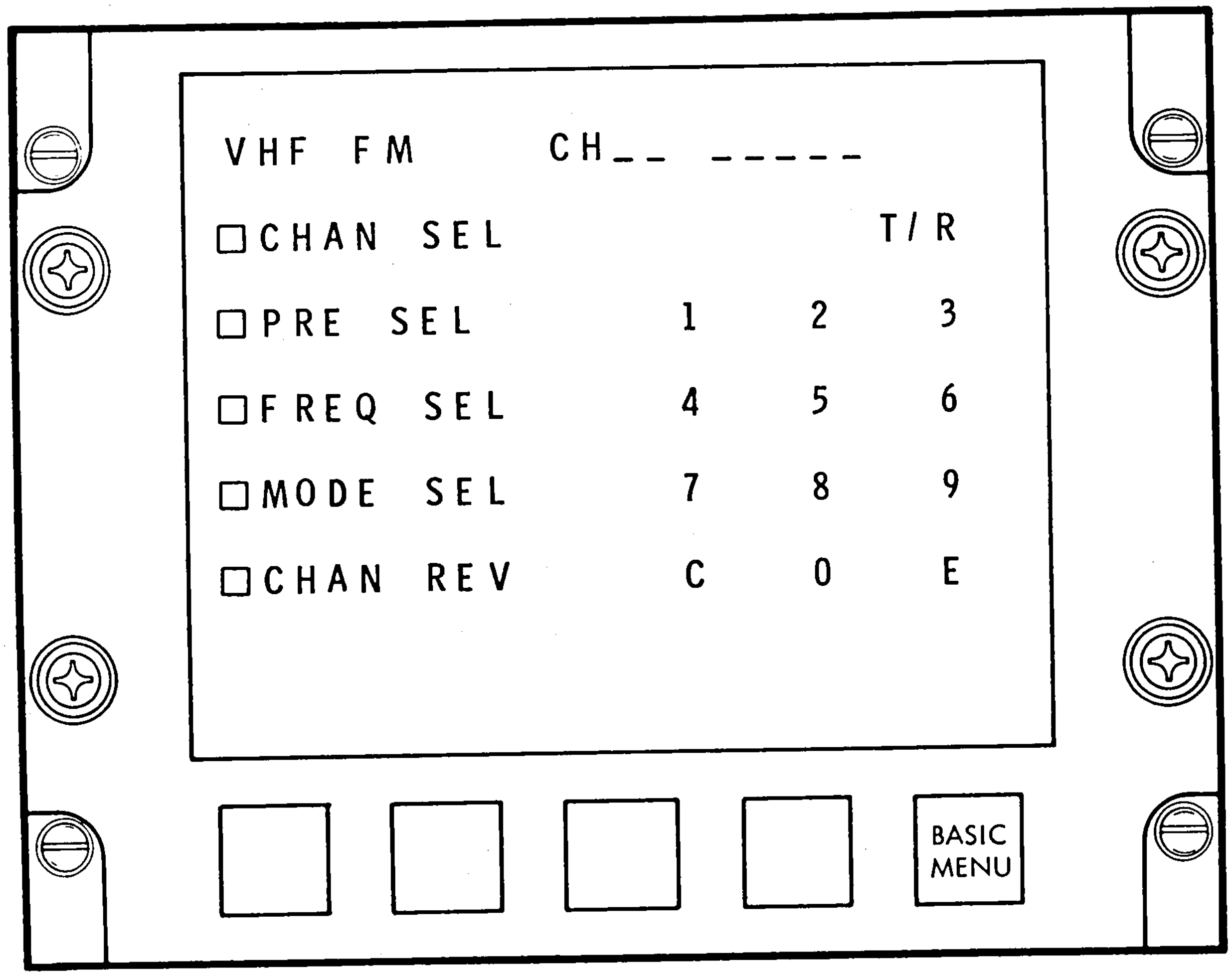


FIGURE 4.2-1

A block diagram illustrating the flight management function is shown in figure 4.3-1. Flight management systems include a control/display unit, a digital computer with flight management software, crew station displays for altitude director indicator (ADI), horizontal situation indicator (HSI), and navigation map displays, and interface with system sensors and elements.

The complexity of the flight systems management task is growing which requires a break in the traditional approach of dedicated controls and displays for each avionic functions as discussed in section 4.2. The use of multifunction controls and displays demands a new approach using interactive displays which simplify mode selection procedures through the use of computer prompts. The new approach is flexible, conserves panel space, and is easy to learn.

The multifunction selection technique requires the use of a multiple level menu concept illustrated by figure 4.3-2 (ref. 123). The multilevel menu concept utilizes a master menu for the top level functions. The selection is accomplished by entering a single digit corresponding to the desired function. The master menu calls up the next level or function menus. The function menus in turn call up the sub function menus.

The lowest level menus present the modes and options for selection by the flight crew. In such a multi-level menu system it is possible to get 'lost' in the maze. A 'homing' selection on each menu allows for quick return to the function menu or the master menu to alleviate the problem of 'getting lost'.

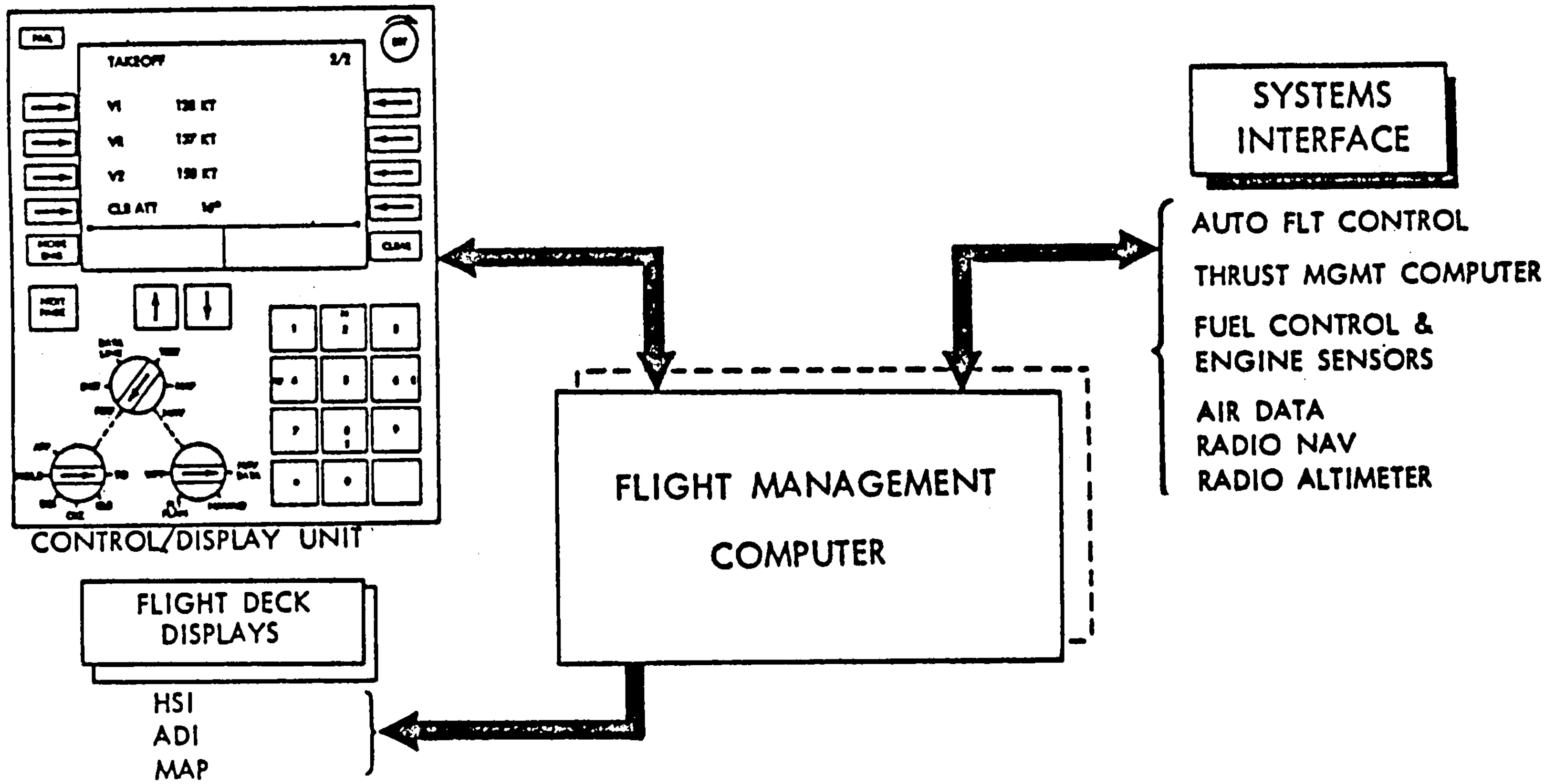
NASA has already begun sponsoring avionic programs to study and implement these multi-function controls and displays utilizing multi level menus. Additional human factors and operations research are required to perfect these techniques for operational applications. However, the potential payoff of this new approach to flight systems management justifies further studies to perfect the concepts.

The electronic displays utilized in the digital flight management systems can include a lot of data useful to the pilot as pointed out in section 4.1.

An EADI display is illustrated in figure 4.3-3 to detail the types of information that can be provided by the digital flight management system. Some of the data shown on the EADI is mode dependent so that the display is not quite as cluttered as indicated on the figure 4.3-3.

Another important function of the flight management system is to provide navigation data base management for the flight plan and navigation map display subfunctions. A typical navigation map display is shown in figure 4.3-4. The data base for the current and next generation flight management systems are stored on a read/write mass memory which is accessed by the avionics digital computers. For example, a technique for storing the data base for all VOR's, ILS's, intersections, NDB's, airports, airways, and associated MEA's is described in reference 122 and is illustrated in figure 4.3-5. These waypoints stored on the mass memory data base can be used for flight plan entry and display, navigation computations, as well as the

FLIGHT MANAGEMENT SYSTEMS



CONTROL/DISPLAY UNIT

- DEDICATED SWITCHES
- COMPUTER GENERATED OPTIONS
- KEYBOARD DATA ENTRY

FIGURE 4.3-1

MENU CONCEPT FOR FLIGHT SYSTEMS MANAGEMENT

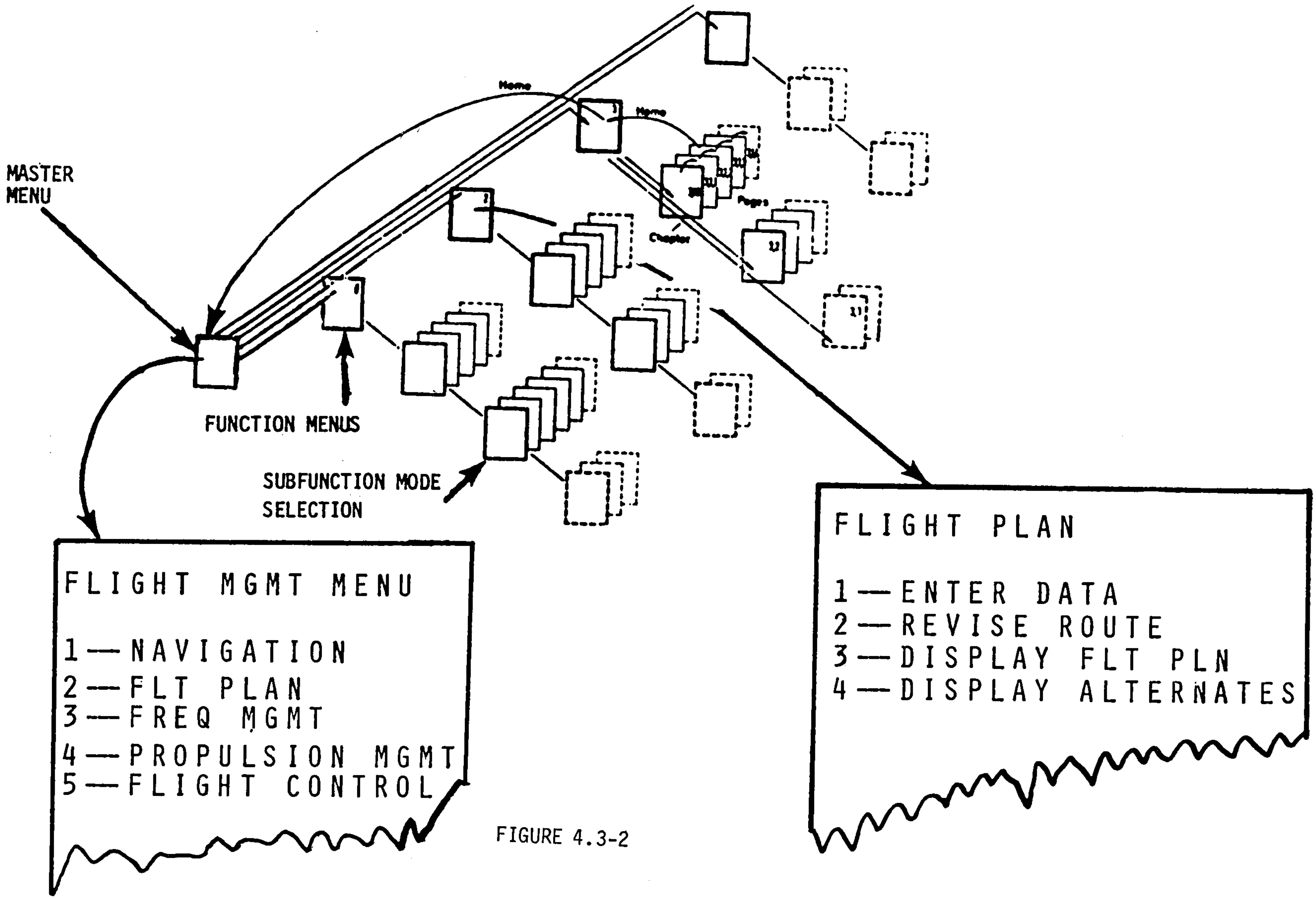
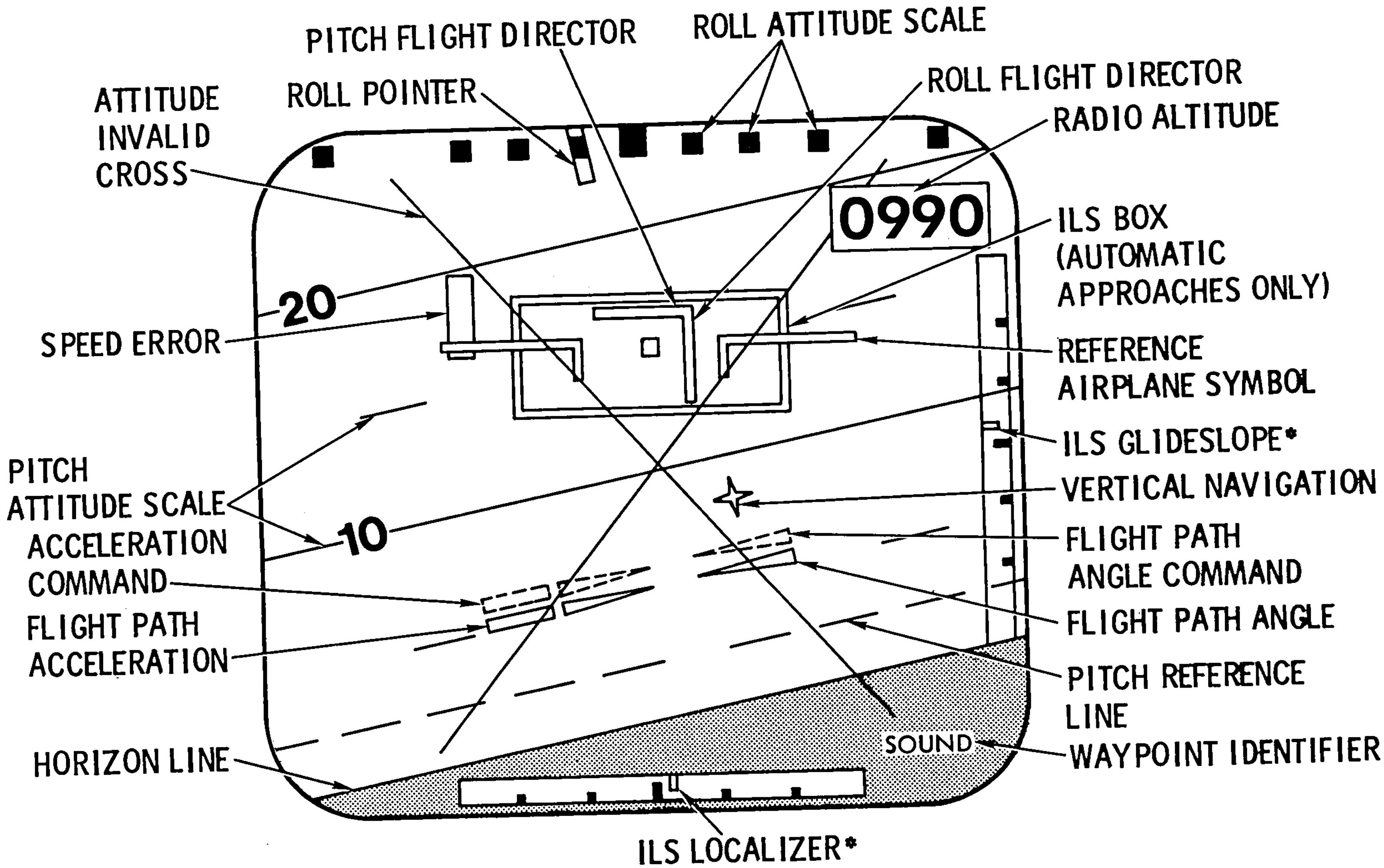


FIGURE 4.3-2

EADI SYMBOLOGY



THESE SYMBOLS ARE DEPLOYED CONTINUOUSLY ON MANUAL APPROACHES AND UNTIL LAND ENGAGE ON AUTOMATIC APPROACHES

FIGURE 4.3-3

BASIC MAP DISPLAY

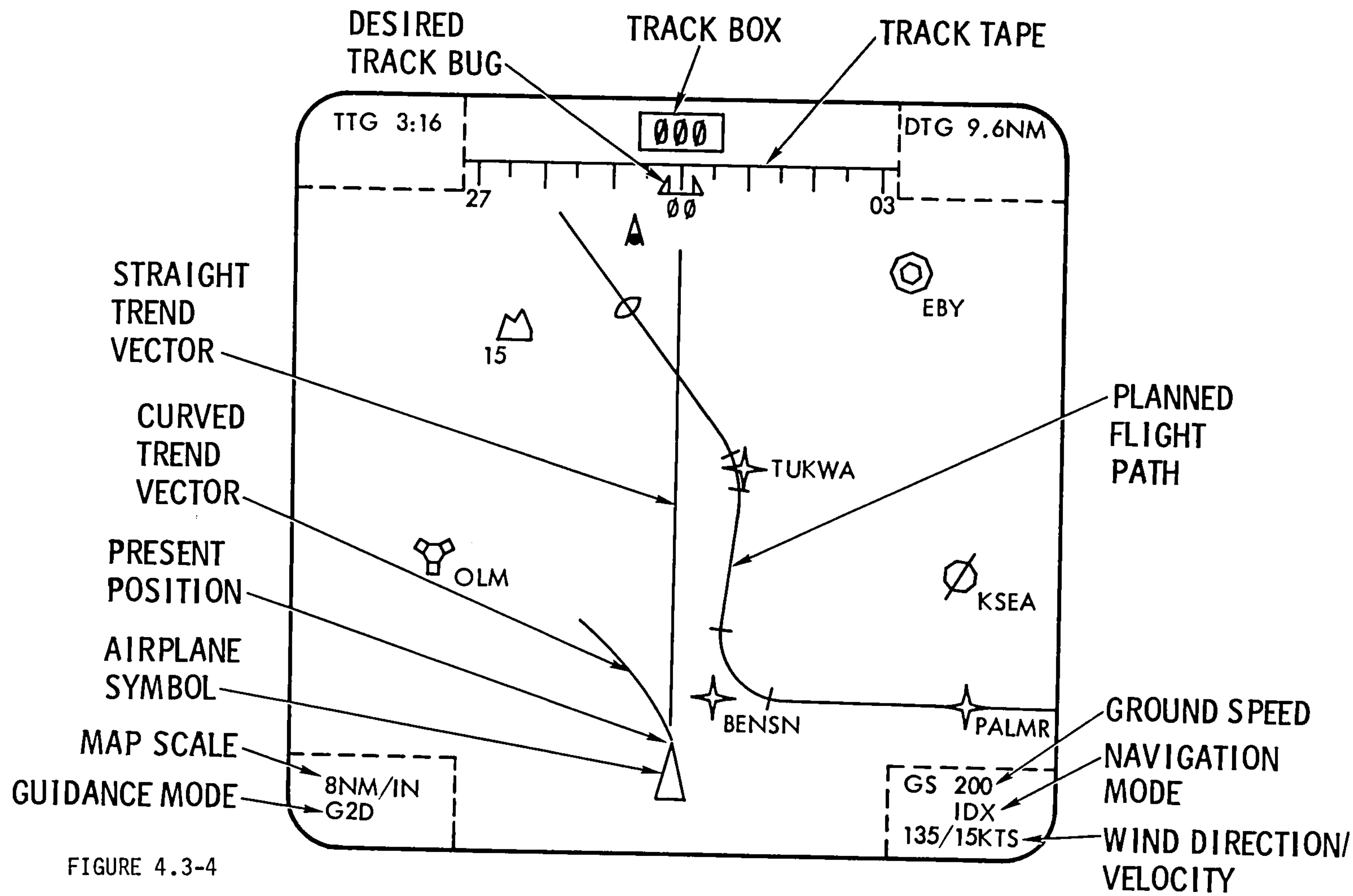


FIGURE 4.3-4

NAVIGATION MAP DIGITAL DATA BASE

- CATEGORY OF WAYPOINTS IN DATA BASE

WAYPOINT TYPE	"TEL" CODE	CALL LTRS.	FREQ.	LAT.	LONG.	MEA	SPECIAL
VOR	3 NO'S	3 LTRS.	5 NO'S	5 NO'S	6 NO'S	3 NO'S	AIRWAY (3)
INTERSECTION	5 NO'S	5 LTRS.	-	5 NO'S	6 NO'S	3 NO'S	AIRWAY (3)
ILS	4 NO'S	4 LTRS.	5 NO'S	5 NO'S	6 NO'S	3 NO'S	DIRECTION
AIRPORT	6 NO'S	6 LTRS.	5 NO'S	5 NO'S	6 NO'S	5 NO'S (ELEV.)	IFR CODE
NDB/BCS	4 NO'S	4 LTRS.	4 NO'S	5 NO'S	6 NO'S	3 NO'S	

- EACH MAP SEGMENT HAS VICTOR AIRWAYS TABULATED WITH WAYPOINTS.
- EACH MAP SEGMENT HAS STORED THE AVERAGE MAGNETIC VARIATION.
- THE MAP DATA BASE IS RECALLED FROM MASS MEMORY BY ENTERING A 4 DIGIT CODE.
- ALL DATA ENTERED FROM TELEPHONE TYPE KEYPAD.
- ALPHANUMERIC DESIGNATORS ARE "ECHOED" BACK.

FIGURE 4.3-5

navigation map display. The advantage of this navigation data base format is that the pilot can designate any waypoint in the data base using a simple telephone type numeric keyboard rather than being required to enter the latitude, longitude, and other data associated with the waypoint. The waypoint mnemonics are coded on the keyboard.

An estimate of the amount of memory required to store all the low altitude waypoints in the CONUS (continental U.S.) is shown in table 4.3-1. The total number of bytes of memory is estimated to be 279K bytes.

A candidate for mass memory to use for the data base storage is magnetic bubble domain memory. Both TI and Rockwell have announced 256K bit bubble chips in 1978.

ESTIMATE OF MEMORY REQUIREMENTS FOR US NAV MAP DATA BASE

TYPE OF WAYPOINT	ESTIMATE NO.	NO. BYTES EACH	TOTAL MEMORY
VOR	924	28	25,872
INTERSECTIONS	5000	27	135,000
ILS	500	30	15,000
AIRPORTS	2000	34	68,000
NDB/BCS	580	26	15,080
AIRWAYS	200	100	20,000
		TOTAL	278,952

TABLE 4.3-1

5.0 INTEGRATION AND INTERFACING TECHNOLOGY

A significant departure in avionics systems architecture was initiated by the USAF DAIS which is a distributed system with functions interconnected by means of a serial digital multiplex data bus. The trend toward functionally modular, distributed avionic system architecture has been accelerated by the advent of low cost microprocessor technology. This distributed, functionally modular architecture is now being applied to both airline avionic systems and general aviation avionic systems.

The explosion in airborne information processing capability is continuing. Knowledgeable technologists in very large scale integration (VLSI) circuits predict another two to three orders of magnitude increase in circuit density and gate speed during the next decade. The mass memory technology is providing a bridge between the relatively slow rotating magnetic media storage systems and the very fast but expensive semi conductor memory. This fast, large capacity mass memory provides the means for storing enormous data bases for navigation and flight management functions in the next generation avionic systems.

The use of fiber optics for electronic system interconnect and for multiplex avionic data busses is emerging from the laboratory to the possibility of an economically feasible replacement for copper wire in the next decade. Such fiber optics interfaces will greatly reduce the threat of EMI and indirect lightning effects on digital avionics.

5.1 AVIONICS FUNCTIONAL INTEGRATION

The current trend toward modular digital avionics is greatly simplifying the functional integration problem. Each avionic function is being implemented with a dedicated digital processor(s) with its associated software (or firmware). The functional element receives its required data from the multiplex data bus and supplies its data output to the bus for other functional users.

5.1.1 SYSTEM ARCHITECTURE

The Digital Avionics Information System (DAIS) is a total system architecture utilizing digital technology to reduce life cycle costs by defining and developing modular hardware and software core elements and standardized interfaces which can be configured and applied to many aircraft.

Historically, mission information requirements have been established along semiautonomous subsystem areas such as flight control, navigation, communication, stores management, weapon delivery, etc. The DAIS approach proposes that the various standard modules be common to all subsystems on an integrated basis. This will not only reduce costs associated with the current proliferation and nonstandardization of modules, but will also provide the opportunity to easily share information between subsystems. This latter feature can enhance mission effectiveness and also provide functional redundancy for increased mission reliability.

The overall DAIS architecture is shown in figure 5.1.1-1. Because of differing redundancy requirements for safety-of-flight, the system is partitioned into an avionics section which handles the traditional avionics functions, and a flight control section which handles the inner-loop stability functions and other information deemed necessary for safety-of-flight integrity.

The avionics portion of the system consists of federated processors communicating with each other and the other system elements (sensors, weapons, and controls and displays) through a standardized multiplex data bus. Centralized system single-point control is performed by a processor resident software executive that can be relocated for redundancy. Application software is structured to provide modularity, reliability, and transferability. This system architecture is flexible to accomodate a wide variety of avionics configurations, missions, and sensors, which provides redundancy to improve availability, and accommodate changes in technology.

DAIS is structured as a federated network where component machines are independent computers that communicate via the multiplex bus. The MIL-STD-1553A standardized multiplex data bus provides dual-redundant information paths between the system resources (each computer and other system elements).

The basic architecture is designed for a broad class of configurations where the number of processors can be reduced or enlarged depending upon the avionics and mission requirements. Standardization, modularity, and application independent executive software allows adaptability of this architecture to a broad class of different applications as well as to making mission-to-mission changes in a particular aircraft.

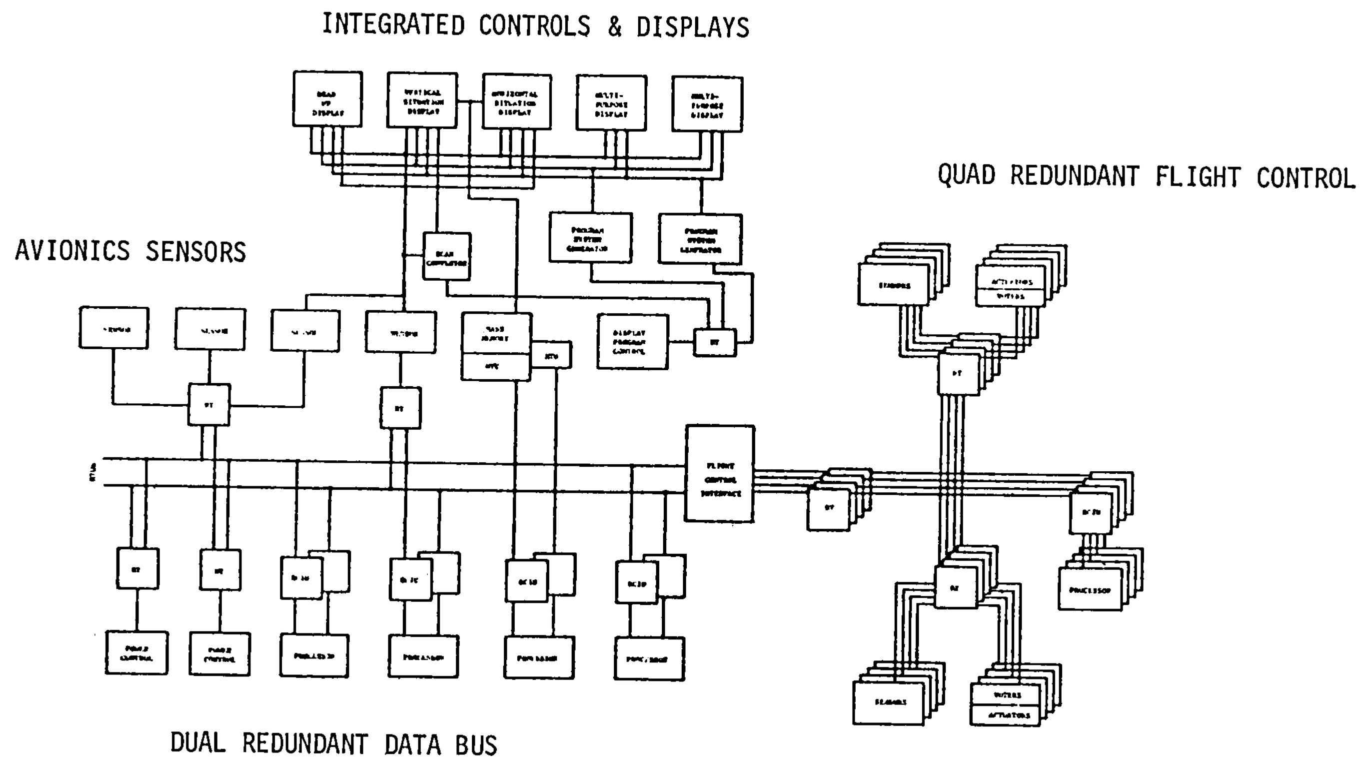
Sensors, weapons, and other subsystems are selected as required for the particular mission and connected to the interface modules of the multiplex system remote terminals or connected directly to the multiplex bus if the subsystem is compatible with the bus protocol. Application modules of the software will also be selected as required by these subsystems.

The basic elements of the DAIS architecture which can be restructured for various aircraft avionic configurations are called core elements (or building blocks) and are composed of the multiplex system, processors, mission software, and controls and displays.

The DAIS architecture and integrated system design results in a special set of function requirements, designated system and bus control functions, which include the control of the bus communication and utilization of redundancy in the event of failures. The system and bus control functions are distinguished from mission avionic functions that support the specific mission tasks. The mission avionic functions could be comprised of navigation, guidance, weapon delivery, communications, vehicle defense, target acquisition and track, auto pilot, stores management, and subsystem management.

A third important group of functions, called on-board test functions, utilize both hardware and software to isolate inflight failures to

USAF DIGITAL AVIONICS INFORMATION SYSTEM (DAIS)



FUNCTIONS

- FLIGHT CONTROL
- NAVIGATION
- COMMUNICATION
- STORES MANAGEMENT
- WEAPON DELIVERY

ARCHITECTURE FEATURES

- DISTRIBUTED PROCESSORS
- HARDWARE/SOFTWARE MODULARITY
- STD DATA BUS FOR FUNCTIONAL EXPANSION
- RESTRUCTURABLE FOR DIFFERENT MISSIONS

FIGURE 5.1.1-1

allow utilization of redundancy, maintain a complete updated status of all equipment on the system, and provide isolation of failures to the LRU levels with a minimum of auxiliary group equipment.

The DAIS multiplex provides information transfer between the elements within the system, including DAIS processors, controls and displays, and other subsystems. It consists of the bus controller interface unit (BCIU), remote terminal units (RT), and the multiplex cable assembly (data bus).

The system is a time division multiplex (TDM) system and a command/ response system with one BCIU controlling the bus traffic at any given time. Each multiplex cable assembly consists of a twisted, shielded wire pair.

The information transfer on the bus consists of messages composed of command, data, and status words. The information transfer consists of three modes: bus controller-to-terminal, terminal-to-controller and terminal-to-terminal transfer.

The BCIU is the interface between a processor and two data buses and shall operate in either of two modes: master or remote. In master mode, the BCIU operates under control of the Master Executive, issues all bus commands, and receives all status words.

In the remote mode, the BCIU monitors both buses for command words and responds to valid commands containing its own address, provides transfer of data in both directions between the processor and either of two data buses, provides status replies on the appropriate data bus in response to command (and special internal operations), and interrupts the associated processor upon receipt of certain mode commands or detection of exception conditions.

The remote terminal provides the interface between the subsystem and the two data buses. The RT transfers data in both directions between the multiplex bus and subsystem via the interface modules, based upon commands received from either data bus, and provides status replies on the appropriate bus in response to commands. The RT will perform special operations upon receipt of a mode command.

The DAIS processors are general purpose digital computers of the type normally referred to as mini-computers. They are specially engineered for airborne use. Operational features include a vectored priority interrupt system, interval timers, and floating point arithmetic. All memory is directly addressable. Indexing as well as single level indirect addressing is available. A small read only memory (ROM) is enabled during the startup sequence. A separate port to memory is provided for the BCIU via a direct memory access (DMA) channel. In a federated processor configuration, each processor/BCIU can only address its own memory unit.

Figure 5.1.1-2 shows a view of the DAIS-configured cockpit. The cockpit is implemented with cathode ray tubes to provide a head-up display (HUD), vertical situation display (VSD), horizontal situation display (HSD), and two (2) multipurpose displays (MPDs). The cockpit also contains a master mode control panel, and an integrated multi-

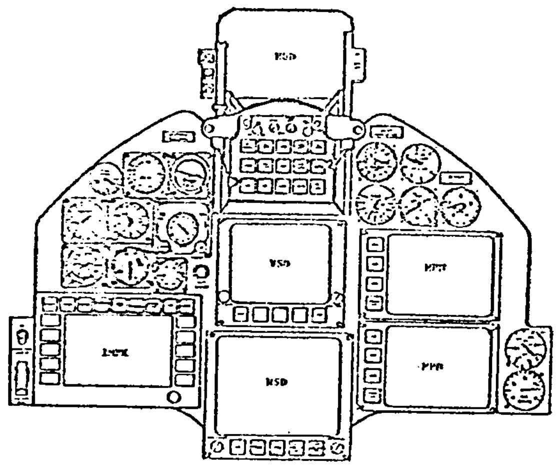


FIGURE 5.1.1-2 DAIS COCKPIT

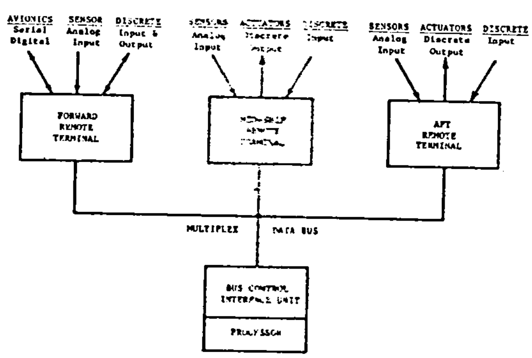


FIGURE 5.1.1-3 SINGLE MULTIPLEX BUS

function keyboard (IMFK). Only that information which is required for a particular flight mode, as brought up by the Master Mode Control Panel, is presented to the pilot. Control of subsystems, such as communications, navigation, stores management, and flight control system mode changes, etc. are accomplished through the IMFK. Display redundancy is achieved by the capability to switch displays among the various CRTs. Backup electromechanical instruments are included to provide backup for critical flight parameters.

The mission software resides in the memory of the DAIS processors. JOVIAL J-73/1 higher order language software is being applied as a standard to implement the mission software including flight control. The major characteristics of the mission software are structured in a modular form to allow easy mission-to-mission sensor/weapon changes, provide flexibility for major modification, and provide transferability of portions of the software to other aircraft applications. The mission software consists of the Operational Flight Program (OFP) and the Operational Test Program (OTP). The OFP is separated between the executive software and the application software. The latter is modularly separable into the mission avionic functional capabilities of navigation, guidance, weapons delivery, communication, vehicle defense, target track and acquisition, subsystem management, stores management and autopilot. The OFP application software also supports the on-board functional test capability. The OTP contains software for use on the ground (on-board the aircraft) capable of isolating failures to the LRU levels. In addition to the OFP and OTP, each processor contains a ROM program to control the startup (cold start) and load of the OFP or OTP from the system mass memory.

The OFP is organized into the executive software and the application software. The executive is organized with the master executive and the local executive. Each processor contains a local executive; the master and monitor processor (if used) also contains the master executive. Only one master (normally the one in the master processor) is in control of the system at any time.

The DAIS flight control system is also implemented utilizing the MIL-STD-1553A data bus. A single bus, as shown in figure 5.1.1-3, consists of a processor, bus controller, and three remote terminals. The remote terminals provide all input and output for the flight control system. Sensor inputs (rate gyro and accelerometers) are provided via direct analog input interfaces, which are centralized analog-to-digital converters in each remote terminal. Discrete inputs (mode and trim) are interfaced with the system via discrete input interface modules. Actuator output commands are provided through the appropriate output interface modules. Additionally, a serial digital channel is provided for interface with the avionics multiplex data bus. This channel passes pilot mode requests, computer mode engagements, attitude, and air data information. The processor executes the flight control algorithms in addition to handling the multiplex data bus traffic.

As shown in figure 5.1.1-1, the system is presently configured as a quad-redundant system. The decision for quad-redundancy was made early in the program and was based on achieving a failure rate of 1 catastrophic failure in 10 exp. 7 operating hours for 2-hour flights. It was also decided that no sophisticated techniques be employed for failure detection and redundancy management. However, the capability does exist to implement more advanced redundancy management techniques such as second generation fault-tolerant or dispersed/reconfigurable methods.

Simple comparison monitoring is being used for failure detection. Redundant sensors are cross-strapped at the input to the remote terminals and are voted upon in software in the flight control computers. Actuator commands from the redundant flight control channels are voted upon in hardware at the actuator. Lower-median select voting has been implemented in both the software and hardware voting planes. The software voting provides a check of the sensors, remote terminals, and the bus controllers. The hardware voting checks the processor, bus controller and remote terminals. Each primary actuator has four secondary actuators which are force-summed.

The four channels of flight control processing are all active and are not synchronized, which simplifies the problem of preventing single-point failures since fail-operational frame synchronization requires fairly complicated computer to computer communication. The offsetting cost of asynchronous operation is that the channels do not have identical inputs or outputs and the actuator commands are not updated simultaneously. The problem of errors inherent in asynchronous operation with no failures present is acceptable and can be lived with. Specifically, the comparison monitor disagreement due to asynchronous operation does not appear to be worse than the disagreement among analog channels with component tolerance error buildup.

Another problem of asynchronous operation is that since integrators will not have identical inputs, and will have different sampling times and finite word lengths, they will tend to drift slowly with respect to each other. This problem is overcome by exchanging integrator outputs across the flight control channels asynchronously.

Mode management discretes are also passed across the interchannel interface to verify that all channels are engaged in the same mode. Mode engagement is voted; otherwise different channels could engage different modes, issue different commands, and declare a channel failed.

An integrated test bed is presently being completed at the Air Force Avionics Laboratory. This test facility is evaluating the avionics architecture with regard to development and integration of both the hardware and software. A Flight Engineering Facility is being assembled in the AF Flight Dynamics Laboratory to examine the integration of flight control functions and evaluate pilot effectiveness of the controls and display system.

To enhance the capabilities of the system, certain areas are noted for future growth. Since all information from the various subsystems is available on a common bus structure, and optimal combination of these processor. Besides elimination of an LRU, it will also reduce external cabling requirements. Imbedding the remote terminal function in a particular subfunction element would also reduce the number of LRUs and the complexity of the interface wiring.

The addition of fiber optics for replacement of the twisted pair data bus will substantially increase the bandwidth of the system and allow the transfer of a broader spectrum of signals on the same bus. This will allow greater integration capabilities.

The emergence of microprocessors on system integration is an area worthy of increased emphasis. The impact on system partitioning, preprocessing of information, redundancy management, and software structures should have very innovative impacts on future architectures.

5.2 AIRBORNE INFORMATION PROCESSING (DIGITAL COMPUTERS)

PROCESSORS

About five years ago (1973) the first monolithic, LSIC digital processors appeared on the market. The development and use of this type of device, which for obvious reasons was called a microprocessor, has accelerated greatly, and at the present time a wide variety of microprocessors (and a further development, the microcomputer) are available commercially.

At this point, it may be well to define the terms 'processor' and 'computer' as they are used here. A computer is an assembly which contains the following functional elements;

- Arithmetic Logic Unit (ALU)
- Processor control/executive
- Input conditioning
- Output conditioning
- Memory (scratch pad and program)

while a 'processor' commonly encompasses only the first two elements and must be accompanied by additional circuitry which performs the remaining functions. Both types require an external power supply and in many cases a separate clock. Figure 5.2-1 illustrates the functional makeup of a complete computer.

A third type of LSIC device in wide use in digital processors is the 'bit slice' ALU. These bit slices are so arranged that two or more can be tied together to form an ALU of word length greater than that of the single bit slice. The other elements listed above are added to form the complete computer. Most bit slices now in use are 4 bits wide though there are a few of 2 or 8 bit size.

Most current airborne computers are 16 bit machines. This word length is required for many applications and is sufficient for almost all applications. There are situations where an 8 bit processor (perhaps with some double precision instructions) is sufficient. There are also some applications where a 16 bit machine is not sufficiently precise and double precision operations must be programmed in. For example, 16 bit operations are sufficient for almost all flight control algorithms

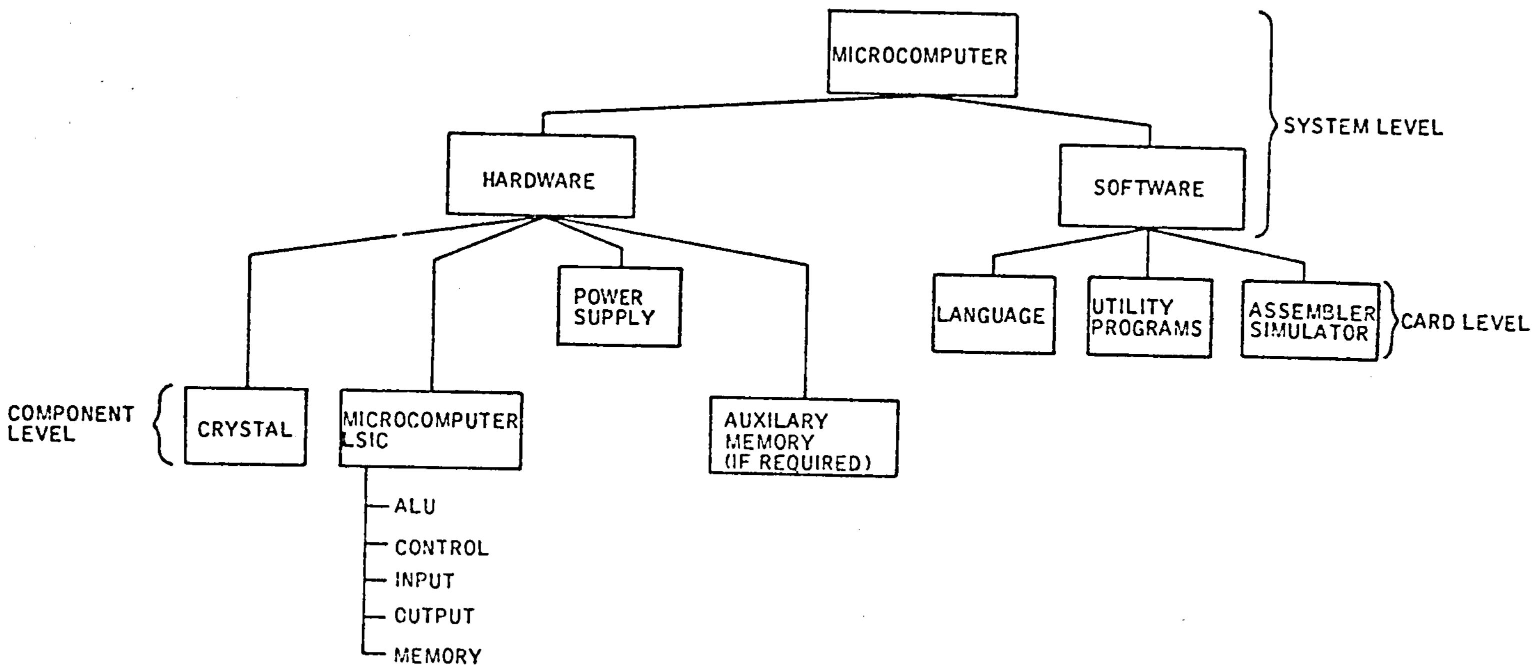


FIGURE 5.2-1 FUNCTIONAL ELEMENTS OF A MICROCOMPUTER

but there is considerable use of double precision operation in implementing a strap down inertial navigation computer in a 16-bit machine.

5.2.1 MICROPROCESSOR TECHNOLOGY & ARCHITECTURE

Prior to the advent of the microprocessor, digital processors had been assemblies of many separate electronic logic devices starting with vacuum tubes and progressing into LSIC logic networks. Physically, airborne processors in the early 1970's varied in size from one printed circuit card (about 35 sq. in.) to perhaps 10 cards. Further it must be noted that the digital processor was, and is, only part of a digital computer. To the processor must be added the input/output (I/O) circuitry, the program and scratch pad memory and the power supply. The end result was (in 1970) a box with 500-1000 cu. in. volume weighing 30-60 pounds. The use of first custom, and later standard, LSIC enabled discrete component processors of moderate throughput (100-200 KOPS or 5 microsec. add time) to be built on one or two cards by about 1973. The microprocessors of that time period, while very small in themselves, required a number of peripheral components to provide control and interface them with the I/O and memory, usually resulting in the use of 20-40 sq. in. of card area. Thus the introduction of the microprocessor itself had a comparatively small effect on the size, weight, and power consumption of airborne computers; i.e., a computer which required 15 cards using a processor assembled from M- and LSIC elements could be reduced to perhaps 13 cards by the use of a microprocessor.

During the past five years there has been continual progress in LSIC technology toward putting more logic and memory elements on one chip to the point that the latest devices are referred to as VLSIC (Very Large Scale Integrated Circuits). The capability of producing more complex chips has resulted in the emergence of the microcomputer mentioned earlier. These microcomputers comprise all the five elements listed above, but to date the inputs and outputs are digital only. Analog to digital, and digital to analog conversions and demodulation must be handled in separate circuitry. Recent design studies of microcomputer-based computers suitable for the military airborne environment indicate that a volume of 300 cu. in. and a weight of 10 lbs. for a computer with a 1-2 microsec. add time and perhaps 8K program memory words is reasonable. Hybrid and/or monolithic converters suitable for many applications such as flight control and inertial navigation computers have recently become available in 8 and 12 bit form and will soon appear in 16 bits. The use of these I/O devices and the latest memory chips (16K RAMS & ROMS) could now result in a total package of approximately 150 cu. in. and 6 lbs. Typical examples of currently available and promised processors and microcomputers are listed in Table 5.2.1-1. The current approximate prices of these units in the military versions vary from $40 for the 8080 to $500 for the TI 9900.

DEVICE MANUFAC.	MODEL	WORD SIZE, BITS	ADD SPEED, μ SEC	MULT/ DIVIDE	MEMORY ADDRESS, K WORDS	ON-CHIP MEMORY, WORDS	TEMP RANGE °C	ON CHIP CLOCK
MICRO PROCESSORS								
Fairchild	F-8	8	?	No	64	S-64 P-0	0 70	No
Intel	8080A	8	2.0	No	64	No	-55 125	No
Intel	8085	8	1.3	No	64	No	-55 125	Yes
National Semiconductor	IN8900	16	10	No	64	No	0 70	No
Rockwell/ Synertek	6500	8	2.0	No	64	No	0 70	Yes
Texas Instruments	SBP/9900	16	2.0	Yes	64	No	-55 125	Yes
Zilog	Z80	8	1.6	No	65	No	-55 125	No
AMD 4-bit slice	2901A	4	1.0	No	NA	NA	-55 125	NA

TABLE 5.2.1-1 SUMMARY OF TYPICAL MICROPROCESSORS/COMPUTERS CURRENTLY AVAILABLE PG 1 of 2

DEVICE MANUFAC.	MODEL	WORD SIZE, BITS	ADD SPEED, μ SEC	MULT/ DIVIDE	MEMORY ADDRESS, K WORDS	ON CHIP MEMORY, WORDS	TEMP RANGE °C	ON-CHIP CLOCK
<u>MICRO COMPUTERS</u>								
Intel	8048	8	2.5	No	64	S-64 P-1K	0 70	Yes
Mostek	3870	8	?	No	2	S-64 P-2K	0 70	Yes
				ANNOUNCED FOR 1978				
Intel	8086	16	0.6	Yes Signed	1000	No	0 70	No
Zilog	Z8000	16	2.5	Yes	8000	No	0 70	No
Texas Instruments	9940	16	2.0	Yes	64	S-128 P-2K	NA	Yes
AMD 4 bit slice	2903	4	1.0	Yes	N/A	N/A	-55 125	N/A

P - PROGRAM MEMORY
S - SCRATCH PAD MEMORY
? - DATA NOT AVAILABLE
N/A - NOT APPLICABLE

TABLE 5.2.1-1 SUMMARY OF TYPICAL MICROPROCESSORS/COMPUTERS CURRENTLY AVAILABLE PG 2 of 2

5.2.2 MEMORY

Definition of Terms

VOLATILE - the stored data is lost when power is removed.

NON-VOLATILE - the stored data remains intact when power is removed and can be read out when power is restored.

DESTRUCTIVE READ OUT (DRO) - the data word is erased from the memory as it is read out. Core memory is DRO; this requires that any permanent data (constants or instructions) be read out into a register in the processor and then immediately read back into the core.

NON DESTRUCTIVE READ OUT (NDRO) - the data word is not erased from the memory when it is read.

ROM - READ ONLY MEMORY - the data on a ROM chip is built in during manufacture and cannot be changed. A ROM is non-volatile and has NDRO.

PROM - PROGRAMMABLE READ ONLY MEMORY - a PROM can be programmed by the user after manufacture. Once it is programmed it cannot be changed. A PROM is non volatile and NDRO.

RAM - RANDOM ACCESS MEMORY - a RAM is a read/write memory. The processor can write in incoming data or intermediate results to a specific memory location and read out the data at any time later as long as power is not interrupted. A RAM is volatile but has NDRO. A dynamic RAM will also lose its data even with power on unless it is 'refreshed' every few milliseconds by a dummy access. A static RAM does not require refreshing.

EPROM - ELECTRICALLY PROGRAMMABLE READ ONLY MEMORY - an EPROM can be programmed/loaded by application of voltage to the bit locations. The EPROM is non-volatile NDRO and will hold its data until the chip is exposed (through a quartz window in the case) to UV radiation for 10-30 minutes.

EAROM - ELECTRICALLY ALTERABLE READ ONLY MEMORY - an EAROM can be programmed/loaded or erased by application of voltage to the bit locations. The write is rather slow (about 5-20 m sec) and the erase is even slower, currently in the neighborhood of 100 m sec.

Status of Memory Technology

Several years ago magnetic core memories were cost competitive with semi-conductor memories for use in airborne computers and were used in several production designs. During the past four years, however, the cost per bit of semiconductor memories of all types (RAM, PROM, and ROM) has decreased markedly while the number of bits per chip has gone up from 4 to 16 times. In this same time period, the cost of airborne core memories has remained fairly constant. Further, the access time requirements posed by the newer processors are exceeding the capability of the current core memories. Thus, almost all airborne computers currently being designed are based upon semiconductor memory, particularly in those cases where more than a few units are to be built. There are some development or limited production applications where the convenient write/erase characteristics and non-volatility of magnetic core makes it a desirable approach, and there are at least two manufacturers that can supply 8-16K 16 bit word core memory assemblies suitable for the military airborne environment. Another form of magnetic memory, plated wire, has also been used for spacecraft computers, and at least proposed for airborne use. Plated wire memory can be made faster and lighter than core and like core it is not vulnerable to radiation. It is, however, quite expensive, and is unlikely to see much use in airborne computers unless specific requirements on speed, weight and radiation resistance justify the added cost.

Even for development work there are now electronic semiconductor devices (see EPROM and EAROM above) which can to some degree duplicate the write/erase and non-volatility characteristics of magnetic core, and at the same time offer advantages in power and size/weight.

The memory portion of a current airborne computer is usually a custom design in which card assemblies of standard LSIC memory devices are designed to meet the specific system requirements for RAM, PROM, and/or ROM memory. The choice between PROM and ROM generally depends upon the number of production models to be built and the stress on minimum volume/weight; i.e., ROM memory is usually cheaper per bit (in terms of recurring production cost) and has a higher bit density (bits per chip). Typical examples of currently available semiconductor devices are listed in Table 5.2.2-1.

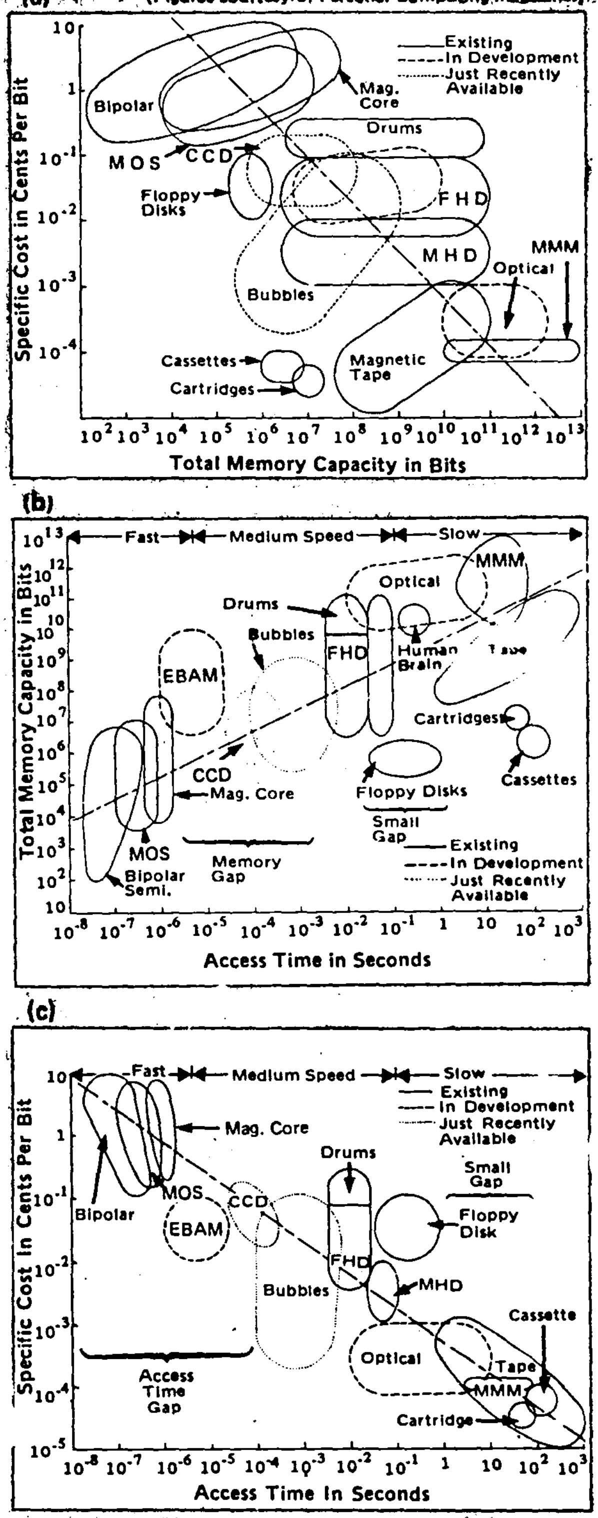
Using either the 16K RAM or 16K ROM devics shown in Table 5.2.2-1 requires about 1 sq. in. of card space per DIP; therefore a typical card of about 35 sq. in. area can contain 32K words memory. When this is compared with the 16K words required for the computer in an advanced redundant autopilot or a strapdown inertial navigator it is evident that memory, like the processor, is becoming a minor part of the airborne computer in terms of weight and volume.

A comparison of memory cost, speech, and capacity for various memory technologies is shown in Figure 5.2.2-1. Note that the human brain is relatively slow, about 1/2 sec. access time.

MEMORY DEVICE	MODEL NO.	ORGANIZATION	ACCESS TIME nanoseconds	VOLTAGE LEVELS	POWER mW OPERATING/STANDBY	COMMENTS
4K Static RAM	2141	4096 x 1	120	+5	385/110	
4K Dynamic RAM	2104	4096 x 1	350	+12,+5,-5	441/25	
16K Dynamic RAM	2116	16384 x 1	350	+5		
64K Dynamic RAM	2164	65536 x 1	350	+5		
16K ROM	2316	2K x 8	450	+5	630	
32K ROM	2332	4K x 8	300	+5	200/75	
64K ROM	2364	8K x 8	TBD	+5	TBD	
16K CCD	2416	--				
64K CCD	2464	--	285	+12,-5		130μs Latency
8K EPROM	2708	1K x 8	450	+5	800	
16K EPROM	2716	2K x 8	450	+5	525/132	
32K EPROM	2732	4K x 8	TBD	+5	TBD	

TABLE 5.2.2-1 TYPICAL SEMICONDUCTOR MEMORY DEVICES

(Figures courtesy of Personal Computing magazine.)



(a) Cost as a function of memory capacity. (b) Memory capacity as a function of access time. (c) Cost as a function of access time. MOS: Metal-Oxide Semiconductor; CCD: Charge-Coupled Devices; EBAM: Electron Beam Accessed Memories; FHD: Fixed Head Disks; MMM: Magnetic Mass Memory (magnetic tape automated library).

FIGURE 5.2.2-1

MEMORY COMPARISONS:

COST, SPEED AND

CAPACITY

5.3 INTERSYSTEM COMMUNICATION

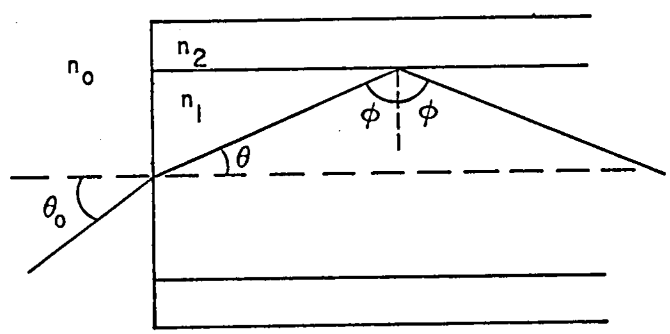
5.3.1 FIBER OPTICS

Fiber optics is the technology by which light is coupled into and transmitted from one point via a glass waveguide to another point. The light is generated at the transmitter end by an optical source such as a light emitting diode (LED) or semiconductor laser and detected at the receiving end by a photodiode (pin or avalanche). The light transmission is accomplished as illustrated in figure 5.3.1-1 by control of the difference in index of refraction (n) of the central core with respect to the cladding. In the step index fiber there is an abrupt change in the core index (n sub core > n sub cladding) with respect to the cladding index thus confining the light ray. With the achievement of low attenuation loss of the light in the fiber optics and reduction in the overall cost, fiber optics has become the forerunner as a transmission medium. Listed in figure 5.3.1-2 are many of the properties of fiber optics transmission lines that make it advantageous to use in avionics.

The major advantages, to discuss a few, are no pickup, RFI or crosstalk, eliminatiion of grounds and shorts in cabling, large bandwidths for the small size and reduced weight of the cabling as well as the high tensile strength and high temperature properties for safety requirements. All of the above properties have been demonstrated in a variety of telecommunications applications and experimental system applications for computers and avionics.

Illustrated in figure 5.3.1-3 are the three main types of fiber waveguides and the various index of refraction profiles. The step-index has the lowest bandwidth and the single mode fiber the highest. For avionic applications single fibers of the multi-mode type will probably predominate as light waveguides until Gigahertz bandwidths are required or optical switching techniques become a major requirement in data processing and handling. Fiber optics cables with a number of fibers of which each is used as an individual transmission line will probably be the main cabling technology replacing the high loss multiple fiber bundles. The multiple fibers in the cables can be used to build in redundancy, provide multiple transmission lines as well as provide spare fibers for new systems or replacements. Currently there needs to be addressed the fiber cabling technology for the development of fiber optics cables which will meet avionics systems requirements for use in an aircraft environment. As wavelength multiplexing (discussed below) becomes of age the problem of fiber optics cabling redundancy in a data bus system will reduce the fiber optics cable requirements.

In summary (since single fiber sizes are becoming standardized), it seems probable that multi-mode graded index single fiber bundles will be the transmission medium in avionic systems. Cabling suitable for aircraft environment needs further development along with couplers, transmitters and receivers which will be discussed below. It is probable that at some future time (1990-2000) single mode fiber systems and components will become available and be used in avionics. Currently much component technology (integrated optics) in the area of sources, planar waveguides, optical switching and couplers must have further development before single mode fiber optics technology becomes viable.



- TYPICAL LIGHT RAY IN A STEP REFRACTIVE INDEX FIBER.

FIGURE 5.3.1-1

SECURITY - NO SIGNAL LEAKAGE

NO PICKUP, RFI, OR CROSSTALK

NO GROUND PROBLEMS

NO SHORT CIRCUITS

USEABLE IN HAZARDOUS AREAS

LARGE BANDWIDTH FOR SIZE AND WEIGHT

SMALL SIZE, LIGHT WEIGHT, FLEXIBLE, EASE OF INSTALLATION

LOW COST

HEAT RESISTANT - VERY HIGH TEMPERATURE

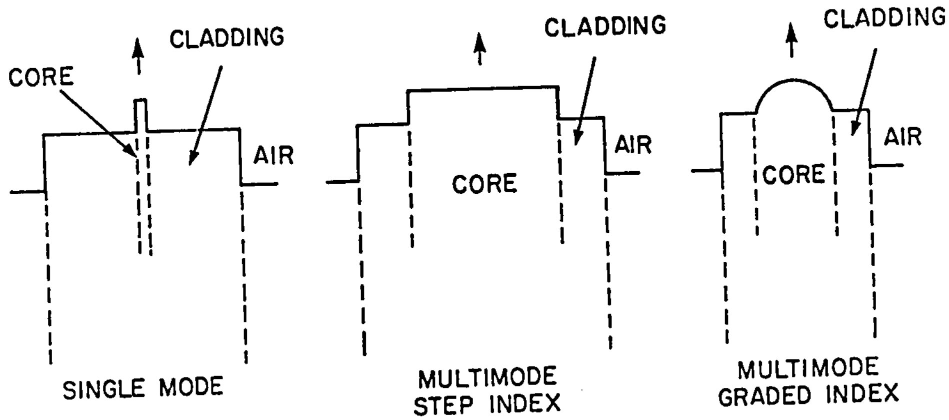
HIGH TENSILE STRENGTH

NO COPPER

NO RINGING PROBLEMS

NUCLEAR RADIATION RESISTANT

FIGURE 5.3.1-2 PROPERTIES OF FIBER OPTIC TRANSMISSION LINES



REFRACTIVE INDEX PROFILES FOR THREE TYPES OF OPTICAL FIBER.

FIGURE 5.3.1-3

5.3.1.1 Transmitters and Receivers

Transmitters and receivers are generally illustrated by the comparative example shown in figure 5.3.1.1-1. As illustrated an LED or semiconductor laser generates a light pulse due to a current pulse through the source from some type of electronic driver. The light output is coupled into a multi-mode single optical fiber wave-guide and transmitted to a receiver consisting of a p-i-n or avalanche photodiode (APD). The detector is mated to some type of impedance matching circuit, a gain stage and some type of comparator (for a digital link) to get back to the electronic system (computer, etc.). Also shown in the example is the electronic system with integrated electronic circuits and coaxial cable and the futuristic integrated optical circuits using single mode fibers.

TRANSMITTERS - Currently optical sources such as LED's of semiconductor laser (based on AlGaAs) have projected life times in excess of 10 exp. 6 and 10 exp. 5 hours respectively. This would be entirely suitable for avionics fiber optics data links and data bus requirements. Much development has gone into this area and devices are suitable for single wavelength applications. Some concern exists as to the use of the devices in wavelength multiplexing. The idea of wavelength multiplexed systems is such that multiple information could simultaneously be coupled into and out of a single fiber at discrete stations along a data bus only identified by a common wavelength selectivity. This would identify by the wavelength discrimination method which station would be talking to which, thus eliminating the time sharing, coding and clocking synchronization between all the stations and points on the data bus. Currently LED's have light emission spectrums from 300-400 Angstroms while semiconductor lasers have spectrum widths from 20-40 Angstroms. This illustrates that semiconductor lasers would provide more channels of data due to the narrow spectral width. If such systems are devised in which one station talks to another through the virtue of identification of signal by wavelength then more development work needs to be done in the area of single-mode narrow linewidth semiconductor lasers. Currently AlGaAs semiconductor lasers could satisfy the requirements for approximately 12 channels. If a greater number of channels were required, single mode narrow line width devices need further development in the AlGaAs semiconductor system or a switch to InGaAsP laser devices. These latter devices require further development in the area of lasers and photodetectors as the devices would operate in a new wavelength region in the 1-1.3 micrometer range. A further advantage of the latter system stems from the fact that the fiber optics attenuation loss would be less, data rates could be higher due to decreased dispersion and the fibers would be more radiation resistant when operated in a radiation environment. The InGaAsP lasers and photodiodes have been demonstrated but are not as highly developed as AlGaAs lasers and silicon photodiodes (silicon response falls off past 1.0 micrometers).

Many manufacturers are developing the transmitter packages which consist of an LED or laser with a pig-tail (short length of single optical fiber) attached to a coupler. The transmitter also consists of integrated drive electronics which is either compatible to a digital or analog system and operates at data rates less than 20 MHz. In terms of the avionics requirements these transmitters are either not

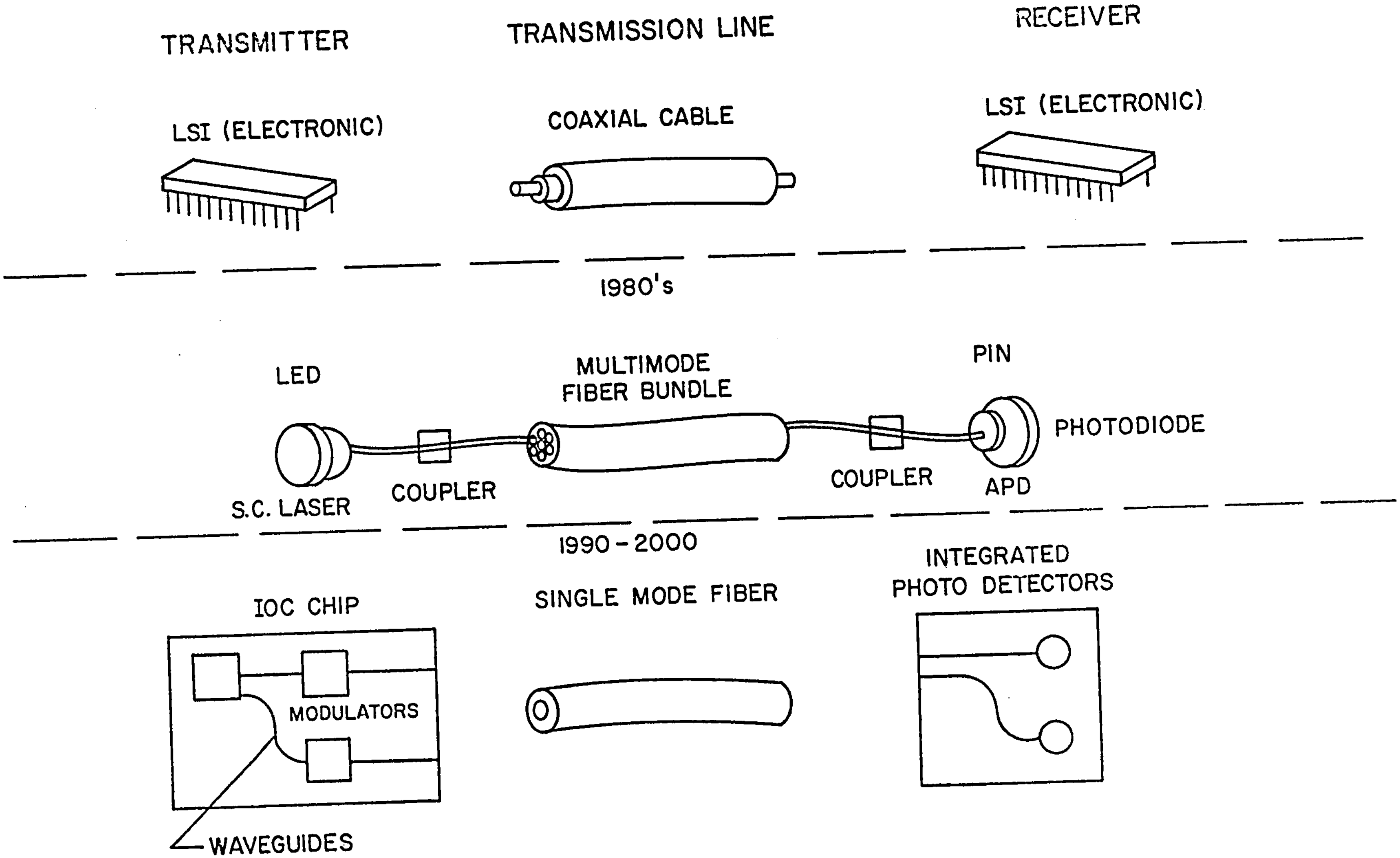


FIGURE 5.3.1.1-1 OPTICAL FIBER TRANSMITTERS & RECEIVERS

miniaturized small enough, do not have a standard and low loss single fiber connector or have not been considered for redundancy (triple or quadruple) or aeronautics use (with the exception of multiple fiber high loss bundles). Therefore, miniature transmitters need to be developed for avionic applications for use in an aircraft environment. The problem of developing different sources which emit at different wave lengths for a wave length multiplexing scheme needs to be addressed as well as the optical mixing and multiplexing techniques and components.

The assumption that has been made in this discussion is that the data bus will be digital and that voice communications and sensor input to analog-digital converters will be the part which has analog requirements. However, the exact extent of the use of digital and analog fiber optics in avionics remains to be determined in future systems analysis and design. Future development is also required in the development of integrated optical circuits (sources, switches, couplers, waveguides, mixers and multiplexers) for single mode fiber systems of the future.

RECEIVERS - Optical fiber receiver technology is sufficiently developed where 10-20 MHz receivers can be bought off the shelf. They utilize silicon p-i-n and avalanche photodiodes as the sensing element of the receiver. However,, miniaturization of these receivers still needs to be further developed, especially for avionics. For avionic applications p-i-n photodiodes are the most desirable from the standpoint of low voltage requirements. If optical sources above 1.0 micrometers are considered for use in wavelength multiplexing systems then more development effort must be provided in this area (as discussed in the transmitter section). Also the problem of triple or quadruple redundancy in receivers must be addressed for data busing.

In summary, further miniaturization techniques for redundancy need to be addressed for current fiber optics receivers. Photodetector development needs further research and development where wavelength sensitivity is required above 1.0 micrometers where silicon response falls off. This will probably require the development of photodetectors in semiconductor systems such as InGaAsP. Also the technology for single fiber connectors and couplers needs to be addressed for inputs to receivers. Integrated optical receivers also need development for future single mode optical fiber technology where high data rates and optical switching techniques are required.

5.3.1.2 Couplers

The mating together of sources, detectors, fiber optical cabling and various optical mixing components is the main source of attenuation in a fiber optics data link or data bus. Misalignment of the fibers to the source, detector, and couplers is the main problem. This alignment feature requires precision parts and active measurements to insure against unnecessary loss. State-of-the-art butt coupler loss is approximately 1 dB. However, there is just now beginning to emerge a standard diameter fiber. Until now there had been a proliferation of different types of couplers and connectors. At this point, a multi-mode single fiber coupler design is evolving with techniques for 'field' use and applications. Methods need to be further refined in which 'field' splicing and assembly of fiber connectors can be made with 1 dB loss or less. Much technology development needs to be addressed in the area where 'star' and other versions of multi-port coupling losses can be further reduced than is now achieved in the conventional 'star' coupler concept. Couplers and components for wavelength multiplexing and de-multiplexing need to be addressed as dispersion techniques at different wavelengths offer methods of reducing coupling loss in multi-port couplers. Systems analysis needs further refinements and definition to minimize attenuation loss and reduction in overall complexity of coupler and mixing components.

5.3.1.3 Applications of Fiber Optics in Aircraft

Fiber optics are now being experimentally used in a variety of military aircraft. Examples of these flight tests are discussed as follows:

YC-14 - The YC-14 aircraft is manufactured by the Boeing Company. The Electronic Flight Control System, which is manufactured by Marconi Elliott Ltd., consists of three digital computers. The communication between the computers is via fiber optics. The communications between computers is a point to point structure with NRZ data on one link and clock on a separate link. In the flight control system, 12 fiber optic links with a data rate on each link of approximately 250K bits/second are utilized. The purpose of the fiber optic communication was to obtain isolation between the computers. The system has been flown approximately 660 hours. The YC-14 is the only preproduction aircraft utilizing fiber optics

A-7 - The Navy tested fiber optics communication aboard an A-7 aircraft in the navigation and weapon delivery systems. The 115 signals of coaxial cable and wire pair were replaced by 13 fiber optic channels. A time division multiple (TDM) was incorporated for the signals in the optical system. The aircraft was flown for 100 hours and all the weapon systems on board the aircraft were demonstrated using fiber optic links. The performance of the fiber optics was satisfactory during the entire testing cycle.

RC-135 - The Air Force Avionics Laboratory is flight testing two wide-band fiber optic links onboard a RC-135 aircraft. The system has been flown over 1600 hours more than any other optical system and has performed satisfactorily. The two data transfer requirements met by fiber optics during these tests were a 30 meter link operating at 160 Mhz carrier frequency with a 20 MHz bandwidth and a video link 20 meters in length, operating with a 20 MHz bandwidth. The advantages of using fiber optics in this system are, primarily, improved bandwidth and EMC, and reduced EMI susceptibility.

P-3C - The Navy has flight tested a 10 M b/s intercomputer channel, a 30 MHz video channel, and a 40 KHz acoustic channel with a 48dB dynamic range on board a P-3C aircraft.

C-131 - The Air Force Flight Dynamic Laboratory flight tested a 500K bit per second fiber optic digital link on board a C-131 aircraft. The aircraft was used as a total inflight test simulator. The fiber optics system did not have a lengthy flight test program but it performed satisfactorily.

5.3.1.4 Fiber Optic Data Distribution Networks

Fiber optic transmission is emerging as an attractive concept in data distribution on board aircraft. Because of the wide bandwidth, light weight, and immunity to EMI and lightning characteristics, fiber optic transmission is an attractive alternative to coaxial cable and twisted pair wire. However, the state of the art of optical technology now available, limits the application of fiber optics in advanced avionic data distribution networks. All the flight tests as discussed in the preceding section, except the C-131, utilize point to point communications and do not employ data distribution networks. To data, no fiber optical data distribution busses or networks, such as MIL STD 1553A have been flight tested. As technology develops for integrated optics and for the union of integrated and fiber optics, many of the more advanced optical data distribution networks can be considered that will meet the reliability requirements of an advanced aircraft with a flight critical data distribution system. Optical networks could be implemented similar to ground based computer networks so signals can be routed through the network via fibers and integrated optical switching modes. The purpose of the network would be to improve data transmission and increase reliability by use of the redundant path between on board systems. A more advanced type of optical data distribution system would be the use of wavelength multiplexing. Wavelength multiplexing would have the potential of increasing the bandwidth and improving system reliability. In wavelength multiplexing each system would transmit data in the optical bus at a given distinct wavelength, which is different from all other transmitters. The receiver portion of the system would receive the incoming light and optically separate the wavelengths before transforming the light into electrical signals. In wavelength multiplexing, each transmitted signal is secure from all other transmitted signals garbling the messages being transmitted on the bus. The bandwidth can be increased because all transmitters can transmit at the same time.

5.3.1.5 Fiber Optics Summary Recommendations for Further Research and Development

Multi-mode single fibers with graded index profile will probably see use in multi-fiber cables for avionics. Development work and definition of cable types need to be addressed so that fiber optics cabling can be developed suitable for use in an aircraft environment. Miniaturized transmitters and receivers still need attention for further size reduction and where redundancy is required. Sources and detectors need further development for wavelength multiplexing concepts. Couplers for connecting fibers, 'star' type couplers, wavelength dispersion multiplexing components and optical mixers need more development as systems analysis and definition become more defined. In the long run, integrated optical circuits need much research and development for use with single mode optical fibers where high data rates and sophisticated optical switching techniques are required. Systems analysis of various network and data bus concepts needs to be more refined. This will help evolve the component configuration requirements especially where multiple port couplers and wavelength multiplexing are concerned.

5.3.2 BUSSING CONCEPTS

The current trend of distributed computation architecture in avionics systems brought about by the advent of low cost microprocessor technology has given rise to the problem of intra element communications. The intra element communication problem is being solved in today's and the next generation avionic system by the use of data busses.

The general philosophy of the data bus is to place all system parameters or data required by two or more elements of the distributed system on the data bus. The data is transmitted over the bus in a sequential fashion such that each user element may access that data needed. The data sequence must be coded in such a way that each user can determine that a particular data subsequence is that needed by the user. Also it is necessary for some system elements to supply sensed data or processed data to the bus. Also it is necessary for one element of the system to act as a bus controller to control and synchronize the data traffic on the bus.

The data bus normally includes three elements:

- Physical Transmission Medium
- Bus Interface Units
- Bus Supervisor (or Controller)

The transmission medium in the current generation of systems uses conductive paths or wires in a cable for the data transmission. The number of wires in the transmission medium depends upon whether the data is transmitted bit parallel or bit serial. There is a trend toward the use of fiber optics for transmission medium as discussed in section 5.3.1 for future systems.

There is also the possibility of using an RF data link as a transmission medium. The JTIDS discussed in section 6.3 and the TDMA data link discussed in section 2.3.4 are examples of using an RF data link for intra system communications.

There are three specifications which cover digital data busses and interconnections which are summarized in table 5.3.2-1. The IEEE 488 is a 16 bit parallel bus which has been considered for use in NASA Ames' Preliminary Candidate Advanced Avionics System Study. The ARINC 419 Spec is a compendium of digital interconnection used by the airlines. The MIL-STD-1553A is a serial digital bus originally adopted by the USAF for the DAIS program which is becoming the standard for military avionics applications.

Table 5.3.2-2 summarizes the key characteristics of the MIL-STD-1553A Serial Data Bus. Figure 5.3.2-1 shows the details of the 20 bit word formats for control words and data words. Figure 5.3.2-2 illustrates additional aspects of the 1553A data bus including interface lines, timing, and an approach to bus redundancy.

The IEEE 488 bus utilizes parallel data transfer and operates at a data rate of 1M byte per second, consequently it is capable of transmitting at 8 times the information rate of the 1553A bus which operates at 1M bit per second. The details of the IEEE 488 are shown in figure 5.3.2-3.

INTEL announced in September 1978 a two chip family which implements the IEEE 488 protocol and interfaces with the microprocessor bus which eliminates the requirement for special IEEE 488 software by the microprocessor (CPU). These chips are the 8291 IEEE Talker/Listener and the 8292 IEEE 488 Controller. This trend towards 'smart' peripheral chips greatly simplifies the system design and software development for distributed computer systems which utilize data busses.

Harris Semiconductor has also produced a chip which implements a portion of the MIL-STD-1553A bus interface unit (BIU) function. It is expected that in a short time a chip family which implements all of the 1553 BIU functions will be available.

The next step as VLSI and ULSI chips are developed will be to integrate the bus interface unit functions on a microprocessor chip in order to reduce the number of pins on the chip.

TABLE 5.3.2-2 KEY REQUIREMENTS OF MIL-STD-1553A SERIAL DATA BUS

- Transmission Rate: 1.0 megabit per second
- Data Transfer: Half duplex
- Multiplex Type: TDM (Time Division Multiplexing)
- Modulation Type: Serial Digital PCM (Pulse Code Modulation)
- Bus Operation: Asynchronous
- Data Code: Manchester Bi-Phase Level
- Word Size: 20 bits, consisting of:
    - Sync Waveform: 3 bits
    - Information Waveform: 16 bits
    - Parity: 1 bit
- Word Types: 3 types, consisting of:
    - Command word consisting of:
      (1) Sync: 3 bit invalid Manchester waveform
      (2) Address of one of up to 32 remote terminals: 5 bits
      (3) Transmit/Receive Command: 1 bit
      (4) Subaddress or Mode Control Command: 5 bits
      (5) Word Count: 5 bits
      (6) Parity: 1 bit
    - Data word consisting of:
      (1) Sync: 3 bit invalid Manchester waveform
      (2) Data Transmission: 16 bits
      (3) Parity: 1 bit
    - Status word consisting of:
      (1) Sync: 3 bit invalid Manchester waveform
      (2) Remote Terminal Address: 5 bits
      (3) Message Error: 1 bit
      (4) Status Codes: 9 bits
      (5) Terminal Flag: 1 bit
      (6) Parity: 1 bit
- Message Formats: 3 types, consisting of:
    - Bus controller to remote terminal transfer
    - Remote terminal to bus controller transfer
    - Remote terminal to remote terminal transfer
- Cable Length of Any Main Bus: Up to 300 ft.
- Electromagnetic Capability: MIL-E-6051 and MIL-STD-461

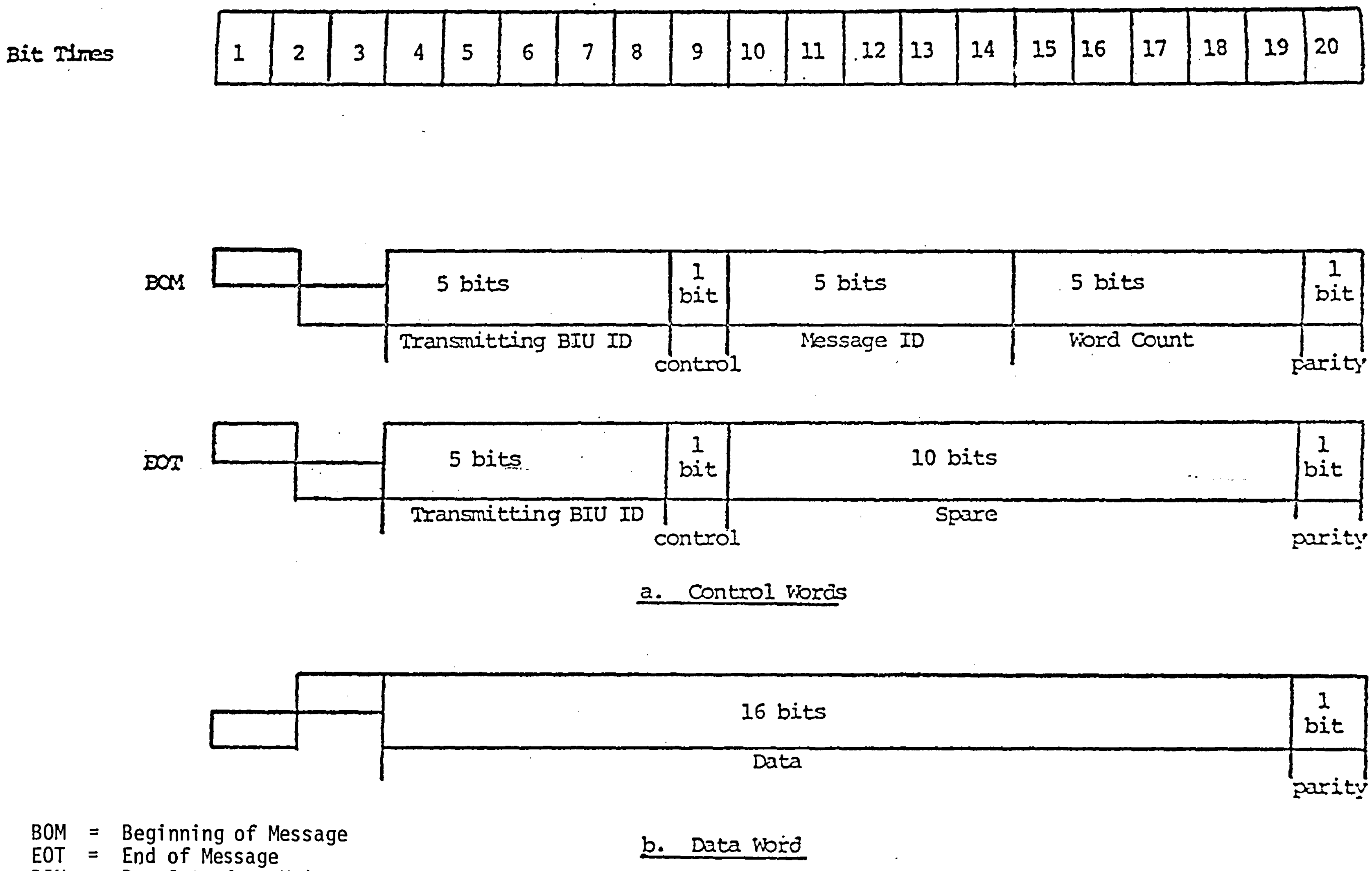
DIGITAL DATA BUSSES & INTERCONNECTION

- IEEE 488
  - 16 BIT PARALLEL, 8 BIT DATA WORDS SERIAL, 8 BIT STATUS
  - ELEMENTS ON BUS MAY BE LISTENERS, TALKERS, AND/OR CONTROLLERS
  - PROPOSED BY BOTH CONTRACTORS FOR NASA AMES ADVANCED GENERAL AVIATION AVIONICS STUDY
- ARINC SPEC 419
  - COMPENDIUM OF AIRLINE DIGITAL INTERCONNECTIONS
  - INCLUDES DIGITAL FORMATS FOR

● ARINC	561	INS
● ARINC	562/581/582	RNAV
● ARINC	568	DME
● ARINC	571	ISS
● ARINC	575	DADE
● ARINC	579	VOR

- USAF MIL STD 1553A
  - 1 MBIT/SEC, TWO WIRE SERIAL
  - 16 BIT WORD PLUS PARITY & SYNCH
  - COMMAND, DATA, & STATUS WORDS

TABLE 5.3.2-1

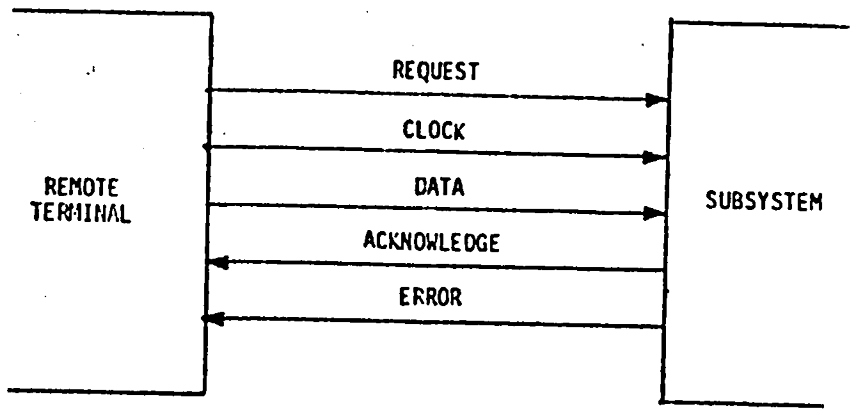


BOM = Beginning of Message
EOT = End of Message
BIU = Bus Interface Unit
ID = Identification

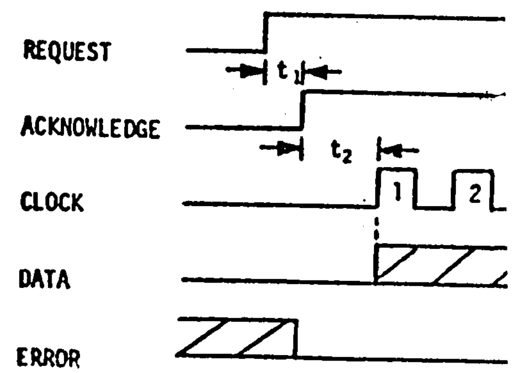
FIGURE 5.3.2-1 WORD FORMATS

MIL-STD-1553A SERIAL DIGITAL BUS

INTERFACE



TIMING



BUS REDUNDANCY APPROACH

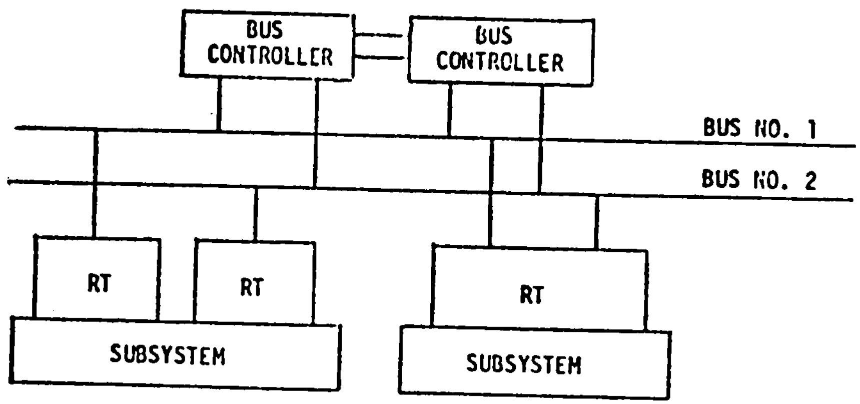
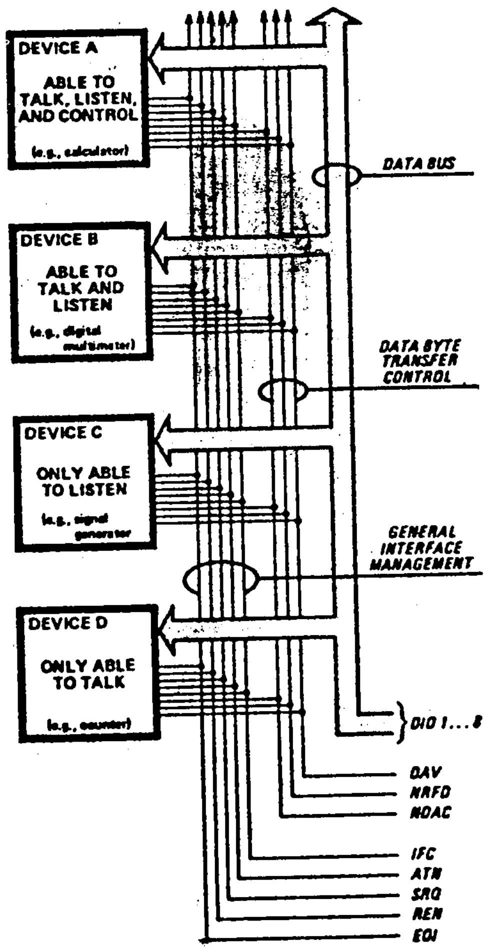


FIGURE 5.3.2-2

IEEE 488 DIGITAL INTERFACE BUS



DATA RATES

- 500,000 BYTES/SEC, 20 METERS WITH 3 STATE DRIVER, 48MA
- 1,000,000 BYTES/SEC, 10 METERS

FIGURE 5.3.2-3

5.4 EXTERNAL INTERFERENCE EFFECTS

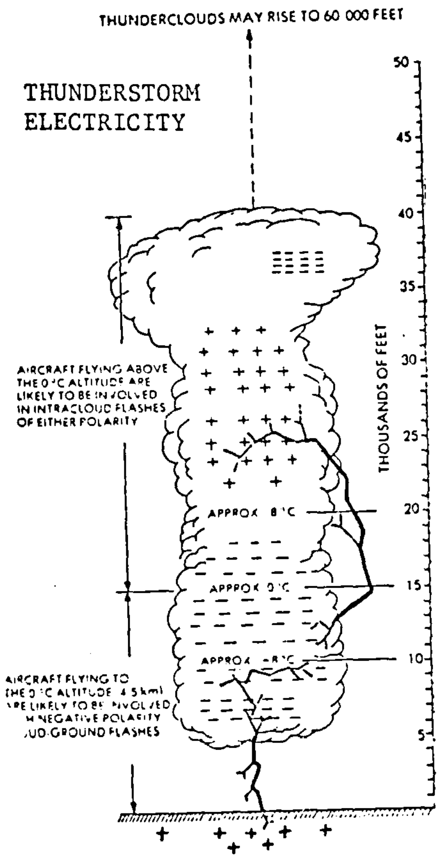
5.4.1 LIGHTNING EFFECTS ON DIGITAL AVIONICS

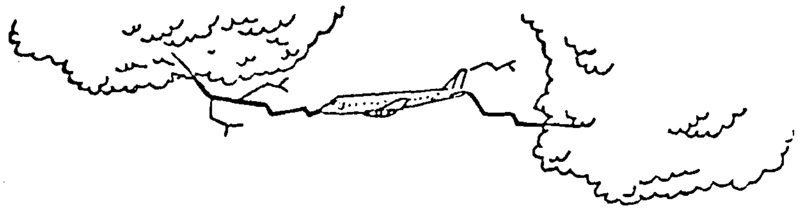
Both lightning and static electricity constitute a potentially serious threat to aircraft electrical and electronic subsystems. In particular, advanced digital avionic systems which in the near future are expected to perform a variety of advanced flight and mission critical aircraft functions must be reliably protected against the effects of voltage and current transients due to directly attached or nearby lightning discharges. The increasing use of high resistivity advanced structural materials may complicate these protection requirements.

Attached lightning can conduct very high currents up to 200,000 amperes or more (ref 79, 82, 90, 91) by direct penetration through thin skin areas, unprotected navigation light circuitry, antennas, pitot booms, radomes, etc., into the interior of an aircraft. Such currents cause serious hazards to crew and electronic, fuel or other subsystems. Even if penetration does not take place, the 'direct' or physical effects of burning, pitting, and blasting of structure may occur, constituting a potential threat to the aircraft, although these are not normally an immediate danger to avionics. Indirect effects such as induced voltage and current transients may be caused in the aircraft interior circuitry and components by lightning currents which couple magnetically to the interior through electrical apertures such as metal joints or seams, or windows, canopies, radomes and other high RF resistivity, low shielding value nonmetallic structures. The detailed behavior of lightning currents in the aircraft strike process strongly influences the magnitude of these effects. For example, capacitive charging current which occurs when the lightning leader first contacts the aircraft may change quickly enough to induce significant voltages in the aircraft circuitry. The rapidly rising currents in each of the microseconds long return strokes which make up a single lightning flash are the most important cause of induced electrical transients. Although numerous measurements have been made at the ground end of the flash, and techniques have been attempted to infer behavior higher in the channel, very little information exists concerning these important electrical characteristics of lightning at flash altitudes. Basic properties of lightning and atmospheric electricity are reviewed in figure 5.4.1-1 and table 5.4.1-1 and given in detail in ref 77-83, 86 88, and 89.

Recent airborne measurements (ref 86) indicate that near miss lightning may also produce significant induced effects approaching in magnitude those from a direct strike. Since these are probably more commonly encountered than direct strikes, they may comprise a new threat regime for sensitive digital avionics.

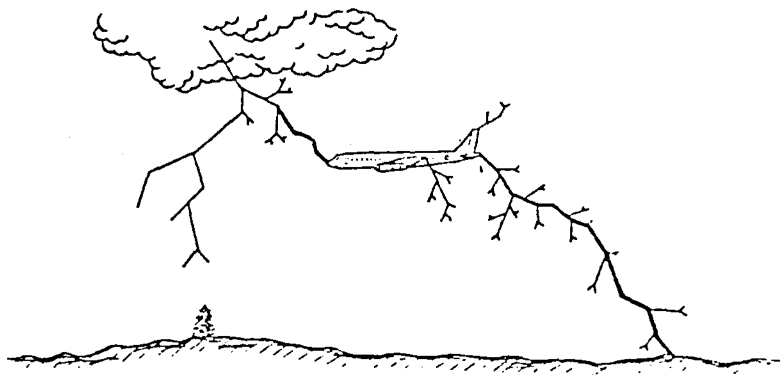
Static electrification due to aircraft passage through precipitation ('p-static'), especially in the high electric field regions found near thunderstorms, can generate corona discharge effects (ref 77, 88) which may cause interference, interruption or damage to sensitive electronics. In extreme cases penetration of canopies has occured. Furthermore, in the recent past static discharges during military aircraft in-flight refueling operations have caused digital memory dumps in on-board avionic systems.





b. INTER/INTRACLOUD LIGHTNING

c. CLOUD-TO-GROUND LIGHTNING



d. EXAMPLE OF TIME HISTORY FOR SEVERE LIGHTNING MODEL

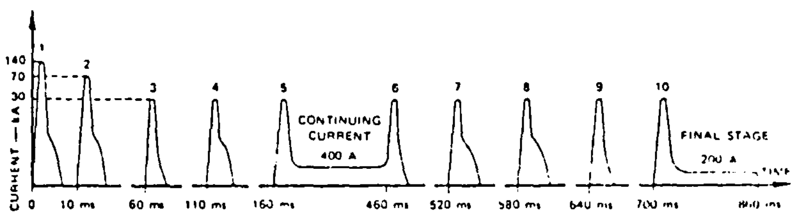


FIGURE 5.4.1-1 THUNDERSTORM LIGHTNING

TABLE 5.4.1-1 LIGHTNING CHARACTERISTICS

ELECTRICAL

- TYPES - Intra/intercloud, cloud-ground, positive, negative
- POTENTIAL - 30-100 milliion volts
- CURRENT - 20-200 thousand amps (peak)
- POWER - 10 exp 12 watts nominal (peak)
- ENERGY - 5 x 10 exp 8 joules nominal (200 lb TNT equivalent per stroke)
- EXTENT - 3-30 km/stroke (path is frequently predominantly horizontal)
- SPECTRUM - Peak energy near 10 KHz, some above 10 MHz
- DURATION -

  STROKE - 100 micro sec

  FLASH - 0.2 sec (1-20 strokes)

OCCURENCE/EFFECTS

- Worldwide phenomenon; 1 flash every 20 sec on average in a storm, 1800 storms simultaneously worldwide; activity varies with climate, season, hour, location, altitude. Turbulence generally correlated with lightning activity.
- Aircraft penetration through high electric field region may trigger lightning strike. Two or more attachment points for each strike.
- Commercial airline data - about one direct strike per aircraft annually, many nearby strikes.
- Air Force data - fewer strikes shown than commercial due to mission profiles, avoidance, reporting procedures. Much greater strike frequency in European Theater due to greater activity and route constraints. During 1968-1977 USAF aircraft dollar value losses averaged $1.5M/year by conservative official estimates.

Military aircraft are increasingly employing relaxed static stability technology. Corresponding avionic controls and digital flight control systems are undergoing design and test. The planned introduction within several years of active aileron load alleviation, (ref 97) digital flight guidance, (ref 98) autoland, and similar avionics in derivative commercial air carrier designs raises concerns for lightning and static electricity protection of digital and microelectronic systems which are obviously shared among DOD, NASA, and FAA (ref 95). These concerns relate to currently existing protection technology gaps which have inspired several joint DOD/NASA/FAA research efforts in the past two years.

The ultimate concern is to provide design guides, specifications and standards to protect aircraft electrical and microelectronic systems installed in advanced structure airframes against the effects of lightning and static electricity. This large scale effort, involving testing and demonstration of various possible protection techniques on a systems basis and formulation of generic design guides and standards should clearly be a joint interagency undertaking. The most serious current technology gap affecting this program goal is the need for additional airborne measurements of the lightning environment to define the threat parameters with greater detail and statistical confidence. These parameters are needed as inputs for current and future analytical model and simulated lightning test procedures. Beginning with the Thunderstorm Research International Program in 1976 (TRIP-76), several joint USAF/NASA airborne lightning measurement programs have been planned and executed on NASA Learjets with contract and USAF/AFFDL recording instrumentation and analysis (ref 86, 87, 96). The 1978 airborne measurement program includes AFFDL, USN/NAVAIR, and FAA participation on larger USAF and contract aircraft to continue the environmental measurement program, examine composite material electrification effects, and evaluate airborne lightning detection and avoidance equipment. To secure the required quality and quantity of airborne data, including high resolution simultaneous external field measurements, aircraft skin currents, internal transient voltages and continuous analog reference measurements, a large scale program with expanded scope will be necessary in order to make a meaningful impact. Such a program is under consideration for joint Air Force, USN, NASA and FAA support. The aircraft should be cleared to fly in a thunderstorm environment and to take direct strikes. Such environmental data, including results of aircraft lightning triggering efforts, are prerequisite to development of test specifications model inputs and lightning avoidance techniques. These two efforts, the in-flight lightning environmental measurement research program, and the systems hardening demonstration and design guide development program for advanced technology aircraft merit and require joint Air Force and NASA support (with participation by other concerned agencies, such as NOAA and FAA).

Toward the goal of providing lightning protection design guidance and standards for new technology aircraft, additional effort is also required in the areas of direct effects testing techniques and for induced effects testing and analytical modeling.

5.4.1.1 Direct Effects

Advances have been made recently in simulation and demonstration of lightning attachment accoustic shock, or blast effects (ref 93) the mode in which apparently the majority of lightning energy is dissipated. Acoustic shock effects can damage structure, spring hatches and possibly affect jet engine operation.

Advances have also been made in techniques and generators for simulating natural direct strike attachment conditions for large test specimens. Although a number of Government and industry facilities are capable of producing a 200,000 Ampere discharge with the standard 2 microsec rise time and 50 microsec half amplitude decay time this test is normally limited to aircraft components such as wing sections, because large structures load the impulse generator. A new high voltage generator has permitted use of arc lengths in excess of 40 feet, compared with the more normal 6 to 12 feet. It provides a continuous, high repetition rate (2000-4000 Hz) electromagnetic field environment, which promotes streamering and is thought to more closely simulate actual aircraft lightning attachment phenomena, aiding determination of the distribution of protection required to prevent aircraft skin penetration by high currents.

5.4.1.2 Indirect Effects

Although the technology to prevent damage to subsystems from direct penetration of lightning currents has been rather well developed over the years, the same is not fully true of the more subtle indirect, or induced lightning effects. The induced effect mechanisim is illustrated in Figure 5.4.1.2-1. A considerable body of component susceptibility data, protection methodology and analytical modeling theory and practice is, however, essentially transferable from research sponsored by the Defense Nuclear Agency and Air Force Weapons Laboratory for protection of aircraft and systems against the Nuclear Electromagnetic Pulse (NEMP) generated by an atmospheric nuclear detonation. In conjunction with the 1977 in-flight measurement program a contract effort was undertaken to model the Learjet interaction with nearby lightning signals and its response to the standard, nondestructive Lightning Transient Analysis (LTA) ground test performed by AFFDL/FES personnel. Although limited by low thunderstorm activity, the analytical model predicted measured transient voltages induced in aircraft wiring within useful tolerances of about 6dB (ref 96). Analytical modeling is expected to provide a valuable interpretive capability and adjunct for lightning susceptibility assessment when used with traditional laboratory test techniques such as the LTA and related simulation test techniques. A typical test configuration is shown in figure 5.4.1.2-2. Originally developed under NASA sponsorship in the late 1960's, the LTA test technique has been modified and refined under the sponsorship of the Air Force to include modern computerized digital multichannel recording and spectral analysis techniques and fiber opptic data links. A recent experimental and theoretical investigation (ref 94) has essentially confirmed as valid several assumptions which had been the source of some concern: (1) That a ground test can accurately produce the aircraft response caused by natural lightning, (2) that lightning energy leaks into the aircraft through electrical apertures, and (3) that the 'system' responds

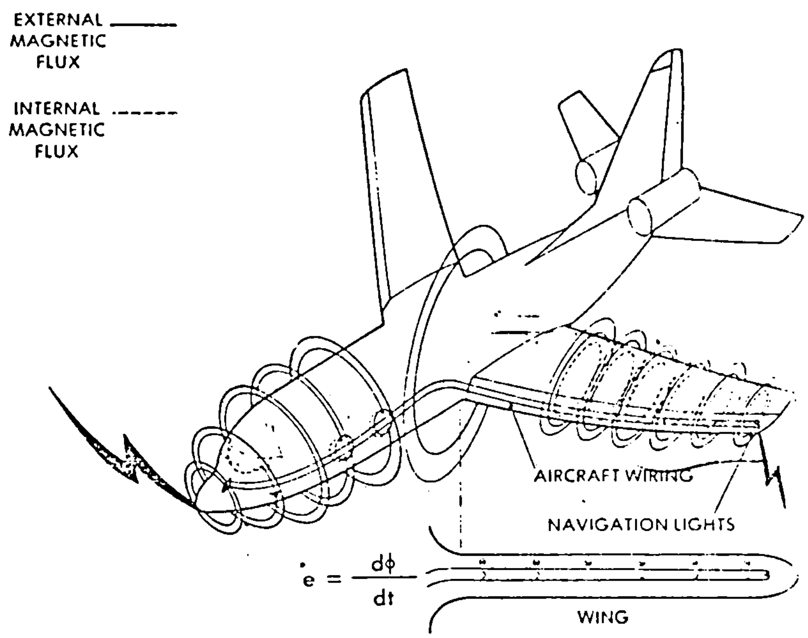


FIGURE 5.4.1.2-1 MAGNETIC FLUX PENETRATION AND INDUCED VOLTAGES IN ELECTRICAL WIRING

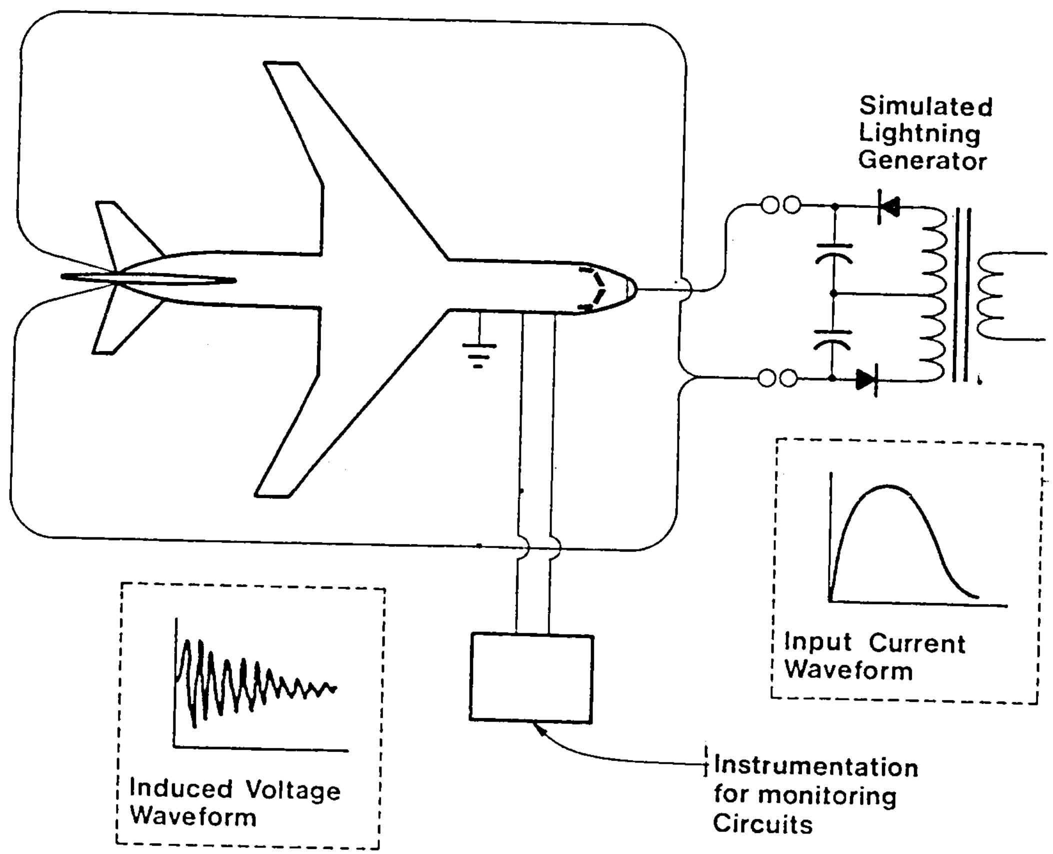


FIGURE 5.4.1.2-2 SIMULATED LIGHTNING TESTING SET-UP

linearly to the input, allowing low level, nondestructive test results to be scaled to any desired threat level. Efforts to define a version of this test as an industry standard are continuing in the Society of Automotive Engineers (SAE) committee AE4L on Lightning Test Techniques.

5.4.2 ELECTROMAGNETIC INTERFERENCE

The control of interference effects on B-1 electronics has been successful using present technology for integration and interfacing.

Suppression or elimination of conducted or radiated interference has been the objective at the interference source, in the coupling path and the receiving circuits. Present technology using filters, shielding, wire twist and shielding, bonding and grounding concepts have been successfully applied as part of the normal design process to meet specified EMI requirements for interference and susceptibility.

One significant design concept used to control EMI was the use of a two (2) wire power distribution system. Power was provided to the using system and load currents were all returned to a single point power ground, thereby eliminating interfering power currents through the vehicle structure. The signal and chassis grounds for each electronic system used the immediate structure support and interfacing systems used differential signals to isolate signal grounds and limit effects of common mode pulses.

Electromagnetic pulses (EMP) generated from a source external to the aircraft are being attenuated by shielded electronic bays and conduits. Additionally, the interfacing circuits contain circuit hardening and devices which limit voltage and current. Analysis and component testing have been completed to date to verify the detail design. A total system aircraft EMP test is scheduled in 1981.

INTERFERENCE BY POWER SUPPLY SYSTEM AND OTHER SYSTEMS. The control of interference caused by the power system or other systems tied to a common bus has been accomplished by (1) providing power in accordance with design requirements and designing the using systems to operate within the acceptable bands for transients and steady state power and (2) suppressing interference generated on the power bus by other systems.

Early program experience caused concern over power system transients interfering with digital systems, however the transient was usually caused by a power system failure or a design deficiency that was identified and subsequently corrected in the using system.

Although transients and related reactions of digital systems have been corrected, it is clearly evident that the application of digital mechanizations to critical systems such as flight controls or air induction controls is an area of concern. If safety is a design requirement, the power transient must be clearly eliminated as a single source capable of inducing or inhibiting control reactions in the using system or power sources must include reliable functions which are free from transients.

5.4.3 POWER SUPPLY SYSTEMS

Very little electrical power technology development has been done with the main intent of protecting against external interference effects. The Air Force Aerospace Power Division, Aero Propulsion Laboratory, is planning an FY-79 program to investigate the means of protecting aircraft electrical systems from electromagnetic hazards such as atmospheric lightning. This is of increasng importance as the trend in aircraft skin and structures moves toward the use of more composite materials, thereby reducing the metal skin and structure electrical interference grounding/ shielding effect. Emphasis will be placed upon design criteria for minimizing the hazard to the electrical power system from atmospheric electrical disturbances and compatibility of the electrical system with composite structure aircraft. Induced disturbances will be determined and protection techniques developed to minimize the loss of electrical power. Design criteria will be verified through tests.

The application of fiber optic technology to control circuits for controlling multiplexed solid state aircraft electrical power generation and distribution systems needs to be investigated. Fiber optic technology offers a substantial reduction in aircraft copper wire costs. Also, the fibers are immune to EMI, EMP, and cross-talk and offer a greater flexibility in control signal cable routing due to their nonsparking quality. This technology is directly applicable to composite materials aircraft for improved lightning protection.

The trend in advanced aircraft electrical power generation systems is toward the variable speed constant frequency (VSCF) system. The high life cycle cost hydro-mechanical constant speed drive (CSD) is eliminated and the electrical generator is driven directly off the gearbox or generator pad varying in speed with the engine speed. The generator produced wild frequency is converted to a high quality 400 Hz or D.C. for supplying the main electrical bus. Present VSCF converters using the cycloconverter principle are extremely complex and are severely penalized in weight, volume, and reliability. A pulse width modulated converter for permanent magnet generator VSCF systems could potentially minimize those penalties. There is a need, also, to develop high voltage transient resistant silicon controlled rectifiers (SCR's) for application in the permanent magnet generator variable speed constant frequency converters. Present SCR's lack sufficient voltage transient capability - resulting in excessive weight, size and power dissipation in the converters.

Most recent development activity in advanced electrical power distribution systems has emphasized solid state distribution and electrical multiplex (E-MUX) technology. Work is underway to develop the technology necessary to maximize solid state techniques in electrical power distribution systems. Advanced solid state power controllers are under development with special emphasis being placed upon high current aircraft power controllers.

In a future planned program an electrical system will be designed for an advanced fighter/attack aircraft which ties together the electrical power control function with an avionics data system. The E-MUX control system will be integrated with a central aircraft integrated avionics data bus and will incorporate advanced concepts such as microprocessor controlled multiplex remote terminals. An electrical system simulator will be used to demonstrate the design performance by conducting 'real time' tests of the electrical system including generators, control systems and loads.

6.0 MILITARY TECHNOLOGY

Military Avionics Technology has an indirect connection to the NASA role which couples through common mechanization elements such as digital processing components and through common system technologies such as modern software development methods.

This SOAS report has included selected military technology areas because of the potential technology transfer from the military to the NASA mission.

6.1 SURVEILLANCE DETECTION AND WARNING

6.1.1 RADAR HOMING AND WARNING

The original requirement, filled by the RHAW systems, was the need for a warning to pilots that they were being illuminated by a threat radar. These radars initially included the Soviet SA-2 surface-to-air missile radar system (i.e., FAN SONG) and the FIREWHEEL triple A's, plus other types such as FIRE CAN and WHIFF. As the Soviets expanded their SAM and AAA capabilities, the U.S. military and the electronics industry updated the RHAW systems to include recognition circuits, expanded RF coverage and improved the pilot displays mostly using analog processors.

The first RHAW installed in aircraft were intended to alert the pilot in a timely fashion, such that he could maneuver his aircraft out of "harm's way". The following generations of RHAWs have included very sophisticated digital processors, RF determination circuitry and angle-of-arrival capabilities. These were in response to requirements to

- Perform very precise maneuvers to avoid worst threat environments
- Attack and suppress air defense radars and networks
- Provide electronic order of battle updates to defensive ECM subsystems
- Effect power management in active counter measure subsystems.

Tomorrow's problem is being demonstrated today in Soviet maneuvers and training excercises. These improvements are based on yesterday's results of tests conducted in Vietnam, the Middle East, and during the Czechoslavakian invasion. Based on DoD's current assessment and forecasts, we will be operating against (without adjectives) a massive number of threat emitters; extensive netting of fixed and mobile resources; improved, mobile, radiator and weapon combined systems; passive alternate sensors; emitters with advanced conceptual innovations (monopulse, multiple, simultaneous frequencies with agility, PRF agility, polarization diversity, etc.); and a protected command, control and communication capability.

The RHAW designer of tomorrow must consider the density of friendly emitters and their contribution to the dynamics of the RF environment. In addition, in the hot war scenarios which have been forcasted, he will find the so-called friendly emitters being utilized by non-firendly forces. The current RHAW systems and those well into development are ill prepared to operated under these conditions. Additional processing time and filtering to address this problem will be detrimental to the response time (crew and aircraft response time) or a decision to maneuver and/or jam and attack.

The studies of the future requirements and their determination resolution have been focusing on the complexity of the environment and the other forementioned concerns. However, a most significant problem is the silence modes. Such as, when the threat radar remains passive using E-O of netting data from other radars. An additional problem is the latest SA-2 modifications which are still not fully understood, but the U.S. systems must be flexible enough to adapt to these innovative improvements in the Soviet systems. Such as remoting the transmitter from the receiving subsystems, a bistatic technique being developed by the DoD. The requirement for our penetrating strike aircraft to remain silent introduces a requirement for passive ranging to locate the threat emitters for avoidace in a dense environment. Passive deployment of weapons, such as the need on the "Wild Weasel" type missions, sets a second requirement for passive ranging. Air-to-air combat is a third.

However, depending on our aircraft weapon's integrated sensors, the overall RF and DF accuracy may not be extremely tight parameters for a RHAW-type system. The RF coverage, however, must be assessed again at this time. The trend forcasted is pushing the limits up and down, but for different reasons.

The RF utilization movement into the K-band regions (20,000 to 40,000 MHz) is anticipated because of the operational advantage in its short range effectiveness. Here, it is believed that the Soviets will have a target acquisition equipment capability prior to the DoD and the industry RHAW designer's sensing the need to cover that portion of the band. Soviet GCA radars are already operational in this spectral region, but only a few of the U.S. intelligence collection systems have been expanded to cover the 20 to 40 GHz regions. The Yom Kippur War exposed many innovative weapon systems and surprises in their efficient use. When the U.S.-USSR confraontation starts, we must be ready for new innovations and surprises.

It is not clear to the writer if NASA interests lie in this area of equipment developemnt. However, it is recommended that the techniques for passive ranging could be and should be considered. The need for RF silence (keep the radar, communications, altimiter and DME equipment in the off mode) is a very pressing requirement, but very difficult to implement. As the RF band becomes more dense, the more difficult it will be to have positive air control and to find a safe solution in emergencies when one's emitters have failed.

6.2 IFF & ECM

6.2.1 IFF INTERROGATORS AND TRANSPONDERS

IFF SYSTEM OPERATIONS

Identification, Friend or Foe (IFF) systems were originally developed for military use, for the purpose the name implies, i.e., identification of targets, depicted on a search radar, into categories of friend or foe. Since the original concept, the technique has also been applied to air traffic control. The IFF Beacon System is becoming the primary means of aircraft location for the Air Traffic Control (ATC) system. In the major traffic areas, the radar beacon system is the prime input to fully automated ATC surveillance systems. Automation of ATC for both civil and military use has focused attention on all performance characteristics of the system. Where performance deficiencies have been identified, a considerable amount of effort has been expended to upgrade system performance. Coordination of the effort for both civil and military requirements has been under the direction of the DoD AIMS program office.

AIMS PROGRAM BACKGROUND

The term AIMS is anacronym of acronyms. The A stands for ATCRBS which is taken from Air Traffic Control Radar Beacon System; I stands for IFF, Identification Friend or Foe; M represents the Mark XII identification system; and S for Systems reflects the many diverse AIMS configurations.

In 1961 President Kennedy directed that the Federal Aviation Administration (FAA) set up 'Project Beacon' to 'conduct a scientific, engineering review of our aviation facilities and related research and development;' and also to 'prepare a practicable long-range plan to ensure efficient and safe control of all air traffic within the United States.' Upon receipt of the Project Beacon report, the President, in November 1961, asked the FAA Administrator to 'begin at once to carry out those recommendations of the report which you believe will move the airways program forward rapidly and efficiently.' Recommendations included automatic aircraft altitude reporting to the ground controllers and an increase of identity coding capability . As a result of Project Beacon, FAA initiated a comprehensive long range system program for improving the utilization and control of the Nation's airspace.

In 1963, the Department of Defense (DoD) joined with the FAA in the implementation of ATCRBS for attainment of 4096 code and altitude reporting capabilities. The DoD AIMS Program, as directed for implementation by the Secretary of Defense, satifies two primary requirements - improved air traffic control (ATCRBS) and a secure military identification system (Mark XII). The ATCRBS portion of the program required DoD participation in the first phase of the FAA plan to upgrade peacetime operational use of the national airspace. Under ATCRBS most military aircraft are equipped with new electronic equipment which gives additional identification and altitude data to ground air traffic control stations. It also results in a major improvement of military air traffic control, including those facilities in overseas areas. Mark XII was designed to satisfy the military operational requirements for a positive identification system through the use of special military equipments.

The DoD AIMS Program was the first major equipment/subsystem program involving tri-service implementation managed by a single department. DoD designated the Air Force as Executive Agent for the AIMS program. Other participating organizations incuded the Army, Navy, National Security Agency (NSA), and the FAA.

The DoD AIMS system functions in accordance with the U.S. National Standard for the IFF Mark X (SIF) Air Traffic Control Radar Beacon System (ATCRBS) characteristics. The most significant program objectives were: standardization of essential system characteristics, generally improved IFF equipment, common specifications for equipment procurement, tri-service coordinated time phase implementation plans, a minimum number of models of equipment (commonality), a maximum use of existing facilities and resources of all services, and a coordinated development program to eliminate unnecessary duplications.

SYSTEM EQUIPMENT DESCRIPTION

The AIMS system consists of IFF transponders, IFF interrogators, altitude computers, servoed altimeters, controls, and other associated equipment. Interrogators are included in most AIMS equipped ground and surface sites, in tactical ground and surface systems, and in certain special task aircraft . Interrogators may or may not be associated with, or slaved to, a primary radar. A typical AIMS interrogator subsystem consists of a: Receiver-transmitter; synchronizer, data processor, displays, controls, antennas, and special military equipment as applicable. The transponders are utilized primarily on aircraft and perform the reply or 'answer' function to the interrogations. A typical AIMS transponder subsystem consists of a: receiver transmitter; control, in-flight test set, associated mountings, antennas, and special military equipment as applicable. A typical AIMS altimetry subsystem, working in conjunction with the transponder set to provide altitude reporting, would include a servoed altimeter, an altitude computer/encoder or central air data computer (CADC), and compensated pitot static tubes. Appropriate test equipment to service the airborne and ground/surface equipment are also provided as a part of the AIMS systems.

In system operation, the ground-based equipment transmits a train of interrogation pulses, through a directional antenna, which are received by an airborne transponder. Upon determination of proper coding, the aircraft automatically retransmits a coded identity signal. The signal is received by the directional antenna, and is transmitted to the receiver which processes this return and displays it either on the radar scope or on a separate indicator.

A system of this type provides accurate aircraft position with respect to the ground site.

NEW IFF BEACON SYSTEM DEVELOPMENTS

The USAF has recently initiated two major radar development programs to replace the existing surveillance and early warning radar sites in Alaska. These programs are titled Seek Frost and Seek Igloo, respectively. The main thrust of these programs is to achieve a very low life cycle (LLC) for the new systems by increasing reliability and reducing maintenance requirements and personnel. Each of these radar development programs contains requirements for IFF functional performance that necessitate the generation of an advanced IFF ground interrogator system design. Each advanced IFF system will provide both civil and military MARK XII interrogation capability and other functional performance, in accordance with DoT FAA and DoD AIMS requirements. Other operational requirements for each of the two IFF systems are vastly different. At the present time, however, neither of these systems operational specifications contains a requirement for DABS compatibility for future implementation of the new IFF system concept.

The Seek Frost program is for the development of a 2D short range early warning unattended radar (UAR) system. Its associated IFF radar subsystem must be an extremely reliable, fault-tolerant design capable of operating without maintenance for extended periods of time. A major constraint on the total UAR system design is that the maximum primary input power must not exceed 500 watts. The IFF system will be allotted only a portion of the input power to perform its functions. Consequently, it is anticipated that both the main UAR and IFF radar antennas will be electronically scanned in azimuth to conserve the primary input power. All circuit design techniques utilized in the IFF system must be fault-tolerant and extremely efficient for the system to achieve its goal of unattended operation for long periods of time. BITE will be used in this IFF system to automatically sense performance degradation, activate standby redundant modules and report system status to a remote location.

The Seek Igloo program is for the development of a 3D long-range surveillance, minimally attended radar (MAR) system. Its associated IFF subsystem does not have a restriction on primary input power, but it also must be a very reliable (MTBF more than 50,000 hours) and easily mantained configuration. High system availability will be provided by fault-tolerant design with self-correcting redundancy at the system and subsystem levels. Extensive use of the microprocessor controlled BITE for automatic switchover and fault isolation to minimize maintenance time is required. The IFF signal processor for the MAR system is required to perform target extraction and correlation functions for all modes, including the secure military mode, in a severe signal environment that includes ECM and multipath. The IFF processor will also quantize and digitize the IFF target information for correlation with the surveillance target information in the main radar processor.

Figure 6.2.1-1 shows a modern IFF interrogator block diagram that is typical of those proposed for the MAR and UAR programs. This system includes the secure military (Mode 4) operational capability. The total IFF Beacon system consists of two complete interrogators with BITE monitoring and automatic switch-over.

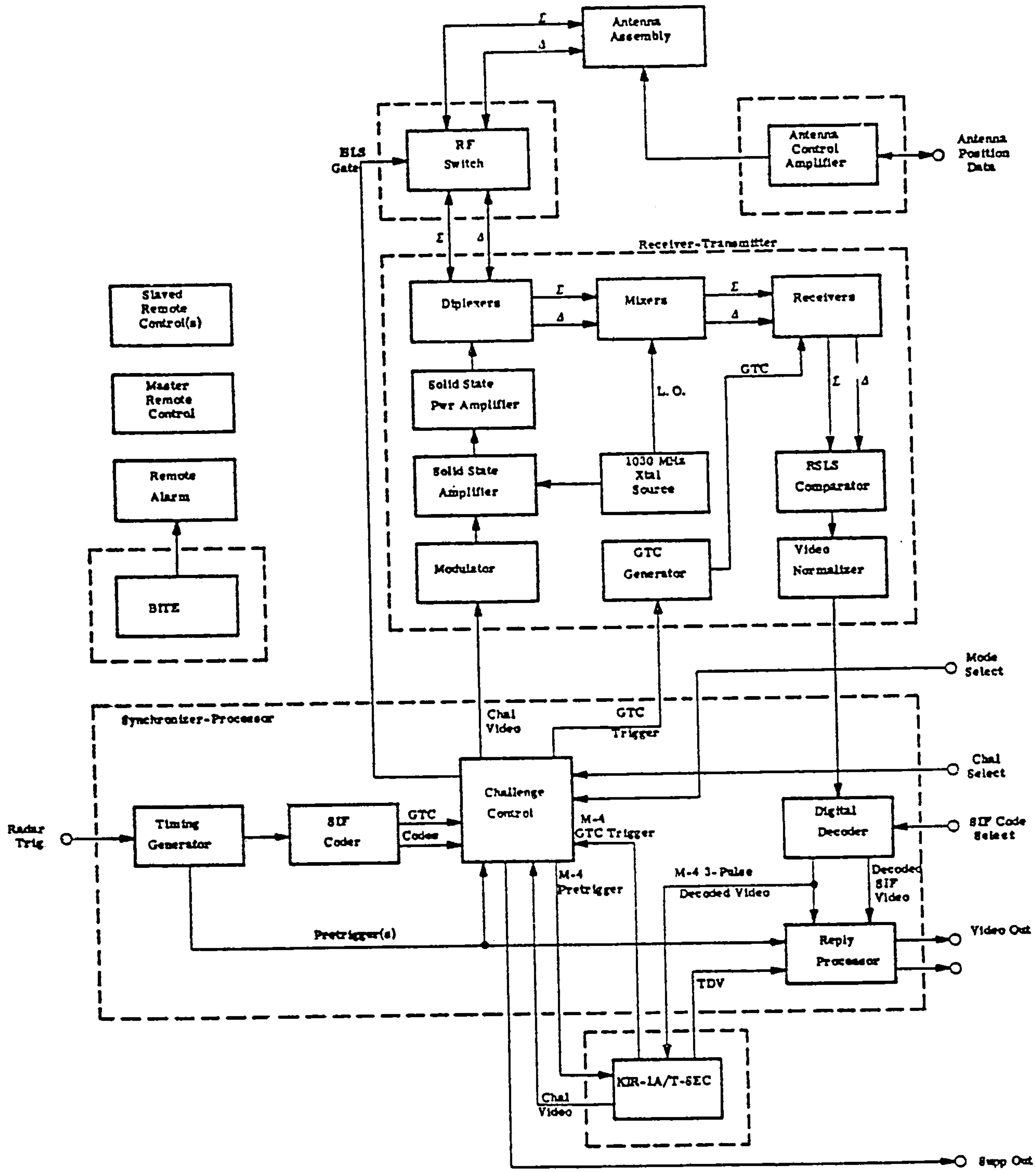


Figure 6.2.1-1 Advanced Ground Based IFF Interogator Block Diagram

IFF TECHNOLOGY ADVANCES

Several technology advances are expected to result from the development of these two IFF systems. Common to both systems is the requirement for a transmitter that can operate for a long period of time without failure. To achieve this, a solid state, fault-tolerant transmitter design will replace the unreliable and inefficient tube design that is presently being used on older equipment. Solid state transmitters will utilize modular arrays of identical RF power modules with independent DC power sources that are inherently fault-tolerant. When an RF module fails, and a reduction in total transmitter output is not allowed, the array will contain M active modules and the N standby modules. BITE circuitry will monitor individual M/N module status and activate the N standby modules as required, to restore full transmitter output power. The BITE circuitry will also report module status for maintenance action to replace the failed module, thus restoring the original M/N module ratio and maintaining a constant confidence level in the operational availability of the transmitter subsystem.

An additional area where BITE-controlled M/N architecture will be utilized is the IFF digital signal processor. The digital processor will incorporate M + N identical redundant channels of hardware to effect specific signal processing functions. Only M channels are needed for full function performance, with N additional channels provided as standbys and which can be switched on line in case of M channel failures. This approach in the extreme, can provide an infinitesimal probability of function failure The actual number of N channels employed, however, would be selected to yield the required reliability at minimum cost.

Figure 6.2.1-2 shows a typical modern IFF beacon processor block diagram incorporating microprocessor architecture for signal processing, BITE processing and I/O control. This subsystem is designed to interface with the main radar signal processing computer for target correlation.

ADVANCED IFF BEACON SYSTEM ANTENNA DEVELOPMENT

The performance of the IFF Beacon system has until recently been limited by the use of conventional linear array antennas and associated omnidirectional antennas utilized for sidelobe suppression (SLS). The conventional linear array (the hogtrough or boom antenna) has a serious performance limitation due to its limited vertical aperture. The small vertical aperture provides a broad vertical pattern that strongly illuminates the ground in front of the antenna. As a result, at many sites located in flat open areas, there is very pronounced vertical lobing which causes signal loss in the lobe nulls and excess interrogations in the lobe peaks.

To avoid signal loss in the deep nulls, the system power and receiver sensitivity must be increased, thus resulting in more false targets from hills, buildings, fences, and other reflecting structures.

An additional problem with the conventional IFF beacon antenna configuration is the use of an omnidirectional antenna for SLS. The problem arises due to the proximity of the omnidirectional antenna with

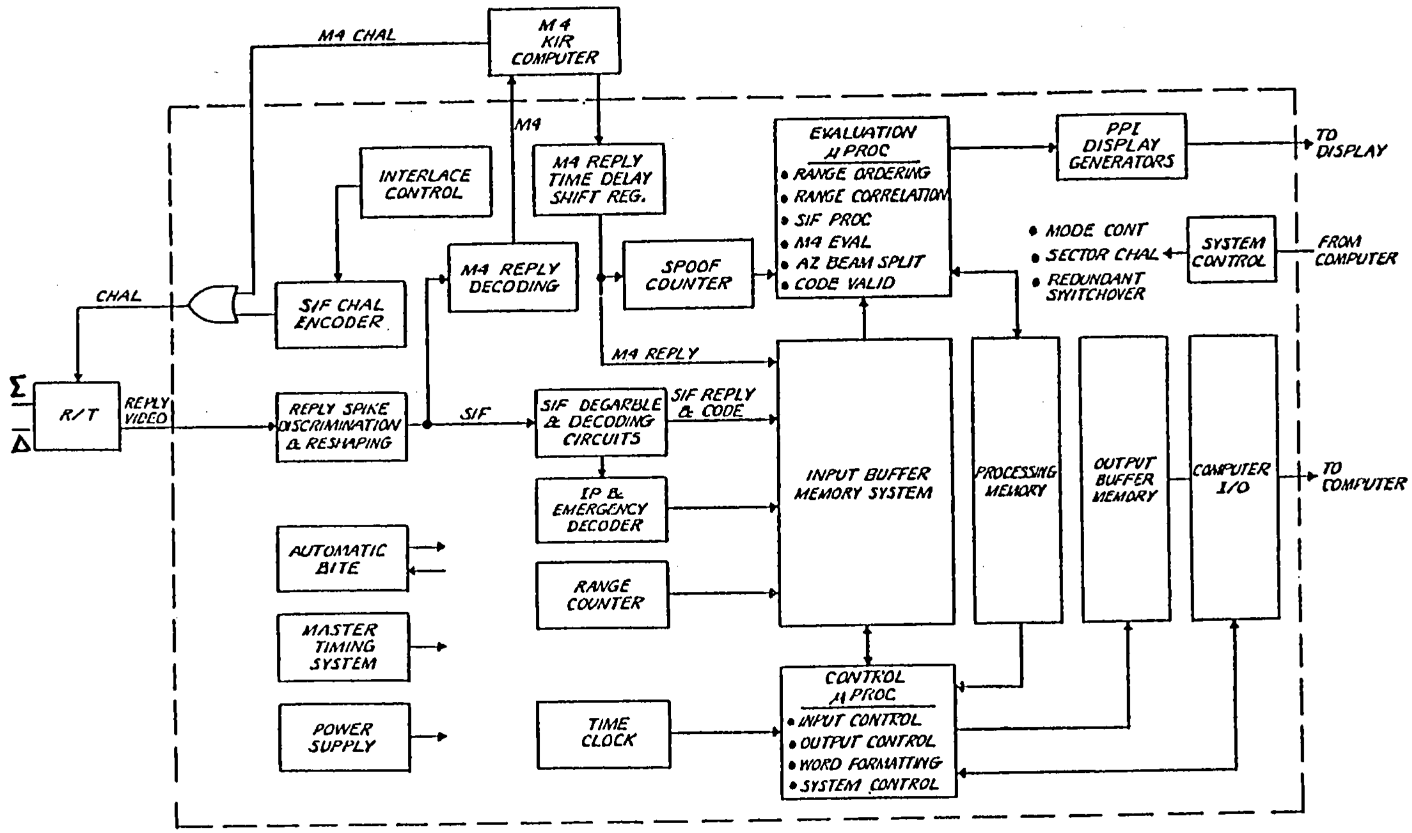


Figure 6.2.1-2 Typical Beacon Processor

respect to the directional antenna. When the omnidirectional antenna is mounted above the directional one , the two antennas yield vertical lobing patterns having different periodicities. The result can be improper operation of the SLS system at particular low angles. There is no way to avoid this differential vertical lobing with one antenna above the other. The differential vertical lobing can be avoided if the two antennas are placed side-by-side, but this either causes blocking, if the antennas are close to each other, or causes pulse timing differences, reflection zone differences and siting problems if the antennas are far apart. A basic solution to the problem is to radiate the SLS pattern from an aperture integral with that of the directive pattern.

A recent antenna development, called the open planar array, has characteristics that significantly reduce these effects and improves IFF beacon system performance. The open planar array has a large vertical aperture that yields an elevation pattern with a sharp cutoff at the horizon. This provides a major increase of the signal strength in lobing nulls at the critical low elevation angles and substantially alleviates the problem of missed targets in the nulls. A corresponding decrease in the lobing peaks reduces the beacon system interference problem that occurs when several interceptors are operating in the same region.

Another significant benefit resulting from the sharp cutoff elevation pattern is the major reduction of false targets that are caused by reflecting obstacles near the horizon. Additional benefits are a major reduction of multiple, in-line false targets caused by reply reflections from distant rising ground and a major reduction of azimuth splits and angle errors caused by reflections from hilly terrain or laterally sloping ground. The open planar array antennas use a sum and difference pattern technique.

The open planar array antennas provide a sum and difference monopulse pattern for increased azimuth accuracy. The open planar array antennas also have monopulse difference patterns that are excited independently from the normal directional sum pattern. This allows the formation of an optimum difference pattern with high angular accuracy and very low sidelobes. The monopulse difference pattern also provides the means of implementing an integral SLS pattern. The integral SLS pattern avoids the differential vertical lobing, blocking and timing problems that occur when a separate omnidirectional antenna for sidelobe suppression is used.

DEVELOPMENTS

A design and development program to replace the AN/APX-76 IFF air-to-air interrogator with a new design, designated AN/APX-104(V), is also in process. A significant portion of this program is the design and development of a solid state transmitter array to replace the tube version used in the APX-76. Siemens of Germany and Hazeltine in the U.S. are each developing competitive designs for the APX-104. Hazeltine has developed its own solid state transmitter array and is presently involved in qualification testing of its version of the APX-104 receiver-transmitter (R/T) unit, including the array. Teledyne

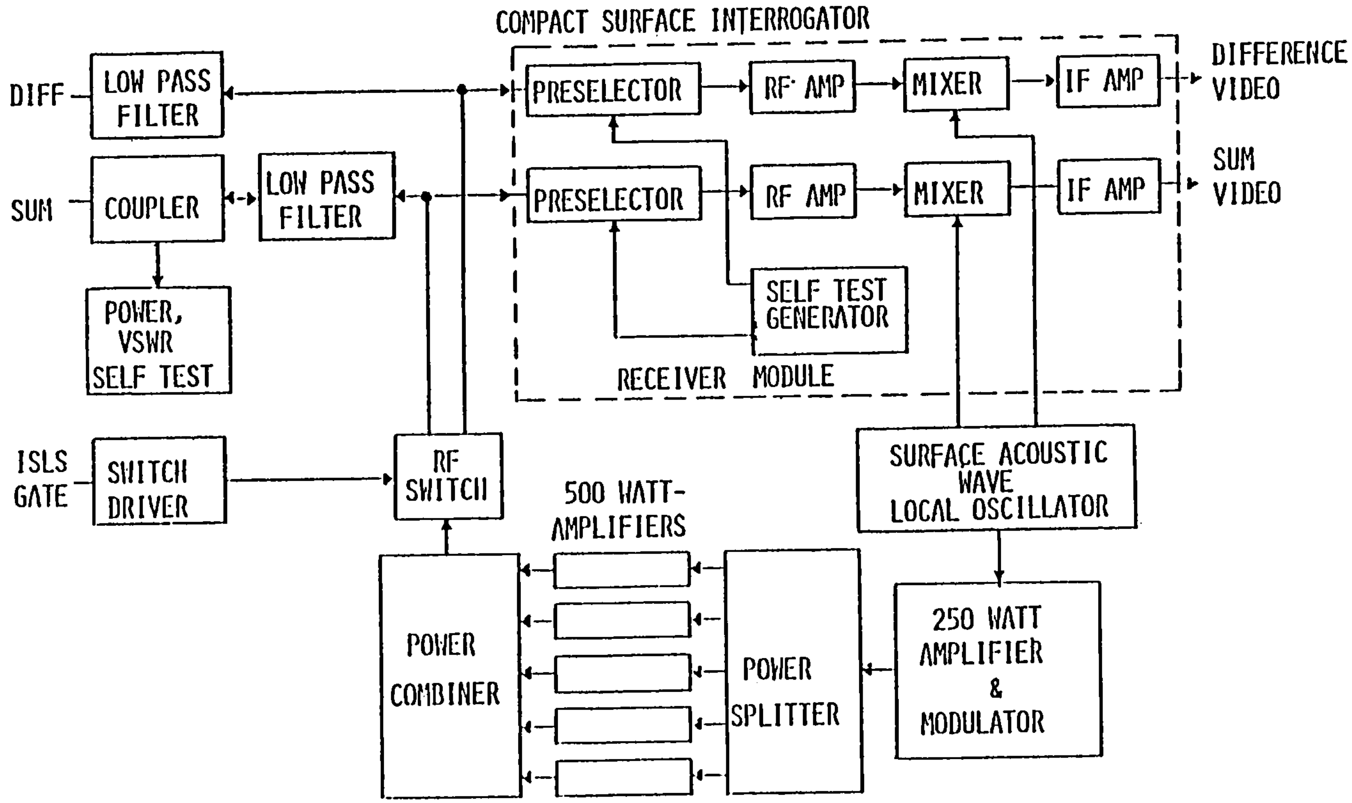


Figure 6.2.1-3 Receiver-Transmitter Block Diagram

Electronics, in the U.S., is presently designing and testing the solid state transmitter for the R/T of APX-104 that Siemens is developing. Figure 6.2.1-3 shows a typical modern IFF beacon interrogator R/T unit containing a solid state transmitter array. This unit is designed to operate with a sum and difference antenna array for improved sidelobe suppression performance in a ground interrogator system. The same basic transmitter array is being utilized in the R/T unit of the Hazeltine APX-104. The modular array technique was also recently used by Teledyne Electronics in their space diversity IFF transponder, the AN/APX-101, for use on the USAF F-15 Aircraft.

IFF SYSTEM INTERFERENCE AND DISCRETE ADDRESS INTERROGATION TECHNIQUE

The present IFF Beacon System utilizes a discrete pulse spacing code to designate its interrogation mode, and a multiple pulse on/off code in the reply format of the airborne IFF transponder. Transponders receive and transmit from a single omnidirectional antenna and will respond to all valid interrogations. Since the IFF system was designed to operate at a 200-mile range, with a safety margin in the signal strength for both the uplink and downlink paths, a single transponder will reply to all interrogators from ground stations in excess of 200 miles in all directions.

At a given IFF beacon ground station, the received transponder signals consist of synchronous replies and non-synchronous replies that result from all other interrogations that trigger the transponders. In a high density air traffic area, a considerable amount of interference is generated by these non-synchronous replies. This interference can cause serious degradation of IFF beacon system performance.

To alleviate this problem, interference blankers have been developed to sort the synchronous replies by comparing all replies to the exact PRF of the IFF beacon ground interrogator. Interference blanking techniques have provided improved system performance, but the technique has inherent limitations that become more pronounced as the density of the IFF signal environment continues to increase.

The present IFF Beacon System utilizes a discrete pulse spacing code to designate its interrogation mode, and a multiple pulse on/off code in the reply format of the airborne IFF transponder. Transponders receive and transmit from a single omnidirectional antenna and will respond to all valid interrogations. Since the IFF system was designed to operate at a 200-mile range, with a safety margin in the signal strength for both the uplink and down link paths, a single transponder will reply to all interrogations from ground stations in excess of 200 miles in all directions.

A new IFF system concept is evolving that includes an interrogation signal format designed to eliminate the problem of non-synchronous replies. The new concept is called Discrete Address Beacon System (DABS). DABS utilizes a unique interrogation code for each transponder, thus greatly reducing the number of non-synchronous replies that are generated.

MARK XII SECURE IFF

The military uses the IFF Beacon systems in tactical airborne, seaborne and ground combat situations, to separately identify friendly and enemy vehicles or other potential targets. The accuracy and stand-off range of modern weapons makes it extremely important to correctly identify the enemy before an attack begins. The Mark XII secure interrogation (Mode4), was designed for this purpose. The development of Mark XII began in 1963. Under the direction of DoD AIMS, special secure military equipments were developed to satisfy the military operational requirement for a positive identification system. These special equipments were made compatible with, and subject to the limitations of the standard ATC Beacon systems. Because of the extreme importance of a positive and secure identification system in a combat situation,it is necessary to investigate advanced techniques that can be used to evolve an identification system that completely satisfies the requirements.

6.2.2 ACTIVE COUNTERMEASURES

In reviewing the state-of-the-art in Active Electronic Countermeasures (ECM), it was interesting to reflect that the start of today's EW capabilities was first seen in 1897 before the turn of the century. One could reflect that there was an earlier start than this. But suffice to say, the Braun tube, built by Professor Ferdinand Braun in Germany in that year, set the stage for the birth of radar which fostered the need for radar defeating capabilities.

Summarizing some of the historical scene, Christian Hulsmeyer's invention, patented in 1904, of the 'Telemobiloscope' consisted of an emitter and receiver colocated, the infant to become radar. The German inventor dreamed of his device aiding ships at sea to sail safely through fog and darkness. Fleming's diode and then DeForest's triode were further prerequisites for radar. Both were announced by 1907. By 1924, pulsed radio transmissions by Americans were being generated. The Japanese professor, Hidetsugi Yagi, in 1928 wrote of the ability to control and direct radio beams.

During the 30's, the Germans appear to be dominant and move the infant into maturity. Using a Holland company's new tube (radio valve), capable of 70 watts at 600 megacycles, the German head of the Navy's Signal Research Department implemented Hulsmeyer's Telemobiloscope successfully. The growth and integration of radar into World War II and later weapon systems led us to today's offensive Electronic Warfare systems.

These are the systems which detect the presence of, or provide tracking information for the purpose of weapon guidance and control. There are many possible descriptions of the EW concepts - guidance and data links between offensive stations, radar used solely for early warning, others used for target acquisition and tracking. One could consider that even SONAR could be defined as an offensive Electronic Warfare system. However, it is not, but the data link of intelligence derived from SONAR to command and control centers is indeed included in the offensive EW consideration.

Before we proceed to the areas of defensive Electronic Warfare or active countermeasures, a brief review of one other aspect of radar's maturity is appropriate. That area is Electronic Cou nter-Countermeasures (ECCM).

Radar systems are categorized in three general classes - search, single target tracking and multiple target tracking. Within these areas, there are two basic approaches used - low duty cycle incoherent pulse systems and continuous wave/high duty cycle coherent systems.

The tracking radars are used for missile guidance and fire control. The pulse radar generally uses a range gate to reduce the noise from objects other thah the target of interest. The CW systems obtain target position from doppler effects. Angle is derived from beam positioning either mechanically, electrically or both. All are implemented in a variety of ways to further classify the radar types.

Conical scan (CONSCAN) radars mechanically rotate their antenna beam around boresight, comparing return signal amplitudes against the instantaneous antenna angle. Sequential lobing radars obtain angle data by sequentially switching their antenna beams in discrete positions and obtain angle data similiar to the CONSCAN types.

One example of an ECCM technique is where the radar illuminates the target with a fixed (non-moving) beam and scans with the receive antenna only. Depending on implementation, this technique could be either Lobe-on-Receive- Only (LORO), Conical-Scan-on-Receive-Only (COSRO), Track-While-Scan-on- Receive-Only (TWSRO), etc.

Other types of ECCM and therefore problems which are encountered by active countermeasures are frequency agility, PRF agility, a Soviet concept defined in open literature as Scan-With-Compensation, burnthrough, leading edge tracking, etc.

The Defenses Electronic Countermeasures (DECM) are the active countermeasures. These systems attempt to deny the enemy data and intelligence which would allow him the ability to detect and destroy our offensive weapon systems. The two major groupings of active CM (jammers) are primarily divided into noise and deception. The noise jammers operate on a principle of outshouting the echo signal sought by the threat radar. In general, the DECM equipment radiates non-coherent energy in a sufficient band of the electromagnetic spectrum to mask the radar echo or, in the case of a data link, to disrupt the transmission of intelligence.

The deceptive jammer accomplishes confusion, masking and denial by using the characteristics of the victim radar system. This is achieved by receiving emissions, modifying them and reradiating in the direction of the victim emitter, thus creating errors in the opponent's data sufficient to render his offensive systems ineffective.

The numbers and types of ECM systems are numerous and not limited to radar and data link emitters as described here. However, communication, navigation and any distance measuring device operate on similar principles and are countered with similar techniques. The following tables summarize the state-of-the-art in ECM techniques versus the current radar types.

Each technique used in ECM equipment requires a countering technique, as outlined above, in ECCM techniques. The DECM must respond with an ECCM capability which may include associated RF, signal processing and control circuitry. Constraints on equipment location, size, weight and power consumption reduce the flexibility and use of the CM equipment. Each ECM, ECCM incorporation must be done at the expense of aircraft payload or range. There is a tendency to anticipate the worst case conditions and to carry more ECM equipment than needed, or not to carry anything and take fatal chances.

The most insidious problem in the offensive versus defensive equation is change. New developments of electronic weapons must result in a technique evaluation by the opposing forces to obtain in-depth knowledge of the weapon electronic characteristics in order to obtain a counter which is practical and effective. Thus EW is a battle of time, as well as control of electro- magnetic spectrum. Time to understand a

TABLE 1-1

Target Tracking Radar Systems

ECM Technique	Search Radars	Missile Beacon Tracking Systems	Angle Tracking: Conical Scan Active	Angle Tracking: Conical Scan Loro	Angle Tracking: Monopulse or SWC (6)	Angle Tracking: Sequential Lobing Active	Angle Tracking: Sequential Lobing Loro	Angle Tracking: TWS Active	Angle Tracking: TWS Loro	Doppler/Range Tracking: Pulse	Doppler/Range Tracking: CW
Range Obscuration											
Spot noise	x	x	x	x		x	x	x	x	x	
Jog detector AM spot noise		x									
Range Deception											
Cover pulse	x		x	x		x	x	x	x	x	
False targets (1)	x		x	x		x	x	x	x	x	
RGPO (noise or repeater) (2)											
RGPI transponder (3)	x		x	x		x	x	x	x	x	
Range gated noise		x	x	x		x	x	x	x	x	
Angle Obscuration											
Instant inverse gain	x		x			x		x			
Buddy Mode Noise or Transponder	x		x	x	x	x	x	x	x	x	x
Cooperative CM Noise or Transponder	x		x	x	x	x	x	x	x	x	x
Angle Deception											
Inverse gain	x		x			x		x			
Wobbulated AM		x	x	x		x	x	x	x	x	
SSW (5) or SS (4)											
Jog detector AM (SSW) or SS		x	x	x		x	x	x	x	x	
Countdown			x	x		x	x	x	x	x	
Second Harmonic					x						
Velocity Deception											
Serrodyne										x	x
Swept CW or VGPO (7)										x	x

Key:
(1) Via either noise or repeater
(2) RGPO = Range Gate Pull Off
(3) RGPI = Range Gate Pull In (or RANRAP = Random Range Program)
(4) SS = Swept Spot
(5) SSW = Swept Square Wave
(6) SWC = Scan With Compensation
(7) VGPO = Velocity Gate Pull Off

TABLE 1-2

TRACKING RADAR TYPE	JAMMING TECHNIQUE	JAM-TO-SIGNAL RATIO REQUIRED (JSRR)	RECEIVER SENSITIVITY INCREASE REQUIRED (RSIR)	COMMENTS
PULSED	Noise	~0-6 dB	0 dB	
	RGPO Range Gate Pull Off	0-6 dB	0 dB	Technique usually used to pull radar off target signal and provide infinite jam-to-signal ratio for angle jamming techniques. JSRR varies with split or contiguous tracking gates, gate widths, gate separation, tracking servo response, pull-off rates of jammer. Relatively ineffective technique against manual operator.
	RGPI/RGPO RANRAP	~0 dB	0 dB	Technique requires predictive gates. More effective against manual operator. However, requires more duty cycle from jammer.
	COVER PULSE, also useful against leading edge tracking ECCM	~0 dB	0 dB	Technique useful to supply noise type response (defeat radars range resolution capability for techniques like Buddy Mode.)

TABLE 1-2—Continued

TRACKING RADAR TYPE	JAMMING TECHNIQUE	JAM-TO-SIGNAL RATIO REQUIRED (JSRR)	RECEIVER SENSITIVITY INCREASE REQUIRED (RSIR)	COMMENTS
CW RADARS	VGPO replaces RGPO velocity gate	0-6 dB	0 dB	Technique usually used to pull radar off the target signal and provide infinite JSRR for angle jamming techniques.
PULSE DOPPLER	VGPO combines with RGPO	0-6 dB	0 dB	Technique usually used to pull radar off the target signal and provide infinite JSRR for angle jamming techniques.
PULSE CODED RADARS Chirp, etc.	Frequency Time Ambiguity Jamming			JSRR dependent upon ambiguity diagrams and coding of signal.
Angle Tracking Conical Scan or Active Lobe Switching	Inverse Gain Scan	10-25 dB for break lock	10-15 dB for break lock	JSRR & RSIR vary with squint angle and radar angle tracking time constants
TWS Auto Radar Track Track while scan	Main Lobe Blanking	10-15 dB	10 dB	JSRR for breaklock varies with angle tracking gate widths, gate separation, and tracking time constants.
TWS Manual Radar Track	JETS	10-13 dB	10 dB	JSRR & effectiveness vary greatly with each specific operator.
	Instantaneous Inverse Gain	~20 dB	~20 dB	JSRR & RSIR depend upon depth of radar nulls and the desired angular width of the jamming signal.
TWSRO Track while scan receive only	JETS	10-13 dB	10 dB	JSRR for breaklock varies with angle tracking gate widths, gate separation, and time constants.
COSRO	Swept Audio or Multiplexed Swept Audio	10-25 dB	10-15 dB	See CONSCAN & the sweep rate of the audio
	Above, with jog detection	10-25 dB	10-15 dB	These techniques are used to reduce uncertainty of threat scan rate. PSD places strigent added requirements on signal processing.
	Passive Scan Detection (PSD)	10-25 dB	10-15 dB	
Monopulse & other passive lobing radars with CAM	Cross-Polarization	20-40 dB	20-40 dB	JSRR & RSIR vary with Condon Lobe (Cross-Polarized) response of victim antenna. The Condon Lobe response varies with F/D ratio, type of feedhorn, illumination taper, and use of polarization screening.
	Cross-Eye	~20 dB at 80' spacing at 20 NM at 1.0° BW threat antenna	~ 20 dB	JSRR & RSIR varies with antenna separation on aircraft in radar angular mils. To jam at maximum range requires maximum JSRR.
	Buddy Mode Radar Angular Resolution Cell Jamming	0-3 dB	10 dB	JSRR will vary significantly only if A/C spacing exceed 1 radar beamwidth. Requires multiple A/C
	Cooperative Counter-measures	0-3 dB	10 dB	Same approximate requirements as Buddy Mode but requires communication amongst aircraft for technique coordination. Generates larger errors.
	Countdown	10-30 dB	10 dB	JSRR varies with AGC time constants and receiver instantaneous dynamic range.
Range and/or Velocity				RGPO, etc. and VGPO may be used in combination with any of the Angle Techniques
ALTERNATE LINKS	MISSILE BEACON TRACKING	0-6 dB*	Requires a C/D band receiver	JSRR quoted here will work but requires new definition from other JSRR's quoted and must be carefully implemented. Technique is effective against command guidance missile systems that use radar to track a beacon in the missile and is effective countermeasure to *optical target* track.

system and respond is currently measured in months and years, whereas safety of movement in battle conditions will, in the next major engagement of nations, be measured in micro- or milli-seconds.

Through techniques sometimes referred to as passive ECM, ELINT (Electronic Intelligence), SIGINT (Signal Intelligence), etc., early development testing of future enemy weapon systems is detected. EXploitation of this data allows the Allied and Free World nations to be prepared for such systems as surprised the Israelis during the Yom Kippur War. In that confrontation, the extensive use of mobile systems with integrated offensive EW capabilities caused great setbacks for Israel before modified tactical and DECM equipments were innovatively upgraded and used. After that conflict, the DOD convened a Joint Technical Coordination Group for Aircraft Survivability. These government and industry people generated and published a two-volume document titled, 'Countermeasure Handbook for Aircraft Survivability', published in February 1977 - a very comprehensive coverage of the current technology used to defeat offensive EW weapons. That classified documentation is a comprehensive review of history, current capability and trends.

The following summary of the Soviet air defense SAM and AAA capabilities highlights their wide use of the microwave spectrum and their push toward the higher frequencies. This trend is believed to include millimeter, infrared, visible, ultra-violet portions of the spectrum.

Priority	Threat	Radar	Frequency	Lethal Radius*
Mobile systems:				
1	SA-6 missile	Straight Flush	7.85-8.01 GHz	13 nmi
2	SA-8	Land Roll	14.2-14.8 GHz	6nmi
3	ZSU-234SP	Gun Dish	14.6-15.6 GHz	1.5nmi
4	S-60(57mm)	Flap Wheel	9.13-9.85 GHz	3nmi
5	SA-4	Pat Hand	6.44-6.68 GHz	4nmi
Fixed systems:				
6	SA-3	Low Blow	8.9-9.6 GHz	9nmi
7	SA-2	Fan Song	2.94-3.06 GHz	9nmi
8	SA-5	Square Pair	6.62-6.94 GHz	9nmi

* Avoidance radius when operating at or below 500 ft.

This Soviet weapon systems summary is as itemized in the Electronic Warfare magazine, dated May 1978. The priority is set as to our need for countermeasures against them.

New technical challenges posed by the probability of Soviet developed and deployed monopulse radar systems are causing DOD plans to include investigation of such techniques as Cross Eye, Terrain Bounce, Cross polarization, Buddy Mode as well as new concepts in sub-audio/servo response loop CM. These techniques when placed in operational use, could operate against such systems as the Ground Controlled Intercept (GCI) Squint Eye and Barlock.

The Cross Eye technique involves the use of retrodirective repeaters installed on the wing tips of the penetrating aircraft, which transmits signals out of phase at the victim target. This causes distortion in the received signals, which the radar attempts to minimize by turning off in angles, thus tracking away from the target direction on an imaginary target in space.

Terrain bounce CM illuminates the ground or terrain surrounding the victim radar. Reflections from this surface cause a distribution of targets across a large angular region. The radar is unable to resolve true target returns in this distributed target signal. This is effective against early warning, GCI and tracking radars. Also a semi-active missile may (hopefully) home-in on the energy reflected from the terrain illumination.

These techniques and others are also needed to defeat, if necessary, our own and our allies missile systems. As mentioned in Section 6.1.1, it is feasible that the domestic and allied systems will be used for non-friendly countries. Modern systems like Rapier and Crotale use ECM signals as a beacon for their home-on-jam (HOJ) seekers. This indicates the need for active countermeasures which are deployable and expendable. The Georgia Tech Tactical Expendable Assessment Study supports feasibility and simplicity of expendables as a DECM system. The arguments for an anti-ARM missile are convincing and realistic except for the space-weight-power arguments. That is, the stores are all taken up by self-protection weapons.

Realistic trades must always be made when seeking self-defense of the air platform. However, certain trades and studies are still needed. The avionics industries have developed for commercial aircraft the integrated navigational-communication concept into operational equipment. That expertise is needed in the development of avionic suites for the military aircraft of today and tomorrow.

6.2.3 PASSIVE COUNTERMEASURES

There are two divisions in this area - Electronic Support Measures (ESM) and passive jammers which utilize reflectors and reflective materials to return spurious and confusing signals to the transmitting radar set. It is not readily apparent that the passive type jammers would have any identity with the roles and missions of NASA, whereas the Electronic Support Measures, which is basically receiver technology, is the most pervasive element of Electronic Warfare and carries over to the NASA charter.

The ESM, for purposes of discussions here, can be referenced in certain genetic receiver types: crystal video, IFM, compressive (microscan) and superheterodynes. There are also tuned RF receivers and combinations of the types listed above, but these will not be reviewed here.

Missions, more than any other factor, dictate the receiver type or types. A second dominant factor is cost. In 1976, the U.S. Air Force Avionics Laboratories convened a conference for Low Cost EW. Working panels were selected to study a number of critical EW system elements; primary interest was focused on low cost receivers.

A synoptic view of the AFAL conference was included in the Third Edition of the International Countermeasures Handbook, plus a summary review of seven receiver types and concepts. This review, with its comparison charts, was prepared by Mr. Ronald G. Brown, formerly of GTE-Sylvania, and presently employed by Antekna, Inc. (Ref. 99).

In addition to the recommendations of the overview, it is appropriate to point out that there are some basic technology developments currently funded by the DOD and other government agencies. The research and development in basic compositions includes such categories as Gallium Arsenide, Indium Phosphide and the super-cool Josephson Junction which promise high performance, small packaging and low power consumption. The promotion of these research and development efforts could preclude the need for dispersive delay lines and provide gigabit logic for signal processing. The February 1978 issue of Microwave System News summarizes the state- of-the-art and the potential of InP and Josephson Junction.

The future requirements for ESM systems include: smaller size plus lighter weight, lower power consumption, reasonable cost and higher reliability. In addition, the NASA receivers, as well as the DOD future units, must be capable of handling denser environments and more complex waveforms.

6.3 JTIDS: AN UPDATE (Reference 100)

6.3.1 INTRODUCTION

The purpose of the Joint Tactical Information Distribution System (JTIDS) is to provide an advanced communication, navigation and identification (CNI) system that will serve a wide variety of users. The system uses a low duty cycle, spread-spectrum waveform and advanced coding techniques to provide secure, jam-resistant and low probability of exploitation (LPE) CNI functions. The system will implement Multiple Access Techniques to provide various levels of connectivity (access) to user elements for simultaneous distribution and receipt of digital information. This presentation will describe the potential of JTIDS, and how it may impact philosophy, concepts and operations for a variety of users. Also new generic channel types which have been synthesized with the flexible structure of the JTIDS waveform to provide a variety of access techniques will be described.

Over the past decade several independent research and development programs were demonstrating features that were part of the total capabilities identified in the Joint Operational Requirements. The Integrated Tactical Navigation System (ITNS) Program was a Navy effort to demonstrate a Time Division Multiple Access (TDMA) System that would perform relative navigation, position reporting, station keeping, vectoring and geographically referenced navigation.

Another Navy program, the Integrated Tactical Air Control System (ITACS), was pursuing the development of a system that would provide a modular group of programmable hardware elements with multifunctional capabilities. The ITACS program emphasized secure, jam-resistant digital data transmission.

Concurrently, the Air Force was developing a secure, jam-resistant digital TDMA information distribution system, SEEK BUS. The development emphasized user connectivity. The system capability was demonstrated in an operational environment during E-3A Airborne Warning and Control System (AWACS) interoperability evaluations in Europe.

The results of these developmental efforts were pooled and a common waveform was adopted to form the basis of the system that would address the requirements that were subsequently approved by the Joint Chiefs of Staff as the Joint Operational Requirements. Consequently, in April of 1975, the Director of Defense Research and Engineering (DDR&E) established a joint service program, with the participation of all U.S. Military services under the executive leadership of the Air Force, with a charter to develop and acquire a Joint Tactical Information Distribution System (JTIDS). Therefore, JTIDS is defined to be an advanced Integrated Communications Navigation and Identification (ICNI) System. The system design is responsive to the following goals: Connectivity; Identification; Survivability and Reconstruction; Relative Navigation; Flexibility; Message Format; Crypto Security; Compatibility with other RF Systems; Jam Resistance; Joint Operations; Low Error Probability; Orderly Transistion; Low Probability of Exploitation; Mutiple Netting; Ready Net Entry; Multi-function; Passive

Operation; Capacity; Range; Unformatted Digital Data; and Relay Capability.

Intrinsically JTIDS will provide digital ICNI services; i.e., digital voice, precision ranging, secure identification and real time digital data functions. As an added feature conventional TACAN and IFF will be integrated into the systems. Figure 6.3-1 illustrates a total JTIDS configuration with representative user elements. The users consist of tactical elements from all services. To name a few; surface and airborne command and control, surveillance, intelligence, surface ships, ground vehicles and combat support. Currently, for development purposes, three classes of terminals for various user elements have been categorized based upon the potential application, link functions

Class 1 - Provides the highest level of capability for use by large scale airborne and surface command and control systems.

Class 2 - Has a moderately reduced capability compared to Class 1 and is intended for use by force elements such as fighter aircraft and smaller ships.

Class 3 - Compact, low cost versions to perform limited functions for use in missiles, RPV's and manpacks.

The classes of users described above and their subsets require varying CNI functions to perform their missions. Therefore, to provide flexibility and functional growth potential, the system has a modular building block structure. The basic JTIDS terminal, which will have the full capabilities of the Class 1 type, will consist of the six major function areas shown in Figure 6.3-2. The antenna function must provide omni-directional radiation. An optional provision is a directional antenna capability to enhance jam-resistance and low error of exploitation. The transmission/ reception function will consist of the RF and associated components necessary to provide transceiver operation and interface with the signal processor.

The secure data function will provide the system encryption/decryption pseudorandom number sequences. The signal processing function will provide the data modulation/demodulation, encryption/decryption and encoding/decoding as well as all timing and control functions. The data processing function will incude message buffering, message formatting, net-entry and synchronization algorithms, navigation algorithms, message acknowledgement algorithms and performance monitoring activities. A terminal will include control and display sufficient to permit operation and monitoring. This structural concept is intended to permit a specific class of terminal to be configured by adding/deleting some of the CNI functional modules,which are subsets of the six major function areas.

The continuing progression of technological developments in the areas of automatic data processing and component miniaturization (i.e., LSI and MIC) are permitting a system of this magnitude and complexity to be developed and designed for implementation on current and future tactical vehicles.

In order to meet current operational demands and all design goals, the Joint Program Office is proceeding with two concurrent development

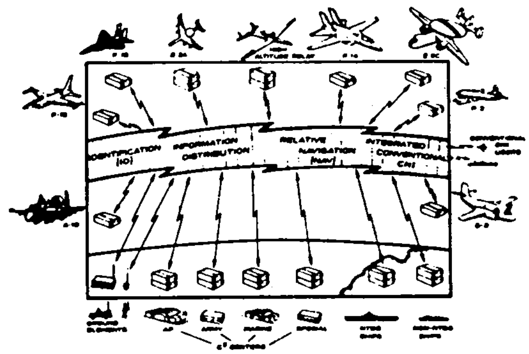


Figure 6.3-1 Joint Tactical Information Distribution System (JTIDS).

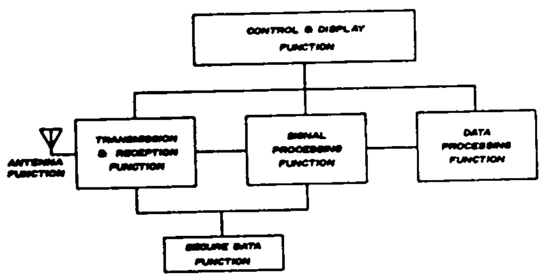


Figure 6.3-2 JTIDS Terminal Functions

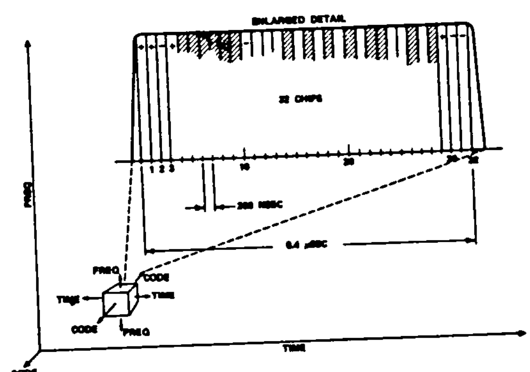


Figure 6.3-3 Basic JTIDS pulse

phases; Phase I includes development of the basic digital, jam-resistant, Time Division Multiple Access (TDMA) architecture with emphasis on connectivity for all users. TACAN and relative navigation capabilities are also included in the design of the Class 2 Tactical Terminal hardware. Phase II is intended to extend the JTIDS capabilities beyond that of Phase I in areas of system capacity, including information rates and number of simultaneous, independent data and voice nets, improved jam-resistance and the incorporation of additional CNI capabilities. The Phase II efforts consist of definition and the design of advanced development hardware to validate concepts intended to enhance the performance of Phase I with the provision that equipment developed during Phase II will be capable of interoperating with that developed for Phase I. The common elements of both phases are:

1. Pulse Timing.
2. Carrier Modulation.
3. Data Modulation.
4. Data (Symbol) encoding: Reed-Solomon Encoding-Decoding (RSED).
5. Spread-Spectrum Frequency Hopping.

Since the features of Phase I TDMA have been well publicized, (ref. 101) this paper will highlight the TDMA Architecture features and describe in greater detail the current Navy effort to develop the Phase II Distributed Time Division Multiple Access (DTDMA) System.

6.3.2 SYSTEM DESCRIPTION

The program is proceeding in two concurrent phases of development. The key difference in concept achieves an increase in versatility and data capacity for Phase II via an innovative, variable time structure, In general, JTIDS has adopted a low duty cycle, spread-spectrum waveform implemented in concert with advanced coding techniques in an effort to provide a comprehensive ICNI system in accordance with the Joint Operational Requirements.

The basic element of information common to both phases is a pulse of 6.4 microsecond duration, spectrum spread by a pseudorandom (PR) phase code modulation of thirty-two, 200 nano-second chips illustrated in figure 6.3-3. The system pseudorandomly selects the center frequencies of these pulses, on a pulse-by-pulse basis, for transmission in the Lx band, 960-1215 MHz. Guard bands have been designated for the 1030 MHz and 1090 MHz IFF frequencies to preclude interference problems.

The advanced coding techniques selected for JTIDS use an inner code M'ary channel which provides five bits per transmitted pulse (M-32). The inner channel decoder uses a maximum-likelihood detector modified to permit a no decision condition, termed an erasure (E). For certain channel implementations where no additional coding is used, performance is limited by the inner channel code capabilities mentioned above. For higher performance functions, additional inner channel code patterns are added. The additional inner code is a polynomial code used for post correction error detection. TDMA uses a (237, 225) polynomial code, while DTDMA uses a (75, 70) polynomial code. The outer code

(Reed-Solomon) is an error correction technique used with M'ary channels which can correct for isolated as as well as clustered errors and is both practical and economical. Briefly, each code word of the Reed-Solomon (R-S) code is a sequence of characters of the 32-ary inner channel. The consideration of code efficiency indicates half-rate operation. The most powerful half-rate code requires the largest minimum distance (a measure of code power). The code parameters selected are (n,k) = (31, 15). For a 15 character data word, a set of 16 parity characters is added; resulting in 31 characters in the encoded word. For this R-S code, any combination of errors (e) and erasures (E) such that $2e+E<16$ or $2e+E=16$ will always be perfectly corrected.

The choice of signal structure was based on detailed analyses and considerations, which developed the interrelationships between the parameters of jam-resistance, intra/inter mutual interference, access, and low probability of exploitation (LPE).

6.3.3 PHASE I

The basic JTIDS Phase I system, with its TDMA architecture, permits all users within line of sight and relay range of one another to be interconnected via a time orthogonal net. Time sharing of a single net is accomplished by assigning each user 'certain times to transmit' information. When not transmitting the user monitors the transmissions of others and extracts only the information required and selected by him. A single net, within the JTIDS-NTSA context, is defined to be the collections within a recurring block of time. The block of time is known as an epoch which is illustrated in Figure 6.3-4. The 'certain times to transmit' mentioned above has been termed a 'Time Slot' and is the minimum interval (7.8125 millisecond duration) assigned to each user for information distribution; i.e., to transmit, receive and relay messages. The time slot assignments can be changed to meet the tactical situation, and any user will be assigned time slots in accordance with net management procedures. To ease the Phase I System Net Management problems the number of recurring time slots per epoch have been reduced by dividing the epoch into three time slot sets (A, B and C) -- illustrated in Figure 6.1-4. For example, a fighter aircraft performing a combat air patrol (CAP) mission may require 32-64 time slots per epoch; while an E-2C would require on the order of twice as many to perform an airborne early warning (AEW) mission. There are 98,304 time slots per epoch. The 12.8 minute epoch represents a Phase I net and defines the cyclic period of information distribution structure. Therefore, a time slot which has been assigned to a particular user must recur at least once every 12.8 minutes. Since an active net user must be assigned at least one time slot in an epoch, this establishes an upper boundary for system capacity and the number of active net participants.

The epoch has also been subdivided into 64 twelve second 'frames' which represent 1536 time slots. Frames are important for certain system timing operations, such as how often a Net Time Reference (NTR) must transmit to ensure a common time standard for the system. To acquire, net time terminals shall synchronize on messages received from the Net Time Reference or on messages received from other terminals that have synchronized to system time. For any given operation, all terminals will enter the system using the common time standard established initially by the Net Time Reference. However, it is important to note, any user can be assigned the duties of a net time reference without the use of any special equipment; but, at any given time, only one net time reference will be assigned for each synchronized netted system structure. Each user will maintain synchronization with the other net users after initially entering the net.

The Phase I system, as a minimum, can provide the capability to operate 15 simultaneous nets within a common area of coverage. The Phase I equipment implements an eight bit code for a maximum possible net selection of 128 nets; but, the number of nets that can be operated in a given geographical area is limited by the statistical probability of mutual interference to approximately 20. A synchronized multi-net structure, illustrated in figure 6.3-5, consists of the stacking of individual nets, with all nets synchronized such that a time slot of each net is coincident in time with the corresponding time slot of every other net. This results in a total of 98,304 time slices per

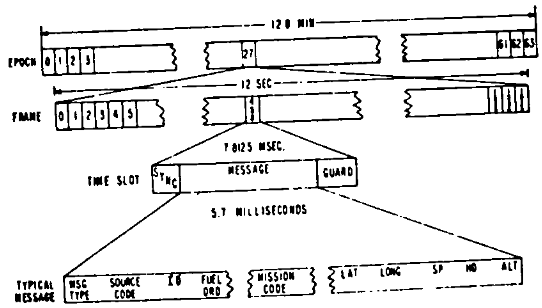


Figure 6.3-4 Phase I JTIDS time division format

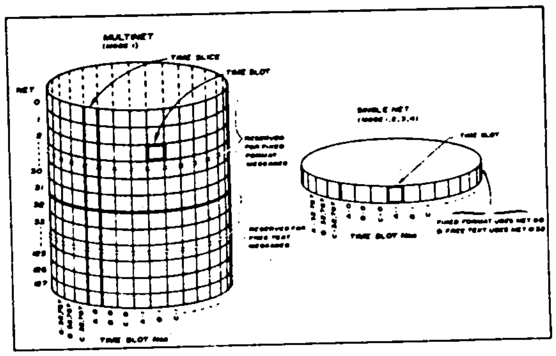


Figure 6.3-5 Phase I JTIDS netting structure

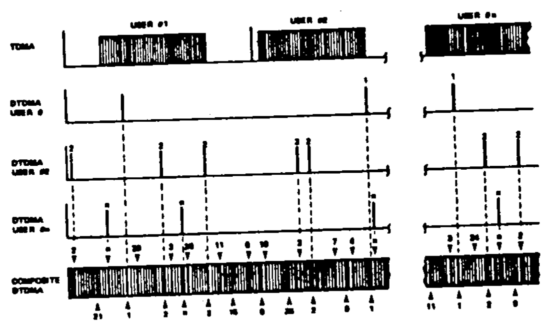


Figure 6.3-6 Phase I TDMA versus Phase II DTDMA

12.8 minute epoch.

Phase I terminals will be able to participate in up to five; but, in only one net in a given time slot. Therefore, if desired a terminal could shift from one net to another in a time slot by time slot basis.

An individual time slot consists of the following three parts shown in figure 6.3-4; a synchronization burst; a message section; and a guard period, which allows transmission to propagate to the user within line of sight of the transmitter before another transmission begins. The message section is comprised of several basic pulses.

The system utilizes standard digital messages to achieve high capacity and accuracy in the distribution of information. A typical status and position message is exemplified in figure 6.3-4. The following four types of digital messages have been defined for JTIDS:

1. TYPE '0' (Free Text) Non-Error Coded: Facilitates several types of digital equipment interfaces, such as digitized voice and teletype.
2. TYPE '1' (Fixed Format) Error Coded: Facilitates active interchange of formatted messages.
3. TYPE '2' (Round Trip Timing - RTT): Facilitates active synchronization procedure.
4. TYPE '3' (Free Text) Error Coded: Same as Type '0' only error coded.

The typical position and status message contains a message label, originator's code, identification of the reporting user, fuel and ordnance status, position, speed, heading, altitude, etc. (figure 6.3-4).

The position reported in the typical JTIDS message, uses a best estimate of the user position, as an important ingredient to the relative navigation feature of JTIDS. The other ingredient is the time-of-arrival of a transmitted message; because, with every message starting time being known by all net participants, the message time-of-arrival represents direct range to the participants as they receive the message. With the range and reported positions of several net participants the community of JTIDS users can determine, without external references, their relative positions within line-of-sight and relay range of one another. This situation is often encountered in open ocean tactical environments where true position is not available. Position information added to the net from sensors onboard user platforms within the relative grid, such as radar and sonar, also becomes part of the grid. This information can be processedd on user platforms to achieve accurate fire control solutions, even if the fire control information is incomplete from an individual user.

A geodetic common grid can be established for a JTIDS community of users if two or more community members have fixed, surveyed positions, or accurate geodetic positions from an independent navigation system, such as the Global Positioning System (GPS) (ref. 102). Every community member shares in the maintenance of the grid's orientation and his own location in the grid to the degree required by his mission and the support of missions of other community members.

This relative navigation feature, which is derived from the Integrated Tactical Navigation System (ITNS) concept, requires no additional radio hardware, however, additional software is required.

6.3.4 PHASE II - DTDMA

Several candidate systems for Phase II are currently being investigated; but, the Distributed Time Division Multiple Access (DTDMA) development is the only one being implemented into hardware. This advanced development effort was undertaken by the ITT Avionics Division with the Naval Air Development Center as the contracting Agency.

A comparison of the DTDMA and TDMA signal structure is illustrated in figure 6.1-6. The time ordered, time sequenced nature of the Phase I structure is represented by a continuous stream of user message transmissions comprised of bursts of pulses. The DTMA signal structure takes the same basic pulses used in TDMA and pseudorandomly distributes them over a longer time interval, making it an orthogonal system.

The lines shown in the composite DTDMA diagram in figure 6.3-6 represent the transmit/receive opportunities for the DTDMA pulses. These opportunities have been termed 'basic event intervals' and occur every 12.8 microseconds (78,125 per second). Each of the basic event intervals is uniquely associated with a pseudorandom code word which is generated at the same time by all users whose terminal clocks are synchronized. Also, the pseudorandom code word uniquely defines all signal and channel parameters. Periodic transmission patterns are not exhibited by any users. Referring again to figure 6.3-6, the time for each user's pulse transmission is pseudorandomly selected from these opportunities, and user's transmissions are interleaved in time. Note that the guard time required in the TDMA structure no longer exists. Consequently, a message uses only the portion of the system capacity which is actually required; thereby permitting system resources to be used and reallocated with a high degree of efficiency. This low duty structure of any one message, together with the pseudorandomly varied pulse patterns of the interleaved messages, reduces coincident pulse interference from different transmissions to a negligible level.

The contiguous stream of all Basic Event Intervals forms the Meta-Channel, which can support a data rate in excess of 300K BPS. The meta-channel is further divided into 512 Basic Channels (BC). This equates to a recurrence rate of approximately 150 Basic Event Intervals per second per Basic Channel (78,125/512). The Basic Channel is the fundamental element of the channel structure in JTIDS II - DTDMA. Each Basic Channel can service a data rate of approximately 750 bits per second. As data rate demands increase, a number of Basic Channels serve a specific function and are designed as Function Channels (FC). Each Function Channel is supported by two types of subchannels, one for data and one for synchronization. The synchronization service for most function channels is supported by one or part of one basic channel. Each function channel is capable of supporting a strong communications net, providing a net-entry procedure and data transfer between several users. The relationship between events, channels and meta-channels is shown in Figure 6.3-7. This figure illustrates that the channel architecture will accommodate the introduction of new functional channel structures in response to user developed operational requirements. Therefore, terminals can be tailored in both overall capacity and functional capability to specific user requirements. The system in general can be considered as a set of different meta-channels supporting all of the active channels. Meta-channels differ in their time/frequency patterns and may or may not be synchronized in time to one another. The superposition of the TACAN and IFF channels is depicted at the bottom of the figure. Three narrowband TACAN channels appear as one overall time/frequency pattern to the system. The IFF channel is simply a wideband channel whose events occur on a fixed center frequency.

The versatility of this channel structure is exemplified by the fact that DTDMA is accommodating the diverse requirements of the airborne Tactical Data System and the Naval Tactical Data Systems by linking basic channels to achieve the required data rates and structures for both Link 4A and Link 11.

Four types of functional channels have been categorized in terms of the access each affords to the users:

1. Demand Access: The information subchannel is shared in an unrestricted manner and used on a first-come, first-served basis.

2. Scheduled Access: The information subchannel is shared but messages are transmitted according to a prearranged schedule. Categorizes a classical TDMA Channel.

3. Command Access: The information subchannel can be shared or dedicated but messages are transmitted on command from a controller. In a function channel this requires either a dedicated information subchannel for the controller or a portion of a shared information subchannel dedicated to controller.

4. Assigned Access: The information subchannel is used by only one terminal for its transmissions.

In order for a community of users to form a DTDMA net for extraction of the CNI information, the users must perform a net entry procedure, as did the Phase I users; but, DTDMA introduces some new concepts in synchronization. The synchronization process takes place on a basic channel(s) specially designed for that purpose. Once synchronization is achieved the principal channel function is performed on other associated basic channels. The following phases must occur sequentially to achieve synchronization:

- Net entry Synchronization
- Source Synchronization

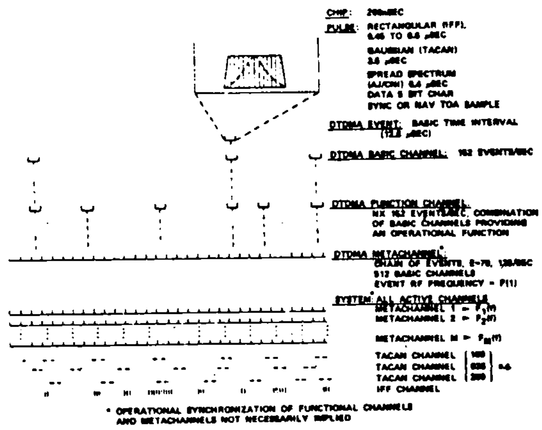


Figure 6.1-7 DTDMA channel architecture

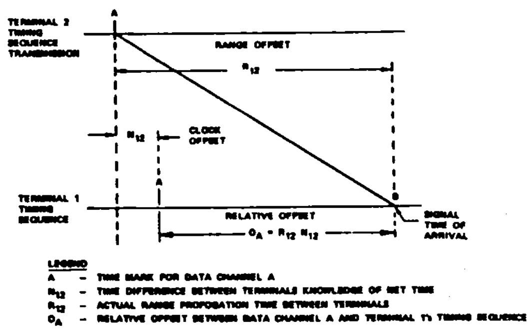


Figure 6.3-8 DTDMA synchronization requirement

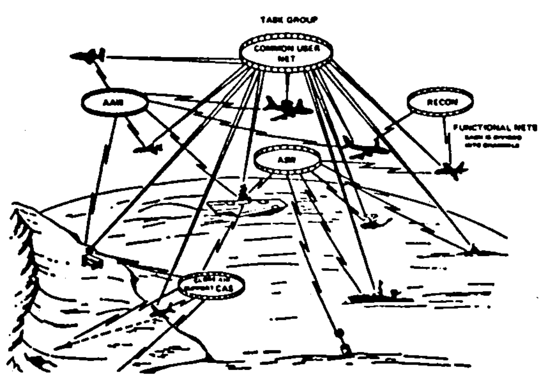


Figure 6.3-9 Navy concept of JTIDS employment

- Fine Synchronization
- Message Start Opportunities

The purpose of initial net entry is to reduce the initial time difference between the terminal's estimate of time and actual net time to one way propagation. In figure 6.3-8 terminal 2 is transmitting a Net Entry Signal referenced to time A. The reception of this signal by terminal 1 at B permits it to determine the net time to within the range offset, R sub 12. Fine net entry is then required to determine R sub 12. Clock offset, N sub 12, will be the error in this range measurement.

The range measurement required for the fine net entry can be accomplished by passive or active techniques. Terminal 1 can compute range, R sub 12, from position information transmitted by terminal 2. Alternatively, terminal 1 can interrogate terminal 2 and request a time offset measurement from terminal 2. In this way, two-way range can be determined, and thereby the magnitude of R sub 12.

Source synchronization is used to maintain the type II servo tracking of the relative offset. This very limited tracking is accomplished by assigning a synchronization subchannel to each terminal operating on a Function Channel within a net. In figure 6.3-8, time A represents one of a series of time marks associated with the synchronization pulse. The rate of transmission is on the order of 5Hz. After net entry has been accomplished; i.e., when the relative offset between the receiving terminal's timing sequence and all sync subchannels is less than or equal to the maximum relative offset which equals the maximum clock offset plus the range offset, the receiving terminal searches for the source sync pulses to obtain the offset to all terminals. Once these pulses are detected, the relative time offset (O sub A) to each transmitting terminal, is tracked using a Type II digital tracking loop. This now permits a terminal to reduce the time of arrival uncertainty of all data channel transmissions from a terminal to a value which is sufficient to obtain fine message synchronization.

Fine Synchronization involves the correction of propagation delays and usually involves the use of the transmitter. In certain cases where the geometric distribution of active terminals is favorable, fine sync can be achieved through trigonometric algorithms on the basis of received signals only. In order to achieve fine sync, the terminal transmits interrogations and receives replies which indicate absolute time error distance to the transponder. Repetition of this process permits the terminal to reduce time error and establish absolute channel time. After fine sync is achieved, quasi one-way range measurements can be enabled. In the latter case, the two-way signal exchange rate is reduced to a level consistent with on-board clock drift rate. Interpolated time-of arrival measurements are interpreted in terms of errors in tracked range.

It is important to note that in the DTDMA system there is a basic independence provided between the basic rate for coarse sync, message start sync (which is essentially the access opportunity rate) and the primary function provided on the main channel. High access low data rate users can now be efficiently accommodated.

A specific basic channel is used to designate unique message start times. That is, on any pseudorandom frequency hopped channel, message start opportunities are constrained to specific times which are known to both parties and which are selected to accommodate operational requirements (for example, opportunities to initiate voice messages occur at least 4 times per second). Having achieved coarse synchronization, a terminal examines the specific message start basic channel at those times and frequencies which are designated for message start signals. If a valid message start signal is recognized by a terminal, the terminal resources for processing the function channel are activated. If no message start is detected, the terminal resources are shifted elsewhere.

Since the JTIDS system is designed with one-to-one correspondence between the net time and transmitted signals, multi-net operation requires a knowledge of the time difference between terminal clock and net time. Once this is achieved, through the net entry prodedure, the terminal then creates a net time base for each operating net (metachannel), either by arithmetic operations on the bits in its terminal clock or by presetting multiple net clocks and driving them from the terminal clock. These net time bases are now available for generating the correct pseudorandom bit stream for each net, which determines the transmission parameters of signals and the time mark sequences. The design of the system message synchronization is such that sync is achieved by sync preambles so that all precise time measurements are made relative to the terminal clock. The DTDMA terminals being developed are capable of sustaining simultaneous communications on up to 15 nets.

The preceding paragraphs have described the salient features of DTDMA that will increase the data capacity, improve LPE, and allow simultaneous time independent netting, etc., over that of TDMA; as well as provide the ability for growth.

6.3.5 EMPLOYMENT CONCEPT

The unique communications needs of the Navy are established by analyzing its basic international mission responsibilities of Strategic Deterrence, Sea Control, Projection of Power Ashore and Naval Presence. The Naval Telecommunications System Architecture (NTSA) 1975-1985, points out that a high capacity, secure, real time, relative navigation, information transfer and identification system -- such as JTIDS -- is needed just to fulfill the essential communications requirements for intra-task force/group operations. JTIDS as an ICNI system has addressed the requirements and will significantly enhance the users' capabilities for all levels of tactical effectiveness.

A Projection of Power Ashore scenario is illustrated in figure 6.3-9. This type of tactical situation depicts a conventional warfare scenario that exemplifies the diverse and complex ICNI requirements of the Navy. Five types of mission oriented groups can easily be identified in this scenario: AEW, ASW, Amphibious Force, Carrier Task Group and Air Support Group. Each of these groups require a unique independent net to support their specific mission. Also, current, real time status, targeting and position reports from each group commander would be invaluable to a force commander in his effort to stay current and keep control of all factors affecting his operation. Many if not all of these events are occuring simultaneously; therefore, reliable (jam-resistant), simultaneous information access/distribution to all affected units is a must in order to synthesize a cohesive and comprehensive battle force.

JTIDS will remove previous limits on how thoroughly and speedily the information can be matched to the tactical requirements; because JTIDS will permit the simultaneous flow of information to all members with a high degree of reliable connectivity in a hostile electronic warfare environment. Also, JTIDS has the capability to operate with a very low probability that the transmission signals can be intercepted sufficiently to provide targeting information or be exploited in any other way. The rings in figure 6.3-9 represent some of the JTIDS nets that would be established for an operation of this type. Note that all the participants share a common user net for exchange of information such as identification and precise position reporting of all force elements (friend or foe). In addition, specific mission oriented nets have been established as required with the common user net information still available as needed. All JTIDS net members will contribute to the information pool. Therefore, the commander can simultaneously be in contact with as many or as few actual data sources as he desires. With this free, simultaneous interchange of information on position and status of deployed elements and known targets made possible by JTIDS, timely and effective resource allocations will be realized. Also, with information simultaneity, force control will not be disrupted due to the loss of one of many elements, even a force commander. Another element in the JTIDS net can sustain control with minimal disruption since he will be aware of current and developing situations.

With the advent of JTIDS, many new scenarios have been postulated which involve the use of future Class 3 terminals for missile/RPV guidance as well as current application of the Class 1 and Class 2 terminals. One example is called 'forward pass'. Forward pass involves two friendly interceptors with multi-target capabilities, one of which is far from friendly forces and heavily engaged with enemy aircraft but has expended all of its air-to-air missiles. The second friendly interceptor is fully armed and has been vectored to assist the first but is still enroute and too far from the battle area to engage the enemy using its own sensors and fire-control facilities. It could, in coordination with the first interceptor, launch missiles in the direction of the battle. Guidance of the missiles would then be assumed by the first interceptor which would, in the meantime, have acquired targets and calculated appropriate fire-control solutions. The first interceptor would then guide the missiles into the targets in the normal manner as though it were the firing platform. These and many other such tactics will be made possible by the high capacity, superior reliability and precise relative navigation capabilities of JTIDS.

All of the capabilities afforded by JTIDS refine and extend the commander's power and span of control, while at the same time giving him more flexibility. These capabilities will be provided with only one major suite of equipment for each user. The next step is to provide these enhancements at a reasonable cost. With this in mind, the Joint Program Office is having several terminals developed.

6.3.6 CURRENT DEVELOPMENTS

The JTIDS program has been taking advantage of the collective background and technology bases that have been established through previous and continuing developments of the individual U.S. Military Services both inhouse and within industry. Current planning is oriented toward development, acquisition, operational testing and evaluation of the Advanced Development Model (ADM) terminals and interface devices for user system/platforms. Additional efforts will focus on transition and implementation plans, net management procedures, protocols and technical control plans and software.

The Naval Air Development Center (NADC), Warminster, Pennsylvania, has been assigned the responsibilities of the Navy's lead laboratory for JTIDS. This responsibility includes system engineering, procurement, test and evaluation and integration of JTIDS terminals into Navy platforms. These efforts are in direct support to the Joint Program Office, Navy Deputy Program Manager. The Joint Program Office is located at the Headquarters of the Electronic Systems Division (ESD), L. G. Hanscom Air Force Base, Bedford, Massachusetts. NADC is being assisted by several other defense facilities and various contractors. Currently, NADC is the contracting agency for the development, design and fabrication of two classes of terminals.

Several Class 2 terminals with a Phase I architecture are being built by the Singer Corporation in Little Falls, New Jersey. These terminals are to be delivered to the Navy and the Air Force for testing in the last quarter of 1977.

The terminal will provide TDMA digital communications, a relative navigation function and a TACAN function. It has a 5 net capability and will handle a maximum data rate of 57.6K BPS. A simplified block diagram of the Singer terminal which has the nomenclature AN/ARQ-40, is shown in figure 6.3-10.

The filter directly after the antenna is notched at 1030 MHz and 1090 MHz to prevent IFF interference. The receiver block represents two independent superheterodyne receivers. These two receivers are time shared between TDMA channels and TACAN. The TDMA channels are single conversion and employ RF gain, tunable RF filters, wide band double balanced mixers, linear-limiting IF amplifiers and surface acoustic wave (SAW) correlators. The IF amplifier, IF converters and SAW correlators are located in the IF processor. The TACAN design satisfies the requirements specified in MIL-N-81207A. The transmitter exciter accepts baseband digital signals from the signal processor and converts to Continuous Phase Shift Modulation (CPSM), which is a modulation technique similar to Minimum Shift Keying. This signal is then upconverted to an Lx band frequency. The signal then exits the exciter and is amplified to 800 watts peak power in the solid-state RF power amplifier. The synthesizer is a digital phase-locked loop capable of switching from any Lx band frequency to any other in microseconds. The signal processor provides TDMA synchronization, ranging, position location, data processing, error detection and correction (Reed-Solomon encoding-decoding) and all other housekeeping functions. The mode control unit contains functional controls for the terminal, TDMA mode control, TACAN channel select and control and necessary controls for the pseudorandom code generator.

The ITT Avionics Division has been contracted to develop Phase II terminals. Class 1 and Class 2 terminals are to be delivered to the Navy for test and evaluation during the first quarter of 1979. The terminals will use the DTDMA signal architecture as previously described which provides the advanced flexibility and increased system capacity and independent multi-net capability in response to the Phase II objectives.

The terminals have been designed to be fully compatible in operations with the Phase I terminals. Additionally, this terminal will provide a multiplicity of concurrently processed functions. These include a number of jam-resistant functions; transparent Air Tactical Data System Link (Link-4A), transparent Naval Data System Link (Link-11), wideband (16K BPS), and a narrowband (2.4K BPS) digital voice, relative navigation and TDMA-JTIDS Phase I; as well as conventional TACAN and MARK XII IFF functions. A simplified block diagram of the ITT Avionics Division Class I terminal (AN/USQ-72) is shown in figure 6.3-11, which shows the five major blocks of the terminal, Power Amplifier (PA), and the Receiver/Transmitter (R/T), Signal Processor (SP), Terminal Processor (TP), and the Control and Display Units.

The Power Amplifier (PA) provides the power gain and modulation control for all transmitted pulses. The broadband low-noise front end of the receiver is also included in the PA unit.

The Receiver/Transmitter is a single unit. It provides the transmitter RF drive and amplitude modulation signals to the Power Amplifier, switches the output of the Power Amplifier to the selected antenna, and provides four channels of received signal correlation outputs to the Signal Processor. The Receiver/Transmitter receives digital data from

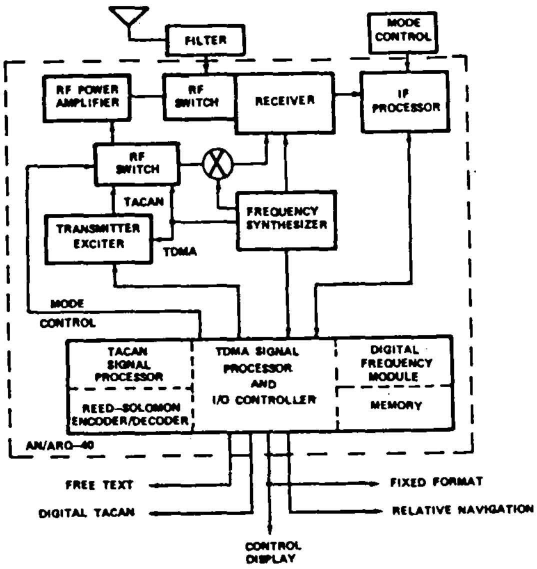


Figure 6.3-1Ø AN/ARQ-4Ø(XJ-1) simplified block diagram

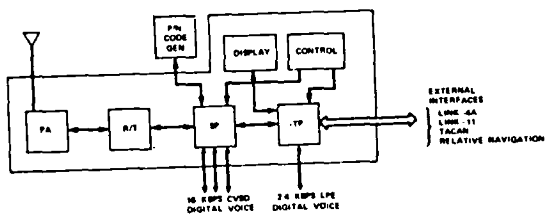


Figure 6.3-11 AN/USQ-72(XJ-1) simplified block diagram

the Signal Processor for the control of each transmission or reception event. This data specifies the frequency, PN code, SAW code, pulse type, (JTIDS, TACAN, or IFF), transmit power level or receiver gain, etc., as applicable. Status monitoring signals (VSWR, Output Power, Synthesizer lock-on) are also sent to the Signal Processor by the Receiver/Transmitter. The Signal Processor provides all digital signal processing for the terminal, controls the function channel structures, and implements the various communication nets using configuration command data from the Terminal Processor. The Signal Processor provides all control and interfacing with the pseudorandom code generator.

The Terminal Processor's primary functions include the provision of terminal mode and configuration control, message buffering, man-machine interface processing, TACAN navigation processing, and built-in test (BIT) control and diagnostics. The Terminal Processor routes digital messages to the Signal Processor for transmission, specifies time of transmission, and receives digital messages from the Signal Processor for buffering and forwarding to other platform subsystems.

The Display Unit (DU) provides the direct man-machine interface in the form of an alphanumeric display, a queued keyboard for data entry, and several control selector switches. The alphanumeric display is also used to display status information, TACAN data, and malfunction isolation information.

The Control Unit (CU) provides the basic TACAN and IFF control functions and is made up of a conventional AN/ARN-84 and APX-72 TACAN and IFF control panel.

The broad applicability of the JTIDS System is assured by the various classes of terminals being developed. Laboratory and field tests of the first JTIDS Advanced Development Models began in late 1977. When operational in the 1980's the Joint Tactical Information Distribution System will assure instantaneous and reliable communication, information distribution, navigation and unambiguous user identification during tactical operations in any theatre.

6.4 WEAPONS GUIDANCE AND CONTROL

6.4.1 AIR-TO-AIR GUIDANCE

The overall objective of this technology area is to develop guidance subsystems, components, and techniques for application to advanced tactical air-to-air missiles. Technology pursuits must take into account several factors, some of which are listed below.

6.4.1.1 Target Discrimination. When the missile is in a look-down mode, the threat aircraft must be distinguished from background clutter. Whether the missile seeker operates in an RF or IR band, the clutter problem is particularly severe when the threat is at low altitudes.

6.4.1.2 Countermeasure Immunity. During the acquisition or tracking phase, the threat aircraft could deploy countermeasures such as flares against an IR seeker or chaff against an RF seeker. The seeker must be capable of recognizing and ignoring the countermeasure deployed while maintaining track on the true target.

6.4.1.3 Launch and Maneuver. The missile must be independent of the launch aircraft after missile separation.

6.4.1.4 All-Aspect Acquisition and Track. The missile must be able to acquire and track the target aspect. For example, long range nose-on acquisition is difficult since the radar cross section of the threat aircraft is minimum, and plume IR energy is masked by the aircraft.

6.4.1.5 Counter A Maneuvering Target. The missile must be capable of a successful intercept on a highly maneuverable threat aircraft. Technology programs being pursued include developments related to both short and medium range air-to-air missiles. Though some requirements are common to both classes of missiles, there are also significant differences. The differences affect the supporting technologies associated with each and are discussed separately below.

6.4.1.6 Short Range Missile. The short range air-to-air missile is primarily a dogfight missile, i.e., it is used in close-in air engagements against highly maneuverable enemy fighter aircraft. Consequently, it must have capabilities of rapidly acquiring the target at any aspect, of being launched off- boresight (relative to launch aircraft centerline), and flying a successful intercept on the maneuvering target. State-of-the-art seeker technology includes passive IR (imaging and nonimaging), active laser, active radar, and combinations thereof. The passive IR concepts are fundamentally based on collecting a sufficient amount of IR energy radiated by the aircraft plume/tail pipe onto the IR detector (or detector array for imaging systems). After target acquisition, the seeker enters a track mode whereby commands are generated to drive the seeker gimbal to keep the target within the seeker field-of-view and simultaneously commands are generated to control the flight path of the missile. The active laser and active radar seeker concepts are similar in that the radiating source is contained in the missile. The beams (several milliradians for the laser beam and a few degrees for the RF beam) are radiated from the missile in a predetermined search scan pattern and when the reflected energy from the target exceeds a pre-set threshold, the seeker enters a track mode.

A particular area requiring more investment of R&D resources includes development of a low cost (less than $2,000) laser capable of high pulse energy (200 millijoules), narrow pulse width (10-20 nanoseconds), and variable repetition rate (20 pps to 200 pps) and packageable in a 4-4 inch cylinder less than 12 inches (approximately) long. Another area requiring additional resources is in the development of low cost focal plane arrays for use in imaging IR systems. Though the number of elements cannot be precisely defined, an array of 1000 x 1000 elements could make possible a strapdown (no gimbal) imaging seeker. Additional efforts are also required in establishing a data base of long wavelength (8-12 micrometers) airborne measurements of targets and various terrains.

6.4.1.7 Medium Range Missile. Efforts related to medium-to-long range missiles include technology and development efforts to demonstrate the capability of acquiring a radiating airborne target, launch of the missile and accomplishing a successful intercept. It is also required to maintain track on the target if, after the missile is launched, the target shuts down its radiating source. A concept under consideration is to use a dual mode seeker in which the acquisition mode is performed by passive radar with the capability to hand-over to an active radar if the target ceases radiating. An alternative for the active radar mode is a passive IR mode.

An area requiring additional R&D resources is to develop the capability of establishing, by passive means, the range to the target. This would be a great aid in determining whether the target is within launch limits. Accuracy of the range measurement is not critical; i.e., 20-30% is acceptable.

Another area requiring added emphasis, and which would enhance performance of active radar seekers, is to investigate the methods of obtaining longer acquisition ranges with lower transmitted power. Innovative techniques of signal and data processing are among some of the possibilities in achieving this goal.

6.4.2 AIR-TO-GROUND GUIDANCE

The overall objective of this technology area is to develop the terminal guidance subsystem and component technologies and demonstrate their feasibility for application to advanced air-to-surface weapons. The technologies which will provide or improve our adverse weather capabilities are being emphasized along with those that have the potential for lowering or reducing the cost of ownership. The goals of the terminal guidance area are the successful demonstration of low cost millimeter-wave and infrared seekers for possible application in small independently guided antiarmor weapons. Expansion of the data base in the millimeter-wave and infrared area is an additional near term goal to permit proper evaluation and application of this technology.

6.4.2.1 & 2 Millimeter Wave (MMW) and Infrared (IR) Guidance

Technology

The objective of current MMW guidance technology program is to provide an adverse weather guidance capability for direct hits on tactical battlefield targets. Current emphasis is placed on two major objectives: (1) demonstration of an autonomous lock-on-after-launch (LOAL) capability and (2) demonstration of terminal guidance accuracy necessary for a direct hit weapon. In order to meet these objectives extensive target and background signature measurement programs are being pursued to establish the necessary data base. In addition, a comprehensive modeling and analysis effort is underway to evaluate expected performance of current hardware implementations and provide technical direction for further sensor/seeker development. This technology program is specifically structured to address adverse weather terminal guidance technology as applicable to conventional weapons and does not promise to significantly contribute to the NASA mission.

6.4.2.3 Map Matching Update Guidance.

The use of position updates, generated by an inflight map matching or correlation process, to correct inertial navigator errors is a viable means of guiding a tactical weapon to high-value, stationary targets in adverse weather. Successful correlation has been demonstrated with optical, radiometric, radar, and altimeter sensing systems. Although good midcourse guidance accuracy has been attained, and with some systems which can map-match on the terminal scene, good terminal accuracy, one or more operational limitations has thwarted the systems implementation in operational tactical weapons. The two biggest limitations are cost and quick-strike capability. The cost of an inertial system, scene sensing system, in some devices pointing capability, correlator, processors, and core avionics to distribute information is high for a midcourse guidance capability. For the systems that also provide terminal guidance, the cost of ineffective weapons lost to ECM at high-value, highly defended targets enters in. Map matching update guidance systems lack a quick-strike capability against targets newly found through reconnaissance. Hours could be lost referencing the recce back to a data base (assuming the data base was available) and then loading the reference data into the weapon for strike.

In view of these limitations and others such as seasonal change, highly adverse weather, availability and cost of source data, altitude limitations, and ECM, the emphasis in map-matching guidance is turning to real-time target/scene acquisition. This 'snapshot' approach has been demonstrated with optical correlators and seems feasible with the high resolution radars being developed. Real time acquisition allows a high probability of kill and thus extends utility to lower-value targets. Resolution may be sufficient to perform terminal guidance without the need for a seeker. This type of technology will have a major impact on weapon guidance in the mid 80's.

7.Ø FUNDAMENTAL TECHNOLOGY

The fundamental technologies form the basis for the other technologies by providing the analytical tools, the software development methods, and the emerging new components. This technology area covers Information and Control Theory, Device Technology, Fluidics, System Analysis and Software Methodology, and Flat Surface Display Technologies.

7.1 INFORMATTON AND CONTROL THEORY

The theoretical foundation for information and control theory as used in modern control today is approximately 2Ø years old. The mathematical formulations were considerably more sophisticated than the classical control methods that had been used previously. As a result there was a longer learning time before the system application implications were fully understood and there was an adequately educated community to accept the modern approach. In some cases, the classical designs have continued to be the designs of choice, appropriately so because of their simple structure, and in many cases, easier accessibility for checkout, and trouble shooting in the field. Inevitably, we have progressed in our challenge to control more complicated systems so that we must rely on the formalism on the multi-input multi-output control theory.

The most significant difference in modern control is the use of a cost function as the criterion for developing candidate designs. The ideas first appeared coherently in theory of servomechanisims by James, Nichols, and Phillips. More detail and applications appeared in Newton, Gould, and Kaiser's book. A quadratic cost function for control which minimized the integral of weighted squares of states and controls provided a sufficiently general criterion that has proved quite successful as a design tool. The physical interpretation of weighting factors to use with such a control design criterion were developed by Bryson when he observed that for systems in which the control dominated, the states and controls each contributed comparable amounts in the cost function. As a result, the weighting factors have the interpretations of the reciprocal of the maximum allowable states and controls respectively squared.

The similar transition to minimizing the variance in the estimates of states has provided a scalar criterion for the development of filters. This method is very powerful and when used in combination with a filter structure which models the plant as accurately as is needed, there is a maximum rejection of sensed information which is inconsistent with possible physical behavior of the system.

Techniques have developed to extend the original formulations and to use specialized design tools for special cases, e.g., when the system can be described by a set of linear constant coefficient differential equations. The eigenvector decomposition available under these circumstances leads to extremely rapid designs on a digital computer which many times can provide insight to first guesses in a truly nonlinear control problem.

In both the control and filter design problems, the evaluation of candidate designs is still performed with simulations. These simulations attempt to verify with more exact models of the plant including nonlinearities and other effects which are expected to be unimportant and more sophisticated models of disturbances. Ultimately the evaluations in the field find hardware and mechanization difficulties which cause performance to be different than expected. Trouble-shooting at this level is aided considerably by having both physical state models and eigencoordinate representations so that the trouble can be identified as hardware vs. mathematical more easily.

7.1.1 OPTIMAL CONTROL

NASA should investigate methods of designing robust optimal control laws. These control laws would either be passively insensitive to plant variation or would actively adapt to variations. Passive insensitive controllers may be more pratical that the active adaptive methods. In general, filters and state estimators, essential components of a complete optimal feedback control scheme, tend to be more sensitive to unmodeled plant variation than state feedback controllers. This phenomenon should be studied. Applications which will require optimal controllers which function well despite plant uncertainties include:

(a) control of flexible structures (e.g. solar power satellites)
(b) Light-wing-loading STOL ride quality control
(c) reliable automatic landing under operational variations in system models
(d) helicopter handling quality (e.g. vibration, gust, response time) and fuel efficiency improvement
(e) 11 flight envelope autopilots

Optimal feedback control laws for nonlinear systems should be investigated. Simple and extremely fast optimal trajectory calculation algorithms might actually be solved in real time by an on-board computer. An important application is the control of a short range air-to-air missile tracking a maneuvering target.

Minimum fuel optimal flight paths for commercial aircraft become more important as fuel costs rise. Problems here include accurate modeling of the aircraft/propulsion system and the incorporation of all hardware and large sale system constraints in the design algorithm. An important element in the acceptance of optimal control methods is their variation on real vehicles under controlled test conditions.

7.1.2 KALMAN FILTER AND STATE ESTIMATION THEORY

Implementation of this technology presents the greatest technical opportunity at this time. NASA should investigate the application of modern identification techniques to the task of optimizing load and ride control system performance. The ability to correctly predict structural mode shapes during the design of an airplane is presently poor. Identification techniques can be used to generate high fidelity airload/structural models from flight test measurements. These models could then be used to fine tune the load/ride control system. The key requirement here is provision by NASA of flight hardware -- including computers -- to allow researchers to further algorithm development and functional checkout. NASA should sponsor this research either through Langley's EET program or Ames' QPLT program.

NASA should reevaluate fault detection technology in light of the F-8 digital fly-by-wire program. The philosophy should again emphasize implementation and experimentation. Too much emphasis was placed on algorithmic approaches as opposed to operational or hardware issues. In particular, transient fault detection logic is but one small part of the requirements: more research should be placed on steady state system diagnosis and a detailed trade-off made of 'customized' versus 'common' base-line data. (Most aircraft systems are usually in steady state.)

The key issue of fault detection, for both transient and steady state operation, is the concept of fault tree search. Other competing ideas are 'banks of Kalman filters' and 'system identification approaches.' These should be further evaluated, through NASA-sponsored studies, in light of potential computer architectures and sensor technologies.

Theoretical studies are recommended in the areas of nonlinear and adaptive controllers. Modern control theory methods which do not account for system parameter variations do not seem to work well in practice. Adaptive control laws are usually too complex. Special attention has therefore been directed toward parameter insensitive controllers. Many new structures for parameter insensitive controllers have been developed and are being evaluated. These controller forms are linear and allow for large variations in parameters without significant degradation in performance.

Nonlinear identification methods have been used in several applications but need further development in the area of model structure determination. Advanced methods are required for state estimation and parameter estimation with non-gaussian non-white noise. Of equal importance is the development of efficient general methods for treating large-scale nonlinear systems by analysis or simulation, to predict such phenomena as limit cycles and jump resonance.

States are the variables chosen to express a mathematical model describing dynamic behavior of the aircraft, the kinematics of approach to an airport, or the dynamics of an instrument, etc. Until recently, states that were needed were measured and filtering was done spectrally. Estimators use the model of the dynamics to infer other states from the measurements of one or more and in doing so provide more sophisticated possibilities for filtering signal from noise.

The estimator is like a simulation of the dynamics. It may be in error initially and it lacks the true noise and disturbance of the physical world. To correct for this, the expected measurement (from the estimated states) is compared with the real measurement and the difference is weighted (by gains) and fed to each estimated state to correct it. In some cases the initial conditions require large gains for quick settling but if sensor noise is the principal contribution to error in the steady state the gains must be small to isolate the estimator from the noise. In these cases a Kalman filter may be used or gains can be stepped discretely during initialization. The concept may be applied to nonlinear as well as linear models though the design is easier to develop and to troubleshoot when a linear model is acceptable.

A low order model of the system is important. The minimum order model which acceptably represents the dynamics for the purpose for which the estimated states are needed will be least sensitive to modeling errors, for example, errors in parameters. No systematic method exists for choosing an acceptable low order model so the modeling becomes part of the iterative process of design.

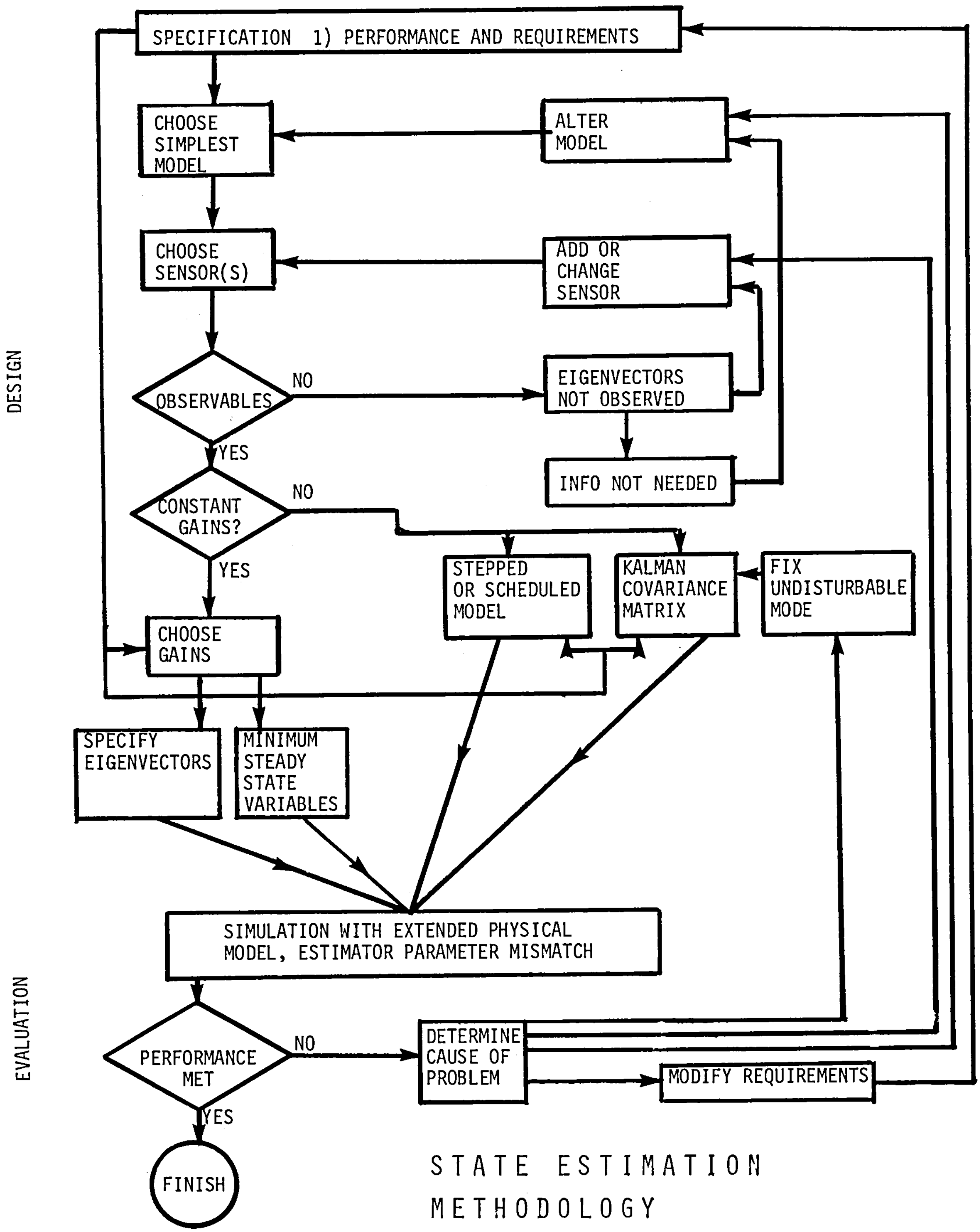
The states must be observable with the measurements available if they are to be determined, but this may not be a sufficient criterion. Unobservable but well damped states cause no problem if there is no interest in them; but to be determined, additional measurements are necessary. Representation of the model in eigencoordinates makes it possible to identify the unobserved mode and thereby see which states participate and are candidates for sensing. The optimum choice of sensors is not a science since there may be many adequate combinations -- the proper choice depends on cost, reliability, etc., as well as performance.

Estimator gain selection may be done in design or an algorithm may be used on-line. Criteria vary and include: specified estimator error equation eigenvalues (for linear, constant coefficient models), minimum variance in the steady state, or on-line as in a Kalman filter.

The Kalman filter will assume it can estimate a steady state perfectly if there are no disturbances because the mechanization is based on an assumption of a perfect model. Since all measurements have noise, a Kalman filter will set the estimator gains to zero for modes which are undisturbed to prevent sensor noise disturbing its 'perfectly estimated' states. If the undisturbed mode is neutrally stable (has an eigenvalue with zero real parts) the filter will diverge. This problem may be prevented by a variety of techniques (ref 1Ø3) (SUNDAR 5Ø5): constrain the real part of the eigenvalue of a minimum variance design, artificially introduce noise in the model though it has no physical meaning (it becomes a design tool not part of the physical modeling), destabilize the system model (unstable modes produce roots with real parts reversed in sign so they do not diverge), and for a Kalman filter restarting periodically resets the gains for the estimated initial conditions which are typically nonzero for the undisturbed mode too.

One of the most important criteria is sensitivity to model errors. Quadratic cost function criteria for control gains have been extended to include sensitivity terms and a similar process is needed for estimator gains and sensor selection criteria. At the present this process is most frequently done by the designer by iteration during the simulation.

The design of estimators therefore is not a direct process but like all designs involves iterations. A systematic approach to this process is shown in Figure 7.1.2-1 where individual steps have been explained briefly in the text above.



STATE ESTIMATION METHODOLOGY

FIGURE 7.1.2-1

7.1.3 DIRECT DIGITAL SYNTHESIS

The trend to digital mechanizations has fostered a re-examination and extension of techniques for discrete systems analysis and synthesis. Most of the control problems of interest involve a continuous controlled element and a hybrid controller which may contain both continuous and discrete elements. Since a major portion of the system may be continuous, and because many system design criteria and procedures have been developed for continuous systems, one very popular approach is some form of emulation.

In general, emulation starts with a continuous controller design and then converts this controller to a digital equivalent. The emulation approach is illustrated in more detail in figure 7.1.3-1. The major part of the analysis procedure is accomplished in the continuous or s (Laplace transform) domain. The resulting control law is converted to a difference equation by, for instance, the Tustin transform. This is accomplished by replacing s in the control laws by:

$$s \Rightarrow \frac{2\ (z - 1)}{T\ (z + 1)}$$

where z = e exp. Ts. The advantages of an emulation procedure are that insights, computer programs, rules of thumb, etc., useful in the familiar continuous system analysis procedures transfer into the discrete domain. The discrete version of the continuous control law is evaluated on the basis of some fidelity criterion, i.e., indicating how closely it approaches the continuous design. The nature of the approximations involved determining the discrete controller are such as to result in a degree of overdesign. In particular the frame rate requirements appear larger than necessary.

The main alternative to emulation is some direct digital design process. This can be reviewed with the aid of figure 7.1.3-2. The procedure begins with the discretizing process which places all elements, continuous and discrete, into a discrete format. The use of zero-order holds to couple the output of the digital computer to the control actuators is usually implied, although other coupling forms can be included explicitly.

After the equations of motion have been made discrete, the direct digital design can be carried out using a wide variety of design aids and tools. Conventional sampled data design using the z-transform is one possible procedure. It has awkward features in that the stability boundary lies only within the unit circle rather than on the entire left half plane, and in complex systems many roots tend to come quite close to this boundary. In fact, an extraordinary number of significant figures must often be carried in calculations to separate the roots which are close to the unit circle. While this has computational burdens, these are relatively insignificant compared to the loss of insight which accompanies the design in the continuous domain. That a design is stable is easy to see; that it will perform well under all circumstances is somewhat difficult to envision.

Because many of the available design procedures suffer from similar problems, especially those involving design insight, a good deal of

EMULATION

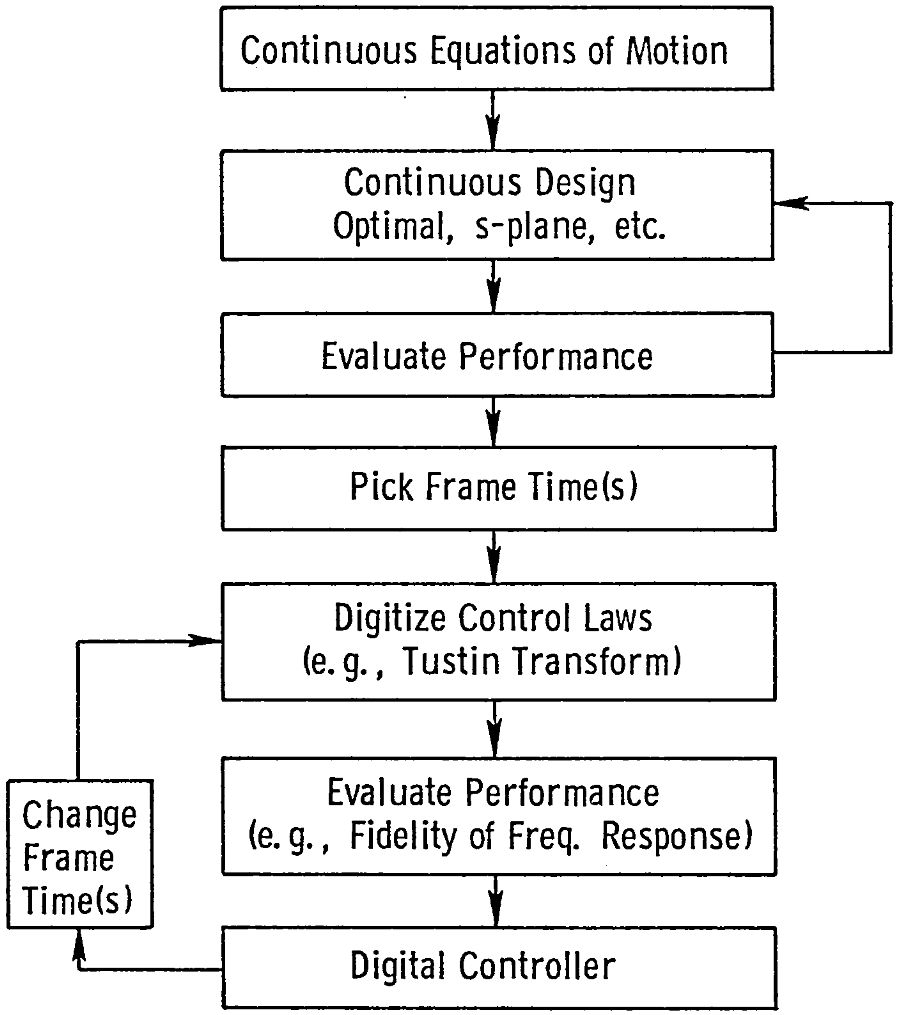


FIGURE 7.1.3-1

SINGLE RATE DIRECT DIGITAL DESIGN

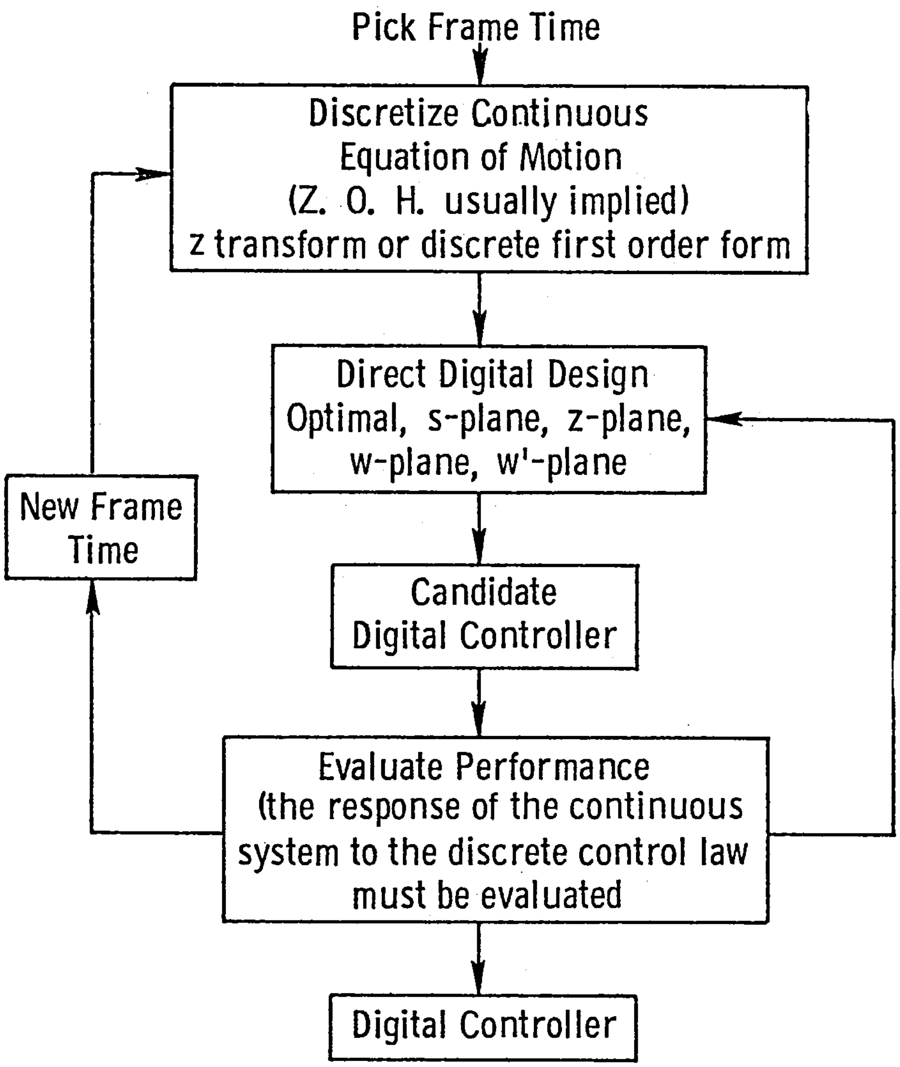


FIGURE 7.1.3-2

attention has recently been devoted to direct design procedures which, like emulation, have fruitful connections with the continuous domain and are readily related thereto. The w' transformation has proved to be an exceptionaly usefull domain because it permits the carryover of many continuous system procedures, techniques, and insights into the digital world without introducing any approximations. The w' transform is a scaled version of the familiar bilateral w-transform (figure 7.1.3-3). It is given by

$$w' = \frac{2}{T} w = \frac{2\,(z - 1)}{T\,(z + 1)} = \frac{2}{T} \tan h \frac{Ts}{2}$$

This equation for w' is similar to the equation for the Tustin transform. The former, however, is used as a direct substitution for s; whereas to transform from the continuous to the w'-domain requires a valid discretization of the continuous equations of motion.

One immediately observes a nice feature of the w' domain, in that as the sampling period goes to zero, w' approaches s. In other words, at frequencies well below the folding frequencies, system characteristics in the w' domain closely approximate those in the frequency domain. In fact, numerical values of gains and time constants in the w' domain are very similar to their s domain counterparts for those modes which are well below the folding frequency.

In the w' domain, the transfer function has the same number of zeros as it has poles, even though the s domain transfer function ordinarily has an excess of poles over zeros. The excess zeros associated with the w' domain approach infinity as sampling time approaches zero. Thus, the continuous transfer functions can be thought of as special cases of w' domain transfer functions as T approaches zero. The excess zeros come about due to the nonminimum phase effects of sampled data and data holds. They thus clearly indicate the effects of these elements in the discrete system. It is, in fact, these additional zeros that are the major 'new' features needed to be considered in the discrete design. Because of the neat analogies between the continuous and w' design domains, conventional multiloop analysis, Bode plot, root loci, and other procedures are useful and valid in the w' domain even in the presence of significant folding. The controller designer can thus synthesize digital controllers using considerably lower sampling rates than are required when an emulation design approach is used, while still retaining insights adapted from the continuous domain. In fact, it is not too much to say that an 'analog' system designer can use the w' domain to literally 'transform himself' into a digital designer.'

The combination of the w' domain with vector switch decomposition furnishes a powerful tool for the direct digital synthesis of multirate systems. It also serves as a basis for extending the concept of frequency response from merely being the magnitude and phase of the sine wave that fits the sample points at the sampling instances to the case of fitting N sine waves to the sample points and N-1 inter-sample points. It thus permits the assessment of a continuous frequency response for a discretely excited system. This then makes a clear distinction between the sampled spectrum, which is commonly but incorrectly understood to be the frequency response of a discretely controlled system, and the actual continuous frequency response.

ANALYSIS DOMAINS

Continuous Domain

$$s$$

Sampling Domain

$$z = e^{Ts}$$

Trapezoidal Integration (Tustin Transform)

$$s \rightarrow \frac{2}{T}\left(\frac{z-1}{z+1}\right) = \frac{2}{T} \tanh \frac{Ts}{2}$$

w' Domain

$$w' = \frac{2}{T}\left(\frac{z-1}{z+1}\right) = \frac{2}{T} \tanh \frac{Ts}{2}$$

FIGURE 7.1.3-3

A comprehensive review of direct digital synthesis procedures which emphasizes, elaborate, and illustrates the above points is presented in 'Analysis of Digital Flight Control Systems with Flying Qualities Applications,' R. F. Whitbeck and L. G. Hofman, Systems Technology, Inc., TR-11Ø1, June 1978 (forthcoming AFFDL TR).

Extensions to the above theory are desirable to include nonsynchronous data and distributed architecture. Also, as is always the case with new analysis and design procedures for complex systems, specialized or modified software packages to support the design efforts are needed.

7.2 DEVICE TECHNOLOGY PROJECTIONS

7.2.1 ELECTRONIC DEVICES

This section presents a review of the current status and projection of the trends of various technologies to 1985-1988. A 3- to 5- year time lag is assumed at that time to incorporate this new technology in production hareware.

7.2.1.1 Silicon Semiconductor Technology

Circuit Technology

Advances in semiconductor state of the art over the last 5 years have been impressive. The basis for much of the recent progress in integrated circuit (IC) technology has been advances in photolithography, semiconductor cell isolation, and ion-implantation processing schemes. Semiconductor chips with the equivalent of 80,000 transistors are available as off-the-shelf items, and microcomputers, microprocessors, programmable hand-held calculators, and complex memory chips are readily available. Development of newer methods, such as electron-beam and ion-beam implantation pattern generation, promise more improvement. To prevent mask damage due to contact printing, efforts are also underway in projection printing and 'near-contact' printing. Feeding these developments is an array of technologies remarkable for their diversity and ability to enhance circuit performance.

As shown in figure 7.2.1.1-1, most of these technologies still use silicon as the base material and are primarily of two basic types: bipolar and metal-oxide semiconductor field-effect transistor (MOSFET). The bipolar technologies can be broken down into many different circuit forms, based on three approaches to circuit construction:

- Epitaxial collector techniques
- Triple-diffusion techniques
- Oxide-isolator techniques

The epitaxial collector device structure is the most common bipolar processing method in use today. It has resulted in a large number of unique circuit forms as shown in figure 7.2.1.1-1. One promising technology for future applications is IIL (integrated-injection logic).

The size and low-power advantages of IIL come directly from shrinking the old direct coupled transistor logic (DCTL) into a single complementary transistor equivalent. By this arrangement, packing densities similar to those of MOS can be obtained. Other names used for logic types that are basically IIL are:

- CHL -- Current-hogging logic
- CCCL -- Complementary constant-current logic
- SFL -- Substrate-fed logic

IIL devices fabricated by conventional bipolar processes are presently limited to a delay of 10 to 30 nanoseconds per gate. If the process is optimized for IIL, it is felt that delays of 2 to 3 nanosec. can be

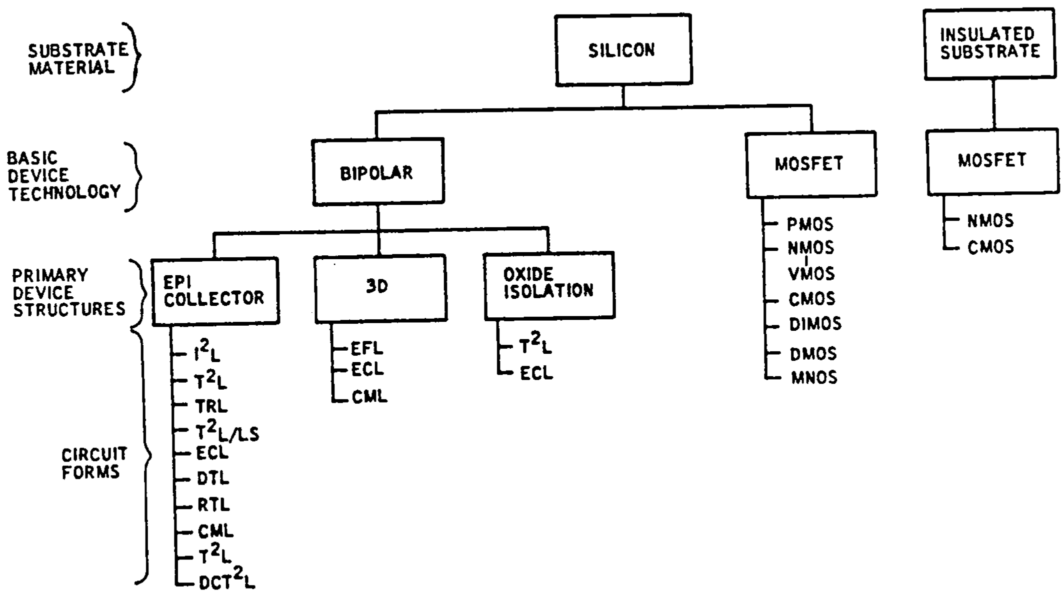


FIGURE 7.2.1.1-1 STATUS OF SILICON SEMICONDUCTOR TECHNOLOGY

achieved. IIL devices can be included on the same chip with Schottky TTL, emitter-coupled logic (ECL), linear circuitry or other circuit forms because of process similarity. This feature can be very useful in the reduction or elimination of special interface circuit requirements.

MOS is being fabricated on both bulk silicon and insulating substrates. While MOS has historically been classified as a very dense and low-power but slow circuit form, new developments are making MOS faster, approaching today's most popular bipolar circuit forms.

Another promising silicon technology is CMOS/SOS. Most of the attempts at circuit improvements have been concerned with improved device isolation. With silicon-on-insulated substrate MOS (SOISMOS), no bulk silicon is used; instead, a thin film of silicon is grown on an insulating substrate, and silicon islands are formed by selective etching. The transistors are then formed in the standard way except that no guardband diffusions are required. To date, almost all efforts in this technology have used sapphire as the insulating substrate. Some work was done using spinel, but it appeared to be inferior to sapphire.

The benefits of this approach are the size reduction and the lower capacitive characteristics that are achieved by the air isolation between devices. This isolation results in improved speed and lower power. A ASOISMOS chip would be roughly 20 to 30 % smaller than an equivalent N-channel MOS (NMOS) silicon-gate chip. Memories built with this process have access times that rival bipolar parts.

SOIS has been limited thus far to MOS circuit forms, with the highest emphasis on complementary MOS (CMOS). This process will provide high-speed and low-power memories.

One important offshoot of the basic MOS device structure is the charge coupled device (CCD) announced by Bell Telephone Laboratories in 1970. The CCD is a MOS integrated circuit shift register, which is made in the form of a string of MOS capacitors. The initial work was in surface channel devices, where metal electrodes were placed on a silicon dioxide insulation layer over a P-type silicon substrate. No diffusions are required for surface channel devices. However, because of the noise caused by the trapping of charge at the silicon/silicon dioxide interface, most effort is now in buried layer CCDs.

Buried layered devices are formed by selective diffusion or implantation of N-type silicon into a P-type silicon substrate. In comparison with MOSFET structures, CCDs are very simple to process, and thus result in good yield over a very large area. No isolation is required between devices, making this a very high-density technology.

CCDs operate as shift registers or delay lines, where the mobile charge stored within a semiconductor element is transferred to a similar, adjacent storage element. Thus CCDs can represent analog as well as digital data by the external manipulation of voltages, the quantity of the charge can vary widely, depending on the voltage applied and the capacitance of the storage element.

The potential low cost and fast access of CCD serial memories make them candidates for replacing random access memories (RAM) where random access is not a requirement. The latency time of a large memory is reduced by creating smaller blocks of stored bits circulating as if they were enclosed in pipelines, with each pipeline being capable of separate access.

Progress in Integrated Circuitry Technology

Until the early 1970's, the only implementation tools available for the digital portion of a system consisted of integrated circuits, which contained an average of about four logic functions per package. As a result, the cost, size, weight, power and reliability of a system were almost direct function of the number of logic gates in the system. Thus, a heavy emphasis was placed on minimizing the number of gates. Because the logic complexity per package was so limited, the design of standard multiuse devices was a simple task.

With LSIC, hundreds of logic functions can be contained in a single package. Designing functional elements of this complexity that have universal appeal is difficult. Nevertheless, from 1975 through 1977 many complex, but standard LSIC devices that perform significant digital computing functions have appeared, and it has become relatively easy to assemble efficient digital processors using standard LSICs. In 1978, the complete microcomputer on one LSIC chip has become available. Now with the advent of electron beam x-ray patterning, the integrated circuit area required by a transistor will be reduced by hundreds of times. This reduction will result in VLSIC (very large scale integrated circuit), where a processor would take up a trivial portion of a chip and the rest would include perhaps a million bits of memory.

Microprocessor/Computer Projectiion

The latest microprocessing devices contain the equivalent of about 8000 gates on a single chip; current development work indicates this may be doubled by 1980. Further, the fundamental optical and electronic considerations indicate that the practical complexity and speed limit for CMOS devices is many times that predicted for 1980. This means that by the mid 1980's single chip computers will have capabilities considerably exceeding today's best minicomputers and at a fraction of the cost. The question will not be "how to get" the computing/ processing capability but "how to use it." Some current thoughts on how to efficiently utilize the coming wave of powerful computing hardware are described in the next section.

7.2.1.2 Computer Architecture and Software

One probable approach to utilizing the new computers will be a move to much greater use of parallel architecture arrangements. Until recently the most economical way of increasing computer throughput was to build faster single machines because all computers were expensive, and it was cheaper to increase the speed, through use of improved logic than to build two or more similar slower machines. Increasingly, however, the software cost was becoming greater in relation to the hardware cost, largely due to th increase in software complexity necessary to take advantage of the faster hardware. More recently attention has been focused on architecture in which the software is divided into more easily manageable 'modules' each of which handles a particular part of a larger overall computing task. Each module can be processed by an independent computer (having its own dedicated memory) which then communicates by a bus with other computers handling other parts of the overall problem. Perhaps one computer will be assigned the task of initializing the problem and controlling bus traffic. Such an arrangement would, by subdividing both software and hardware, offer two advantages. One, the total software task would be lessened because software design time is an exponential function of the total instructions involved; two, the computers would be identical except for program memory and perhaps I/O conditioning and thus the design would be that for one less complex unit. Further, the several computers can probably be assembled from the standard VLSIC devices which will be in production in the next few years.

Another probable effect of inexpensive computing capacity will be an increase in the use of higher order languages for writing software programs. Up until now the cost of the memory required to accommodate higher order language programs and the decrease in net output has required almost all programs for production airborne computers to be written in an assembly language. This has resulted in efficient machine language programs which minimized the recurring cost of the hardware needed to process them. This efficiency in hardware was gained at the cost of more programming work by software designers intimately familiar with the processor being used. Further, each computer required specialized code-writing techniques even when the instruction sets were similar. With processing and memory hardware becoming a minor portion of system cost it becomes feasible and desirable to increase the hardware content somewhat in order to minimize the software design and validation costs. Obviously, this effect will be noted first in relatively complex systems with low production potential but as the hardware costs decrease the effect will extend to high production systems. The greatest impediment to this trend may be the lack of any standardization in higher order languages. The widely used languages like BASIC, COBOL, and FORTRAN are not well suited to real time processing of control law and navigation algorithms, while none of the more specializedlanguages have gained wide enough usage to become defacto standards.

ARPA is currently funding two contractors to develop prototype compilers for a new real time programming language designated DOD I, which was designed and specified under prior contracts. After the prototype compilers are evaluated it is planned to have operational compilers developed for some computers of the Military computer family.

The target date for the operational compilers is 1980. Presumably after this time it will be required to have compilers for all computers designed into military vehicles. Eventually this will result in a few languages becoming standards and in the development of compilers for the higher level microprocessor/computers.

7.2.1.3 Gallium Arsenide Technology

Gallium Arsenide is an emerging technology which promises to bring a further revolution to circuit technology beyond that possible with silicon technology. The basic physical characteristics of GaAs provide an electron mobility (mu) five times that of Si which means GaAs has a great potential for smaller power-delay products than for equivalent Si devices. Furthermore, GaAs has the potential of operating above 400 deg Celsius and will sustain greater nuclear hardening than with Si (10 exp. 15 to 10 exp. 16 neutrons per square cm. and 10 exp. 5 to 10 exp. 6 rads of gamma radiation). Currently there are three GaAs technologies being exploited for circuit application:

- Enhanced Junction Field Effect Transistors (E-JFET)
- Metal Semiconductor Field Effect Transistors (MESFET)
- Transfer Electron Devices (TED)

The E-JFET has the potential for the smallest power-delay product in the area of 10 fempto Joules (fJ), MESFET/SDFL has the potential for the highest circuit densities (100,000 to 1,000,000), and TED has the potential for the shortest propagation delays, 30 to 50 picosec. but at relatively low power-speed product (i.e., high power) approximately 2 picoJoules (pJ).

The relation of the three GaAs technologies to the competing Si technologies is portrayed in figure 7.2.1.3-1. The MESFET technology divides into two branches: Schottky Diode FET Logic (SDFL) and MESFET's which do not use SDFL. The SDFL technology is being pursued vigorously by Rockwell Science Center for application to Very Large Scale Integration (VLSI) and Ultra Large Scale Integration (ULSI). Hewlett Packard is pursuing MESFET technology for application to Medium Scale Integration (MSI) circuits.

McDonnell Douglas Astronautics Company is developing E-JFET technology and has produced 3 micron devices with a power-delay product of 100 fJ and a delay of 1000 ps (1 ns).

The Rockwell SDFL MESFET technology has produced small scale integration (SSI) devices having a power-delay product of about 50fJ and a gate delay of about 80ps.

Hewlett Packard MESFET (depletion mode) technology has produced SSI devices with gate delays of 250 ps and a power-delay product of 10 pJ (10,000 fJ).

As may be seen from table 7.2.1.3-1 a number of devices have been produced and tested as of September 1978. Rockwell has produced a 30 gate CCD device, but the performance figures were not published nor available. However, Rockwell is projecting a CCD capable of operating at a gigabit/sec. within a few years.

The GaAs device technology is currently utilizing ion implant techniques and optical lithography for the circuit chip mask layout. The resolution limit for optical lithography is about 1 micron line width which means the minimum logic gate length is also about 1 micron.

Both Dr Zuleeg of McDonnell Douglas and Dr. Liechti of Hewlett Packard indicated that their companies are projecting the use of sub-micron lithography using electron beam technology in order to increase circuit yield.

Projections made by Drs. Eden, Zuleeg, and Liechti are presented in table 7.2.1.3-2. Dr. Eden's projection is a dramatic example of what can be expected of the new GaAs technology when ultra large scale integration (ULSI) is achieved. The super chip (first item of table 7.2.1-2) has the capability of the Amdahl 470v super computer central processing unit (CPU) which is packaged in a unit about 0.9 m in diameter utilizing ECL LSI. The Amdahl CPU utilizes 10KW of power and has an instruction time of 10 ns.

The GaAs super chip which emulates the Amdahl 470 super computer utilizes 20 watts of power, is 1 cm square, and has an instruction time of 1NS. This means the GaAs super chip

- uses 500 times less power
- is ten times faster
- uses 6000 times less area

than the Amdahl 470 super computer.

SPEED/POWER PERFORMANCE OF VARIOUS TECHNOLOGIES

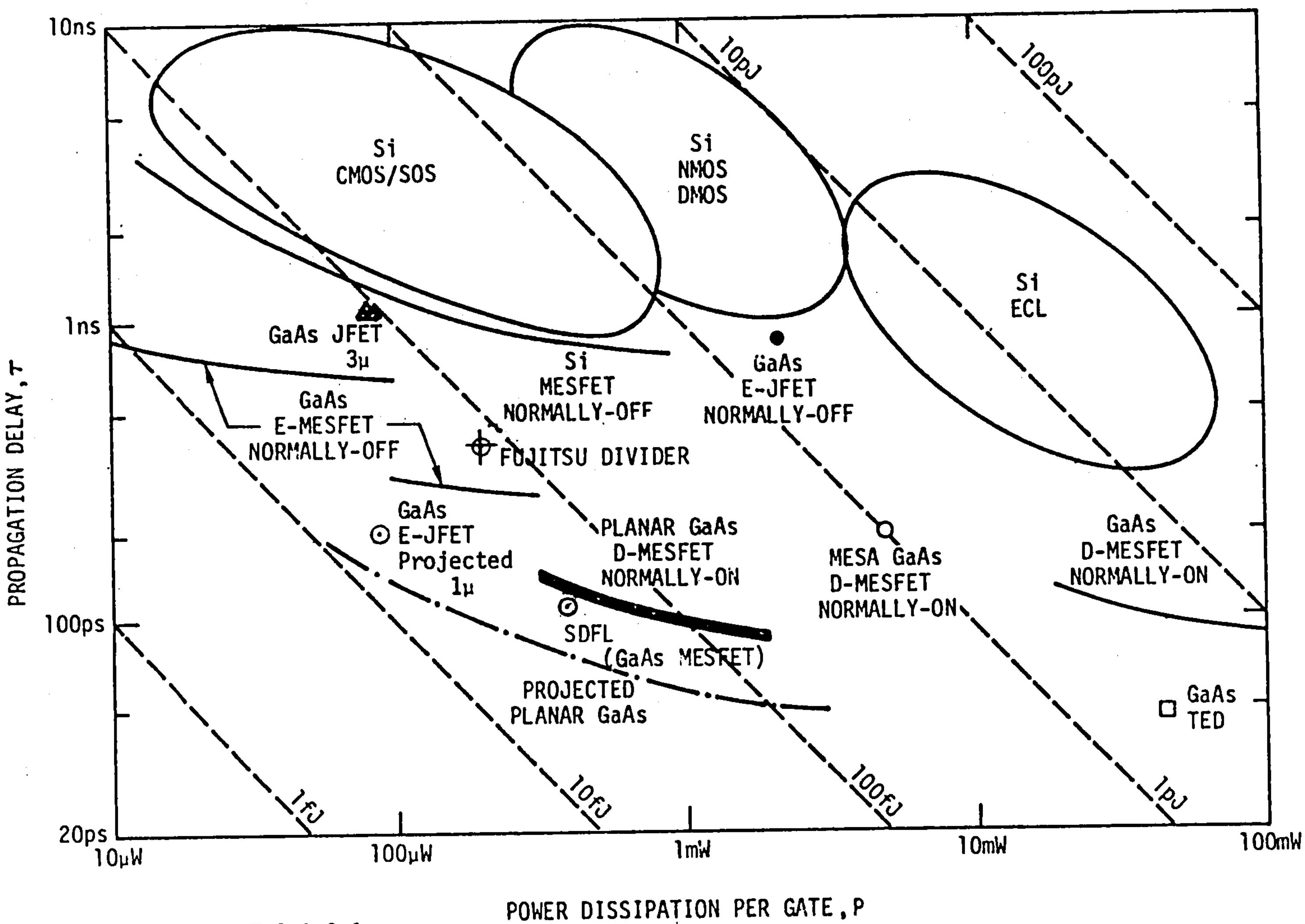


FIGURE 7.2.1.3-1

GALLIUM ARSENIDE DEVICES AVAILABLE SEPT. 1978

TECHNOLOGY	NO. GATES	τD GATE DELAY	P POWER/ GATE	$P\tau D$ PWR DELAY PRODUCT	SIZE CHIP/ LITHOG.	PWR SPLY VOLT	TYPE
ROCKWELL 1978 SDFL (MESFETs)	9	141psec	450μW	47fJ	7mmx7mm 1μ	1.7V	9 stage ring OSC
ROCKWELL 1978 SDFL (MESFETs)	4	120ps	335μW	47fJ	7mmx7mm 10μ	+2V,-2V	NOR GATE CHAIN
ROCKWELL 1978 SDFL (MESFETs)	7	82ps	3049μW	50fJ	UNK 20μ	UNK	7 stage
ROCKWELL 1978 SCHOTTKY BARRIER GATE	30*	UNK**	UNK	UNK	UNK 1.4μ	15V	CCD
MCDONNELL DOUGLAS 1978 E JFETs (Enhancement mode)	9	1000ps	100μW	100fJ	2.3x2.3mm 3μ	1.2V	9 stage ring OSC
HEWLETT PACKARD 1977 MESFETs (Depletion mode)	20	250ps	40mW	10pJ	0.2x0.2mm 1μ	4V	Binary Freq. Divider

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TABLE 7.2.1.3-1

E JFET = Enhanced Junction Field Effect Transistor
MESFET = Metal Semiconductor Field Effect Transistor
SDFL = Schottky Diode FET Logic

* Charge transfer efficiency 97% at 1MHz
** Expect 1GHz, Unit operated at 1MHz

GALLIUM ARSENIDE TECHNOLOGY DEVICE PROJECTIONS

SOURCE/ TECHNOLOGY	NO. GATES	AREA/ GATE	GATE DELAY	POWER/ GATE	PWR DLY PRODUCT	CHIP SIZE	LITHO GRAPHY	YEAR
ROCKWELL (Eden) SDFL (MESFET)	10^5	$300\mu^2$	1ns	200μW	100fJ	1 cm^2	1μ	≃1985
MCDONNELL DOUGLAS (Zuleeg) E JFET	2000	$2250\mu^2$	200ps	100μW	20fJ	2.25mm^2	1μ	UNK
HEWLETT PACKARD (Liechti) MESFET (Depletion mode)	10^2-10^3	--	200ps	1000μW	200fJ	--	0.25μ	1983
HEWLETT PACKARD (Liechti) TED	10	--	67ps	14.9mW	1000fJ	--	0.25μ	1983

TABLE 7.2.1.3-2

been characterized by an almost insatiable appetite for larger and faster memories.

The technology of digital storage is perhaps the most rapidly changing sector in all microelectronics. Over the past decade, operating speed and reliability have increased by at least an order of magnitude as physical size, power consumption, and cost per bit of storage have been reduced by factors ranging from 100 to 1000. Improvement of comparable magnitude can be envisioned for the near future before fundamental physical limitations enforce a slowdown. Important characteristics of memory in addition to size, power, and cost per bit are speed of operation (access time), cycle time, and data transfer rate.

Today, memory devices can be conveniently classified into two basic categories of either moving-surface devices or entirely electronic devices, with subdivisions in each category. Moving-surface memories have the information stored in magnetic mediums and are usually nonvolatile. Moving-surface memories usually serve as mass (or file) memories in computer systems where the information stored is changed much less often than it is read. Today's cost per bit of moving surface storage is lower by one to four orders of magnitude than storage in electronic memory (roughly 10 exp. -5 cent per bit for the moving-surface storage as compared with 10 exp. -1 cent per bit for microelectronic memory, with both being based on the least-expensive mechanism). Moving-surface memories are serially accessed and generally transfer blocks of data. Storage capacity and access time of today's typical moving surface memories are:

- Cassette:
  - Storage: 10 exp. 6 to 10 exp. 7 bits
  - Access: 10 to 100 seconds
- Disk:
  - Storage: 10 exp. 9 to 10 exp .10 bits
  - Access: 20 milliseconds (typical)

Microelectronic memories now have access times in the tens of nanoseconds, which is six to eight orders of magnitude faster than moving surface memories. Between these two basic categories is a large memory access time gap. Work is continuing to bridge this access time gap. Figure 7.2.1-1 compares the price and access times of the two categories. The price shown is estimated to be reduced by a factor of 10 or more in the next 5 to 8 years.

There are a great many technologies that are suitable for fabricating storage systems. This discussion will not attempt to evaluate them all, but will be limited to those considered to be most applicable to civil airborne use.

The moving surface memories previously mentioned for background information probably will not be used in future airborne systems because of the slow access time and large volume.

The memory categories previously mentioned can be broken down as

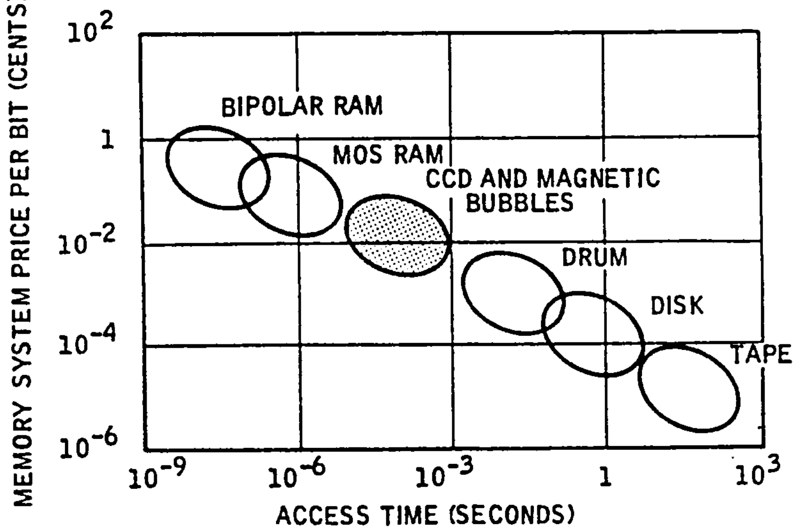


FIGURE 7.2.2-1 ACCESS TIME AND PRICE OF VARIOUS MEMORY TECHNOLOGIES

follows:

- Electronic devices:
  * Bipolar memory
  * MOS memory
  * CCD memory
- Magnetic/Electronic
  * Magnetic bubble

Semiconductor Storage -- Semiconductor storage is primarily divided into three technology areas:

- Bipolar for high speed
- MOS for low cost
- CCDs for serial memories

Both bipolar and MOS technologies can be used to fabricate RAMs with fast read/write characteristics, or ROMs where data are not alterable. In either technology, read-only devices can be programmed at the mask level or by the user in the field. With MOS technologies it is also possible to fabricate electronically alterable ROMs (EAROMs). An EAROM is a non-volatile memory device that is meant to operate in a read-mostly mode, but can be altered when desired. Altering an EAROM is a slow process and is seldom performed on line.

Approaches are presently under development in MOS which may result in high speed read-write RAMs that are nonvolatile. All currently available semiconductor RAMs will lose data if power is interrupted.

Bipolar Semiconductor Memories -- As in the case of semiconductor logic, bipolar technology offers highest speed in memories. Bipolar memories consume more power and have less device complexity than other semiconductor approaches and can be fabricated using a number of circuit forms to provide some speed/power flexibility. At the present time, bipolar RAMs are available with up to 4096 bits per chip and access times in the range of 50 to 125 nanoseconds. RAMs with 16K bits will probably be available early in 1979. Present day bipolar ROMs are available with up to 16K bits per chip with mask programming and 4K bits in field programmable form. These devices operate in the 30 to 140 nanoseconds access time range and will achieve speed and complexity improvements in the future. The power dissipation at present is about 0.5 milliwats per bit. Bipolar memories are used only where high speed is required.

MOS Semiconductor Memories -- In addition to volatile RAMs, MOS technology is used to produce ROMs, EAROMs, and nonvolatile RAMs. MOS ROMs of 32 and 64K bits per chip are available in today's technology, and field programmable MOS ROMs are available with capacities up to 16K bits per chip.

Three semiconductor approaches have been used to produce electrically alterable ROMs. Two of these, floating avalanche MOS (FAMOS) and amorphous semiconductors, have not as yet received the emphasis of metal nitride-oxide semiconductors (MNOS). Data alteration differs from a conventional RAM in that an erase is required prior to write. Some EAROMs erase on a block basis and the entire memory must be rewritten to change a single bit. The erase/write cycle is much slower than the read cycle (millisec. versus nanosec.), and a fatigue phenomenon limits the number of erase/write cycles to the range of 10 exp. 6 to 10 exp. 10. The main advantage of EAROMs over RAMs is nonvolatility; over ROMs, it is alterability. It is expected that EAROMs will be used for microprogram store, and for program and secure data areas of main memory.

In addition to RAMs, CMOS is being used to realize content addressable memories. A 64-bit chip is presently available that can perform a number of search operations in 200 nanosec. The large number of pin outs required may limit growth in this area.

Charge-Coupled Device Memories -- Although a CCD memory can be configured in a number of ways, all are basically serial in form and hence are block oriented rather than word oriented. The CCD is characterized by high packing density, low power dissipation, and a structural simplicity that will lead to low cost.

Present day CCD memory devices operate in a digital manner where charge represents a 'one' and lack of charge represents a 'zero'. Chips are available today with 64 bits of storage. CCD memories are strictly serial and exhibit access times in the 300 nonosec. range and latency time in the 130 microsec. range. Typical power dissipation is 20 microwatts per bit at 10 MHz and 4 microwatts per bit at idle speed. Because of transfer inefficiencies, repeaters (sense/inject circuits) are required about every 64 bits. Because the devices are dynamic, a minimum clock rate of 50 to 100KHz is required to ensure data retention. Refresh rate is a function of operating temperature.

CCDs offer significant speed, power, and reliability advantages over today's disks and drums. Because of the volatile of CCDs, some applications may require magnetic bubble memory for mass storage.

Magnetic Storage -- For years, magnetic storage has been the most common type of memory in use. Magnetic storage has had the cost advantage over semiconductor approaches until just recently, and is nonvolatile and inherently radiation hard. The main problems with magnetic storage in the past have been the difficulty and inefficiency in interfacing with the semiconductor devices with which they must communicate. This factor, and now access time, has almost completely forced magnetic memories into large capacity applications such as main memory and beyond.

Memory Technology Projections -- This subsection describes the characteristics of memory technologies expected in the 1985 time frame with applicability to avionics.

Bipolar Semiconductor -- It is expected that a 32 bit bipolar RAM with access times in the 20 nanosec. region will be available by 1985. An IIL 4K bit memory array with 100 nanosec. access time is presently available. The present power dissipation of 0.5 milliwatts per bit will most likely be cut to one third by 1985. It is expected that nonvolatile semiconductor RAMs could be developed with 2 to 4K bits per chip and read/write speeds in the 200 ns range by 1980.

CMOS Semiconductor -- CMOS RAMs with access times as low as 80 ns and complexities of 4K bits per chip are available now, by 1985, 8K RAMs with 50 ns access time should be available.

MNOS EAROMs -- MNOS EAROMs of 8K bits per chip are currently available and extension to 16k bits should be possible by 1985.

Charge-Coupled Device -- A 128K bit CCD should be available for military applications by 1985. CCDs operating at 20 MHz and with access times in the 200 ns range (latency time in the 80 microsec. range) should also be available for high speed mass storage applications.

Magnetic Bubble Memories -- Magnetic bubble memories have been constructed using single crystal garnet films and amorphous cobalt films. The amorphous material is currently more difficult to process but promises higher speed and can be put on almost any substrate material. Two manufacturers are currently releasing the crystal garnet bubble memories in sample quantities. One is designated a 92K bit unit and the other a 256K bit unit. Both have minimum access time of 4-6 millisec., and at present are restricted to operation in the commercial temperature range (approx. 0 to 50 deg. C).

7.2.3 DATA BUSSING AND MULTIPLEXING

Bussing and multiplexing techniques for interconnecting separate computers within a system and for connecting I/O terminals to computers are now common in all types of real time control systems.

A major consideration is to minimize box pin-outs. To accomplish this, data transmission between boxes and systems will have to be in serial form. Because of the large amount of data to be handled due to redundancy management and more sophisticated operation, the serial transmission then dictates the use of high frequency clocks which in turn dictates low signal levels in order to minimize power. Fiber optic transmission lines will meet the requirements for transmission speeds (wide bandwidth) in addition to offering the following: 1) low cross talk between signals (i.e., between multiple fibers); 2) relative immunity from electromagnetic interfaces (EMI) and radio frequency interference (RFI); 3) reduced conductor weight and size; 4) with regard to cable faults, eliminates the failure mode of 'shorts' and 5) elimination of ground loops and voltage shifts caused by common grounds.

Fiber optic transmission between boxes and other systems can provide the following advantages to each interfacing box:

- The Receiving/Transmitting (R/T) terminals in the box require less power to operate than the present MIL-STD-1553A multiple data bus.
- The R/T terminals require less volume than the present MIL-STD-1553A terminals which require isolation transformers.
- The fiber optic receiver (PIN diode detector) can be easily coupled to a CCD mass memory cell when the transfer of blocks of data is required.

7.2.4 LOW COST SENSORS

Perhaps the most important impact on the cost of low cost sensors may be the information processing technology that has just been discussed in the previous sections. This will make it possible to use fewer sensors since there is a great deal of duplication in the panel instruments presently used today, and sensors which do not directly measure quantities that a pilot would like to have displayed. The combining of information computationally, and the calculations necessary to put it into a desirable form of display for the pilot are functions which can be increasingly carried out at small cost and high efficiency.

As a result, the first considerations in reducing the cost of sensors is the removal of sensors. Recent studies to see whether the gyros could be removed have resulted in mixed results. It is not clear at the outset that any one sensor can be removed and the information, though inferred by others, supplied adequately by them. Though adequate accuracy may be available from an alternate source, the bandwidth of this information may be inadequate. Reciprocally, the high frequency parts of desired information may be adequately presented but the low frequency parts might be important enough that the sensor cannot be replaced unless the full spectrum is available.

The second major effect on cost is the reduction of cost through improved engineering, or the introduction of new technology. Improvements in engineering have continued to take place in all sensors. Improved manufacturing technology, the introduction of new materials -- particularly plastics, and improved alloys -- have in the past and will continue to drive costs down. The dramatic changes are more likely to come from new technology. Two areas are already making their appearance as important candidates: silicon technology, and the introduction of fluidic sensing. The silicon technology has grown as a fallout from the manufacturing requirements of integrated circuits. National Semiconductor introduced a pressure transducer nearly ten years ago and it was the first of what we can expect to be a series of transducers using the silicon techniques. Silicon is a very good mechanical material with virtually no internal loss in hysteresis, and it can have its properties changed with varying amounts of doping or with overlays. Strain measurements can be made by either of these two techniques and is the method for reading deformations produced, for example, by pressure. More recently, accelerometers are taking advantage of the silicon technology and costs in both cases are promising to be dramatically lower as the basic silicon elements can be produced by the mass production techniques developed for electronic devices.

The fluidic rate sensors include at least two types: the vortex, and the laminar jet rate sensor have been experimentally demonstrated in general aviation aircraft (ref. 104).

One can entertain the sensors that are needed to obtain various aircraft states. Pressure measurements, both absolute for altitude and differential for airspeed, are fairly straightforward. The use of a magnetometer to develop magnetic heading, however, is complicated by the fact that the magnetometer in body axes is a vector device and therefore the north component of the measured magnetic vector can only be interpreted if the orientation of the aircraft in pitch and roll is known. This leads to the ever-present problem associated with establishing vertical on a moving base. This has been solved in aircraft with artifical horizons that isolate the vertical through gimbals and carry a memory of the vertical in a vertical gyro. A variety of nonlinear erection techniques are used to maintain the vertical so that a satisfactory compromise of speed of erection and isoloation from maneuver accelerations is obtained. There is a temptation to assume that the very inexpensive accelerometers that may become available could be used to replace the vertical gyro. The time constant for filtering out accelerations based on incremental velocity changes is of the order of a minute or longer. It is therefore necessary to remember the orietation during this filtering process and therefore some angle information is necessary during the filter of gravity from the acceleration environment. Gimbals are nice in that they isolate the instrument and it becomes a nulling device rather than one that requires dynamic range and accurate scale factor. If angular velocity or its high frequency equivalent, the integration of an angular accelerometer, are to be used, the memory needs to be of the order of 0.01 deg/sec, while the maximum rate of the aircraft may be 100 deg/sec. Thus, the use of body mounted rate measuring devices places an extraordinary dynamic range on the instrument if it is to work directly with the accelerometers and filter out accelerations spectrally.

The hope that one can realize the good potential of these low cost instruments, and possibly drop the use of some of the more expensive devices, must be based on some modeling of the aircraft behavior itself. If assumptions about coordination are accepted, then needle ball airspeed and magnetic heading are an adequate basis for determining the necessary information to fly an airplane. Furthermore, the magnetic field vector and the gravity vector represent four components where only two are needed, and the proper correlation of these two quantities improves the information processing. However too much reliance on aircraft behavior must have additional information from the controls and power setting which brings us full circle to requiring more sensors again.

There is little question that the conventional panel sensors will experience a reduction in cost and may take on the first revolutionary change since aircraft was first flown in the next few decades. New displays will be the key to permitting the freedom in evaluating what sensors will provide the necessary information. Many of these sensors will be less costly because they will not have to have integrated displays but can give information directly to a information processing center. In other cases, some instruments may be omitted but it is not entirely clear at this time which those will be.

7.2.5 ELECTROMECHANICAL DEVICES (ACTUATORS)

Significant advances in aircraft systems technology, in the form of new, efficient electromechanical actuation devices, will lead to improvements in performance, guidance, and control for many types of aircraft, including rotorcraft. The extension of the use of electromechanical devices from their present role as servo devices and actuators for secondary control surfaces, to that of providing actuation for primary control surfaces, has been made possible by recent developments in electrical and materials technologies and is the subject of numerous investigations at the present time. Both new and improved systems capabilities will result.

The basic feasibility of new electric motor actuators has been demonstrated, and if progress continues in actuator power and reliability the replacement of some aircraft hydraulic systems with electric, 'power by wire' systems is likely. Progress thus far has been made possible by: (a) new magnetic materials yielding lighter, more powerful electric motors; (b) improved solid state circuitry to control brushless DC motors; and (c) microprocessor computer capability to obtain improved control of motor firing circuitry. Similar developments are being pursued for applications in the industrial controls field.

The development of these devices could be accelerated by certain NASA activities, including the following:

(1) Sponsorship of criteria development relative to the application of these new devices to current and future aircraft types, particularly light aircraft and rotorcraft;
(2) Sponsorship of a review of the broad spectrum of actuator technology, including DOD and other industrial applications;
(3) Basic R&D in materials technology to seek improvements in system reliability;
(4) Sponsorship of system refinement activities: modeling, controller design, overall design optimization; and
(5) Provision of flying testbeds to prove out elements of this technology, and general laboratory facilities for component R&D efforts.

Modeling, in particular, is a difficult task for these discrete devices, but is essential to solving certain control problems, such as RPM limit cycling, that have been observed.

This new technology is particularly well suited to take advantage of recent advances in microcomputer technology. Over the next decade, one of the most active areas of R&D may well be the joining of actuator and computer technology to develop actuation systems that are precise and optimally fast and function as satellite elements in a distributed flight control system. Full exploitation of actuator capabilities will be made for improved structural load relief and flight control tasks. Sponsorship of system R&D in this area -- the combining of computer and actuator devices -- is an additional area in which NASA support, in the form of funded analyses and experimental laboratory facilities, would be very effective.

For maximum effectiveness, NASA should not directly undertake the development of hardware or systems other than to support basic R&D, but rather should fund selected activities in these areas, particularly including criteria development, on the part of contractors.

In attempting to identify emerging concepts in the area of electromechanical (EM) devices one is immediately struck by the fact that many of the advancements are electronic in nature, having the objective of eliminating EM devices for reasons of cost, reliability, life, size, maintenance and performance. This is particularly true in the case of EM displays, gyros, air data systems and stable platforms.

However, there are areas where it appears that mechanical elements will be present in the 1980 timeframe. Following is a listing of some of these areas:

- Pliot Tactile Interface Devices such as Cockpit Controllers and Control Panels
- Actuation
- Certain Sensors as Accelerometers
- Electrical Power Supplies
- Control Moment Generation

7.2.5.1 Pilot Tactile Interface Devices

Cockpit controllers are changing as a result of the trend toward Fly by Wire (FBW) flight control. The greatest change is toward sidearm controllers instead of centersticks in high performance aircraft to permit better pilot performance under high 'g' flight and better viewing of displays.Although this trend has not been started in transport aircraft, it is very likely to follow in the future.

Thrust controllers for FBW engine controls and direct lift controls for VTOL aircraft are areas where development is needed. In both of these areas a great deal of work is needed in human factors to define performance characteristics for good 'feel'. At this point, criteria and specifications for controller design are non-existent.

Most operational cockpit display devices and instrumentation are electromechanical. However, the trends are toward electronic displays in the form of cathode ray tubes, light emitting diodes, liquid crystals, etc., for reasons of cost, multimode capability and human factors. In the future it does not appear that there will be significant use of electromechanical displays except as possible backup or in small general aviation aircraft.

7.2.5.2 Actuation

Most modern aircraft employ fully powered hydraulic actuators, a practice started over 20 years ago. Prior to that time, one of the techniques used to augment the pilot's force capability was the use of servo hinge tabs as aerodynamic power boost. Unfortunately, hinge moments and tab effectiveness are highly nonlinear and functions of Mach and Reynold's number, making it difficult to design satisfactory servo tab control systems. The arrival of hydraulics presented a convenient solution to a difficult design problem with the result that servo tab systems for primary control have been virtually abandoned. However, in the interim there have been tremendous strides in the field of feedback controls. Servo tab systems should be reexamined with the use of electronic feedback in mind, to reduce the effects of tab/surface nonlinearity. This should be particularly effective for subsonic airplanes. If so, the actuation would be a small fractional horsepower tab hinge actuator replacing the presently used hydraulics resulting in improvements in cost, reliability, survivability and maintenance.

In an additional area, present hydraulic actuators achieve virtually all the power gain hydromechanically. Torque motors accepting all the power inputs under a watt in power are used in conjunction with jet pipe or flapper first stage valves to control flow to a hydraulic servo actuator which in turn strokes the main power control valve (PCV).

With the advent of rare earth magnets it is now possible to drive the PCV directly thus replacing the low power electrohydraulic control valve and servo actuator. Using electric power amplification to replace the contamination sensitive low powered valves is desirable from a reliability viewpoint. It also simplifies the electronic/hydraulic interface by reducing the required number of hydraulic power supplies for those instances where redundant secondary actuators are used.

High pressure hydraulics is an emerging technology which shows promise for reducing actuation size and weight. For many years 3000 psi has been standard for aircraft systems. Recent work in the 6 to 8000 psi range has shown a trend toward higher pressure systems.

7.2.5.3 Sensors

For years EM gyros and accelerometers have been essential to control and navigation instrumentation. Although laser gyros have made significant inroads there still continues to be a need for high accuracy EM gyros using electrostatically suspended rotors. At the present time there appears no way to eliminate the proof mass of accelerometers so this type of instrument will be with us for the foreseeable future.

Inertial platforms have been one of the more important users of EM technology. These devices are feeling the impact of electronic technology with the result of strapdown configurations where the gimbal structures are replaced with analytic representations.

Air data systems have also felt the pressure of electronic mechanization. In addition to the computations even the pressure transducers themselves are more electronic than mechanical.

The availability of high strength rare earth magnets and their application to sensors can be identified as an area where further work should be carried out. Magnetic suspensions can eliminate conventional bearings for increased life, reliability and performance.

7.2.5.4 Electrical Power Supplies

Aircraft electrical power generation and distribution systems have provided 400 Hz power generated by constant speed generators utilizing EM constant speed drives. A number of significant changes have been taking place recently.

Efforts are being made to eliminate the constant speed drives by allowing the generator to run at speeds proportional to engine speed and constructing the 400Hz output using cycloconverter principles. The objective is to increase reliability and life by eliminating the constant speed drives.

Permanent magnet generators using rare earth magnets are being developed to replace the more conventional wound rotor machines in order to eliminate slip rings. This has brought about a number of interesting problems such as magnet containment and a resettable shaft disconnect required to shut down the permanent magnet generator.

High voltage DC systems are being considered for aircraft use to replace the 400Hz systems. Although attractive from the viewpoint of generation and distribution, there still remains work to be done in efficient inexpensive conversion from the high voltage, i.e., 270 volts, to user levels.

7.2.5.5 Control Moment Generation

The most common method for aircraft control moment generation is through use of control surfaces. Alternate moment generation techniques are emerging and should receive attention for further development.

VTOL aircraft require non-aerodynamic control in the form of reaction jets or thrust vectoring of various means as proposed by the organizations developing VSTOL B concepts. This technology is in its infancy and will require considerable innovation before suitable operational concepts are available.

Considerable work has been done in the control of flow fields by control of boundary layers using various blowing and suction techniques. A relatively new field is that of Electroaerodynamics along the lines described in the April 3, 1978 issue of 'Design News'. Flow is controlled using magnetohydrodynamic principles. An extension of the work into control would have interesting results.

7.2.6 HIGH POWER ELECTROMECHANICAL ACTUATORS

Recent advances in rare earth permanent-magnet materials and in high power semiconductors have made the electromechanical (EM) actuator an attractive alternative to the electrohydraulic actuator for use as primary flight control actuators. The use of rare earth permanent-magnet material in brushless d.c. motors results in a lightweight and highly efficient design. Such motors output a high torque, have a low rotor inertia and are highly responsive. Simple logic sequences high power semiconductors to control both motor torque and velocity. This technology is of immediate interest to the space program where fuel cells and batteries are the primary sources of power. It is expected that the use of high efficiency battery powered flight control actuation systems will result in a lightweight system with reduced maintenance requirements. However, it will be necessary to develop a high voltage power distribution and control systems along with the high voltage electromechanical actuation systems. The Naval Air Defense Center is currently working on high voltage d.c. distribution and control systems for use on advanced fighter aircraft.

The development of EM actuator systems should result in the displacement of electrohydraulic actuators in many flight control applications. Low power EM actuators, using brushless d.c motors as the prime mover, are already used to gimbal the Space Shuttle Orbital Maneuvering System rocket motors and as flight control actuators on the CRUISE missile.

The Air Force is looking at using EM actuators in flight control applications. A contract is being managed out of Wright-Patterson Air Force Base for the development of a hinge line actuator for use in fighter and transport aircraft.

In general, the basic feasibility of using EM actuators as primary flight control surface effectors has been established; however, additional work remains to be accomplished to update the design base in terms of system and program considerations.

The interaction of the aerodynamic loads and the EM actuator as a power system should be studied to develop ways to take maximum advantage of the regenerative capability of the EM actuator. The EM actuator system should be analyzed in terms of system parameters to identify the most promising areas of weight reduction and performance improvement, and to identify those technologies with the most potential for significant payoffs.

Power switching components are of particular significance. Such components should be developed specifically for use in EM applications and should have minimum base-drive requirements, should be lightweight, should have low conduction and switching losses, etc.

A high-power linear mechanical actuator should be developed and tested to establish the characteristics of linear actuators under dynamic conditions and to identify any potential problem areas.

Since the EM actuator is a unique power system, potentially capable of significantly reducing energy storage requirements because of its high efficiency and regenerative capability, it should be flight-tested to evaluate hardware performance against design specifications (based on operational requirements) and thereby to demonstrate hardware feasibility in a flight environment.

7.2.7 ANALOG TO DIGITAL AND DIGITAL TO ANALOG CONVERTORS

The rapid trend toward digital processing is forcing a new look at the old problem of the interface between analog devices and the digital processor. The current trend is to provide analog to digital convertors (ADC'S) and digital to analog convertors (DAC'S) on dual inline packages (DIPS) which are compatible with microprocessor busses and packaging methodology. These ADC and DAC DIPS are either monolithic devices or hybrid thick film devices. At the present time hybrid thick film devices predominate but the trend is towards monolithic devices on a silicon substitute.

A trend expected in ADC/DAC's in the future is the incorporation of these analog conversion devices on the microprocessor chips. The first step in this direction was taken with the announcement in the Spring of 1978 of the Intel 8022 single chip microcomputer which includes two multiplexed 8 bit ADC'S on the chip. Figure 7.2.7-1 shows two families of hybrid ADC/DAC's which have become available recently. The TRW Hybrid ADC's fill the needs for very high speed conversions often needed in high speed signal processing systems. For example, one 6 bit ADC provides a conversion in 2.5 n sec.

The Beckman family of ADC/DAC's (announced in 1978) utilize CMOS technology for low power dissipation and are compatible with 8 bit microprocessor data busses. The units provide 12 bit resolution and excellent linearity (.012%) and costs are in the range of $50 per unit in small quantities. These devices utilize 32 pin and 36 pin DIP's.

A more mature set of ADC/DAC converters exist which in general are longer and more expensive than the new devices, but span a wider spectrum of types for a variety of applications. Illustrative of the mature category ADC/DAC devices are the analogic device characteristics shown in Table 7.2.7-1.

Integrating analog to digital conversion devices provides the most resolution, linearity, and noise rejection for a given cost but these devices are slow. Successive approximation ADC devices provide high speed but are more costly than the integrating ADC's.

In addition to the ADC/DAC devices it is also necessary to use sample and hold circuits, amplifiers, multiplexers and filters.

Data acquisition modules are available which provide multiplexing, sample and hold, and ADC/DAC conversions.

Two sample data acquisition module characteristics are summarized in Table 7.2.7-2.

TABLE 7.2.7-1 Analog to Digital & Digital to Analog Converter Device Characteristics

DEVICE TYPE	RESOLUTION	CONV. TIME	SIZE	APPROX. COST
ADC Integra.	12 bit	2.5 m.sec.	1.4xØ.6	24
ADC ''	16 ''	16-1ØØ m.sec.	2x4x.4	21Ø
ADC Succ.Approx.	8 ''	16 mic.sec.	''	161
ADC ''	1Ø ''	3Ø ''	''	99
ADC ''	12 ''	24 ''	''	199
ADC ''	12 ''	4 ''	2x4x.44	25Ø
ADC ''	14 ''	1Ø ''	''	419
ADC ''	16 ''	25 ''	3.1x5x3.1	1395
DAC ''	8 ''	5 ''	2x2x.4	85
DAC ''	1Ø ''	1Ø ''	''	99
DAC ''	12 ''	1.8 ''	24 pin DIP	42
DAC ''	14 ''	15 ''	2x2x.4	136
DAC ''	16 ''	2Ø ''	2x4x.4	485

TABLE 7.2.7-2 AD Data Acquisition Module

ANALOG CONVERSION TABLE	RESOLUTION	AQUIS.TIME	APPROX.COST
16 Channel ADC	12 bits	1Ø mic.sec.	5ØØ
16 Channel ADC	12 bits	3Ø mic.sec	3ØØ

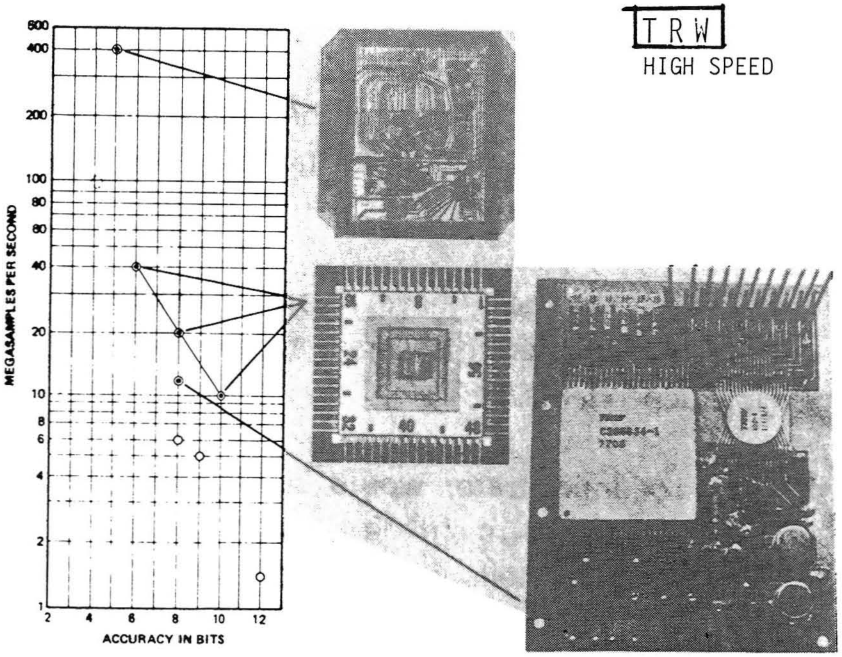
ANALOG-DIGITAL/DIGITAL-ANALOG CONVERTERS

KEY COMPONENTS FOR COMMUNICATING WITH THE ANALOG WORLD

● HYBRID LSI A-D CONVERTERS

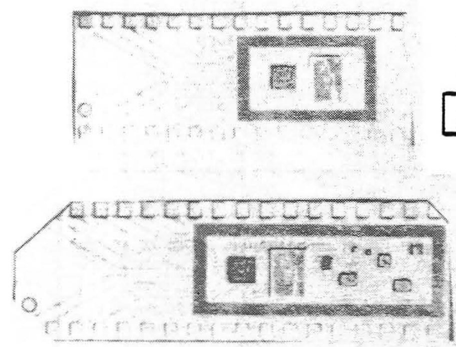
TRW

HIGH SPEED



INFO: 213/536-1977

BECKMAN



32 pin
7545
DAC

36 PIN
7556
ADC

- 12 BIT ACCURACY
- 8 BIT MICROPROCESSOR COMPATABLE
- .012% LINEARITY
- CMOS TECHNOLOGY
- DIP PACKAGE

INFO: 714/871-4848
X 1776

FIGURE 7.2.7-1

7.3 FLUIDICS

The field of fluidics was organized, in the early sixties, by personnel at the Army's Diamond Ordnance Fuse Laboratory to embrace a class of devices which employed the flow of fluids in aerodynamically shaped passages and chambers to perform the functions of signal amplification and processing, logic operations, phenomena sensing, and mechanical actuation, traditionaly assigned to electronic and electromagnetic devices. Ideally these functions were performed without the use of moving parts other than the motion of the fluids themselves.

In the following decade, considerable effort was expended by many different organizations in the development of fluidic components and systems. Most of these fluidic developments were in direct competition with existing electronic technology, which, in general, offered more acceptable solutions to the various problems, either because of its intrinsic suitability or because the more advanced state of development of electronic components resulted in overwhelming advantages in economy or physical size. This situation has led to a general disenchantment with fluidics and the relegation of effort to certain specialized areas where thermal or radiation environments precluded the use of conventional electronic devices.

NASA's current effort in fluidic technology has been directed toward certain carefully chosen avionics applications in which fluidic devices would appear to offer some real advantage over more conventional systems in terms of reliability, economy and simplicity. Some low cost fluidic elements for general aviation are shown in Figure 7.3-1.

7.3.1 WING LEVELERS

The existence of several fluidic angular rate sensors, which offer a low cost, no moving parts substitute for the rate gyroscope, has led to a considerable development effort, both at a components level and at a systems level. This work has resulted in the development of a simple wing leveler type lateral and directional autopilot suitable for light aircraft, which has the potential for low cost manufacture, and, because of the deletion of all gyroscopic instruments, should have an almost infinite, maintenance free service life (ref. 110 and 111). Much of the technology from this project has been used in the Air Force RPV program.

Current systems employ fluidic rate sensors, but use electronic signal amplification and processing. Some work has been done on an all fluidic wing leveler powered by ram air, which would have the advantage of complete independence from the aircraft's power supplies and, possibly, a higher reliability potential. Development work done at Langley on the all fluidic wing leveler has resulted in a quantum improvement in the state of the art of low noise, high gain fluidic amplifier technology (ref. 112).

7.3.2 MAGNETIC HEADING REFERENCE

A spin off from the electrofluidic autopilot has been a gyroless magnetic directional reference which utilizes a fluxgate magnetometer,

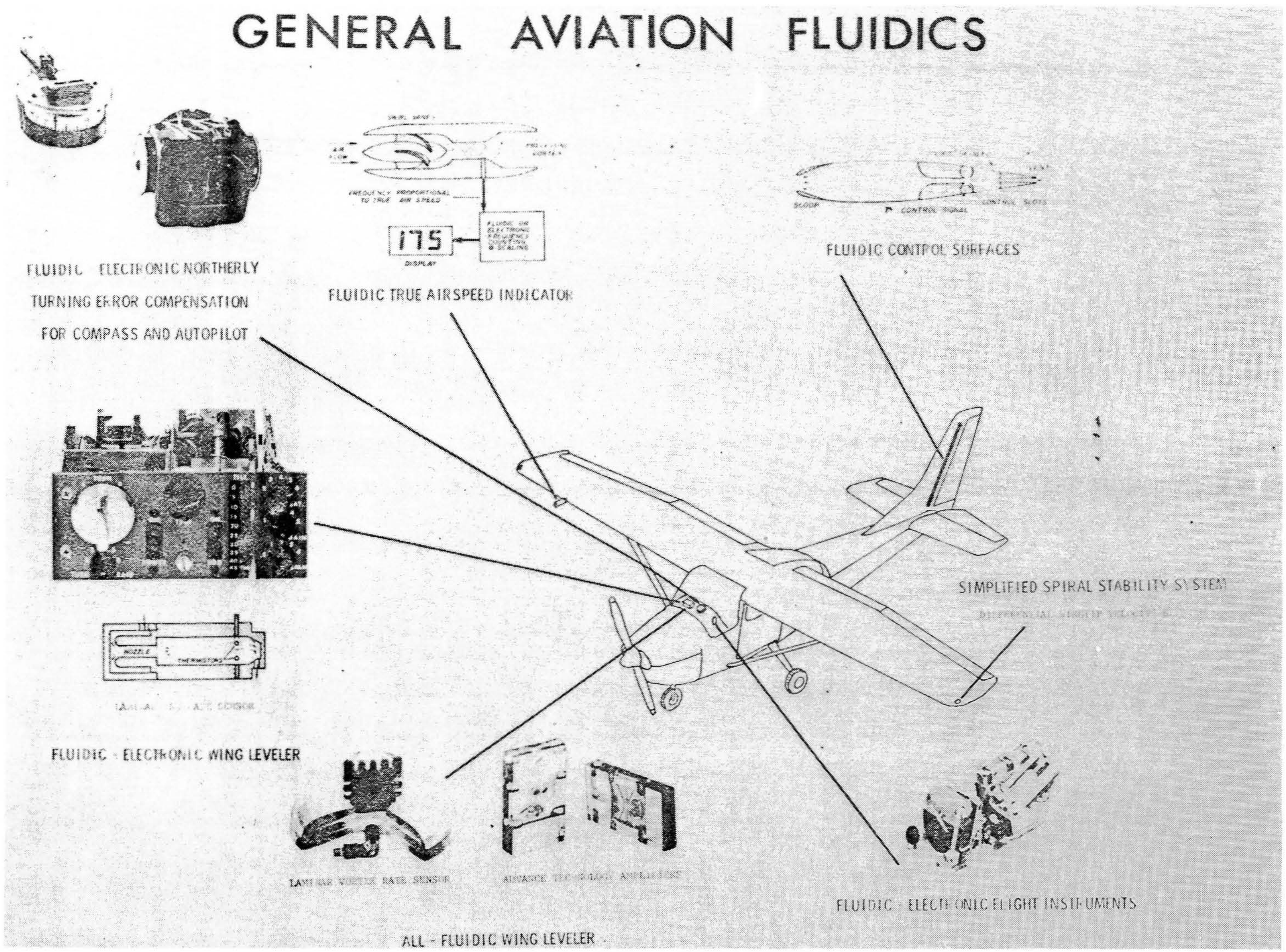

GENERAL AVIATION FLUIDICS
FLUIDIC - ELECTRONIC NORTHERLY
TURNING ERROR COMPENSATION
FOR COMPASS AND AUTOPILOT
175
FLUIDIC TRUE AIRSPEED INDICATOR
FLUIDIC CONTROL SURFACES
SIMPLIFIED SPIRAL STABILITY SYSTEM
FLUIDIC - ELECTRONIC WING LEVELER
FLUIDIC - ELECTRONIC FLIGHT INSTRUMENTS
ALL - FLUIDIC WING LEVELER

FIGURE 7.3-1

compensated for northerly turning error by signals supplied from an electrofluidic rate sensor, so that it can supply usable heading data during maneuvering flight (ref. 113).

7.3.3 FLUIDIC CONTROL SURFACES

An off shoot of the all fluidic wing leveler program has been the development of fluidic control surfaces, in which control torques are applied to the airframe by means of fluidically regulated air flows from slots in the aircraft's control surfaces without recourse to conventional servos or mechanically articulated control surfaces (ref. 114 and 115). These slot flows are strategically located to maximize changes of lift with airflow. The optimization of airfoil and slot geometry is especially critical to the current program, as this work is directed toward small, piston engine aircraft which provide no source of pressurized air other than ram air.

Although this work was initiated as a logical interface between fluidic control systems and the dynamics of the airframe, the low time constants achieved have suggested the use of fluidic control surfaces in conjunction with more conventional electronic stability augmentation systems. Rather than use an expensive, high performance hydraulic servo to position a conventional, mechanical control surface, the interface could be made at a very low power level by means of a simple electromagnetic torque motor driving some sort of air deflector to provide an input to a fluidic control surface.

7.3.4 FLUIDIC DIGITAL TRUE AIRSPEED TRANSDUCER

Work is currently in progress, via a university program, on a fluidic true airspeed transducer operating on the principle of the vortex whistle (ref. 116). This device produces an acoustic note, in the audible frequency range, which is a direct function of the volumetric flow of fluid through the instrument, and thus a direct function of true airspeed, if the device is properly exposed to the airstream. The relatively high level of acoustic power in the output of this instrument promises simple, inexpensive data pickup and processing, and the digital output of the device recommends it as an airspeed input to various navigational computers.

7.3.5 FLUIDIC ARTIFICIAL HORIZON INSTRUMENT

A gyroless artificial horizon indicator is being developed under contract to Flightcraft Inc. This instrument derives roll attitude from a differential pressure signal supplied by wingtip mounted aspirating nozzles and pitch attitude from airdata signals. The absence of high speed moving parts and the independence from external power supplies should offer a substantial improvement in reliability over gyroscopic horizons, and the simplicity of the mechanisim should result in reduced manufacturing costs.

7.3.6 COMPONENTS AVAILABILTY

One of the greatest problems related to fluidic systems development is the availability of fluidic components. Although several manufacturers have engaged in the production of individual logic devices, amplifiers, sensors, etc., these have generally been of a rather crude nature -- more suitable for breadboard arrays or industrial applications than for avionics systems.

Certain successful avionics applications have been produced, especially in the field of gas turbine engine controls and helicopter flight controls. These systems have required the closest cooperation between the system designer and the fabrication personnel, and the resulting hardware has been highly specialized and extremely expensive.

This situation is inevitable in the early stages of application of any new technology, and about all that can be done at this time to ease the problem is to develop techniques for the simplification and cost reduction of components fabrication.

Several production techniques have been used: photoetching in both metal and ceramics, electroforming, fine blanking in metals, and injection molding and lost wax casting in plastics. All of these, with the possibel exception of the photoetching processes, require large investments in tooling for each new component configuration and all require tight dimensional controls throughout the production process.

Langley, in cooperation with the Harry Diamond Laboratories, has investigated several of these processes in an attempt to choose an optimum approach. Considerable work has also been done on a related problem -- that of reducing the sensitivity of the performance of the device to production variations in geometrical tolerances. One approach to this has been 'vertical lamination', in which the profile of the device lies at right angles to the plane of the laminations rather than parallel to it. By this stratagem, the critical dimensions of the fluidic component are defined by the thicknesses of the various laminations, rather than by the fidelity of reproduction of the pattern machined into the lamination.

Langley is also investigating another approach to the easing of dimensional tolerances, 'megalithic construction,' in which the device is simply scaled up in size -- tolerances and all. In the case of light aircraft applications, size is not necessarily a problem, especially in wing sections and the tail cone area, if weight can be kept down. The present concept calls for the fabrication of components from foamed plastics with suitable surface finishes.

It should be noted that the rate sensor employed in the current electrofluidic wing leveler utilizes such simple, non-critical geometry that fabrication has not been a problem, even with the most primitive of tooling. In fact, these sensors are being successfully fabricated in home workshops by many amateur aircraft builders, resulting in the first practical homebuilt autopilots (ref. 117 and 118).

7.3.7 PROJECTED APPLICATIONS

Since air data is, in general, derived from pressure signals, and, since control torques are applied to the airframe by manipulating the pressure distribution on control surfaces, fluidic instrumentation offers a most attractive lack of interfacing problems in many aircraft control concepts. Some examples of such schemes, which take advantage of this natural interface situation, but which currently lie outside the budgetary and personnel limitations of the fluidics group at Langley are as follows:

7.3.7.1 Angle of Attack Indicator

There has long been a need for an angle of attack indicator as simple, rugged and inexpensive as the airspeed indicator. Angle of attack can be derived from differential pressure taps on a fixed cylinder or sphere exposed to the airstream or from taps on the leading edge of the airfoil itself, avoiding the usual delicate vane or servoed probe. Since the resulting differential pressure is also a function of q, a computation must be made to obtain a pressure signal proportional to attack, only, which can be used to position an indicator. It would appear that this computation could be effected by state-of-the-art fluidic variable gain amplifiers or through the mechanical characteristics of the indicator itself, resulting in a simple instrument, not subject to damage by routine ground handling of the aircraft.

An extension of this concept would tie the angle of attack sensor into either a fluidic elevator surface or a servo-positioned elevator travel- limiting mechanism to prevent elevator motion resulting in stall conditions. Many 'stall-proofing' systems have been developed in the past, but a fluidic implementation would appear to offer decided advantages in simplicity and reliability.

7.3.7.2 Autothrottle

The safety and convenience of an autothrottle system is presently foregone in light aircraft because of cost and weight penalties. Coupling pitot pressure into a vortex valve in the intake manifold of the engine via a suitable fluidic amplifier chain could provide this service at a low cost in a self-powered, no-moving-parts package of minimum weight.

7.3.7.3 Fluidic Propeller Pitch Control

Circulation control airfoils are currently being developed for helicopter rotors (ref. 119). An extension of this technique could be applied to aircraft propellers, to provide a simple, no-moving-parts variable-pitch propeller for light aircraft. Speed control could be provided by fluidic circuitry feeding the slots of the airfoil through a pressure seal at the hub.

An interesting characteristic of this type of airfoil is the relatively small effect that angle of attack has upon coefficient of lift within a large operating range. This effect would result in a certain degree of inherent self-regulation, and might allow for satisfactory performamce, with no additional regulating devices.

7.4 SYSTEMS ANALYSIS

A great many facets of systems analysis have already been covered under other headings in previous sections of this report. For many guidance and control and other avionics purposes the available system analysis theories are completely adequate.

However, for the stability and performance analysis of complex high-dimension nonlinear and time-varying systems, the support tools of computation and data presentation are, at at best, treated as separate special cases. Approaches which can be used to classify, arrange, and bring order, clarify, and perspective to vast masses of data are simply not available. Thus, we can analyze almost anything, yet can appreciate and fully comprehend very little. To address these problems requires a hierarchical approach at the one extreme and a limited case/simplified approximation at the other.

Because the development of insight so often depends upon establishing connections between easily understood, but simplified and approximate, near solutions to a problem and the exact, but much more complex, actual solution, it is pertinent to emphasize approximation and simplification procedures in this connection. In addition, a number of systems analysis and synthesis techniques, such as Kalman filtering and optimal control problems, require a detailed knowledge of the controlled element characteristics, and in many cases these can or must be simplified. Consequently, for reasons of design appreciation and assessment and for practicality in optimal procedures, means to simplify the dynamic description of system elements to their essentials when viewed in a given context are extremely important. To this end, much work remains to be done on the approximation of higher order by lower order systems. In the frequency domain this leads to the equivalent system concept in which a lower order system is an adequate representation of a complete system over a limited frequency band. In the time domain, the methods of variable time scales offer great appeal to accomplish similar purposes.

Another practical aspect involved in systems analysis is associated with various optimal control procedures. Here the fundamental problem is to interpret system requirements into the specifics of performance indices such that 'good' (as opposed to optimal) controllers are induced in the analytical design process. This problem has been with us since the dawn of optimal control and has been gradually attacked by practitioners on on iterative basis for each specific case. It is, in fact, an art rather than a science and should be addressed on a more systematic basis. Studies of correlations between the controller (induced) and the performance index weighting (assigned), for both simple and complex systems offer a good starting point.

An associated, but higher level, problem in systems analysis is that which confronts the designer as opposed to the analyst. The designer has a number of criteria to consider, some quantitative and others qualitative, which are in general incommensurate. Thus, the optimum or best system in a practical case is determined on the basis of judgements involving combined criteria. A hierarchical approach in which intermixes of decision theory, Bayes' rule, and specifically-stated designer-evaluation-factors and judgements offers a great deal of promise. For this to be useful, any theoretical construct should be exemplified with specific examples drawn from past practice in what is currently the 'art form' of system optimization.

In connection with digital systems we do not at present have a good analysis tool for assessing the tradeoffs between data rate, word length, and limit cycles. All present theories show that digital modeling problems disappear as the frame time gets shorter but this is of course not the case with finite word lengths. The modeling of quantization effects, roundoff, etc., as additive noise does not reveal what happens in actuality.

7.4.1 ANALYTICAL METHODS FOR SYSTEM PERFORMANCE ANALYSIS

NASA should sponsor research on improved analytical techniques for predicting the overall performance of systems relative to operational, user-defined criteria. Present techniques to achieve this involve system simulation and the calculation of error covariance or density function propagation, often using a Monte Carlo approach.

The areas for which these techniques are most appropriate are of great importance to avionics systems designers, and include the following:

- aircraft touchdown point dispersion for automatic landing systems;
- missile or projectile impact circular error probability (C.E.P);
- navigational waypoint error magnitudes;
- human operator performance models, and optimal display/warning systems design;
- effects of system failure modes.

Further, such analytical capability is particularly applicable both in the early system design stage, to select among candidate system configurations, and in the final design evaluation stage, to augment experimental verifications of system capability.

7.4.2 EXPERIMENTAL INTEGRATED SYSTEM EVALUATION

A requirement exists for NASA to construct a flight control system laboratory which would be used to assess the performance of new flight control systems. This laboratory would support NASA's role in the field of aeronautics research. As NASA (and NACA) built wind tunnels to evaluate the aerodynamic performance of new aircraft designs in the past, a control system laboratory is required for aircraft of the future.

The proposed flight control system laboratory would complement the development of new powered-lift aircraft and rotorcraft. These vehicles will have flight control systems that use digital processors and electrical reduction, flight envelope expansion, mission reliability, mission efficiency and mission flexibility. These systems may be designed with fault-tolerant, reconfigurable flight control system architectures. The control laws will be designed for a broad spectrum of functional requirements: e.g., stability and control augmentation, structural load control, automatic landing, and special pilot assist modes such as air-to-air refueling. In order to achieve maximum design benefit, some of these functions may be flight-critical, where total loss of a function could destroy the aircraft. Because flight-critical applications will be considered for future research and production rotorcraft and VTOL aircraft, it is necessary to evaluate their performance and failure modes in the laboratory. Specifically, the flight control system laboratory would be used for:

- Consideration for integrated system performance in simulated missions;
- Assessment of failure modes and effects during critical mission phases in terms of degraded performance and flight safety, pilot roles and pilot acceptance;
- Prediction of reliability;
- Generation of validation and certification methodology and data for certification criteria;
- Development and evaluation of advanced sytstems architectures and concepts;

A NASA flight control systems laboratory would also complement industry's development of flight control systems. The laboratory could be used by industry to validate control systems designs before they are committed to production and to validate vendor components. In the past, industry has built 'iron birds' to validate the mechanization of a flight control system after it has been committed to production. Thus, NASA's laboratory could be used to support design decisions at a time when management still has some leverage on program costs.

7.5 AVIONICS SOFTWARE

The trend in avionics is to increase the number of functions implemented in digital processors. As a result, the avionics software complexity has continued to increase. The trend toward distributed processing architecture is alleviating the problems of large software programs by dividing both the hardware and software into manageable modules.

The use of large real time software programs in large central computer complexes as exemplified by the F111 Mark II avionics and the Shuttle avionics gives rise to difficult software validation problems. However, this type of architecture is diminishing in its applications.

The proportion of software costs to hardware costs is growing with each new generation system as low cost digital microprocessor/memory technology is introduced.

Most current generation avionic and control systems have utilized assembly language programming for the software. There is a strong trend toward the use of higher order language, (HOL) for software development. The use of HOL increases the programming productivity considerably and reduces both the initial software development costs as well as software maintenance costs. A comparison of HOL with assembly language programming is presented in figure 7.5-1.

The efforts to reduce software costs has resulted in a collection of technoques referred to as Modern Software Programming Practices (MSPP). The key features of MSPP are summarized in figures 7.5-2 and 7.5-3. These simple steps, if followed, can significantly reduce the effort on software developments. The emphasis in MSPP is to eliminate clever tricks in favor of straightforward software modules which are easy to understand.

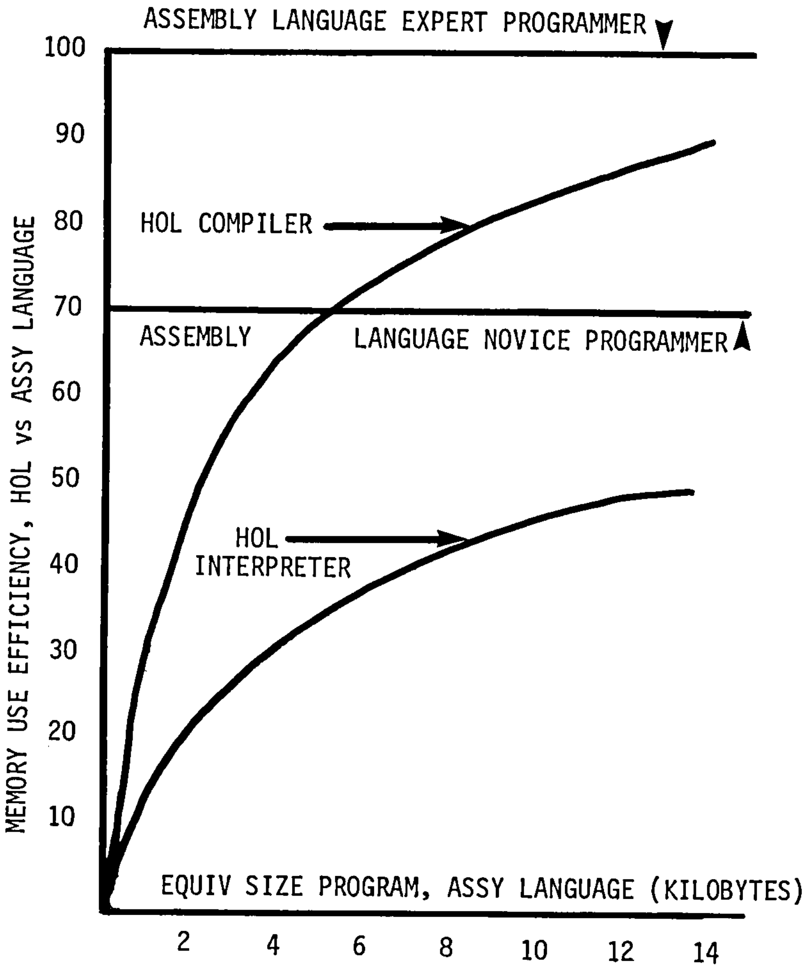
7.5.1 The Software Problem

SYMPTOMS:

Software almost always takes longer to develop and costs more than originally estimated. Furthermore, it is difficult to obtain meaningful completion status information, e.g., there is the 90% done but 90% left to be done syndrome in attempting to assess the schedule status.

Software is unreliable. Software often fails to meet the specifications and contains undetected coding errors which appear later after more thorough system testing has taken place. Software causes limitations on system performance.

Software is fragile in that a validated software program is vulnerable to modifications often in an unpredictable manner. Software often has a poor tolerance to off nominal use of the system, particularly, in regions which were not tested during validation.



- COMMON MICROCOMPUTER HOL's
  - BASIC INTERPRETER/COMPILER
  - FORTRAN INTERPRETER/COMPILER
  - PL/M COMPILER
  - PL/Z COMPILER

- SPEED COMPARISON
  - COMPILER APPROX 3.5X FASTER THAN INTERPRETER
  - ASSEMBLY LANGUAGE APPROX 1.2X FASTER THAN COMPILER
- MEMORY COMPARISON
  - COMPILER APPROX 60% OF INTERPRET MEMORY
- LINE OF HOL SOURCE CODE EQUIV TO ABOUT 40 LINES OF ASSEMBLY LANGUAGE CODE
- COST COMPARISON
  - APPROX $20/LINE OF ASSY CODE
  - APPROX $10/LINE OF INTERPRETER CODE
  - APPROX $25/LINE OF COMPILED CODE
- PROGRAMMING PRODUCTIVITY COMPARISON
  - 15-20 LINES OF HOL SOURCE CODE/8 HR DAY
  - 8-12 LINES OF ASSY CODE/8 HR DAY
  - 2-5 LINES OF REAL TIME MICROCODE (e.g.,BIT SLICE PROCESSOR)/8 HR DAY
- SOFTWARE EFFORT BY PROJECT PHASE
  - DESIGN & DEFINITION 30%
  - CODING 20%
  - SYSTEM INTEG, DEBUGGING 50%

FIGURE 7.5-1

MICROCOMPUTER SOFTWARE DEVELOPMENT

MODERN SOFTWARE PROGRAMMING PRACTICES

●CHIEF PROGRAMMER TEAMS

- ●COORDINATION OF SEVERAL PROGRAMMERS ON LARGE PROJECTS
- ●CHIEF PROGRAMMER PROVIDES PROJECT COMMUNICATION, REDUCES COORDINATION "MINDS" BY FACTOR OF 5 or 6

●DEVELOPMENT SUPPORT LIBRARIAN

- ●MAINTAINS SOFTWARE PRODUCT LIBRARY
- ●INCLUDES BOTH MACHINE/HUMAN READABLE DOCUMENTATION

●TOP DOWN DEVELOPMENT

- ●DEFINE SOFTWARE IN HIERARCHY OF LEVELS
- ●START WITH TOP LEVEL, WORK DOWN
- ●USE DUMMY CODES OR "STUBS" FOR LOWER LEVEL FOR INITIAL TESTS

●MODULAR DECOMPOSITION

- ●INTERFACE BETWEEN MODULES DEFINED
- ●INDEPENDENT MODULES EASE PROBLEMS OF CODING, TESTING, CHANGING

●STRUCTURED DESIGN

- ●INDEPENDENT (SINGLE FUNCTION) MODULES
- ●MODULES ARE PORTABLE
- ●EFFICIENT, REDUCED BUGS

●PROGRAM DESIGN LANGUAGE

- ●COMPARABLE TO HARDWARE DRAWING
- ●COMMUNICATE SOFTWARE DESIGN CONCEPT IN DETAIL
- ●"PIDGIN" ENGLISH (PSEUDO-CODE)

FIGURE 7.5-2

MODERN SOFTWARE PROGRAMMING PRACTICES (CON'D)

●PROJECT WORKBOOK

- SOFTWARE DESIGN PROJECTS PRODUCE MUCH MATERIAL
- "CAPTURE" & ORGANIZE MATERIAL
- MAKE AVAILABLE TO ALL PROJECT PERSONNEL FOR USE

●HIPO — HIERARCHY/INPUT-PROCESS-OUTPUT

- PART DOCUMENTATION/PART ANALYTICAL
- HIERARCHY CHART --SIMILAR TO ORGANIZATION CHART
- SHOW EACH FUNCTION/SUBFUNCTION
  SHOW INPUT/OUTPUTS WITH INBETWEEN PROCESSING

●STRUCTURED PROGRAMMING

- STRAIGHT LINE (NO GOTO'S)
- ONE ENTRY, ONE EXIT

●STRUCTURED WALK-THROUGH

- PEER REVIEW (KEEP THE BOSS OUT)
- REVIEWEE PLANS/RUNS SESSION
- MODERN PRACTICES PROVIDE UNDERSTANDABLE STRUCTURE FOR "WALK-THROUGH
- EMPHASIS IS ERROR DETECTION

NON-DEFENSIVE ATMOSPHERE

REVIEWEE SOLELY RESPONSIBLE FOR CORRECTIONS
FIXES LATER

MODERN PRACTICES HAVE BIG PAYOFF
IN REDUCING SOFTWARE EFFORT

FIGURE 7.5-3

CAUSES:

Software development is an intellectual process which is resistant to an orderly structure, is difficult to document clearly, and requires special disciplines to accomplish.

Software is complex which makes it difficult to understand and to communicate its features to others.

Software requirements are usually not adequately explicit, which means programmers must interpret the meanings of the requirements which gives rise to mismatches between the system requirements and the first pass at the software code.

There are often hardware dependencies of the software not fully understood by the programmer or the system architect in the beginning.

Avionics systems require real time avionics usually with multiple level interrupts which give rise to many system states which are difficult to test thoroughly.

SOME SOLUTIONS:

Structured programming which is an element of MSPP provides some help in solving the software problem. Structured programming utilizes single function modules which have single entry and single exit routines. The use of GOTO's are avoided to prevent unexpected paths as modules are linked. Single page programs are used to keep the modules manageable in size.

Structured programming utilizes the discipline of functional decomposition and top down design and construction of the single function modules. The use of top down design permits the delay of the detailed programming of some functions without impacting other functions. The validation and testing of the modules as they are completed provides a continuous testing environment during software development which reduces surprises during system level testing.

The use of problem oriented HOL compilers simplifies the development process by making the source easy to express and comprehend. Such HOLs deal in problem constructs which include both operations and the associated data. Problem oriented HOLs reduce machine dependencies and enforce structure in the development as well as provide diagnostics and statistics for the programmer.

Software development methodology and tools include:

- Static code analyzer such as cross reference lists and flow charts generators
- Dynamic code analyzer such as debuggers and functional simulators
- Software configuration control
- Use of simulation to provide real time testing and exercise of all functions in a dynamic environment.

REMAINING PROBLEMS:

Avionic and control system software demand a discipline in real time design including the control of concurrent processing; sharing of code, data and other resources between modules; prediction of duty cycles and response times; selecting sampling times which are adequate for closed loop stability and response quality but which do not over tax the available throughput; defining satisfactory test procedures which exercise as many system states as possible within the test constraints.

A continuing problem in avionics software is the management of the data bases. Many problems with the avionic software originate in data management not in the software code per se.

WHAT HOL SHOULD BE USED:

There are a number of HOL's which are available to use in avionics and controls software development. Probably one of the most widely used HOLs is FORTRAN, although it has not been widely used to date in real time avionics and controls software. The advent of microprocessor versions of FORTRAN IV compilers is making this possibility a reality for the next generation systems. Other higher order languages which are widely available for microcomputer based systems include PL/M and PL/Z, which are microprocessor adaptations of PL/1. PASCAL is becoming available and is a language with a simple yet powerful structure.

HAL/S is a HOL developed for avionics and used on the shuttle avionics by Intermetrics since 1973. This language was standardized by NASA in 1977 and has been utilized on a number of computers including the RCA CMOS COSMAC microprocessor. The HAL/S compiler is available and is supported by a number of development tools including debuggers, functional simulators and compiler statistics.

DOD has an interim list of approved HOLs (ref. 126) which include:

- FORTRAN IV, ANSI version
- J3 JOVIAL
- J73 JOVIAL
- TACPUL
- SPL-1
- CMS 2
- ANSI COBOL

At the present time four companies are working on a PASCAL derived common language for DOD imbedded computer applications including Intermetrics, Honeywell Bull, SRI International, and SofTech.

GLOSSARY

ACT	active control technology
ADC	analog to digital converters
ADM	advanced development model
AEW	airborne early warning
AFAL	Airforce avionic laboratory
AFAPL	Air Force Avionics propulsion Laboratory
AFCS	automatic flight control system
AFFDL	Air Force Flight Dynamics Laboratory
AFT	advanced fighter technology
AFTI	advanced flight technology integration
AGC	automatic gain control
AIMS	an acronym of acronyms A = ATCRBS air traffic control radar beacon system I = IFF identification friend or foe M = MARK XII identification system S = SYSTEMs many diverse AIMS configurations
AM	amplitude modulation
ANPRM	advanced notice of proposed rulemaking
ANSI	American National Standards Institute
APD	avalanche photodiode (p-i-n)
ARINC	Aeronautical Radio Incorporated
ARM	semi active missile
ART III	enroute controls automated - terminal areas -
ASCII	American Standard Character Identification Index (digital code for alphanumeric characters)
ASDE	airport surface detection equipment
ASTC	airport surface traffic control
ATARS	automatic traffic advisory and resolution system
ATC	air traffic control
ATCRBS	air traffic control radar beacon system (transponder)
ATCSF	air traffic control simulation facility
ATIS	Automated Terminal Information Services
ATR	air transport rating
AV-WOS	automatic aviation weather observation station
AWACS	airborne warning and control system

BCAS	beacon collision avoidance system
BCIU	bus controller interface unit
BIT	built in test
BITE	built in test equipment

CADC	central air data computer
CAP	combat air patrol
CCD	charge coupled device
CDTI	cockpit dislayed traffic information
CEP	circular error probability
CG	center of gravity
CLGP	cannon launched guided projectile
CMOS	complementary metal oxide semi-conductor
CMS2	a higher order language
CNI	communication, navigation and identification
COBOL	a business orientated higher order language
COMM	communication
CONSCAN	conical scan (radars)
COSMAC	complementary MOS microcomputer
COSRO	conical scan on receive only
CPSM	continuous phase shift modulation
CPU	central processing unit
CRT	cathode ray tube
CSD	constant speed drive
CTOL	conventional take off and land
CU	control unit
CW	continuous wave

DABS	discrete address beacon system
DABSEF	DABS experimental facility
DACs	digital to analog converters
DAIS	digital avionics integration/information system
DDR&E	director of defense research & engineering
DECM	defenses electronic countermeasures
DF	direction finding
DFBWS	digital fly by wire systems
DIP	dual inline packages
DMA	direct memory access
DME	distance measuring equipment
DOD	Department of Defense
DoD	Department of Defense
DOT	Department of Transportation
DoT	Department of Transportation
DPSK	differential phase shift keying
DTDMA	distributed time division multiple access
DU	display unit

E	erasure
e	errors
EADI	electronic attitude director indicators
EBAM	electronic beacon access memory
ECCM	electronic counter-countermeasures
ECL LSI	emitter coupled logic large scale integration
ECM	electronic countermeasures
EEE	energy efficient engine
EHSI	electronic horizontal situation indicators
EJFET	enhanced junction field effect transistor
EL	electroluminescent
ELINT	electronic intelligence
ELM	extended length message
EM	electromechanical
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMP	electromagnetic pulses
E-O	electro optical
EPCS	electronic propulsion control system
ESD	electronic systems division
ESM	electronic support measures
ETABS	electronic tabular display
EW	electronic warfare

FAA	Federal Aviation Administration
FADEC	full authority digital electronic control
FBW	fly by wire
FLIR	forward looking IR
FORTRAN	formula translation (a higher order language)
FPCC	flight propulsion control coupling
FSS	flight service station
FTMP	fault tolerant microprocessor

GA	general aviation
GaAlAs	gallium aluminum arsenide
GaAs	gallium arsenide
GAO	general accounting office
GCA	ground control approach
GCI	ground controlled intercept
GPS	global positioning system

HAL/S	HOL for avionics language/space
HF	high frequency
HOJ	home on jam
HOL	higher order language
HSD	horizontal situation display
HUD	head-up display

ICAO	International Civil Aviation Organization
ICNI	integrated communications navigation and identification system
IF	intermediate frequencies
IFF	identification, friend or foe
IF2	intermediate frequency No. 2
IFR	instrument flight rules
IIL	integrated injection logic
ILS	instrument landing system
IMKF	integrated multi function keyboard
IMU	inertial measuring unit
InP	indium phosphide
INS	inertial navigation system
IPC	integrated propulsion control
IR	infrared
ITACS	integrated tactical air control system
ITNS	integrated tactical navigation system
JFET	junction field effect transistor
JOR	joint operational requirements
JOVIAL	a USAF sponsored higher order language for avionics
JTIDS	joint tactical information distribution system
LAWRS	limited aviation weather reporting stations
LC	liquid crystal
LCD	liquid crystal displays
LED	light emitting diodes
LLLTV	low light level TV
LOAL	lock-on-after-launch
LORO	lobe-on-receive-only
LPE	low probability of exploitation
LRU	line replaceable unit
LSI	large scale integration
LTA	lightning transient analysis
M	active modules
M&LSIC	medium and large scale integrated circuits
M&S	metering and spacing
MAR	minimally attended radar
Mark XII	a secure military identification system
MESFET	metal semiconductor field effect transistor
MIC	micro-integrated circuit
MLS	microwave landing system
MMW	millimeter wave
MNOS EAROM	metal nitride oxide semiconductor electrically alterable read only memory
MOS	metal oxide semiconductor
MOSFET	metal oxide semiconductor field effect transistor
MPD	multipurose displays
MSI	medium scale integration
MSPP	modern software programming practices
MTBF	mean time before failure
MTD	moving target detector
mu	electron mobility

N	standby modules
NACA	National Advisory Committee for Aeronautics
NADC	Naval Air Development Center
NADIN	National Airspace data interchange network
NAFEC	National Aviation Facilities Experimental Center
NASA	National Aeronautics and Space Administration
NAS	National Airspace system
NDRO	non-destructive readout
NEMP	nuclear electromagnetic pulse
NOAA	National Oceanic and Atmospheric Administration
NOTAMS	notices to airmen
NRZ	non return to zero
NTR	net time reference BC basic channel
NTSB	National Transportation Safety Board
NWS	National Weather Service
OFP	operational flight program
OTP	operational test program
PA	power amplifier
PCV	power control valve
PL/M	programming language/microcomputer
PL/Z	programming language/Z-80
PL/1	programming language/one
PR	pseudorandom
PRF	pulse repetition frequency
PSK	phase shift keying
PWI	proximity warning information
q	symbol for dynamic pressure
QPLT	quiet propulsion lift technology
QSRA	quiet research aircraft
QPSK	quadriphase phase shift keying
RAM	random access memory
RBX	radar based transponders
R,E&D	aviation and weather research, engineering and development
RF	radio frequency
RFI	radio frequency interface
RHAW	radar homing and warning
RNAV	area navigation
ROM	read only memory
RPV	remotely piloted vehicles
R-S	Reed-Solomon code
RSED	Reed-Solomon encoding-decoding
RT	remote terminal units
R/T	receiver-transmitter
RTCA	radio technical commission for aeronautics

SA-2	surface to air
SAW	surface acoustic wave
SDFL	Schottky diode field effect transistor logic
SELCAL	selective call
SFCS	survivable flight control system
Si	silicon
SIGINT	signal intelligence
SLS	side lobes
SOS	silicon on sapphire
SP	signal processor
SPL-1	a higher order language
SSB	single sideband
SSI	small scale integration
TACAN	tactical air navigation
TACPUL	a higher order language
TAGS	tower automated ground surveillance
TCV	terminally configured vehicle
TDM	time division multiplex
TDMA	time division multiplex access
TED	transfer electron devices
TIPS	tower information processing system
TLM	telemetry message
TP	terminal processor
TRSB	time reference scanning beam
TWSRO	track while scan on receive only
ULSI	ultra large scale integration
UHF	ultra high frequency
VAS	vortex advisory system
VHF	very high frequency
VLF	very low frequency
VLSI	very large scale integration
VNAV	vertical navigation
VOR	visual omni range
VORTAC	visual omni range and military TACAN system
VSCF	variable speed constant frequency
VSD	vertical situation display
V/STOL	vertical/short takeoff and land
VTOL	vertical takeoff and land
WVAS	wake vortex avoidance system

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16. Abstract
The state of the art survey (SOAS) covers six technology areas including flightpath management, aircraft control systems, crew station technology, interface & integration technology, military technology, and fundamental technology. The SOAS included contributions from over 70 individuals in industry, government, and the universities.

Flightpath technology includes a description of the current navigation systems and air traffic control systems as well as a preview of the next generation systems including GPS, BCAS, DABS, and other planned ATC techniques.

Aircraft control system technology includes automatic flight control systems, digital fly by wire systems, fault tolerant systems, propulsion control systems, integrated flight/propulsion control, and active control systems.

Crew station technology includes a review of digital displays, flat surface display technologies, data entry and controls, and flight systems management.

Integration and interfacing technology includes avionics functional integration and architecture, microprocessor/memory technology, fiber optics, bussing concepts, and external interference effects.

Military avionics technology includes surveillance, detection and warning systems; IFF and ECM systems; JTIDS; weapons guidance and control.

Fundamental technology includes information and control theory, optimal control, Kalman filter and state estimation theory, direct digital synthesis, electronic device technology including silicon and gallium arsenide technology, low cost sensors, electromechanical devices, analog to digital and digital to analog conversion devices, fluidics, systems analysis, and system software including higher order language and structured programming.

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