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JOINT FAA-NASA SEMINAR

GLOBAL POSITIONING SYSTEM FOR GENERAL AVIATION

OCTOBER 16 AND 17, 1978

SUMMARY REPORT

The
FEDERAL AVIATION ADMINISTRATION
and the
NATIONAL AERONAUTICS
AND
SPACE ADMINISTRATION

NOTICE

FOREWORD

On October 16-17, 1978, FAA and NASA held a seminar to examine the potential utilization of the Global Positioning System (GPS) for general aviation. This format was chosen to provide the broadest possible participation and discussion on a most challenging and difficult subject. Based on the material contained within this report, it appears that this objective was well-satisfied.

GPS has the potential to become a single, universal navigation system meeting the needs of a broad variety of users including, but certainly not limited to, civil aviation. At the same time it represents a new technology and a new way of doing things, many of which have yet to be proven. Thus, we are faced with the difficult question of how can we, or perhaps more significantly, should we use this emerging technology?

It was not the intent of this seminar to answer these questions. Rather, it was intended to provide all parties concerned--Government, industry, and the user community--with the opportunity to review their programs; express their views on the subject; and, hopefully, provide some insight as to where we go from here. It is our belief that working together in this way will help us find the answers and assure that the needs and desires of civil aviation are met in the safest and most efficient way possible.

A. P. Albrecht
Acting Associate Administrator
for Engineering and
Development
Federal Aviation Administration

Dr. James J. Kramer
Associate Administrator for
Aeronautics and Space
Technology
National Aeronautics and
Space Administration

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FAA WELCOMING ADDRESS

A. P. Albrecht
Deputy Associate Administrator
for Engineering and Development
Federal Aviation Administration

Dr. Kramer and I would like to welcome you to this seminar in which over the next 2 days we hope to examine in considerable depth the potential application of the Global Positioning System (GPS).

I'm sure that our distinguished speakers and panel members will provide a very comprehensive look at this most interesting subject.

Before we begin, however, I would like to say a few words about how we in the aviation community perceive the problem. At the present time, navigation is not one of our major issues. Most of our users are reasonably well-satisfied with current operational systems, but that doesn't mean we don't have problems.

Many users would like better navigation and nonprecision approaches to airports at significant distances from VOR/DME ground stations. Helicopter and short-haul aircraft operators need and must have precision navigation capability at very low altitudes in circumstances where VOR/DME is by no means at its best.

Users interested in area navigation will insist on improvements to VOR coverage, especially where VOR's are located in difficult terrain and where there are unusable service areas. General aviation, or that element of general aviation which travels over oceans, would like a far less expensive way than Omega to get across. Military and large commercial aircraft operators and pilots would like improvements in altimetry to permit vertical separation of 1,000 feet above flight level 290. So, there are indeed problems; and as you will hear later today, we are attempting to attack many of these in our navigation program.

GPS holds the promise of a single, universal navigation system meeting the requirements of aviation and perhaps other modes of transportation. The possibility of major savings to the country and to the users of such a system is important. NAVSTAR/GPS offers a new possibility and deserves our close scrutiny, but that scrutiny must be realistic and hard-nosed.

In our view, NAVSTAR/GPS or any new navigation system must meet one important criterion. It must offer us a better navigation service than we now enjoy, and it must offer it to the largest possible number of prospective users in transportation and at a cost no greater than systems we are currently supporting.

FAA has a number of priority efforts underway to get at the facts--technical, operational, and institutional. We hope that this seminar and our joint efforts with NASA will help in that effort. During this seminar, we expect to cover a broad spectrum of issues. We will first review what Government is doing to examine potential civil uses of NAVSTAR/GPS, and we will later hear from the technologists and their aspects of the problem. Also, since any new system impacts our user community from technical, operational, and economic standpoints, we will find out from this community how it feels about GPS. And lastly, we will hear from the industrial community who supplies the equipment needed to use GPS.

Thank you again for coming.

NASA WELCOMING ADDRESS

Dr. James J. Kramer
Associate Administrator
for Aeronautics and Space Technology
National Aeronautics and Space Administration

It is a pleasure to also welcome you to this seminar. I think it is particularly fitting that NASA and FAA work closely on this particular issue examining the potential for application of space-related technology to the aeronautical world.

I am very enthusiastic about this particular kind of format for discussion of an emergent issue like NAVSTAR/GPS I hope that you will maintain an informal atmosphere and have the most frank and open discussion possible. I think that it is entirely appropriate to sort out the wheat from the chaff in an issue like this.

I appreciate your coming, and I hope you have a very good 2-day meeting.

N80-21300

FAA NAVIGATION PROGRAM

NEAL A. BLAKE
DEPUTY DIRECTOR, OFFICE OF SYSTEMS ENGINEERING MANAGEMENT
FEDERAL AVIATION ADMINISTRATION

The FAA navigation program, which forms a part of the DOT National Plan for Navigation, includes two major activity areas: those associated with certification of navigation systems to meet current requirements and those associated with building the data base needed to define future system improvements.

The near-term activities include the VORTAC upgrading program, the development of the technical data base needed for certification of LORAN-C and OMEGA as a part of the current air navigation system, and the completion of development of area navigation standards. It also includes a realistic assessment of the operational suitability of Differential OMEGA to provide supplementary coverage to the VORTAC system in meeting special user requirements in Alaska. A new initiative in the near term program this year is the Helicopter IFR Program, which includes, as a part of the overall program activity, an assessment of the operational suitability of the several navigation system alternatives for meeting helicopter navigation requirements for CONUS and offshore operations.

Our future system activities include analysis of alternative system configurations made up of system elements including VORTAC VOR-DME, OMEGA and Differential OMEGA, LORAN-C, and GPS. This analysis includes cost-benefit tradeoff studies, as well as technical evaluations. In conducting this activity, we are placing emphasis on examining the potential future role of the Global Positioning System (GPS) for air navigation.

Figure 1-1 shows the interrelationships between the near and far term programs. The second generation VORTAC upgrading program will result in a replacement of the current obsolete equipment during the 1980-1984 time period. We fully expect that the ICAO nations will request extension of the VOR-DME protection date from 1985 to 1995, as many of the third world nations have only recently made, and many are now making, substantial investments in both the ground and airborne portions of the system. We believe that the United States is likely to support this position.

The offshore and remote area activities include the programs needed to certify LORAN and OMEGA for special user needs and oceanic area navigation in the near-term and to provide the data base needed for determination of the potential role of these systems as a part of the future navigation system. In oceanic areas, OMEGA has already been certified as an updating aid to systems like Inertial and Doppler. Our current program encompasses the activities needed to establish the data base for certifying OMEGA as a primary aid for air carriers operating in oceanic areas. We plan to have this latter work completed in time for a decision during FY-80.

The future systems work is keyed to completing the studies, analysis and feasibility tests needed to make the decision on the future roles of each of the system elements by the 1983-85 time period. After the decision is made, we expect that the transition will take some 10 to 15 years. Our cost studies have indicated that this time period results in the lowest overall costs to both government and users.

VORTAC UPGRADING PROGRAM

The goal of the solid-state VORTAC VOR-DME replacement program is to replace obsolete VOR-DME and TACAN electronic equipment, which are up to 34 years old, with new equipment. We expect the modernization program will reduce the current operations and maintenance costs for the VORTAC system from $37 million to about $16.4 million, - for an expected annual savings of $20.6 million. Of this, approximately 60 percent of the savings will result from use of solid-state technology. The remaining 40 percent will derive from reduction of operation and maintenance costs through use of a remote maintenance monitoring capability. The program will provide full recovery of investment costs by the late 1980's, and seems to us a very sound investment.

LORAN-C

The objective of the LORAN-C program is to determine the suitability of this system as a supplement to and possible replacement for the VOR-DME system. This program addresses the issues of LORAN-C signal availability and reliability; the performance of the LORAN-C system for en route, terminal, and non-precision approach operations; and the feasibility of developing low-cost avionics, particularly for general aviation.

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The activities being carried on under the LORAN-C program are part of a joint program between the FAA and United States Coast Guard. This joint effort includes establishing a LORAN-C data base, developing a LORAN-C monitoring system, evaluating various avionics equipments, developing low-cost avionics equipment, developing geographical grid corrections, and determining the impact of using LORAN-C navigation on air traffic control (ATC) and flight inspection procedures.

There are several cooperative interagency activities in the program to establish a data bank on LORAN-C performance. FAA is providing a portable ground test facility to determine short-term variations in LORAN-C signal stability. This facility will be used in support of flight tests at airports where we will be evaluating use of the LORAN-C signals for non-precision approaches. FAA aircraft will be used to gather data at airports located in the Northeast Corridor, offshore along the East Coast, in Alaska and along the West Coast. During the same time period, NASA will be examining the long-term variations in the LORAN-C signal to determine seasonal variations.

FAA is also participating in the overall DOT program to assess the utility of LORAN-C for the State of Vermont. FAA will be supplying a calibration system consisting of portable DME stations and an associated airborne measurement unit. A NAFEC aircraft will be equipped with a TDL-424 LORAN-C receiver as well as normal calibration equipment, and will be taking data. Simultaneously, data will be gathered on the performance of the low cost Teledyne TDL-711 receiver. At the completion of this phase of the program, comparisons will be made between the performance of the two receivers. The low cost receiver will then be installed in a Vermont Air National Guard aircraft, to be used in assessing the feasibility of defining non-precision approach procedures based on LORAN-C for a number of Vermont airports.

FAA is also developing a LORAN-C monitor system which will provide a real-time system input to FAA Flight Service Stations (FSS) on the status of LORAN-C stations, identifying stations that are unstable or off the air for maintenance, and providing data relating to planned outages. The FSS specialists will use this data to prepare Notices to Airmen (NOTAMS) on the status of the various LORAN-C chains. This activity is currently planned for FY-1979 funding, with FY-1980 delivery.

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While the flight test program is primarily to evaluate the LORAN-C signal, it will allow FAA to evaluate both the top-of-the-line LORAN-C avionics, the TDL-424, and the relativly low-cost avionics, the TDL-711, in a side-by-side comparison. This will aid in the activities to develop avionics at a lower cost than the TDL-711. Our objective is to develop LORAN-C avionics suitable for IFR flight that can sell in the $1,000 to $3,000 price range.

OMEGA

The FAA OMEGA program is to determine the utility of OMEGA and VLF as a supplement to VOR-DME. It includes activities to determine the suitability of OMEGA as a sole means of oceanic navigation for air carrier aircraft, the use of OMEGA as a remote area supplement to VOR-DME, and the feasibility of developing easy-to-use low-cost OMEGA avionics, with a careful eye on the lane ambiguity problem. The program approach is similar to that for the LORAN-C program and includes the establishment of a World-Wide OMEGA Data Bank to assist FAA in assessing the suitability of certifying OMEGA as a sole means of navigation for air carrier aircraft when operating on oceanic routes. This activity will include recording data on the quality of the OMEGA signal on the oceanic routes and also comparison of the accuracy of the OMEGA positions over land check points. A meeting to establish a World-Wide OMEGA Data Bank held on August 2-3 at Philadelphia was attended by a number of organizations representing both suppliers and users of OMEGA. As a result of this conference, 20 recorders for collecting data will be allocated such that business jets will have four, domestic carriers will have six, foreign carriers will have six, and NAFEC will have four. The degree of participation by the different groups is expected to be determined by November.

Another activity in the OMEGA program is the development and evaluation of an OMEGA-VLF monitor system. At the present time, a model of the OMEGA portion of the system is available at NAFEC and is undergoing evaluation. This sytem builds a nominal archive of OMEGA signals, compares OMEGA signals against this archive, and detects signal outages, sudden ionospheric disturbances and polar cap absorption events. It provides warnings on poor signal-to-noise ratio signals and identifies the stations of choice for use in each geographical area. This information is provided to FSS's and centers, and will be passed on to the pilots through NOTAMS. We are

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planning to extend the monitor system to include VLF monitoring capability and later to add use of information from the SOLARD system - a satellite system which detects and reports information on solar flares.

Since the OMEGA system operates at very low signal-to-noise ratios, one program activity has been to develop a low noise antenna. This antenna has received some testing on a National Oceanic and Atmospheric Administration (NOAA) aircraft; however, the time available for such testing has been quite limited and the antenna is being transferred to the FAA Alaskan Region flight inspection aircraft for further testing and evaluation. Future activities under the noise reduction program include studies of alternative methods of noise reduction, further antenna research and determination of improved methods of discharging and bonding aircraft.

An OMEGA simulator is being developed to permit rapid evaluation and certification of new OMEGA receiver designs. It will simulate a variety of signal-to-noise conditions of the OMEGA signal as well as station failure conditions.

This fall, we hope to start an evaluation program with Canada on a Differential OMEGA system. Three nondirectional beacons will be equipped to transmit the Differential OMEGA corrections to the aircraft. The evaluation will be conducted over the next year in the Alaskan Region, and will involve the FAA flight inspection Convair, a Twin Otter owned by the Canadian Government, and some cooperating commercial aircraft operators. It is anticipated that six sets of avionics will be available for the program.

The future program activity will include development and evaluation of low-cost OMEGA avionics. At the current time, low-cost equipment is available in the $6,000 to $8,000 price range. It is hoped that this amount can be reduced to the $3,000 to $4,000 range.

HELICOPTER IFR PROGRAM

A new start for FAA this year is a program to examine the special requirements of helicopters for operation within the air traffic control system, both within the CONUS and in offshore areas. The portion of this program, relating to navigational requirements covers the operational evaluation of LORAN-C and OMEGA as well as VOR-DME and DME-DME for operations on area navigation routes within the CONUS and on specially defined routes suitable for supporting offshore oil

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exploration. The program will also examine the use of airborne weather radar in conjunction with supplementary equipment to assist in locating and making approaches to offshore oil rig locations. This latter activity will examine the effectiveness of several techniques including active beacon systems, passive reflectors, corner reflectors, and a variety of RF lenses for this purpose. Data collection will be conducted using a NASA CH-53H helicopter operating along the area navigation routes between Boston and Washington National Airports. Initially, the TDL-424 LORAN-C receiver will be used to take the data. Later tests will take comparative data on both the TDL-424 and the lower cost TDL-711 systems. Another FAA effort will be data collection taken by the FAA/NASA helicopter operating in the offshore area in the vicinity of Atlantic City. The data collection system will simultaneously be taking data from the VOR-DME (where available), LORAN-C, and OMEGA systems on board the helicopter.

In addition to the FAA activity, the Coast Guard will be operating a helicopter equipped with TDL-424 avionics equipment along a route between Otis Air Force Base in Massachusetts and Washington National Airport. Position data will be taken from the ARTS III facilities located along the route to assess the performance of the LORAN-C system in helicopter operations.

FUTURE NAVIGATION SYSTEM REQUIREMENTS

FAA has also undertaken the very difficult task of developing area navigation standards for the future system. This activity is addressing the question of defining requirements for systems where the characteristics of the error are random. Current systems such as VOR-DME, INS, Doppler, tend to be characterized by bias types of errors. The requirement work is also addressing the effect of error buildup during aircraft maneuvers and the effect on the pilot of intermittent updating of the flight display. The output of this activity will be a set of requirements which will be non-system specification. This activity also includes consideration of new user requirements for increasing STOL and VTOL IFR operations; assessment of the benefits that could be derived from higher accuracy navigation signals providing more complete coverage; and analysis of the system characteristics of potential future navigation systems. In conducting this activity, it is envisioned that a navigation management computer will become the heart of the future navigation system on many aircraft. Navigation will become less route-oriented and will depend on the navigation computer to select different navigation sensors as the phase and route of flight vary. Systems providing inputs to the area navigation computer are expected to include VOR-DME, DME-DME, INS, LORAN-C, OMEGA and MLS.

GLOBAL POSITIONING SYSTEM

FAA has initiated an extensive program to define the potential future role of Global Positioning System (GPS) as an element of the civil aviation navigation system. The United States Coast Guard (USCG) already has a program underway for the development and evaluation of GPS receivers for maritime use. The DOT is in the process of preparing an intermodal development plan which in turn will be coordinated and intedgrated with similar programs in other agencies in the GPS area so as a department, we are placing every increasing emphasis on this program. We have defined the activities needed to address a number of institutional, cost, and technical problems, which must be resolved if GPS is to form a part of the future navigation system.

Institutional Factors in GPS

Since GPS is being designed as a U. S. military position location system, a number of institutional problems must be addressed before such a system can become an integral part of the domestic and international civil navigation system. I'd like to mention a few of the key issues:

The availability of signals of adequate accuracy at all times, including times of stress, is perhaps the most important institutional factor. A preliminary evaluation of the GPS signals as they are currently proposed indicates that many of the civil requirements could probably be met with the clear acquisition (C/A) channel signal. Currently the Department of Defense is studying the questions of signal accuracy and availability which might be offered for civil navigation and has provided the results of the first portion of this study. If the currently hoped-for accuracy of the clear/acquisition signal were available at all times, except for conflicts involving the immediate safety of the United States, then GPS becomes an attractive alternative for the future civil navigation system. We believe the civil user community will be very much interested in GPS if it can offer a better service than current systems at a lower user cost.

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A closely related issue is the suitability and international acceptability of a U. S. military system for international civil aviation use.

Technical Factors in GPS

While it is believed that avionics can be built for large air carrier aircraft that will perform satisfactorily, there is still a question on the feasibility of developing low cost user equipment that will operate satisfactorily with the GPS signal. Of particular concern is the ability to achieve the necessary accuracy for non-precision approaches using low-cost equipment, when the aircraft is in a maneuvering configuration at low altitudes in the terminal area. In this configuration, the aircraft is subject to the greatest amount of ground-generated radio frequency interference (RFI) which is added to that generated locally on the aircraft. It is also in that environment that the aircraft is most subject to multipath problems.

Aircraft antennas become a consideration as it is necessary to obtain suitable signal-to-noise ratios even when using satellites at very low satellite elevation angles, such as 5^{o} above the horizon. This is necessary in order to track at least four satellites in good geometry throughout non-precision approaches.

Acquisition time becomes a consideration both on initial code acquisition and on airborne reacquisition after signal loss. It is also a consideration when it is necessary to receive ephemeris data when picking up a new satellite. This condition will occur whenever one of the satellites required to achieve a good position fix is just coming into view over the horizon. A related issue currently under study is the effect of satellite failures on system accuracy, particularly as it might affect aircraft involved in non-precision approach operations.

Alternative signal formats are being examined to determine the potential for reducing avionics cost. Although some cost reduction appears achievable with a different signal format, the change offering the greatest gain seems to be the provision of additional power in the satellite utilizing the current signal format.

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The human factors area must also be considered as the GPS system, by definition, is an area navigation system. Such a system represents an increase in pilot workload over the VOR system, particularly for single pilot IFR operations. It also increases the possibility for blunders in entering way-point information.

Use of GPS signals for more accurate aircraft height determination has been proposed as a method of reducing altitude separations above flight level 290. While this possibility is being investigated, questions relating to adequacy of the GPS signals to provide the increased accuracy on a continuing basis, particularly when only the clear-acquisition signal may be available to civil users, have yet to be fully answered. Analysis conducted to date tend to indicate that the signals are not adequate to perform this function. A further consid eration is the problems that conversion from a pressure referenced altitude measurement system to an absolute or geometric referenced system may entail, particularly during the transition period.

An additional technical factor is that of undetected failures. It is possible, in a system as complex as the GPS receiver, to have failures which will not immediately be detected by the logic and may not be presented to the pilot. This affects the safety of operations -- particularly those conducted in close proximity to the ground.

Cost Factors in GPS

The most significant cost is that of the avionics for the majority of the general aviation users. This cost, more than any other cost, will determine the acceptability of the GPS system to the civil community. At the current time, industry estimates of the production costs of GPS avionics for general aviation indicate that such avionics could probably be built for costs in the range of $5,000 to $8,000. This must be compared to the cost of the current VOR equipment, which is widely used by general aviation, and is generally available at unit costs of $900 to $1,400.

Another area that must be considered is the distribution of operations and maintenance costs between the major system users. Most of the cost studies conducted to date have assumed that the Department of Defense would pay all of the operations and maintenance costs of the system. If, however, GPS becomes a part of the civil navigation system, the question of distributing the costs among civil and military users, and particularly those questions relating to international agreements on cost sharing, must be addressed. Current estimates indicate that the operations and maintenance costs may be as high as $100 to $200 million per year. If the civil aviation community must absorb a good portion of these, it will represent a significant increase over the operations and maintenance costs of the current civil navigation system. Since GPS, by definition, is an area navigation system, the cost of providing that capability must be considered and the transition costs of jointly operating two systems -- VORTAC and GPS -- for the lengthy transition period must also be considered in the cost studies.

Figure 1-2 shows a summary of a study conducted by FAA of some of the alternatives for the future civil navigation system. The three sets of bars represent the cost to the system users, to the FAA and total costs for five different scenarios. The first scenario represents the case of continued use of the VOR-DME system for CONUS navigation, supplemented by OMEGA for oceanic navigation. The second scenario is similar to the first, but adds Differential OMEGA for use in Alaska. The third scenario represents the alternative of using LORAN-C for CONUS and OMEGA for oceanic navigation. The fourth scenario represents a GPS-only system and the fifth represents a GPS system, supplemented by VOR-DME for general aviation users.

Some of the assumptions used in generating the cost information include:

- o GPS receivers initially would cost about $14,000, but would drop to $5,700 within three years, and then increase at the rate of about 1.9% per year thereafter.

- o VOR receiver costs were assumed to be $1,400, which represents a high quality general aviation set, with costs increasing at about 1.9% per year.

- o LORAN-C receivers initially would cost $6,700, but would drop to $3,000 within three years, and then increase at the rate of about 1.9% per year thereafter.

- o The replacement cycle for general aviation avionics equipment was assumed to be 11 years, with 14 years assumed for air carrier equipment.

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- The operations and maintenance costs, or FAA costs, for the VOR system include the total costs of the VORTAC upgrading program as well as the operations and maintenance costs for the time period 1978 through 2005. The LORAN-C FAA costs include the difference in operations and maintenance as well as establishment costs between those systems meeting maritime requirements, which are supported by the Coast Guard, and the additional requirements for air navigation. They include the cost of establishing operating and maintaining two additional chains consisting of seven stations. In the case of the GPS scenario, it is assumed that FAA assumes none of the operations and maintenance costs of this system.

The shaded gray areas shown on each of the bars represent a difference in cost which is related to the length of time taken to transition from the current system to the new system. So far as the system users are concerned, the longer the transition period, the less the cost. Alternatively, the shorter the transition period, the greater the cost. Hence, the shaded area for system users may be interpreted as a transition period of five years representing the higher cost, and a transition period of 15 years representing the lower cost.

When one considers FAA costs, the reverse is true. The quicker the transition, the less the cost; the longer the transition, the greater the cost. The cost bars at the right represent the combinations of user and government costs. The figures show fairly clearly that GPS is the highest cost system solution for aviation. The ranking stays the same if one assumes a 10% discount rate and 0% percent inflation, which is the method recommended by the Office of Management and Budget (OMB). It's worth noting that the right-hand bar which represents a system based on GPS plus VOR-DME for general aviation represents a cost of about $2 billion less than a system based on GPS alone. This difference relates to the cost to the general aviation user of equipping with GPS receivers.

The model used the best assumptions available on costing to achieve the relative system ranking shown in Figure 1-2. The model also provides a vehicle for determining the effect of varying individual cost items and hence can be used to establish cost targets. Figure 1-3 shows the effect of GPS receiver costs that are 25%, 50%, and 75% of our current best estimates. This indicates clearly that GPS receiver costs must be reduced by half to provide a cost equivalent system. If technology would allow us to bring costs to the GPS receiver down by half, that same technology might also allow us to bring LORAN-C and VOR-DME costs down by some amount, so this tends to be a little misleading.

In any event, it looks to us like a cost target of about $2,500 for a low cost receiver, which is a reasonable value if we are to achieve the system where the total overall costs are roughly the same as our current system, but I have to say, however, that the costs to the small general aviation users is the difference between $2,500 and $900 and still represents a fairly large increase in the cost of navigation equipment to the minimum equipped users.

GPS PROGRAM

The program includes activities to define future civil navigation requirements and to evaluate the performance of the GPS system in meeting these requirements. It includes use of GPS simulators to rapidly test receiver equipment, and flight tests to evaluate the performance of existing equipment and to determine the noise and radio frequency interference environment as it exists at a number of airports where non-precision approaches are currently being conducted.

A continuing cost analysis is being conducted on the various aviation navigation system alternatives. FAA has already completed a preliminary evaluation of alternative navigation systems for civil air navigation. This effort will be expanded in FY-1979 to examine additional alternatives particularly with respect to distribution of operating and maintenance costs among the civil users. FAA is supporting the Office of the Secretary and the Transportation Systems Center in cost analysis studies of various navigation system mixes applied not only to aviation, but also to maritime and land users.

A third major effort relates to design studies for a low-cost GPS receiver. There are a number of activities associated with developing low-cost GPS user equipment, including the design of avionics specifically to meet the needs of the low-cost aviation user; an evaluation of the potential of using alternative satellite navigation signal structures for reducing cost; a forecast of future technology and its potential impact on receiver cost; design and evaluation of low-cost antenna systems; measurement and

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analysis of radio frequency interference to determine its effect on receiver operation; and costing of potential avionics designs.

While much of the preceding material on institutional, technical, and cost factors raises questions, we believe that GPS may well play a significant role in future civil air navigation. In oceanic and low density traffic areas worldwide, we believe that there may indeed be an incentive for air carriers and commercial operators to carry such a system, since it offers a potential for the elimination of the need to carry systems such as INS, which currently have high maintenance costs. Hence, GPS may offer a cost effective system for operations over as much as 90% of the earth's surface. Aircraft equipped with GPS will be able to utilize the systems within the CONUS airspace. Initially such use might be possible in the high altitude route structure providing a direct routing capability much like that available from the INS system today. This would require no changes to current ATC procedures. In the future, it might also provide the possibility of non-precision approaches; however, new charting and new waypoint systems will be needed which match the capabilities of the GPS system. GPS may also meet some special user requirements, such as in offshore oil exploration. Initially, the cost of receiver equipment appears to be comparable to that of existing OMEGA receivers. For the longer term, particularly if the low-cost user GPS avionics cost goals can be met, it may also become competitive to the cost of LORAN-C receiver equipment.

While we can foresee GPS in meeting these requirements, it is not yet clear whether GPS can meet the requirements for low cost user avionics, which represent the majority of the civil users within the continental United States. GPS should not be considered as a replacement for VORTAC until avionics are available in the $2,500 or lower price range, and until we are sure that such avionics can provide an adequately high level of failure detection and safety.

SATELLITE PROGRAM

Although our discussion has focused on use of GPS for navigation, the FAA satellite program includes two other major objectives: one is to examine the potential for improving service in the oceanic area through their use. As part of this effort, a working group composed of representatives from government, the user community and international airlines has been established to define and redefine the requirements for improvement of oceanic services, and to evaluate both satellite and non-satellite alternatives for meeting these requirements.

Our other objective is to continue to evaluate the use of satellites as a supplement to the domestic ATC system, looking at communications, navigation and surveillance services, primarily, and, of course, the examination of the role of GPS as a part of the system.

The last point I want to cover is that the various satellites salesmen and proponents have told us for some time that they felt strongly that satellites were in our future, and that they could provide a better, cheaper system. While it seems probable that they could provide better services in the form of more continuous coverage, when we get down to the cheap part, that is where the whole story seems to come unglued. But we are continuing to look at various concepts, and we hope to be starting a joint effort with NASA in the coming months to look at what might be done to build a system around GPS that is cost effective and which could possibly provide additional functions within the CONUS environment.

NAVIGATION

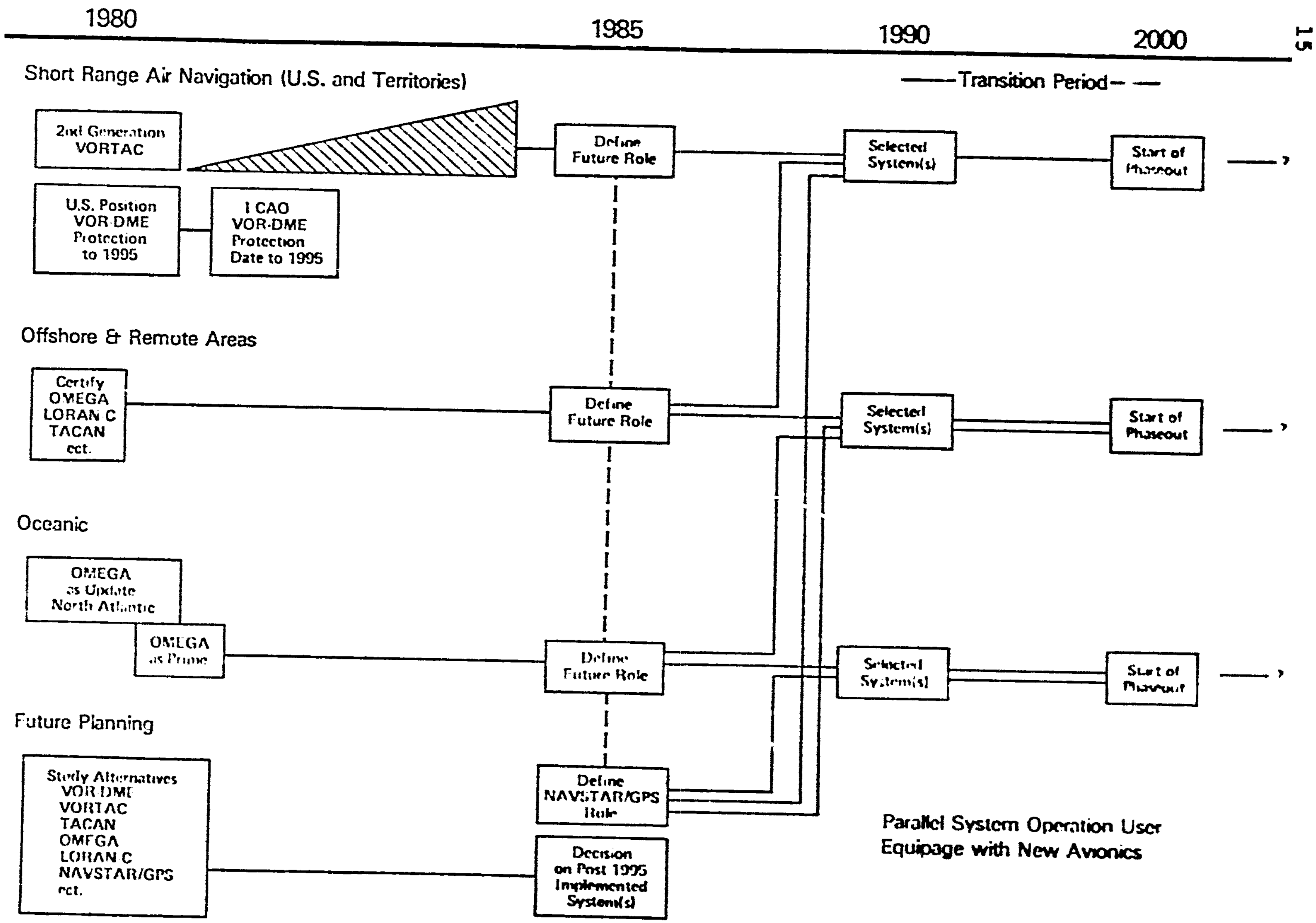

Figure 1-1

CUMULATIVE COSTS
(7% INFLATION)

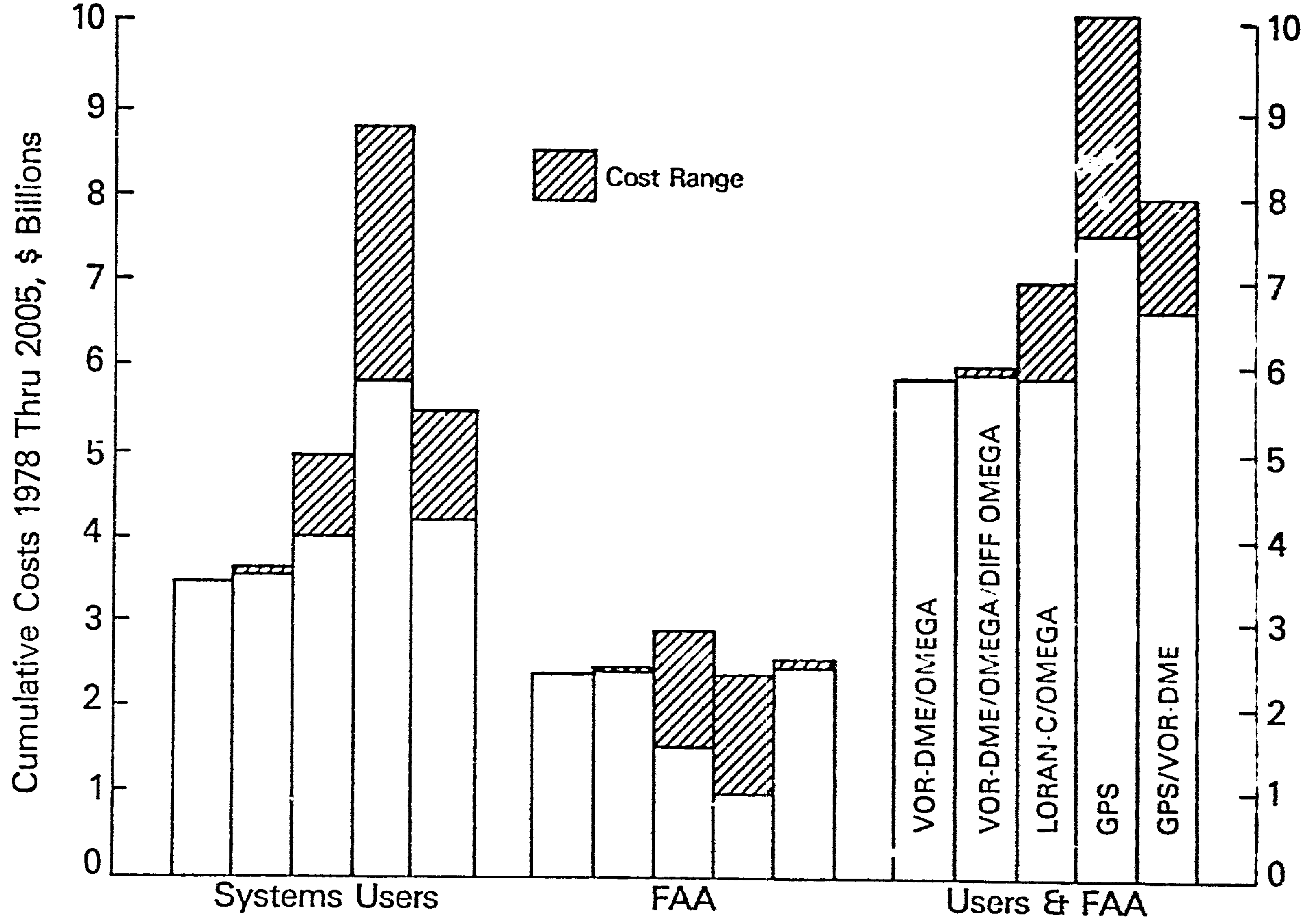

Figure 1-2

GENERAL AVIATION USER COST CONSIDERATIONS

(ASSUMING 100% O&M COST RECOVERY)

- VORTAC

System O&M	Total	Prorated-200,000 AC
Today	$37.0 M	$185
Post Modernization	$16.4 M	$ 82
Receiver		$900

- GPS

System O&M	Total	Prorated-200,000 AC
ASP Estimate	$127.0 M	—
50% for Aviation	$ 63.5 M	$317.5

GPS Receiver Excess Cost*

Current Estimated Range	Excess Cost
$8,000 to	2.1
$5,000	1.2
Design Cost Goal $2,500	.35

Annual GPS O&M Cost Penalty 0.64 B

*Excess Cost Represents All Costs in Excess of $900 VOR Receiver Plus $82 VORTAC System Prorated O&M Costs

Figure 1-3

DOD PROGRAM

LTC Stephen Gilbert
Department of Defense

The Department of Defense has been involved in the NAVSTAR Global Positioning System program since 1973, at which time we formed the GPS Joint Program Office and initiated the concept validation phase. We are nearing completion of this phase of the program, and we are very encouraged by the test results to date.

I would like to discuss some of the rationale upon which the Department of Defense proceeded with this program, why we are pursuing a satellite-based navigation and positioning system. I will discuss briefly the system concept and the status of our Phase I or concept validation program, and I will give a few comments on the application of this system for both military and civil use.

The Joint Chiefs of Staff Master NAVPLAN is the best source that we have in the Department of Defense that combines all Service and agency inputs into one document, looking primarily at the long-range navigation systems.

Turning first to the characteristics considered essential for the typical navigation and positioning needs of the Department of Defense, our number one requirement is to have a worldwide capability to operate anywhere at any time. Also, we want our users to remain passive; we want the capability to deny the use of such a system to unauthorized users; we want it to be unsaturable; and, of course, we want it to operate in any theater of operations and be resistant to natural disturbance/hostile attack. We consider interoperability with our allies to be very important, and we are proceeding to bring NATO and other allies into the program and let them determine for themselves the benefits to be derived from such a system. Other essential characteristics are effective real-time response, provision of a common grid for all users, accuracy during high-energy maneuvers, and maintainability at the operating level.

Also among the essential characteristics are continuous fix capability and self-contained capability for obvious strategic reasons. When taken together, these essential characteristics lead us to conclude that there is no single navigation system either existing or planned that can meet them all.

The point is that we are driving toward a hybrid application of self-contained and external radionavigation systems such as the NAVSTAR Global Positioning System to achieve the accuracy and global coverage we require.

We do see deficiencies today: we do not have global coverage and we cannot operate in all weather conditions; the cost and complexity of our systems have been growing and continue to grow and the number of systems that we employ for specific applications continues to grow; we have new and emerging requirements surfacing as technology and weapons system requirements become more stringent and their accuracy requirements become more severe.

The purpose of the NAVSTAR Global Positioning System program is to enhance our capability on a global scale to deliver weapons in all weather, at any time, and to support other military operations. We also expect this system to reverse the trend toward proliferation of equipment and systems designed to meet specific and unique requirements.

The GPS system concept, as shown in Figure 2-1, consists of a satellite segment, a control segment, and a user segment. The satellite segment, when it is fully deployed, will consist of 24 satellites. The control segment monitors and updates the satellites on a daily basis to maintain the system in an optimum configuration. The user segment spans the entire requirements of the Department of Defense, and this is principally why all the Services and agencies are directly involved in the program.

The system concept, as shown in Figure 2-2, requires continuous transmission of synchronized navigation signals from each satellite, each of which carries information on satellite ephemeris, clock bias errors, ionospheric propagation corrections, and system health status.

The user can then employ a relatively simple quartz oscillator in his receiver to synchronize his own clock with the satellite signals and measure the range to four satellites simultaneously to determine his three-dimensional position and system time.

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The accuracy of the most complex type of equipment is of the order of 10 meters in three dimensions as shown in Figure 2-3. One must understand the conditions under which this type of accuracy can be achieved. This is a predicted capability on a 90 percent confidence level for a single fix from an aircraft in subsonic flight, straight and level, unaccelerated motion using the most sophisticated type of equipment. This is germane to the subject of this seminar because I believe system capabilities and user requirements must be specified in the same context (i.e., Under what conditions can a given level of accuracy be achieved?).

The schedule that we are following and we hope to maintain throughout the next several years is shown in Figure 2-4. I mentioned that we are in the concept validation phase and have been since late 1973. The Defense Systems Acquisition Review Council (DSARC) reviewed the program progress at about this time last year, with a positive decision to continue the program through the next major milestone. This milestone, scheduled in the spring of 1979, will determine whether or not the program will enter into full-scale engineering development. This implies a commitment to deploy the system at a later date.

The second phase of the program, if approved, will continue on with system testing on an engineering development level and initial operational test and evaluation and proceed on beyond 1982 into the operational deployment of the space segment, the control segment, and of course the user equipment for all DOD use.

In the first phase of the program, our plans include the deployment of six satellites, of which we now have three in orbit. I might point out that we just had the third successful satellite launch, and so far the "bird" is operating beautifully. It will be turned over later next month to support the user equipment testing at the range.

In December 1978, we plan to launch the fourth satellite which will round out the initial constellation we need for four-satellite testing of the user equipment. In 1979, an additional two satellites will be launched to fill the complement of six satellites required to support the Navy's FBM Improved Accuracy Program, and that configuration will be maintained throughout Phase II as well.

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In Phase III of the program, the operational deployment will build the system to what we call an initial operational capability (IOC) which is an 18-satellite deployment. This deployment will provide a minimum of four satellites in view from any point on or near the surface of the earth. The full deployment of 24 satellites will occur about a year later under our current plan, and that will provide the full accuracy, giving the optimum geometry any place on or near the surface of the earth.

I might point out that the 18-satellite deployment is the minimum required to give 4 satellites continuously in view. The additional satellites provide redundancy that will allow outages of one or more satellites in the system without degrading the positioning accuracy significantly over any point on the earth.

With the full deployment of 24 satellites, the minimum number in view at the equator is about 6. At the mid-latitudes you will see about 8 to 9 satellites; and near the polar regions, up to 11 satellites will be in view.

The first phase of the program has the following objectives: provide information to make the next decision; validate the GPS concept; validate the preferred design; define system costs; and demonstrate military value. We are doing the necessary testing to provide the statistical estimates of total system performance and user equipment performance and to establish cost estimates for the system. We are also conducting certain tests at the Yuma range and elsewhere to demonstrate the military value of this system. I will show some of the test results later.

The program office is located at the Air Force Space and Missile Systems Organization (SAMSO) under the Air Force Systems Command. The program office has in-house the expertise of Army; Navy; Marine Corps; Defense Management Agency; and, of course, Air Force personnel, and the Air Force is the executive agent for DOD.

We are, as I mentioned, bringing NATO into the program; and we are expecting to see NATO representatives within the program office in the near future. The U.S. Coast Guard has also established liaison with the GPS program office on behalf of the Department of Transportation.

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The GPS Team is illustrated in Figure 2-5. The satellite segment is being developed by the Rockwell Corporation, and they are having good success with three satellites in orbit.

The user equipment segment is being developed by Magnavox, Texas Instruments, and Rockwell-Collins. The control station for GPS is being developed by General Dynamics Electronics Division.

The Phase I launch vehicle is the Atlas F, using an upper stage developed by Fairchild, which has so far performed flawlessly.

The inverted range shown at the bottom of Figure 2-6 is the heart of our test program, and I will go a little deeper into that function.

The inverted range was established to allow us to test user equipment before we launched any satellites. We deployed four ground-based transmitters that transmit continuous signals to the user to simulate the satellites. The user can then fly over the transmitters instead of under them as they would with satellites and hence the "inverted range."

Also deployed on the range is a very precise system of laser trackers that provide near real-time capability for trajectory estimates to compare to the NAVSTAR solution.

That range has been in full operation for about a year and has provided excellent support to the test program. Typical results on an aircraft mission, for example, are in the neighborhood of 10 to 20 meters, in 3 dimensions.

Figure 2-7 shows a picture of the Rockwell satellite in thermal vacuum testing. The three satellites that are in orbit and that have been turned over for testing are providing signal power levels at least 4 to 5 dB above the nominal specification value. We are looking at the possibility of increasing the power even further beyond that point, perhaps another 2 to 5 dB. This will have a significant impact both on the system's military utility and in the jamming environment and to its potential civil utility by allowing less expensive equipment to be manufactured.

The GPS user equipment, of course, is the major thrust of the program. Figure 2-8 shows the six classes of equipment that were originally identified by the Services and agencies in DOD. They generally span the types of equipment that operate in the high-jamming and/or high-dynamic environment, a class for utility navigation purposes, a class for the ground vehicles which may be spinoffs of the other versions, MANPACKS, and a special class for submarines.

Typically, all these equipments fall into three basic categories. There is the multichannel continuous receiver and the single- or dual-channel sequential receivers, the difference being the mode in which four satellites are tracked by the receiver. The third type of receiver uses only the so-called "coarse/acquisition" signal for navigation. The coarse/acquisition signal was initially intended as an aid to acquire the precise (P) signal; but it became obvious that once you put the navigation data on the coarse signal, equipment could be developed that employs just that data. Although it is not necessarily as accurate as the precise signal, the coarse/acquisition signal probably has the most potential for civil use because of the lower-cost equipment that it can provide.

Figure 2-9 shows the GPS Phase I Test Elements. The test program has proceeded and is proceeding with a variety of host vehicles. We have done a considerable amount of testing on helicopters and on board the NC141A, which is our principal test bed. We also have a Navy F4-J flying at the range to evaluate the enhanced blind-bombing capability offered by GPS.

The additional testing on various other vehicles will be completed by next year, and the results of all this testing will be brought to our DSARC review in the spring.

The user equipment is listed in Figure 2-9. All the user equipments have been or are about to be delivered with the exception of the Magnavox low-cost receiver, which was scheduled to be delivered later in the program. That particular receiver is the one we think has a great application toward civil use because it is the only one that operates on the coarse/acquisition signal. It was designed from the outset as a low-cost receiver wherein we accepted degraded accuracy in favor of lower cost.

Also shown in Figure 2-9 are the test locations. The principal test site is at the Army's Yuma Proving Grounds, where the inverted range is located.

As shown in Figure 2-10, the primary frequency is L_1: 1575.42 megaHertz. On that frequency, we have both a coarse/acquisition signal and a precise signal transmitted in phase quadrature. On the secondary frequency, L_2, we have a choice between the coarse signal or the precise signal, but not both. This was done principally as a measure to allow us to remain on the Atlas F booster without exceeding its weight limitations. We are currently looking at the possibility of putting precise and coarse/acquisition signals on both frequencies.

Another feature here is the increased power level that I suggested earlier. One of the major questions that must be resolved is the proportion of increased power to be applied to the precise signal to give higher antijam capability or to the coarse/acquisition signal to give lower-cost civil user equipment. An interesting question. It may be that we can split the power in some way to do both. These possibilities are being investigated. We don't have the answers yet, but we certainly are looking at them.

Figure 2-11 is the Magnavox four-channel "X set" that has been the workhorse on the test range.

This set was designed using off-the-shelf components. There was no intent to minimize the size. The basic ensemble involves the power supply, the battery, the control display unit, the preamplifiers, and the receiver/processor unit.

The X-set has been installed, as I said, in several types of vehicles. One of the most interesting, I think, is the installation in a pod underneath a Navy F4. This F4 has been flown by two line Navy pilots at all times of day and night on the range to demonstrate the blind-bombing capability of GPS.

Figure 2-12, which shows a picture of the holes in the ground, speaks for itself.

The military applications for the NAVSTAR Global Positioning System span a wide variety of environments. Shown in Figure 2-13 is just a partial list of those applications. The highlighted applications with boxes around them deal directly with weapons delivery and the targeting and mapping required to do precise weapons delivery.

It is interesting to note that the potential civil applications have a very similar type of listing as shown in Figure 2-14. Taking out the weapons delivery, you still have the requirements for en route navigation, time transfer, area navigation, application to air traffic control, et cetera. I don't intend to go into all these in detail, but I think the point is that a system like GPS certainly has both civil and military applications.

I think this potential has been demonstrated by the current activity within the Federal Government. The GAO report that you are probably all familiar with entitled "Navigation Planning - Need for a New Direction" and the Office of Telecommunications Policy report entitled "Federal Radio Navigation System Plan" both proposed a mix of systems including a satellite-based system like NAVSTAR GPS to meet military/civilian radionavigation needs of the future.

The House Appropriations Committee Surveys and Investigation Staff is currently involved with DOD and others to study position location technology, which is a look at the entire spectrum of position navigation and other ancillary functions associated with navigation.

The latest revision of the Department of Transportation's National Plan for Navigation recognized clearly that GPS was coming, stating that we need to look at the application of this system as a potential replacement for various other systems. The Joint Chiefs of Staff's Master Navigation Plan describes a plan for the incorporation of NAVSTAR/GPS into the military. The DOD initiated several months ago a so-called phase-in/phase-out plan to establish a consolidated phase-in schedule for GPS and a phase-out of those systems that can be replaced by GPS within the DOD.

Most recently, we have been involved with other agencies in the Federal Government in a working group chaired jointly by the Office of Management and Budget and the Department of

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Commerce National Telecommunications and Information Administration (NTIA). This working group and all the other activities mentioned earlier have GPS pretty much as their central theme. The question of GPS and its potential civil application is being addressed. We are proceeding to look at the issues, to get them on the table; and we are trying to deal with the technical and institutional questions that must be answered before this system can be considered a national resource.

DOD, for example, has for the past several years had a structure within the Office of the Secretary of Defense to look at total military needs in both navigation and the more broad function of combined communications, navigation, and identification functions. These subcommittees report directly to our DOD Positioning and Navigation Executive Committee chaired by Dr. Dinneen.

Figure 2-15 lists "What's Next" in DOD. One of the biggest issues facing us today is the question of how much of the GPS capability will be made available for civil use. For the past several months, we have been conducting an in-depth study of the threat and the exploitation potential of GPS. We have for many years been investigating the techniques by which one could in fact deny and/or degrade the accuracy of GPS to unauthorized users.

These investigations will be reviewed during the DSARC-II decision milestone and will form the basis for a DOD position with regard to system availability for civil and international use.

In forming this position, we are working with the Department of Transportation to establish civil user requirements and the potential user population for various levels of accuracy. The requirements and the user population at various levels of accuracy will be very important parameters to the final decision on signal availability. I believe this issue will end up being established as a national policy for satellite navigation and positioning systems, not limited just to GPS.

In summary, we have, I think, a very meaningful test program underway. The testing has gone well to this point, and we have reason to believe it will continue to go well.

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For that reason, I think that there is every reason to believe that GPS will, in fact, be deployed within the next 5 to 10 years. Our current plan calls for having it available by the 1985-1986 time frame. We see that there is a great potential for civil applications, and we in DOD are working very closely with every responsible Government agency at this time to ensure that they have a full opportunity to evaluate the system's capabilities.

QUESTION (Mr. Edward C. Krupinski, Air Line Pilots Association) - I am not real clear on the overall design capability of the system. In terms of communications and surveillance, is there any capability to that degree?

ANSWER - There is no communication function inherent in the NAVSTAR system. It is strictly a positioning and navigation system.

QUESTION (Mr. Krupinski) - Your list of potential civil applications (Figure 2-13) showed a potential for air traffic control. Beyond en route navigation, I fail to see any further application.

ANSWER - GPS has potential application to the function of air traffic control by providing a means for determining three-dimensional position on a global scale. I did not intend to imply that GPS is to be an air traffic control system.

QUESTION (Dr. Herman Vanolevenne, MIT) - Will a decision be made during DSARC-II on the availability of space, weight, and power for an additional package on the GPS satellites for possible alternative weight forms?

ANSWER - Yes. We have been considering that possibility for several years. In fact, this is being addressed within the OMB working group. It may be that the additional power being considered for the coarse/acquisition signal may obviate the need for a separate signal format.

QUESTION (Mr. Peter S. P. Hui, NASA/Goddard Space Flight Center) - Are there any plans for the Phase III to operate a timing standard to a hydrogen maser?

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ANSWER - Yes. We have in the program the technology necessary to bring a hydrogen maser into the control segment. We have looked at and are still looking at the possibility of hydrogen masers in the satellites themselves. Currently, we are using the rubidium and plan to go to cesium clocks. The performance to date of those clocks has been exceedingly good; in some cases, better than we expected. The question still remains, Do we have a requirement for the hydrogen maser for longer-term stability, et cetera? Those tradeoffs will be made between now and DSARC-II.

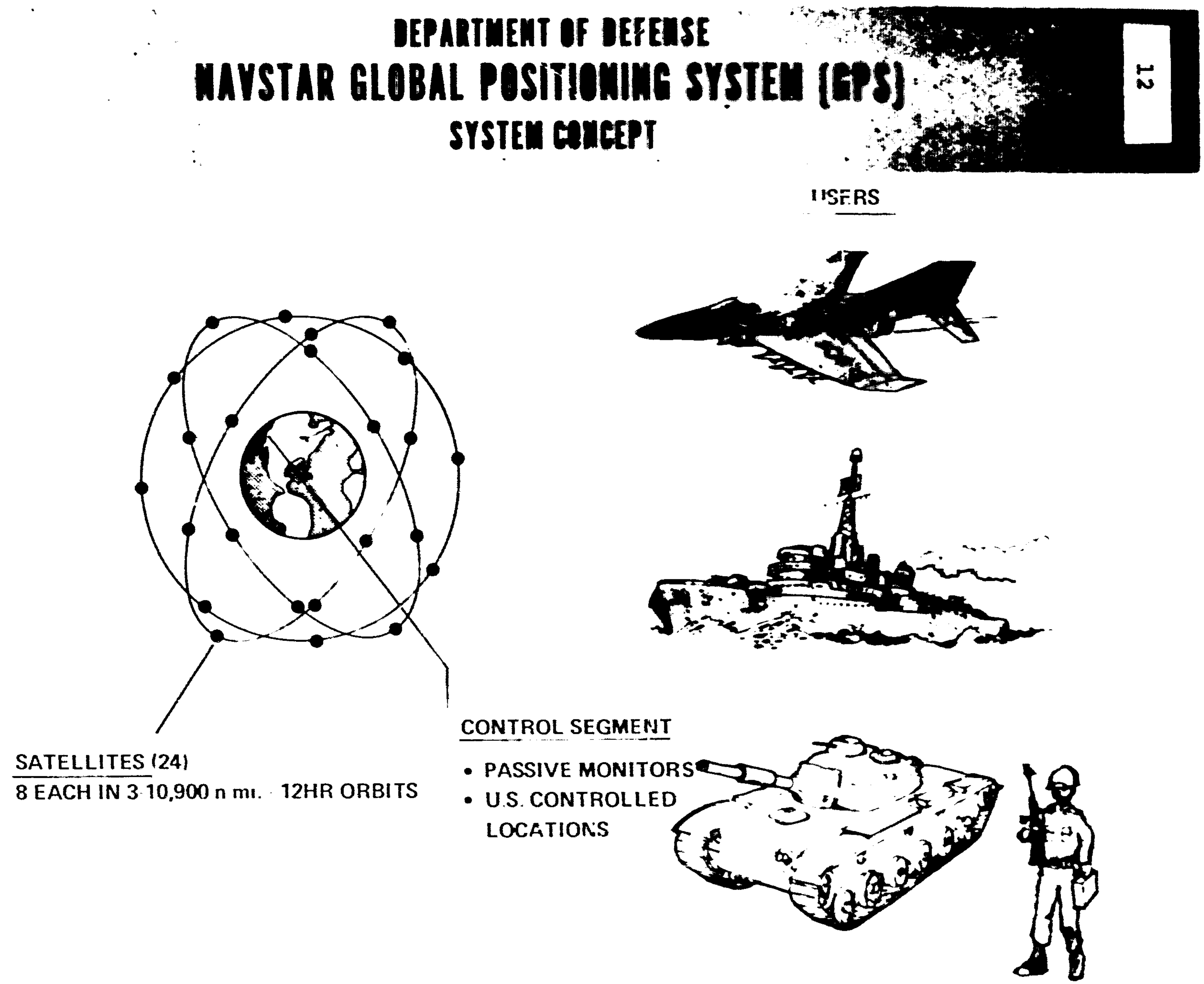
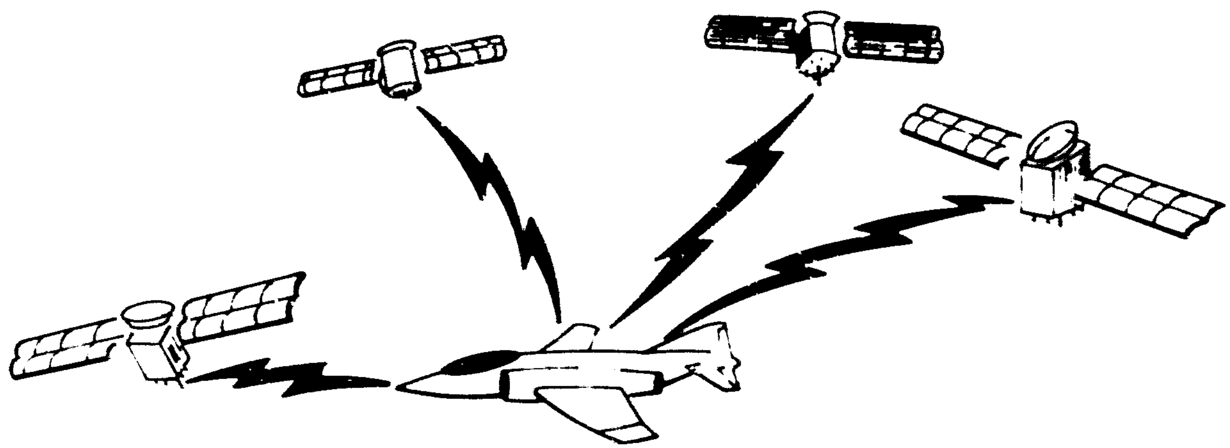

DEPARTMENT OF DEFENSE
NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)
SYSTEM CONCEPT
12
USERS
CONTROL SEGMENT
• PASSIVE MONITORS
• U.S. CONTROLLED LOCATIONS
SATELLITES (24)
8 EACH IN 3 10,900 n mi. 12HR ORBITS

Figure 2-1

SYSTEM TECHNIQUE



USER

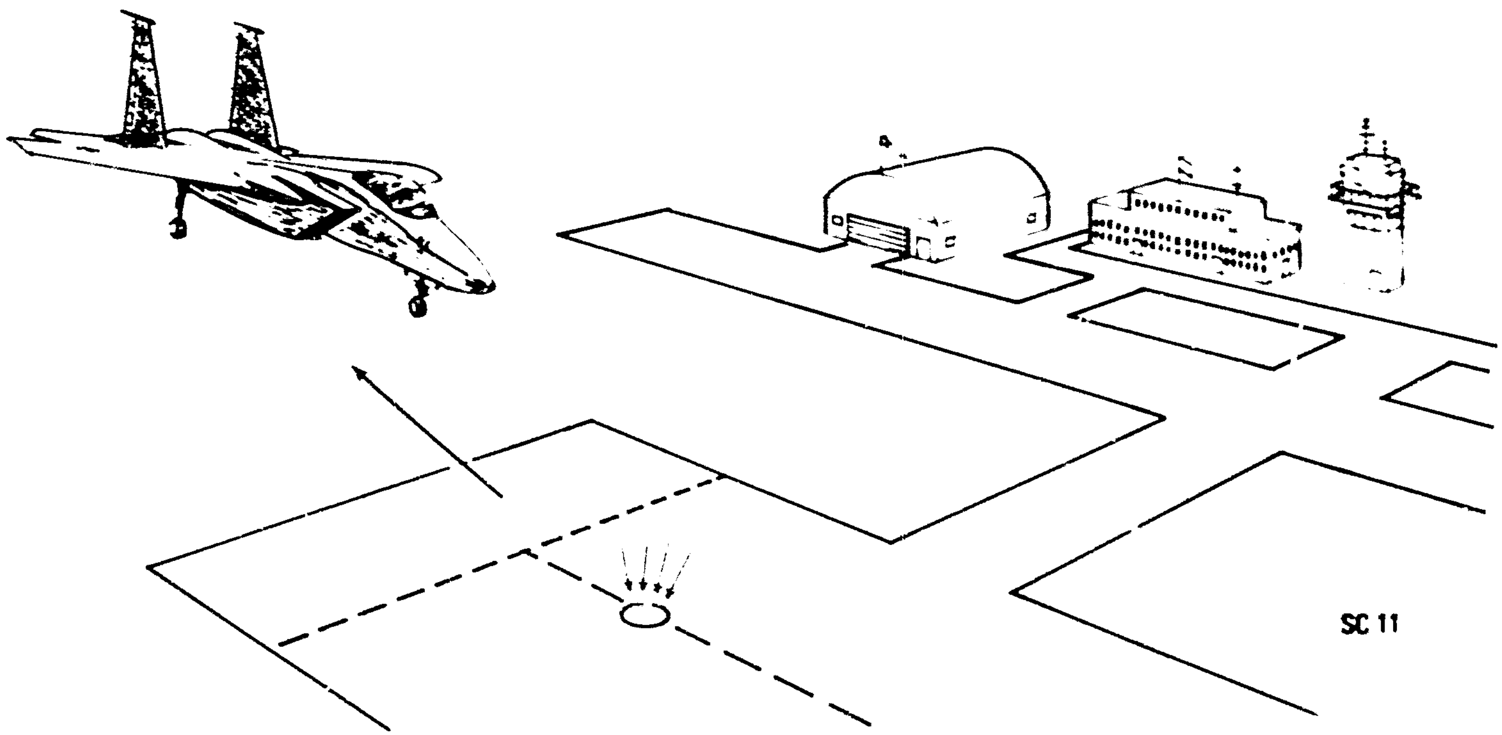
- RECEIVES SYNCHRONIZED POSITIONING SIGNALS FROM SATELLITES (CONTINUOUS, GLOBAL COVERAGE)
- COMPUTES 3 DIMENSIONAL POSITION AND VELOCITY
  - COMMON GRID
  - SYNCHRONIZED TIME

SC-56

Figure 2-2

EXPECTED GLOBAL POSITIONING SYSTEM ACCURACY

	HORIZONTAL	VERTICAL
50% OF TIME	5m	7m
90% OF TIME	8m	10m



NAVSTAR GLOBAL POSITIONING SYSTEM SCHEDULE

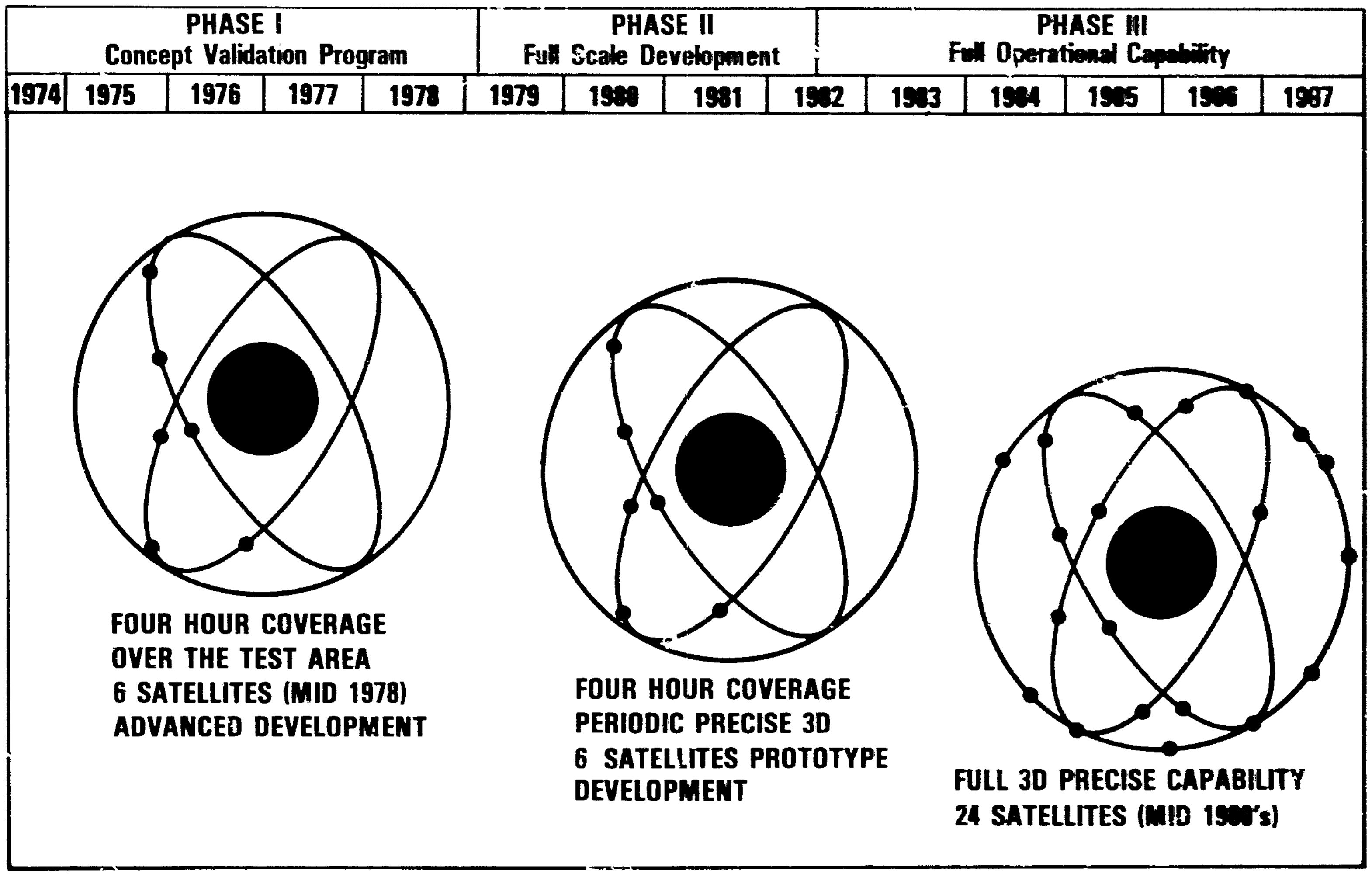


Figure 2-4

GPS TEAM

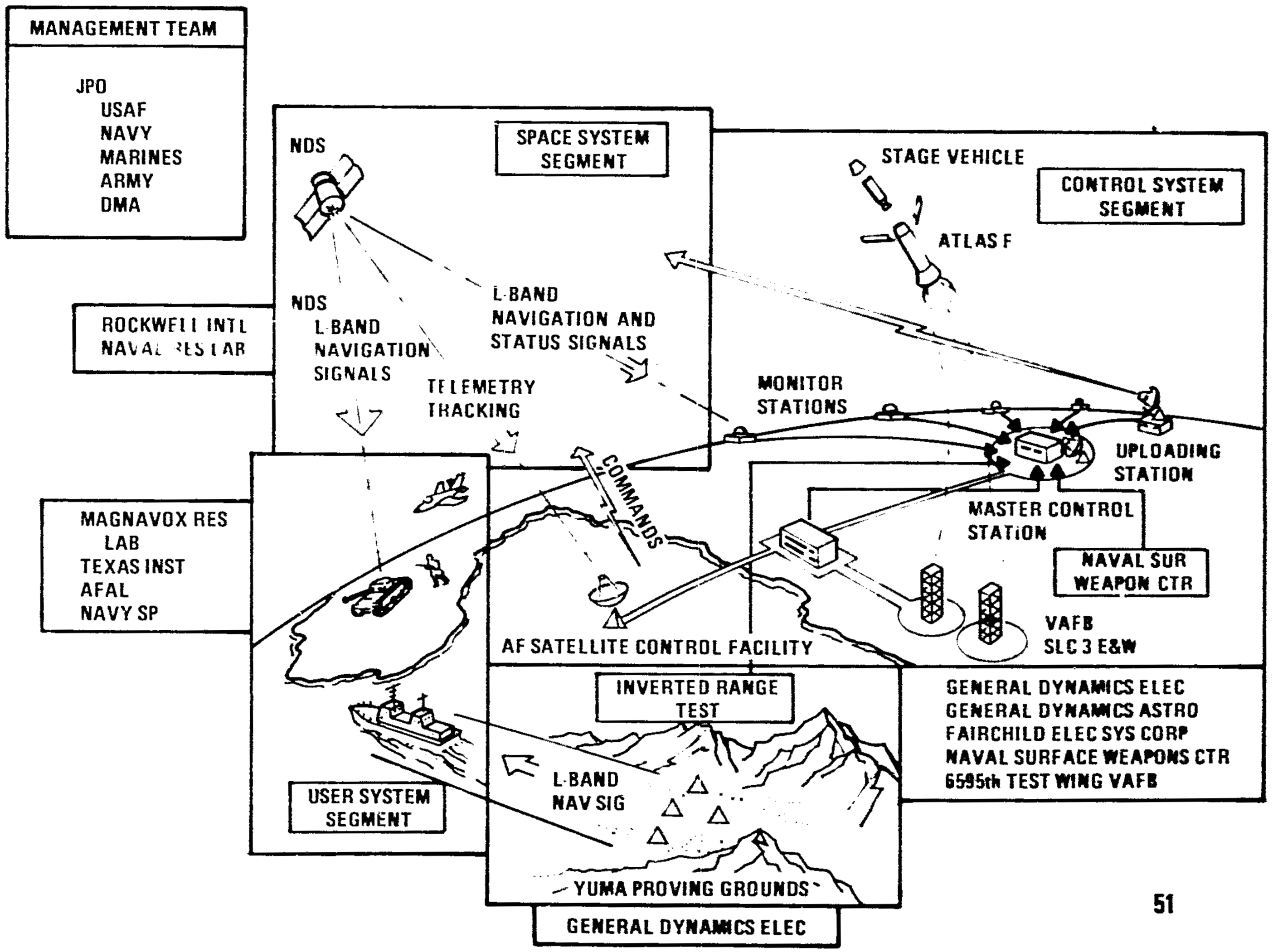


Figure 2-5

INVERTED RANGE

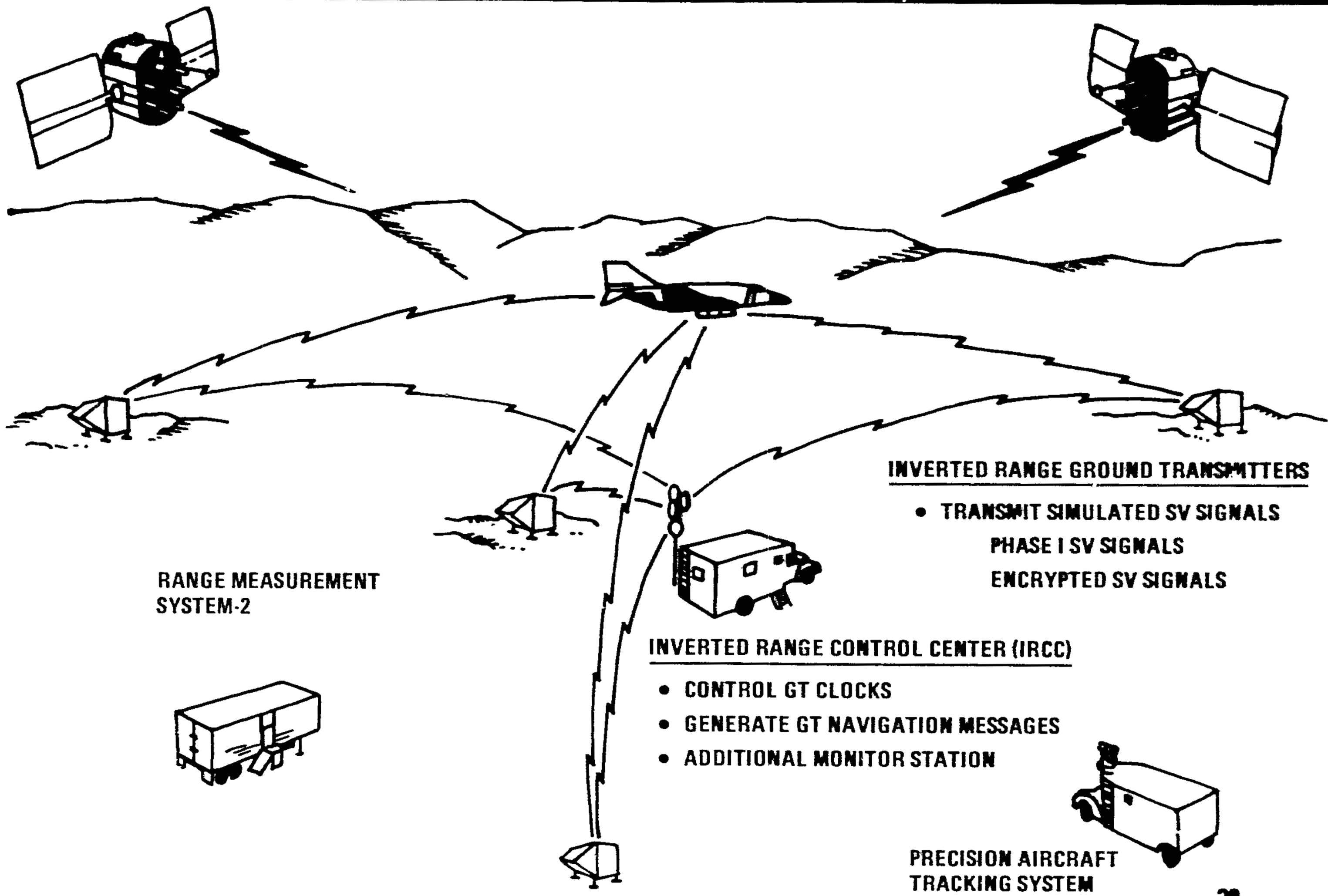


Figure 2-6

Figure 2-7

GPS User Classes

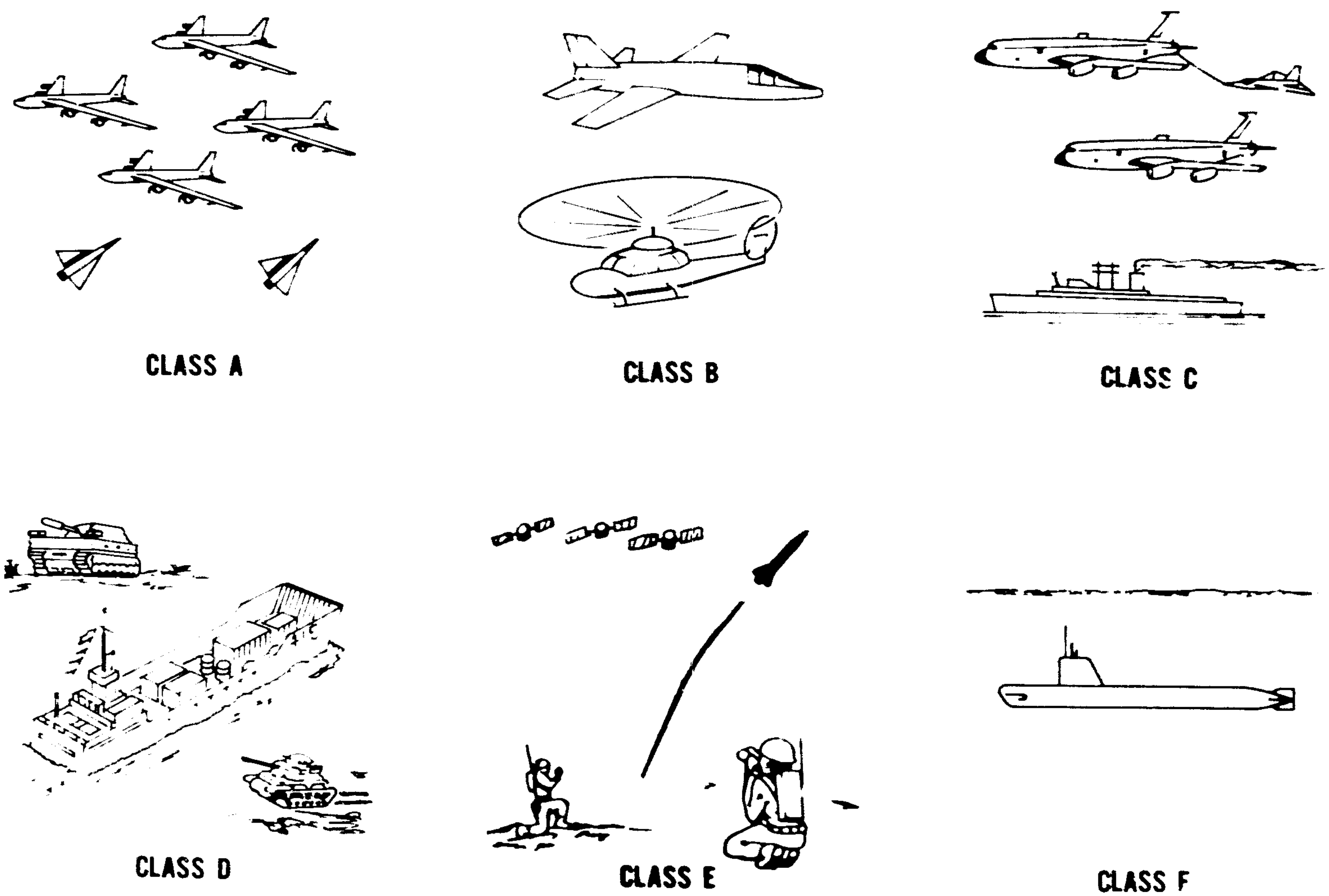


Figure 2-8

GPS PHASE I TEST ELEMENTS

HOST VEHICLES

- UH-1H
- NC-141A
- F-4J
- P-3B
- M-35 TRUCK
- M-151 JEEP
- M-113 APC
- MAN
- FAST FRIGATE
- MOBILE VAN

USER EQUIPMENT

- Mx 4 CHANNEL
- Mx 4 CHAN AIDED
- TI HIGH DYNAMIC
- R/C MAX ANTI JAM
- TI MANPACK/VEH
- Mx MANPACK
- Mx LOW COST
- Mx SINGLE CHANNEL
- Mx SINGLE CHAN AIDED
- AZIMUTH BEARING UNIT

TEST LOCATIONS

- YUMA PROVING GROUNDS
- EL CENTRO, CA
- FORACS/SAN CLEMENTE IS
- SAN DIEGO HARBOR
- HOLLOMAN AFB, NM
- WRIGHT-PATTERSON AFB, OH
- FT BELVOIR, VA
- CHEYENNE, WY

MX=MAGNAVOX

TI=TEXAS INSTRUMENTS

R/C=ROCKWELL/COLLINS

Figure 2-9

NAVSTAR SIGNAL STRUCTURE

	COARSE/ACQUISITION	PRECISE
L_1: 1575.42 MHz	X	X
L_2: 1227.6 MHz	SECONDARY	PRIMARY

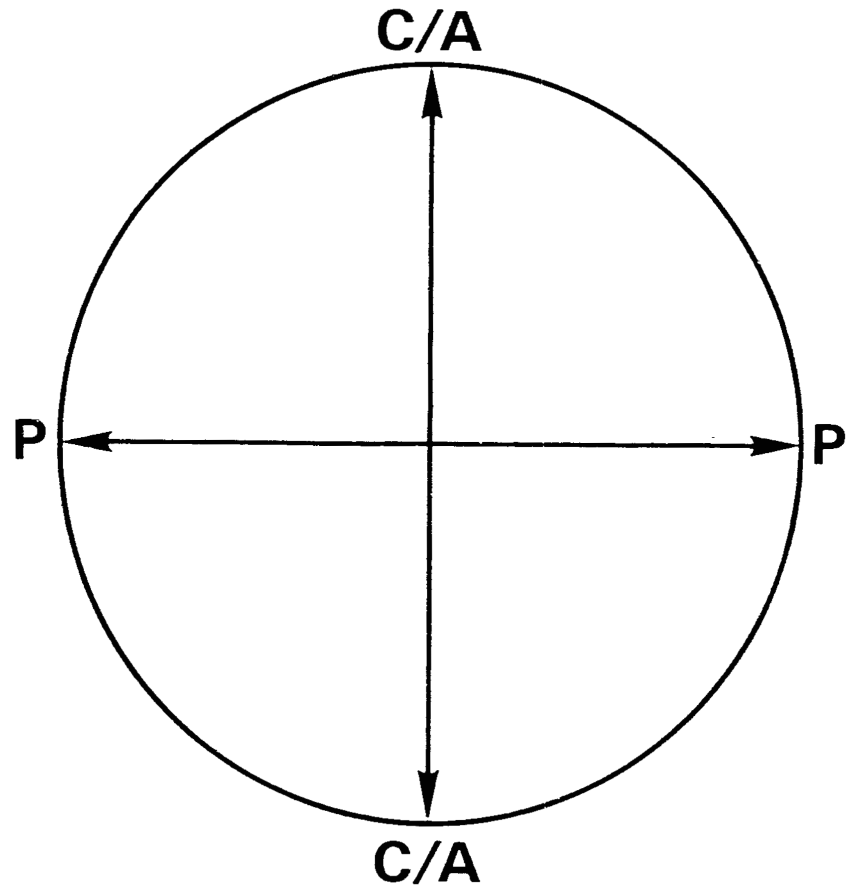


Figure 2-10

USER EQUIPMENT

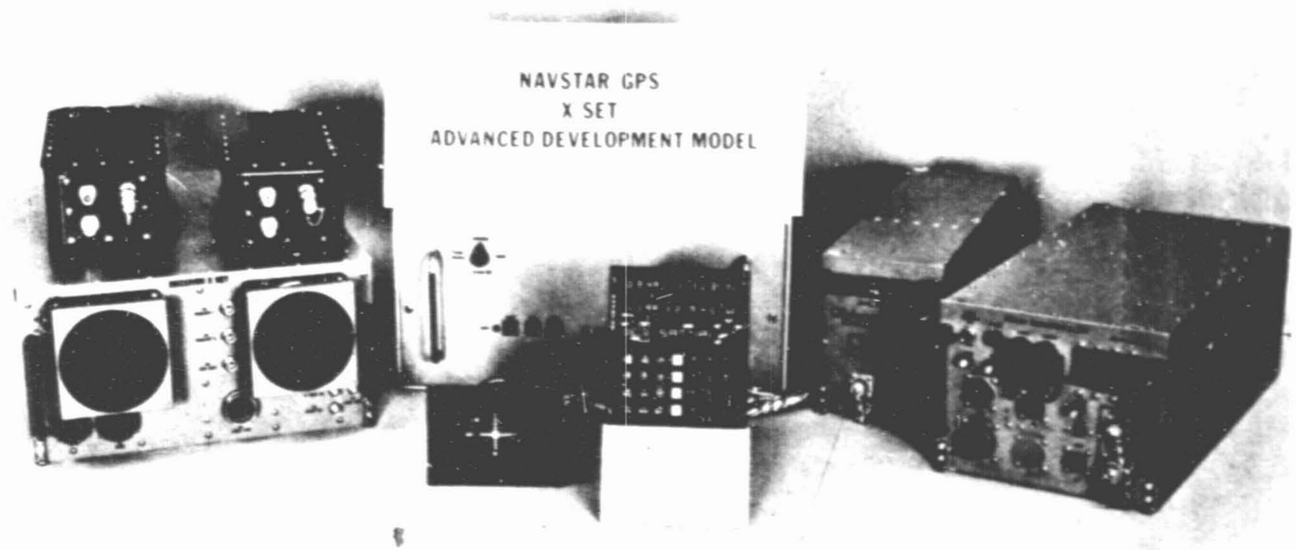


Figure 2-11

SC-070

Figure 2-12

GPS APPLICATIONS

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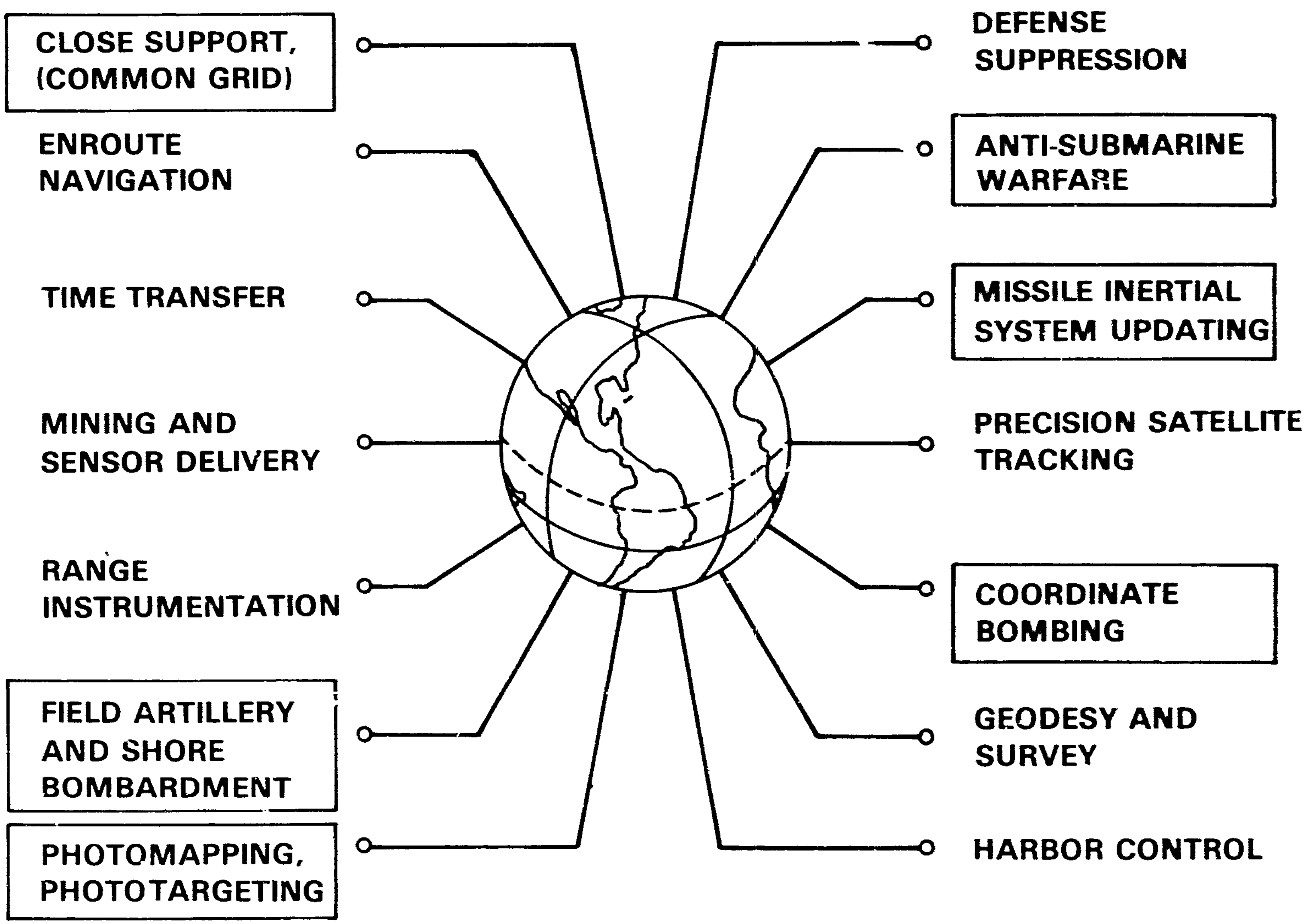

Figure 2-13

POTENTIAL CIVIL APPLICATIONS

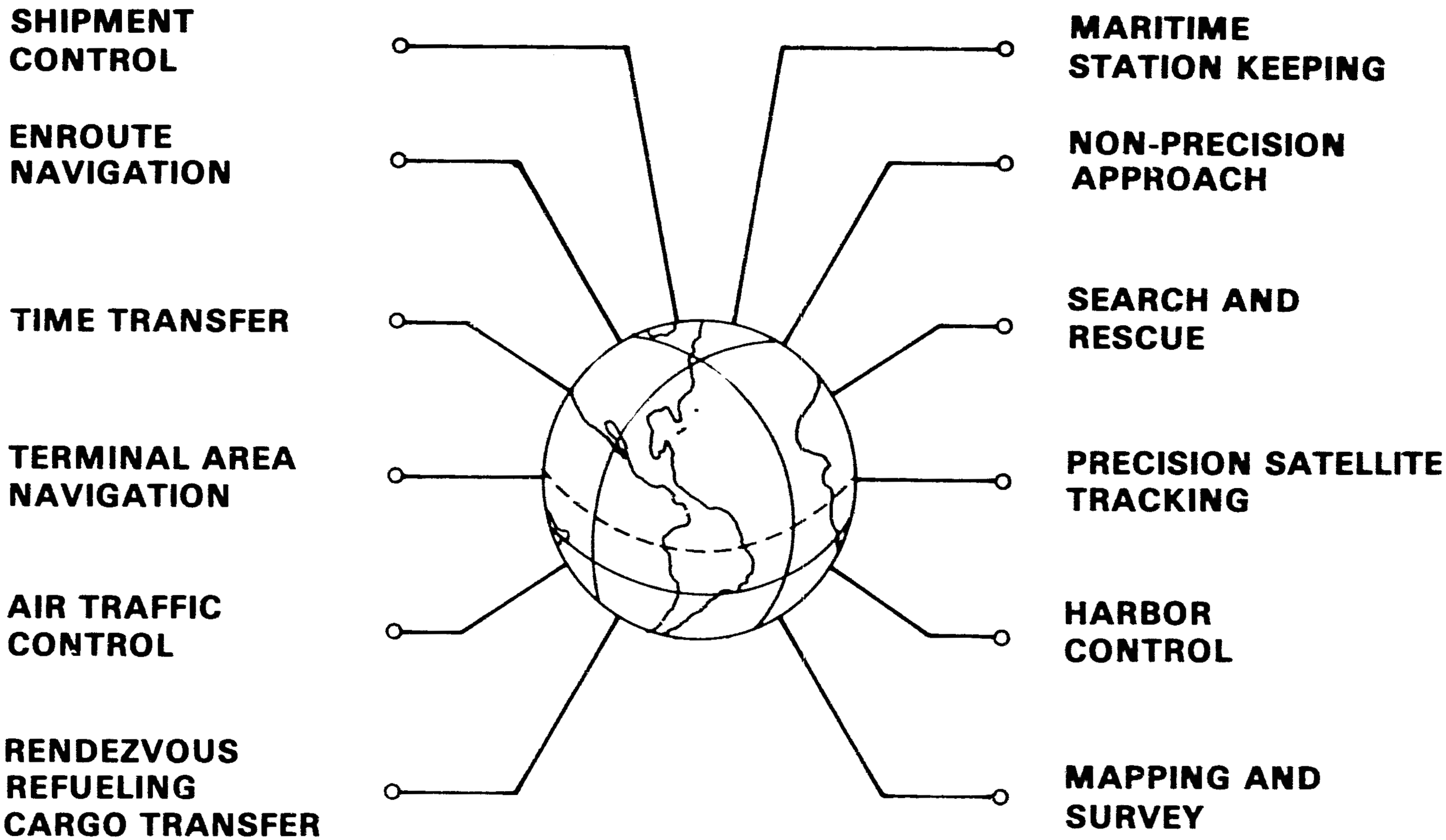

Figure 2-14

WHAT NEXT?

- DOD POLICY
  - EVALUATE THREAT, EXPLOITATION POTENTIAL
  - ASSESS TECHNIQUES FOR DENIAL/DEGRADATION
  - ESTABLISH GENERAL POLICY
  - DSARC II DECISION ON TECHNIQUE(S)
- REVIEW CIVIL REQUIREMENTS
  - DEVELOP LAND, AIR, MARINE REQUIREMENTS
  - DETERMINE USER POPULATION IN EACH CATEGORY
  - ASSESS SENSITIVITY OF POPULATION TO AVAILABLE ACCURACY
- NATIONAL POLICY
  - FORMAL AGREEMENTS
  - OPERATIONAL CONCEPTS AND PROCEDURES

Figure 2-15

N80-21302

FAA GLOBAL POSITIONING SYSTEM PROGRAM

Anthony Buige
Program Manager, Advanced Concepts Staff
Office of Systems Engineering Management
Federal Aviation Administration

Basically, the FAA program is very straightforward. We are looking at potential applications of the Global Positioning System to civil aviation. In pursuing this effort, we have discovered that the driving force seems to be general aviation. It is the purpose for getting us together at this conference, and it is where we have concentrated most of our activity. But before I get into that, I would like to give an overview of the whole GPS program from my standpoint.

GPS Program Approach

First and foremost, we are monitoring DOD's development, test, and evaluation activities. We have had any number of meetings, both here in Washington and out at SAMSO, to keep tabs on what is happening. We intend to monitor the test activities at Yuma when at least four satellites are up.

Our primary effort is investigating low-cost user equipment technology, and we are approaching that from several standpoints. We have conducted a number of studies in-house, and we have had a contractor, through SAMSO, look at the same question. We have also established an interagency agreement between FAA and NASA to concentrate our forces in addressing that very subject. We are not going to stop with paper studies. We intend to get some actual technical and operational experience with GPS, and we will do this in several ways. We are negotiating the loan of some test equipment, actual receivers--either the Z or X class--to test on FAA aircraft. We are also going to develop some of our own test equipment so we can evaluate the concepts and address some of those problems that we are concerned with.

We are also looking at potential improvements and/or modifications to the system. Briefly, there have been two independent studies on this subject. One was conducted by the MITRE Corporation as part of an overall study that was addressing the use of GPS in air traffic control, and the other was performed by Lincoln Laboratory. Both studies came up with almost identical results.

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My own personal belief is that there has been so much investment in GPS that if we are going to use it, we ought to stick with the present design, use the CA signal, and do whatever is necessary to make it feasible.

There is a broader question, and that is, Should there be a universal, worldwide navigation system? We are not specifically addressing that question. I think if we did, we might take a different approach.

Finally, we want to try to identify what technology development is going to be needed to satisfy cost/performance requirements. If we are going to use GPS, we need to answer such questions as: Where do the advances have to be? What types of advances are needed? What is it that industry has to do to make this a civil system?

GPS Program Concerns

If you take a serious look at GPS from the civil aviator's standpoint, you immediately find a host of problems which may be broken down into three general categories: signal-to-noise ratio; system performance; and cost/performance considerations.

Signal-to-Noise Ratio - The satellite was not designed with civil applications in mind. The signal levels, the signal structure, the whole system was designed for military application. The power levels from the spacecraft are not what we are used to. We have to take a different look at that problem. When you start putting L-band antennas on aircraft, particularly those that will give you hemispherical coverage, you automatically run into the classical problem of trading beamwidth for gain. You want the broadest coverage possible to receive signals from the low-elevation satellites because that gives the best geometry.

As soon as you do that, if you are using a single antenna, you run into an immediate problem. The signals from space are circularly polarized. However, when the aircraft antenna views the horizon, it is going to be linearly polarized. You throw away 3 dB off the top. Also, in trying to get the coverage down at low elevation angles, overall gain is down. If you talk about putting multiple antennas on the aircraft and using switching networks and combining networks, you are starting to

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defeat the purpose of low cost. Obviously, we have some serious concerns in this area.

Another concern is just what is the RFI environment seen by the general aviation aircraft? There are a lot of radars, FM stations, and other signals around. We don't know the answers to this problem yet, but we are working on them. We are currently putting together a test bed to measure the general aviation RFI environment so th we can analyze this specific problem.

System Performance - Our principal concern is system performance during certain kinds of maneuvers. The typical general aviation pilot out on a VFR flight is not going to be making standard rate turns. He is going to lay that aircraft over at any angle he wants to make the turn. What happens during that turn? Even if a standard rate turn is used, at 90 knots it will mean about a 15-degree bank angle. If you are looking at a satellite that is five degrees on the horizon, you have lost that satellite. What does that do to your tracking performance?

We are particularly concerned with the question of tracking performance during a nonprecision approach. If GPS comes into being, people will start using it. There is going to be a transition period where a pilot will be given an ATC directive to fly a nonprecision approach during which he is expected to do certain maneuvers. The question is, When he rolls out of that last maneuver and is inbound, is he really inbound? We don't know. We have done a lot of study on this, and we are continuing to analyze the problem. These are all problems that you must examine in considerable depth; and after you have examined them, you still have to go out and evaluate them through flight tests. This is exactly what we intend to do and is why the FAA is taking a very cautious and very thorough indepth approach to this whole problem.

Cost/Performance Considerations - Finally, there is the question of cost/performance tradeoffs. I happen to be one of the people who believe that GPS can be used as a navigation system. I also believe that you can get adequate performance to do any of the things I have just talked about if you are willing to pay the price. The question is, What is that price? and, particularly, Can the community afford it if GPS becomes a mandated system as opposed to an optional system?

So, we and NASA together hope to address this problem to identify what the tradeoffs are, what technological development is needed, and where we go from here.

The "Ideal" GPS Receiver

In my opinion, to get the optimum performance out of GPS, we ought to be looking at an ideal and then back off from there. To me, the ideal receiver is one that meets four requirements: complete LSI implementation, continuous versus sequential operation, minimum pilot interface, and maximum performance. If we can make a completely LSI-implemented receiver, you can see the economies of scale involved there. A classic example is the pocket calculator. I think that those kinds of economies of scale would apply here. We are not there yet; and, in fact, we may be a long way from there. But I think, and I am offering this as a private observation, not as a policy statement, that is the way we have to go.

Most of the receivers we are looking at to bring the cost down are sequential receivers--such as the Z set or modifications to the Z set. We have looked at our own designs. In all cases, they are sequential receivers. Ideally, a continuous receiver, which is tracking all visible satellites at all times, appears to me to be a more tenable view.

A problem that has barely been touched on is the pilot interface question. I think that as a pilot, I would not want to be carrying a chart around where I would have to, in flight, try to determine a latitude-longitude to hundredths of a degree to insert as a new way point.

Now, it doesn't have to go that way. There are other ways of doing this. One method is to chart the entire United States and put it on a chip which is part of your receiver. This is feasible, but it would cost. Just how much it would cost will be examined in some depth in our studies.

As a pilot, you want the system to be as simple as possible to use. You don't want to be concerned with the satellite orbits, which satellites to look for, those kinds of questions. All a pilot wants to know is, I am here and I want to go there, and be able to turn a dial that will point him in the right direction. So, as much of the thought process as possible should be in the receiver.

Finally, you want to get the maximum performance possible out of this thing; and in our studies, maximum performance and low cost just don't equate. Maximum performance means the P code and two-frequency operation; and I don't think we can afford that. We may not even get the P code, so what is the maximum performance available from CA code, single-frequency operation? That is a question that no one has answered yet to any depth. We think we know what the answers are, but we also know that there is some question of modifying the accuracies. There is also the question of how much precision DOD will actually give the civil community.

I would like to get it all. I think the military would like to give us some. I understand the reasons why; but as a civil user, I would want to get the maximum I could out of this thing.

Technology Implications

What does the ideal receiver imply? It implies the following:

Low-cost general aviation antenna, one that gives us the maximum gain achievable with the broadest coverage possible and at the same time is low-cost. We are addressing this problem through a number of studies. TSC has a contract to build some prototype antennas. NASA is also looking at the problem. We intend to have some prototype, scale-model antennas put on some general aviation aircraft models at NASA/Langley and then see what the patterns really look like.

LSI RF technology is to me a very interesting subject and one in which I think the key to GPS utilization lies.

Digital matched filters lend themselves directly to the question of RF LSI. But more than that, as previously pointed out, two studies were conducted that came up with an alternate signal structure. Both of these envisioned a pulse system, as opposed to a spread-spectrum system; but to get the satellite data, they use a PN-coded structure and intend to use a digital matched filter to strip the code. Whether you use GPS with the CA code or with some of the alternate signal structures being proposed, it looks like digital match filters are one way to go.

Low-cost, high-stability oscillators. When looking at a GPS receiver, one of the problems that comes up is signal dropout. For example, if you are tracking four satellites and you go into a bank, you lose one satellite. If you have a stable enough clock, you can fly through that dropout. The degradation of accuracy is a function of the stability of the clock. We are conducting studies looking at off-the-shelf oscillators, but ultimately we may require more stability than that. The more stable an oscillator is, the more it costs; so here again we need some inventive work done on getting us high stability at low cost.

Heading and Altitude Aiding

It turns out that in examining a receiver, the more information you can give it about the status of the aircraft, the better it is going to perform. In particular, if you are solving an equation for position, you are smoothing the data. In essence, you are tracking and you are trying to predict where you are going to be. If you can tell the receiver that you are doing something other than flying straight and level, that information can be used to help the receiver. The two types of help we see are heading information and altitude information. Many aircraft carry digital encoders. Many do not. Digital encoders are not cheap. Present ones are in the $400 to $500 range to maybe $1,000.

If these have to be an integral part of the receiver, I would like to bring their cost down. The same thing applies to directional gyros. At the present time, they are not cheap, although I am sure somebody is going to talk about bringing the cost down and putting them into all aircraft. This is another piece of technology that general aviation aircraft at the present time do not have which would be nice to have, if you are going to fly the GPS system.

Two-frequency operation simply goes back to the question of accuracy. If we are going to get the ultimate accuracy, we have to take out the range variations that occur in the ionosphere, which you can do if you have two-frequency operation. I think this is probably the least of the problems; but if I am going to get maximum performance, I have

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to do it. I would think, ultimately, that with a good ionospheric model and some practical experience, two-frequency operation may not be necessary.

N80-21303

NASA PROGRAM

Henry J. Reid, Jr.
National Aeronautics and Space Administration
Langley Research Center

NASA has been interested in GPS and what it can do for the civil sector for some time now--several years as a matter of fact--and that interest has not just been in aviation. Some of the areas of the NASA GPS-related programs are:

Satellite/Navigation Tracking
Shuttle Applications - Inertial Initialization
Land/Sea Applications
Civil Aviation Applications

We have hardware now for satellite applications. This hardware was originally intended to go on SEASAT (Sea Satellite); but because of a scheduling problem, it is now going on LANDSAT (Land Satellite). It will be available for testing as soon as we get enough satellites up to look at its application for both navigation and tracking of the satellites. There is a potential there for doing away with a good portion of the tracking radar network.

In shuttle applications--obviously, shuttle has a rather monmouth problem with navigation--there has been an extensive requirements study done. This study resulted in a set of specifications; and the last I heard, which was a few weeks ago, the hardware procurement decision was still pending. One of the principal requirements for the shuttle application is a little bit unusual in that we earthbound folks don't generally think about blackout problems. But there is a significant portion of the shuttle flight, the entry phase, where they just don't get RF signals so they go on the basis of the inertial navigator. It is a rather critical portion from the standpoint of navigation. GPS provides an excellent system to give the inertial initialization prior to the entry maneuvers.

In the land-sea application, the NASA Goddard Space Flight Center is looking at a number of applications--marine and land use and emergency locator studies. There is a design/requirements study that is currently being carried out by Magnavox, I believe. There is also a considerable amount of in-house work going on on both hardware and software concepts.

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So, NASA is looking at some of the space applications and some of the extended navigation applications in terms of technology, but we are going to be talking principally today about the civil aviation applications.

In starting to look at these civil applications, NASA let a contract with Research Triangle Institute (RTI) in 1976 to do a brief study of the NAVSTAR application to GPS, and that has resulted in a contractor report (number NASA CR-145059). That contractor provided several recommendations, including the recommendation that we look at something the Omega folks had been interested in for some time--a differential or perhaps a pseudo satellite at a given location, an application that could improve the terminal area performance and accuracy of the system.

There was another strong recommendation that we look at the application of the GPS system in conjunction with a data link which provides the capability of doing surveillance, collision avoidance, and various and sundry other things. So we have a continued study going on at RTI to examine these and some other applications.

Another study was conducted by Texas A&M University (TAMU). They have had a grant for a couple of years now to look at acquisition and tracking concepts that might lend themselves to lower cost or higher dynamic range operations. Some of the low-cost navigation algorithm development that they have been doing there will be discussed later in the program by Dr. Philip Noe.

We also have a design study of a low-cost civil aviation GPS receiver system going on. We are in the business of research and technology development; so what we are asking to be designed here is not a set to be built, but we are looking for a design that will identify what the current state-of-the-art restrictions are in terms of both performance and cost but weighted toward the cost standpoint. This is a paper design, and what we want is to have the contractor (Magnavox) examine the cost sensitivity based on projected or anticipated or even imagined technology development so that we can see the area in which the maximum effort should be put in the technology development. We will have a report on that due next summer (1979).

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For our 1979 effort, we want to get hold of a Research Receiver System so that we can become familiar with the system operation and its limitations and characteristics so that we can begin to understand what the problems are. Also, we want to be able with this receiver to perform experiments related to four-channel and three-, two-, and one-channel sequential operations.

We would also like to look at some of the simplified navigation algorithms that are being developed and perhaps at some receiver-aiding techniques which might help performance during maneuvering. To do this, we would like to get some sort of a variation of an X set or GDM (Generalized Development Model) type equipment that would allow software reconfigurable capabilities to examine some of these characteristics and concepts.

These parts of our program are currently operating within our Research and Technology Base Program, but we have at NASA Headquarters now a proposal for a new initiative which would continue and considerably extend NASA involvement in the civil use of GPS.

Due to these studies and a lot of meetings of this type; technical society meetings; discussions with the various interested people and Congressional Committees; and just the huge investment that the country is going to have in the GPS system, it became kind of obvious that GPS is going to be used by the aviation community in some way or another. As a research organization, it is NASA's responsibility to kind of step back and look 10, 15 years down the road and see what this implies in terms of research requirements. We wondered how to do that, and we took a path that may or may not be the optimum one. What we decided to do was remove ourselves from the constraints that Mr. Blake mentioned earlier about having to phase into various kinds of programs and systems that exist; and we said, "Hey, what happens if you take GPS and try to use it to the absolute maximum extent?" and "What kind of system could we postulate that would make maximum use of the GPS?"

Well, we came up with a little scenario that said what we really ought to do is take advantage of the positioning accuracy and the velocity capabilities of this GPS system and also the time capability to allow us to mechanize a simplified data link. This scenario is JTIDS (Joint Technical Information Distribution System) revisited and, as illustrated in

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Figure 3-1, is a time-division, multi-access data link where each user gets a time slot to input his data. He may need more than one time slot; but he, too, qualifies as a user. Each user then would tell the data link his position, velocity, and identification, of course, and perhaps wind data because now you have got ground velocity, so you can determine local wind, turbulence data, whatever. Now everyone operating in this system has the capability of listening to everybody else. So if you have a microprocessor in your aircraft that is smart enough, it can start listening only to the people that are of interest to that particular user. For ones that are maybe getting too close, it can define, if you will, a multi-dimensional sphere of influence that might be based on X, Y, Z, velocity, bearing angle, and rate of change of bearing angle.

These kinds of things can give you very valuable information in terms of generating a pretty sophisticated avoidance capability with potentially a low false-alarm rate. That information can also be used to generate an on-board traffic situation display or cockpit display of traffic information. It could be used for in-trail guidance considerably more accurately than we can do it now. If the accuracy trends continue, you might be able to use this system for precision approach; and particularly if you augment it with a ground system of a differential GPS type, you might be able to do all of your close-in curved descending approaches that are so popular these days in discussions and vector into a precision ILS. So there are a whole lot of capabilities in such a conceptual system.

For such a conceptual system, there would be the requirement that everybody be equipped with at least some minimum operating system. It would have to give at least identification, position, perhaps velocity, to the system; and it would have to be able to accept commands at least from the ground.

If we take full advantage of the system, it also says that that is a safety flight-critical system, and as such it is going to have to have the equivalent--in today's technology--of a dual-fail-operational capability. To do all of that, at "low cost," you have got a pretty good research and development program defined.

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That is what we think we should be working on because this defines, as we see it, the maximum use. Any other use below that would be encompassed within a program like this.

The elements of such a program as we see it are as follows:

<u>Low-cost spread-spectrum L-band</u>. The hardware and software related to this element will require us to put large chunks of this on chips. The current DOD program in VLSI (Very Large Scale Integration) and VHSI (Very High Speed Integration) should contribute greatly to that end. There is about $200 million going into that program; and maybe with just a small addition, we could get some civilian applications considered also.

<u>Redundancy management</u>. From the standpoint of software and hardware, we think that we can call on some of the developments that are going on now in terms of ultra-reliable computers for use in flight control systems to provide us with the dual-fail capability in a system like this without having to go triple- or quad-redundant.

<u>Antennas</u>. As Mr. Buige mentioned, antennas are a problem if you want to operate while you are maneuvering, and I think you will want to operate at least while we are making reasonable maneuvers.

<u>GPS data link integration</u>. This one is peculiar to the scenario that we have selected; but if we say that we are going to stick with that scenario, we have to get the two together in a cost-effective way.

<u>Simplified navigation-guidance algorithms</u>. This is one area that is of quite a bit of interest when you combine it with the low-cost, spread-spectrum L-band element and find out that, I saw somewhere the other day, the equivalent computer would be available maybe 15 years hence on six chips, and that is memory and all. Maybe simplified algorithms are not all that important; but again, in the interest of keeping costs down, we don't want to overlook it.

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Input/output. The input and output devices and techniques are certainly a critical part because of the blunder rate of 3 percent which "kind of scares you to death."

Now, these are the things that are required in order to get a cost-effective minimum user equipment; but then you can add to this technology base and you can get the kinds of capabilities shown in Figure 3-2. These go all the way from basic RNAV up to full automation that will tune your radios for you or whatever, depending on the thickness of your pocketbook. Of these, the high accuracy (P-code) is really the only one that involves hardware development or additional hardware requirements, with the exception of input and display devices. The rest of it is principally software so this is why we say that the real driver for the technology program is the low-cost user and not the fellow who wants the maximum performance out of the system.

As I previously said, we have proposed a program to NASA Headquarters that is being considered for fiscal year 1981 funding, and it would include the development of the technologies previously described. It would include the building of Breadboard Systems to evaluate these concepts as developed. We would anticipate that that would be 4 to 5 years down the pike before we had the hardware available for evaluation. It would also include flight experiments under simulated and real traffic conditions so that we could get a data base on how well such a system could perform.

We think that the output from a program like this would provide industry with the technology that they would require to design and build low-cost equipment, and I have heard numbers under $1,000 if this wonderful VHSI Program really comes through. Such a program would also provide a performance data base that would allow FAA and DOT to make very realistic evaluations of future ATC concepts using such systems.

We hope that we will be funded in that program and get underway here in about another year.

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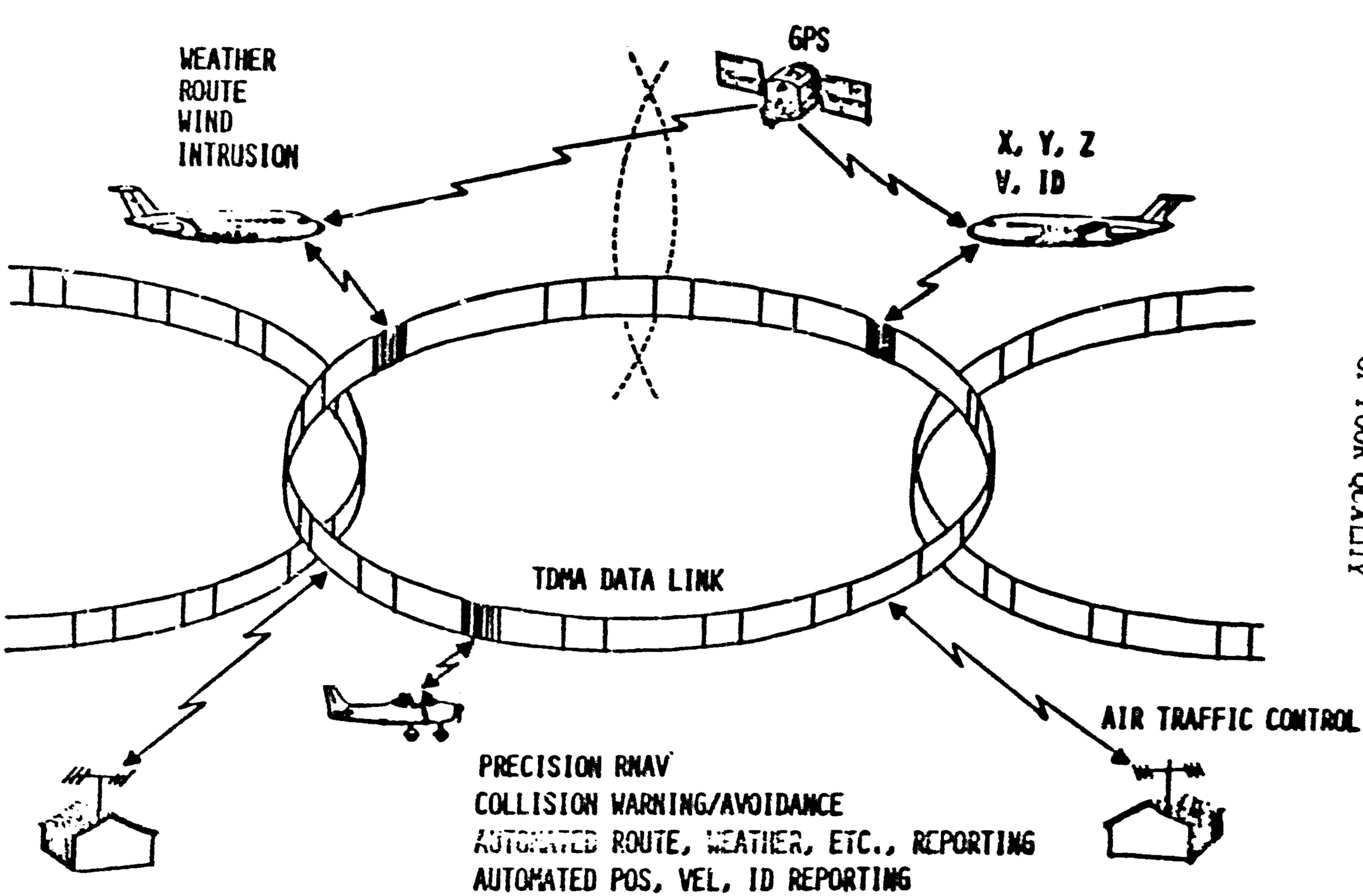

Figure 3-1

BUILD ON MINIMUM SYSTEM TECHNOLOGY FOR HIGHER CLASSES

0 2, 3, 4-D R-NAV

0 LOW FALSE-ALARM CAS/PWI

0 CDTI

0 INTEGRATED GUIDANCE/CONTROL/AUTOPILOT/DISPLAY

0 HIGH-ACCURACY (P-CODE)

0 FULL AUTOMATION

0 BLENDED SYSTEM - INERTIAL, AIR DATA

Figure 3-2

N80-21304

Dr. Norbert Hemesath
Collins Avionics Group

What I will discuss is essentially a quick overview of the activity that we have been engaged in at Collins for some time on the generalized development model of GPS user equipment under contract to the Air Force Avionics Lab. I want to tell you a little bit about that system and express a few thoughts about how that activity might relate to future work, particularly in the civil applications area.

First of all, a little bit on the program and its background. The Generalized Development Model (GDM) Program was intended to establish just exactly how well GPS user equipment can perform under a combination of jamming and dynamics. Obviously, the combination--the simultaneous existence of the two--is the problem. The whole objective of the program was to do everything that we possibly could to establish the performance limits of a GPS user set under this combination of conditions. As a consequence, what we have designed for the Air Force is really a very capable piece of test equipment rather than a prototype of any user equipment. It really is a laboratory piece of equipment intended to have a great deal of flexibility and the capability to explore various operational modes.

We started work on the GDM program early to mid-October 1975, and it was delivered in the summer to the Air Force Avionics Lab and subsequently sent to the Yuma test range.

A brief top-level description of the characteristics of the GDM is as follows: It is a five-channel system. It has a steered beam antenna system. It features full inertial aiding on both code and carrier loops, and it has a multiplex bus interconnect structure, using the Mil Standard 1553A. That is a feature that was put in to demonstrate the 1553A capability in a high-performance application. Clearly it is not appropriate for a commercial application.

For reasons of convenience, we grouped the system into the major subsystems. The receiving subsystem consists of the antenna, RF units, signal processing functions, and what we call a receiver controller, which is nothing more than a software program to implement tracking loops and data decoding.

The navigation processing function utilizes the pseudorange measurements out of the receiver and turns them into the

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navigation parameters, that is, 3-D position velocity and related quantities.

The interface and auxiliary equipments consist of the inertial system, which provides the aiding, and a bus control assembly, which controls the traffic on the 1553A bus. There is also an I/O unit called an interface assembly and a control display unit which is the operator interface to the system.

With respect to the architecture of the system, the high-performance antenna or the steered beam antenna is a unit capable of developing four simultaneous beams.

The beams are steered with pointing commands from the data processor. The four outputs of that antenna are derived from four separate satellites and go to the RF receiver unit.

We have used four separate RF inputs to the receiver although because this is a code-multiplexed system, a single RF channel would be adequate. The reason we did that is related to maximum A/J performance.

That is, by using four separate RF ports, we get the benefit of not folding four separate noise spectra into one RF channel. In this arrangement, each channel sees only its own portion of the sky; and, secondarily, any one of the beams can be severely jammed or overcome by noise and the other three will remain operational. If there were a single RF channel, a single severe jamming occurrence in any one of the four beams could take the whole unit out of operation. Again, this is an elaborate design feature we put in a piece of test equipment that we would certainly not expect to see in a piece of production equipment, either military or civil.

The RF unit has five outputs feeding five signal processors. Another element in the system internal to the RF unit is a software-controlled 8-by-5 switch. That switch interconnects any one of the eight RF outputs, that is, L-1 and L-2 on each of four satellites, to five signal processors.

Normal mode of operation would be with one signal processor dedicated to each of the four satellites listening to L-1 with the fifth signal processor listening to L-2 on one

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of the channels and slowly sequencing among the remaining three. That, of course, is to get the data for ionospheric correction.

The switch is controlled by software in the data processor and ultimately by the operator inputs on the control display unit, so there is a great deal of flexibility in terms of establishing system configuration and interconnect right from the operator panel in this particular system.

The signal processors perform the correlation function, i.e., the despreading, narrowband tracking, and so on. The actual tracking loop functions, though, are implemented in software in a digital processor. Each of the five channels is serviced by that processor, and both code and carrier loops are actually closed in software. The software implementation is another feature of this system that supports easy modifications to the design of those loops.

At this point, we have discussed the complete receiving subsystem. It outputs pseudo range and delta range, which subsequently go to the data processing. The data processor implements the navigation functions. It contains very sophisticated filtering algorithms that blend the pseudo range and delta range data with the velocity and position outputs from the inertial system.

The tracking loop aiding is derived in the data processor and sent back to the signal processors for a narrowband tracking. The antenna is steered out of the data processor and, of course, all of the navigation algorithms having to do with guidance and present position are also implemented in the data processor.

In summary, the GDM is a very, very capable test unit, and it is really an architecture that can provide quite a variety of test configurations; but in no sense is it an architecture that would be a prototype of ultimate user equipment. Functionally, it is equivalent to a variety of user equipment, but the hardware used to support the implementation is far in excess of what would be reasonable for any user equipment implementation.

Concerning the high-performance aspects of the system, I indicated there is a steered beam antenna in the system that

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is capable of generating four simultaneous beams. It provides up to about eight or eight and a half dB of gain to each of four satellites' signals; and each one of the four beams, by the way, enjoys the full aperture gain. It provides 15 dB or more of discrimination against noise sources which are out of the beam.

Additionally, we look at the nulls between side lobes. These have minimum depth of about 25 dB, and we have implemented an A/J algorithm that is a simple form of null steering to take advantage of these nulls.

In inertial aiding use, the high-quality velocity outputs of the inertial system assist the tracking loops in the receiver and thereby are able to provide substantial bandwidth reductions. Within the system, to demonstrate how far we could go, we implemented bandwidths for code tracking as low as .03 Hertz.

What the inertial system offers in terms of added noise rejection is 12 to 15 dB of added noise immunity.

The above elements are the principal A/J elements of the system beyond what is available in the basic signal structure.

Turning next to civil use, Phase I, which is the concept validation phase of GPS, for us was GDM. Presently, we at Collins and other contractors also are working very hard on Phase II, which represents transition from the laboratory environment into a full-scale development of prototype equipment to address a wide variety of military applications. A substantial number of vehicles have been defined by the Joint Program Office as targeted for the equipment that is to be developed in Phase IIB. The work that is in Phase IIB will fill military needs, and also a lot of work that is done there we feel strongly will flow directly into civil applications. We at Collins believe that there is a great future for GPS in civil aircraft applications--as a matter of fact, in civil applications in general.

Now, if we take a look at GDM as I have defined it for you and ask what are the really big differences between the elements of that system in terms of its capabilities and what

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we might see as requirements in the civil user arena, basically they fall into the following categories. If we look at the civil aviation needs, we can say that yes, we would like to see accuracy better than we can get today, but we can't honestly see many requirements that would demand the extreme accuracies the military is seeking for dropping blind bombs.

Moreover, if we look honestly at the requirements in the civil arena, we don't have anywhere near the dynamic requirements that the military imposes. That is, we do not expect to see F-15's flying 7G maneuvers in the civil environment. They will be flying in airspace but won't be using civil equipment.

If we take a look at what we have, it is primarily a transport and general aviation environment; and the dynamics of those vehicles are considerably lower than the high-performance military vehicles. That has certain implications in terms of simplified design that we would take advantage of.

Finally, I have discussed jamming and electromagnetic interference as being a key objective of GDM. If we look at the civil environment, we clearly have a much less severe electromagnetic environment than the military has to cope with. That is not to say that there isn't EMI at places like O'Hare. We all know that is a potential area of concern that must really be looked at; but in general, it is true that we do not have anywhere near the severe EMI problems that exist for the military applications.

What does that imply? If we look at it from the top down, the implications are fairly obvious. Figure 4-1 shows a four-channel system that would be designed as a basic user equipment for the military requirement. It would have four-channel simultaneous tracking capability, four satellites, that is. It would have both L-1 and L-2 RF channels so that ionospheric corrections could be made in real time; and it has very high accuracy, 10 to 20 meters. In addition to that, in certain military applications, we would expect to see this design augmented with an inertial system, that is, inertial aiding for the receiver; and we might also expect to see the simple antenna replaced with a high-performance antenna for the A/J protection that it would provide.

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Now if we interpret our reduced requirements for the civil sector, it is pretty easy to come down to the simple and straightforward architecture of Figure 4-2 and say plausibly that this might meet the civil requirements. We drop back to one signal processing channel; we dropped L-2 and are saying that we will not make real-time correction for ionospheric refraction; we will make that correction with a mathematical model. If it only makes 50 percent of the correction, we will live with that because we don't need the added accuracy. We don't have hard test data yet, but I think a reasonable expectation is that this system can achieve an accuracy of a hundred, two hundred meters. By the way, I didn't say it, but we are also talking about a system that tracks CA only, not the P code. So there are some substantial simplifications that come about here. We have a simpler RF receiver and one signal processor versus four. Other elements which don't show directly are that with lower vehicle dynamics, the throughput requirements on the data processor will not be nearly as great as they are in the military environment; and so we expect to see some rather substantial simplifications in the hardware for a system of this kind.

One point should be made before we go too far overboard. We have talked a lot about GPS receivers. I think when people are using that term generically, they are really describing what I refer to as a GPS system, i.e., a piece of user equipment that does something for the end user and not just an RF receiver in the conventional sense. Recognize that when we talk about simplification of RF receivers and signal processors and all the neat things that advanced LSI can do for us, we are talking about only half of the user equipment. At the point where the pseudo-range measurements are made, approximately one-half the user equipment costs are accrued; the remaining half is for data processing and control/display. We shouldn't lose sight of that fact as we go on.

In summary, then, we have heard a lot of talk about technology, and we will discuss it further. The technology to make all this happen is very important, but I firmly believe that what we need worse than technology at the present time, in the civil applications, is an environment. We need to have an environment created where the set of users will recognize that GPS has value for them and will do something for them. When that is generally recognized and GPS becomes very attractive to users, then it in turn will become very, very attractive

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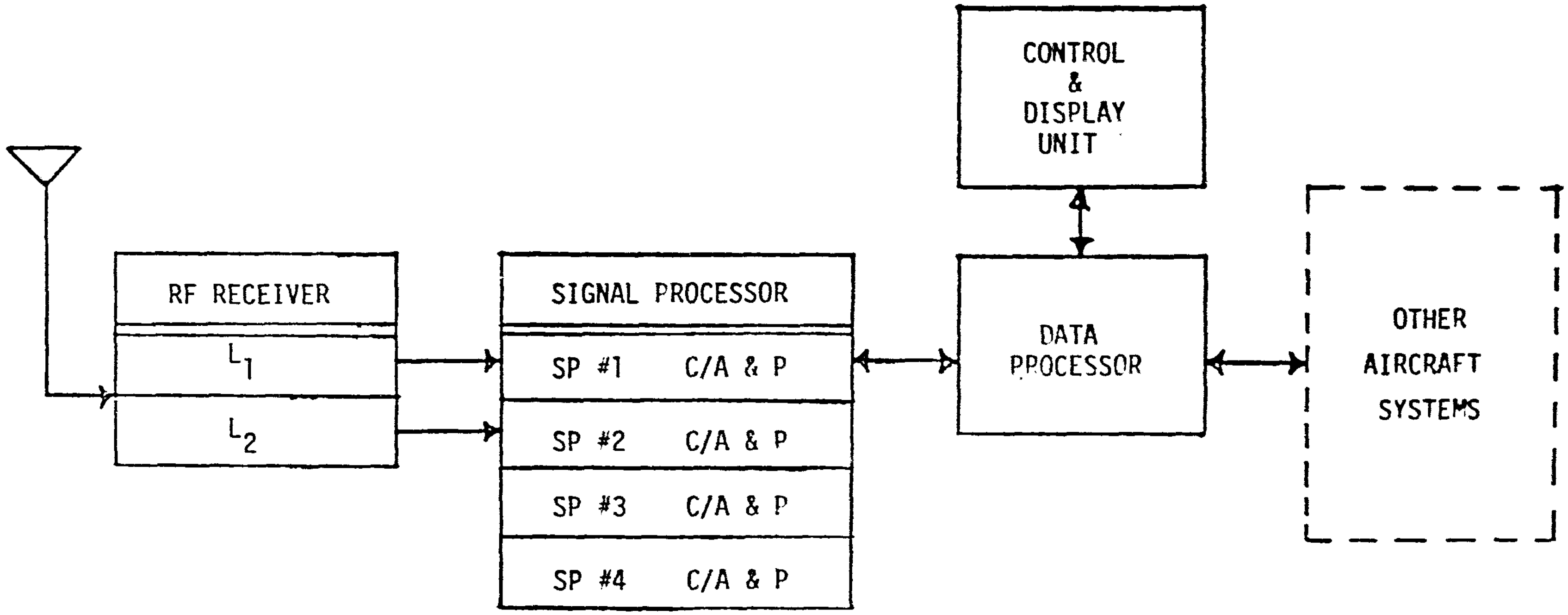
for the manufacturers to go off and create the equipment to fill that need. When that environment exists and that chain of events is put into place, the technology will take care of itself just as it has done in the past. So if we go too far out on a limb starting to design LSI and special chips, we are really not working the right part of the problem at this time.

QUESTION (Mr. Leslie Kline, Transportation Systems Center) - Would you please expand on your remarks concerning the data processing and control/display representing 50 percent of system cost?

ANSWER - I firmly believe that control/display units and processors represent 50 percent of system cost and that that number can be supported.

Half or less of the cost will be in the receiving subsystem; the other half is going to be not only in the processor. We can talk about low-cost microprocessors and they are low-cost and they will become lower cost and memory will become dirt cheap and all those good things; but you still need to, in every aircraft installation, interface with a pilot. That means a control display unit that is usable so he can fly in controlled airspace under true IFR conditions. In addition to that, you need to interface with his aircraft instruments, his primary aircraft flight instruments, probably an autopilot, and so on, maybe an altimetry system. The cost of interfacing, while it is coming down, is not on the same slope that microprocessor costs are. If you start looking at all those pieces that show up in support of the processor, I would agree that the microprocessor itself isn't a large element of that; but I would also say that I think the control display unit, if well-designed to communicate with that system, as it must be, will be a very substantial cost in that system.

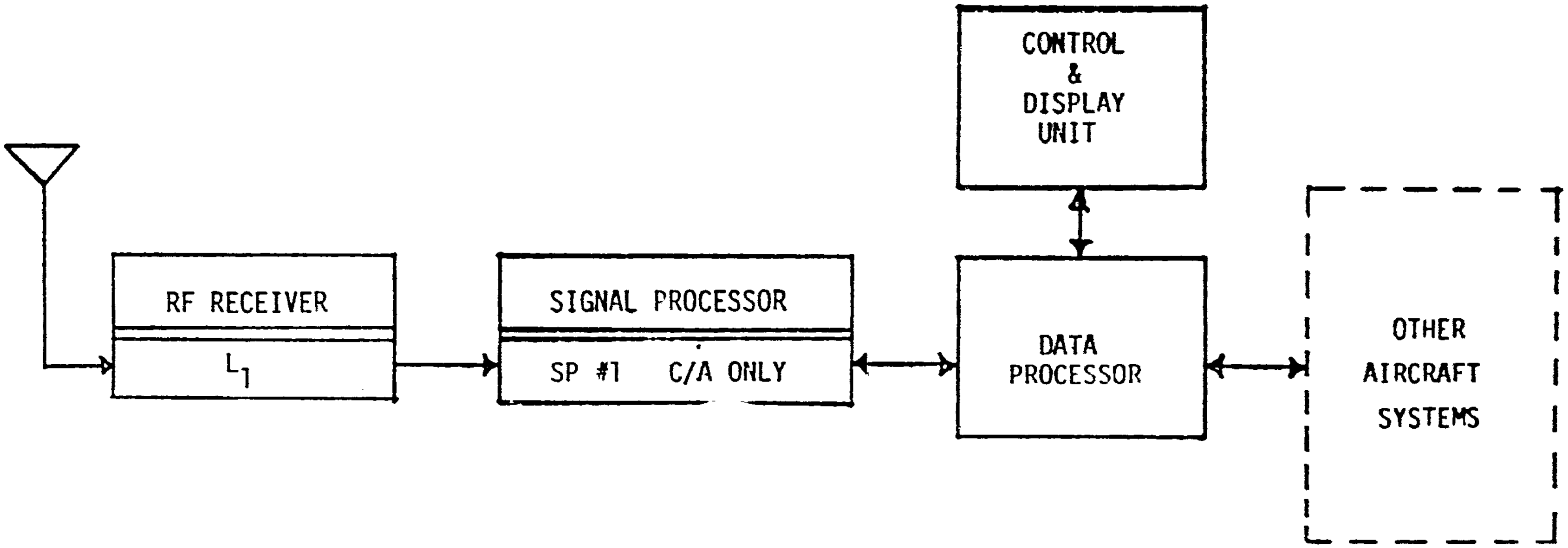
BASIC USER SYSTEM



- TRACKS FOUR SATELLITES SIMULTANEOUSLY
- CORRECTS IONOSPHERIC EFFECTS WITH DIRECT MEASUREMENT AT TWO FREQUENCIES
- MOST ACCURATE
- ACHIEVES 10-20 METER ACCURACY

Figure 4-1

SINGLE FREQUENCY C/A-TRACKING SYSTEM



- TRACKS ONE SATELLITE AT TIME USING C/A CODE ONLY
- COMPENSATES IONOSPHERIC EFFECTS WITH MATHEMATICAL MODEL
- ACHIEVABLE ACCURACY AWAITS TEST VERIFICATION BUT EXPECTATION IS ON ORDER OF 100-200 METERS

Figure 4-2

N80-21305

Vito Calbi
Magnavox Advanced Products Division

I would like to discuss where we are going in the area of civil applications of GPS, particularly with regard to requirements as we see them. In addition, I will talk a little bit about the Z-set, which, at the present time, is probably the only available GPS receiver that is an example of a low-cost set which might meet the civil requirement.

We have chosen to look at general aviation as being made up of several classes of users with different levels of requirements. The first category we considered is the small aircraft operating at 100 knots or less. For this class of aircraft, we feel the requirements are minimal, i.e., that the set must meet the basic requirements for IFR using already existing methods and procedures. Further, the set must operate off existing power supplies, would have a limited set of manually entered waypoints, and would not be interconnected with other onboard sensors; and the receiver processor would drive a course deviation indicator similar to that used with VOR.

The next category of general aviation we considered is more complex in that it would operate up to 200 knots; have about a thousand waypoints called up by frequency or channel number; have interfaces which run from simple course deviation indicators to full flight director systems; and would likely have an encoding altimeter as an available device, which was included as a possibility of an external sensor.

The airline is much more complex and primarily deals with waypoints, waypoint entries and methods, duality of system for redundancies, types of displays, and also interconnected sensors.

We are not really concentrating on the airline. We are concentrating on the below-100-knot and above-100-knot general aviation.

To summarize what we think is the set of requirements with the general aviation class from below 100 to above 100, we are looking at control displays of the type that I have described; and we are looking at the accuracy required during the standard types of approaches and, also, in the case of high-velocity aircraft, at the 4-minute type of situation.

There is a primary direction that people are following about Geometric Dilution of Precision (GDOP). That primary direction is to pick one or more low-elevation-angle satellites for best performance.

This creates a sensitivity to losing those satellites in turns. The usual solution to this is to compensate for that loss by more costly architecture, more channels, or external aids.

There is an alternate direction. That is to trade some performance in level flight for turn improvement, that is, select satellites above a maximum bank angle, particularly for the less-than-100-knot aircraft, and minimize the loss of signals and, therefore, the need for aids or more costly architecture.

In order to evaluate that concept, we did some analysis. What we used was a dynamic approach profile over 180 degrees as illustrated in Figure 5-1. The speed we chose is at the top end of the civil aircraft that we are looking at, and it is 0.5 G turn with a bank angle of 27 degrees.

We have evaluated an architecture very similar to the Z-set architecture and a sequence of 1.2 seconds per satellite. We used the criterion of ionospheric error or tropospheric error and signal strength at the present level of -163 dBW.

Also, we used the implication that an L-band-type emission would be around to give you some kind of AJ of about the specification that the Z-set has.

The results of this simulation indicate that as you start shadowing, particularly when you start shadowing two satellites, you do in fact create a loss in performance.

However, when satellites from the Phase 3 constellation were selected with the criterion of being above 25 degrees, the simulation indicates that the accuracy is somewhat worse during the average but does not in fact have the larger error growth characteristics of turns.

3

Summary of the runs to date indicates that for the case of good GDOP with shading, the accuracy obtainable from a set using the C/A, L-1 signal only is between 11 meters and 32 meters when straight and level, while during a turn it goes to about 490 meters RMS.

For the case of no shading, that inaccuracy levels out somewhat to a point where from 45 meters to 60 meters is the performance throughout the flight.

At this point, I would like to indicate why this might be a very viable partial solution to your problem. The Phase 3 constellation will have sufficient redundancy to where if you can accept reduced accuracy or increased GDOP, the lowest elevation angle satellite that you will ever see anywhere in the world at any time is about 97 percent probable of being above 15 degrees, and the second lowest satellite that you will ever see anywhere in the world at any time is about 99 percent probable of being above 25 degrees, so some advantage of the redundancy in the system can be taken advantage of.

That does not imply, however, that for the highest speed aircraft and higher turn rates, augmentation is not the answer; but for a 100-knot vehicle which would probably use a single-channel receiver without any augmentation, it appears to be the right one.

I would now like to address the Z-set which is a single-channel, sequencing receiver designed to operate with only the C/A, L-1 signals. The configuration consists basically of a receiver processor unit and a control display unit but has been built for various installations, including the possibility of growing into and replacing a TACAN or 118 type and also into the Navy and shipboard installations where the receiver processor assembly display unit is installed in a Navy shock-proof housing.

It consists of about 11 modules built out of 1976 technology. The control display is very close to the HF-type display and has one line of display keyboard entry capability for data entry and/or requests for display and functions to perform and alert the operator as to what the situation is with the Z-set itself.

4

Its system partitioning is that the receiver and antenna system and the processor subsystem interact directly with the software modules indicated. The set is automatic in that the operator does not have to select what satellites he wants. That is automatically done. He does not have to do anything at all involving the satellite sequence. He just indicates some initialization date, including rough timing, and the set takes over from there.

The 1976 technology base that was used for the Z-set design led to the 11 modules indicated, including the interface module, which presently connects directly to the AIMS altimeter--which is the military equivalent of the digital encoder altimeter for the civil application.

This technology base led to the 11-card design. The cost apportionment of the Z-set, which is shown in Figure 5-2, has held for about 2 years.

What is shown in this figure is a comparison study and summary of the percentage changes. Seen here is the indication of the reduction in processor costs, even with the same processor elements being postulated which occurred over an 18-month period; and the receiver increase wasn't really a cost increase. It is a percentage increase in association with the reduction in the processor.

In addition to our activity reported to the joint program office on the design of the Z-set, there have also been some other studies associated with the 1976 technology and 1977 prices in quantities of one thousand.

The indications are that the Z-set can sell for less than $4,000 to general aviation and less than $13,000 to air carriers.

Where we are in the conclusions and projections phase of the civil low-cost user design is that we feel that the simple architecture is sufficient to meet the requirements for the general aviation, below-100-knot or at-100-knot vehicle but that a simple augmentation of that with the turn rate indicator or a barometric altimeter would solve the problems in turns and be the way to go.

5

Further, the 1.2-second sequence for satellites can go down or up, as the case may be, to a longer sequence such as 3.6 or 4.8, particularly at the lower velocity where the performance data indicated 270 knots would be about comparable.

The projection of the 1976 technology MSI and LSI, particularly the military design, is within the reach, we feel, of the required cost of 1984; and there would be a substantial reduction in price as a result of getting away from the mil spec package and mil spec parts requirements.

The technology base of civil designs in 1982 to 1984 will reduce the cost to the user as indicated by a number of other people. The computer components, which in the presentation I have just given is equivalent to a present eight-bit microprocessor, would come down substantially in cost, and the percentages would decrease.

Also, those applications could find themselves into that time frame using those devices for receiver processing tasks themselves. It is in the receiver, particularly the RF and IF areas, that we feel that some customizing is required and ought to be contemplated.

COMMENT (Mr. Sawicki) - Again, if I have 100-foot incremental steps, that means I have the dead band of 100 feet. I don't know what to do, so that more or less says the airplane can sit at 100-foot increments.

ANSWER - That wouldn't happen in terms of the output. What would happen is that the output would be continuous or continuous on the basis of an update rate.

DYNAMIC APPROACH PROFILE

- SPEED = 500 KMH ≈ 270 KTS
- LATERAL ACCELERATION = 1/2G
- BANK ANGLE = 27^{0}
- SINGLE CHANNEL SEQUENCING SET (1.2 SECS PER SATELLITE)

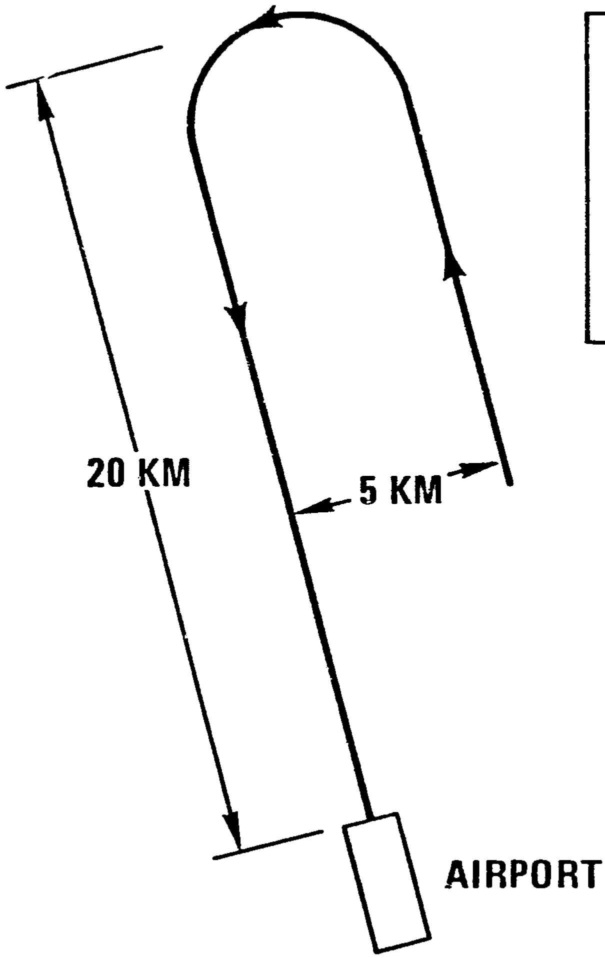
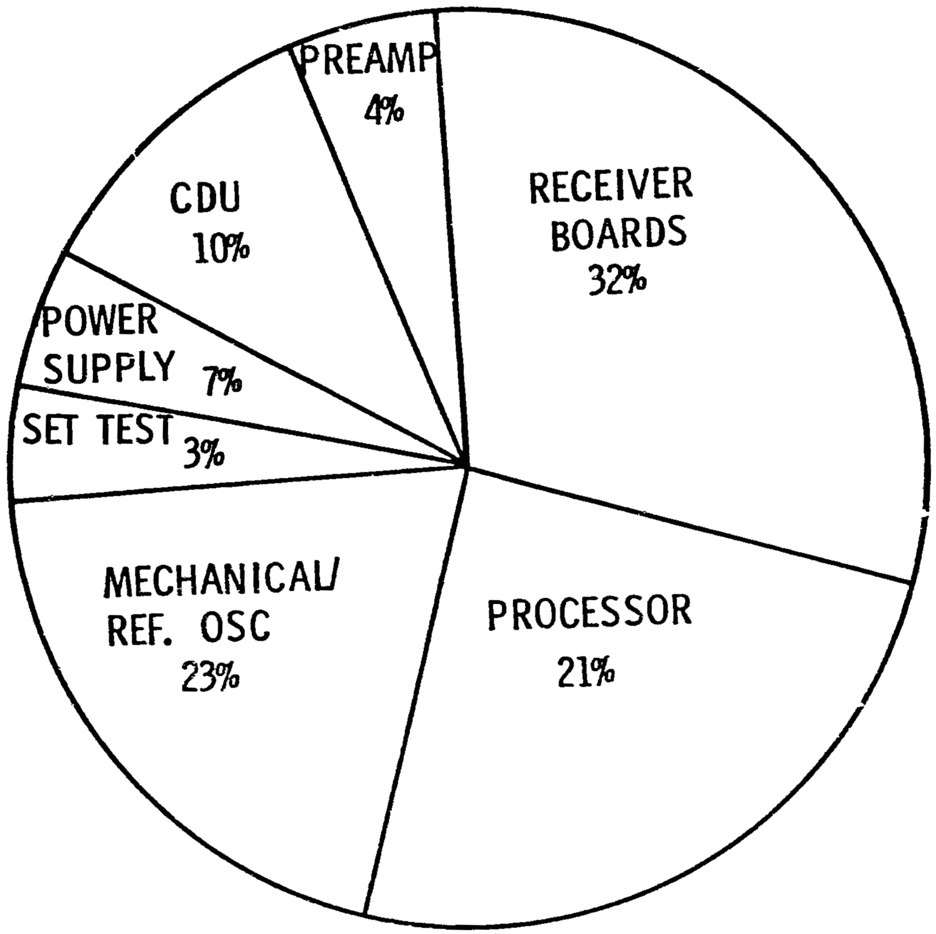


Figure 5-1

Z COST ALLOCATIONS
(DECEMBER 1977 $)



COMPARISON SUMMARY

	7/26/76	1/18/77	6/15/77	12/13/77
RECEIVER BDS	21%	24%	32%	32%
PROCESSOR	30%	26%	25%	21%
CDU	11%	12%	10%	10%
PREAMP	5%	6%	5%	4%
POWER SUPPLY	5%	5%	5%	7%
MECH/REF OSC	26%	23%	18%	23%
SET TEST	0%	4%	4%	3%

Figure 5-2

N80-21306

Melvin Gilreath
NASA/Langley Research Center

What I would like to do is to just briefly review the status of our aircraft antenna prediction program at Langley.

I would like to start by reviewing the program objective, the problem area, and the approach as shown in Figure 6-1.

We want to provide the technology needed for antenna designs, which would include suitable antenna locations, that will meet the requirements for the 1980's navigation and communications systems. Applications would be made on both commercial and general aviation aircraft and include such systems as the Microwave Landing System (MLS), the emergency locator transmitter (ELT), and the GPS system.

The data that I will present will be primarily concerned with the MLS; however, the approach can be used on the GPS problem.

The problem area is that most current aircraft antenna designs are determined experimentally, utilizing sections or scale models of aircraft, which is extremely time-consuming and expensive.

New antenna systems will make this problem even more severe since they are requiring more precise airborne antenna coverage and performance on a wide range of commercial and general aviation aircraft.

Our approach to the problem has been to develop analytical techniques and computer programs for antenna siting and performance prediction. We are utilizing scale-model aircraft to obtain experimental data for verification of our analytical results.

At this time, I would like to present some examples, for both commercial and general aviation aircraft, which demonstrate the capabilities of the pattern prediction program.

In our program, once the aircraft type and the antenna location have been selected, computer models of each of the three views of the aircraft are developed, and this information is used in our computer program for predicting the

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antenna performance on the aircraft. Figure 6-2 shows the computer-generated models for the Boeing 737 with the antenna located at station 220 on the top forward fuselage. The application is for the Microwave Landing System. Program areas needing improvements are shaded.

The wings were simulated by flat plates and the vertical stabilizer by a bent plate. The fuselage cross-sections, in the roll and elevation planes, are simulated by using composite ellipses.

Once we have developed these computer models, we can proceed to do the antenna pattern calculations. Figure 6-3 shows a comparison between the calculated and measured principal plane patterns obtained for the model described in Figure 6-2. All three patterns show very good agreement was obtained between the calculations and the scale-model measurements.

What we would like to know is, What is the complete volumetric coverage around the aircraft? Our computer program has the capability of doing the complete volumetric plot which requires the calculation of 91 patterns such as those shown in Figure 6-3.

Figure 6-4 shows the calculated and measured volumetric plots for the Boeing 737. Theta, or the elevation angle, is plotted vertically. Phi, or the azimuth angle, is plotted horizontally. The nose of the aircraft is located at Theta equals 90 degrees and Phi equals 0 degrees. Also shown plotted in Figure 6-4 are the antenna gain values.

Very good agreement was obtained between the calculated and measured volumetric plots as shown in Figure 6-4. Although very good agreement was obtained between the calculations and the scale-model measurements, there still may be some questions as to how well we are actually predicting the coverage on the full-scale aircraft. So, in order to answer these questions, we conducted a flight test using the airborne MLS antennas and the FAA MLS facility at NAFEC (National Aviation Facilities Experimental Center) to determine the performance of the actual airborne antennas on the NASA 737 aircraft.

3

The antenna that I will be presenting data for will be the C-band monopole (shown in Figure 6-5) on the top fuselage, at station 239.

We flew a number of different flight profiles into the NAFEC facility, and one of these is shown in Figure 6-6. Also shown in Figure 6-6 is a plot of the errors between the predicted and measured signal strengths as a function of the aircraft look angles. The elevation angle is plotted vertically, and the azimuth angle is plotted horizontally with the various symbols representing different error ranges. The two curves represent the data obtained for the elevation (El_1) and azimuth scanning beam antennas for the flight profile shown. In the calculations, corrections were made for variations due to changes in ground antenna gain as a function of scan angle and also for aircraft position. Considering the complexity of the problem, the agreement as shown in Figure 6-6 is quite good.

To demonstrate the capability of the program to do calculations for other types of antennas, something representative of the type that might be used for a GPS application, Ohio State was asked to do calculations for the Lindberg crossed-slot antenna that was designed at MIT. The antenna was designed for a satellite-to-aircraft application on a KC-135, and the antenna location is shown in Figure 6-7. Figure 6-8 shows the computer-generated model for the KC-135. Figure 6-9 shows the calculated and measured results obtained for the principal plane patterns. The vertically polarized components are shown in Figures 6-9(a), 6-9(c), and 6-9(e), and the horizontally polarized components are shown in Figures 6-9(b), 6-9(d), and 6-9(f).

It was pointed out earlier at the conference that it's extremely difficult to obtain good circular polarization for Theta values approaching 90 degrees. The horizontally polarized component reduces drastically when Theta approaches 90 degrees, and this is why the patterns of a CP antenna essentially degenerate to those of a linearly polarized antenna in that region.

4

Figure 6-10 shows a volumetric plot for the Lindberg RHCP crossed-slot on the KC-135. This presentation was generated using a series of pens of different colors. For this application, complete coverage above the aircraft from Theta equals 0 to Theta equals 90 degrees, for all Phi values, is desired. As shown in Figure 6-10, there are several holes in the coverage for values of Theta less than 90 degrees, which is undesirable.

There is some blockage due to the vertical stabilizer which will also be a major problem for the GPS.

In addition to the commercial aircraft work, we have constructed a number of scale models of general aviation aircraft, and I have shown a list of those in Figure 6-11. These are typical of the different types of aircraft that comprise the general aviation fleet.

Figure 6-12 shows a computer-generated model of the Cessna 402B, and the shaded areas on the three views indicate those areas that need to be added into our computer program. The engines, fuel tanks, main landing gear, and horizontal stabilizer need to be added to allow us to do a better computation of the complete volumetric coverage.

This is very important for the MLS system where coverage down to 30 degrees below the horizon is desired since anything below the horizon would have a very definite effect on the volumetric coverage.

For the GPS application, it appears one of the most severe problem areas will be the vertical stabilizer since complete upper hemispherical coverage is needed.

Figure 6-13 shows the calculated and measured elevation plane patterns for two possible MLS antenna locations on the Cessna 402. Very good agreement was obtained for the elevation plane patterns for the top fuselage antenna location.

For the location on the forward nose, forward of the cockpit area, very good agreement was obtained except in the region towards the tail, and the reason for this is that we did not model the cockpit area in the calculations. Therefore, we are appearing to get more radiation in that region,

5

which is actually not present, as can be seen from the scale-model data.

Figure 6-14 shows another example of the computer modeling of a general aviation aircraft, a Gates Learjet. The three views of the aircraft are shown with the computer-generated models for those views. Figure 6-15 shows the calculated and measured principal plane patterns obtained for a monopole on the top forward fuselage.

One of the areas I would like to point out where we did not obtain good agreement between the measured and calculated results is in the tail region.

The reason for this is the way the engines were modeled using a flat plate attached at 90 degrees to the fuselage and extending up farther than the actual engine would along the fuselage.

Therefore, we are appearing to get more blockage than we would actually have, if we had modeled the engine correctly.

Figure 6-16 lists some of the program accomplishments. We have a computer program available for predicting the volumetric patterns of fuselage-mounted antennas on large aircraft, and we have had quite a bit of interest in this program. We have received requests for the program from those companies listed in Figure 6-16, and copies have been supplied to them.

We have conducted a computer study of MLS antennas on commercial aircraft. This was completed for the aircraft shown in Figure 6-16, and a report is available containing that information. A flight test was conducted which gave us full-scale aircraft antenna data to compare with our scale-model and computer-generated data.

Figure 6-17 shows our current activity. We are currently working to improve our computer program capability for handling more complex aircraft. We are developing a computer program for analyzing the low-frequency ELT antenna on general aviation aircraft. We are conducting experimental studies of MLS and ELT antenna locations on scale-model general aviation aircraft, and we are also conducting a computerized study of MLS antenna locations on general aviation aircraft.

6

In the GPS area, we have just started looking at some possible antenna designs during the last few months. We are working to develop a suitable antenna design for providing acceptable upper hemispherical coverage. Once an acceptable antenna design is developed, experimental data will be obtained on a scale-model general aviation aircraft and then compared with calculations.

After our analytical capability has been verified, we plan to use the program to do a computerized study of the GPS antenna on many different types of general aviation aircraft.

7

AIRCRAFT ANTENNA PERFORMANCE PREDICTION TECHNIQUES

OBJECTIVE

PROVIDE THE TECHNOLOGY NEEDED FOR ANTENNA DESIGNS, INCLUDING SUITABLE ANTENNA LOCATIONS, THAT WILL MEET REQUIREMENTS FOR 1980'S NAVIGATION AND COMMUNICATIONS SYSTEMS. APPLICATIONS WILL BE MADE ON BOTH COMMERCIAL AND G/A AIRCRAFT AND INCLUDE SUCH SYSTEMS AS THE MICROWAVE LANDING SYSTEM (MLS), EMERGENCY LOCATOR TRANSMITTER (ELT), AND GLOBAL POSITIONING SYSTEM (GPS).

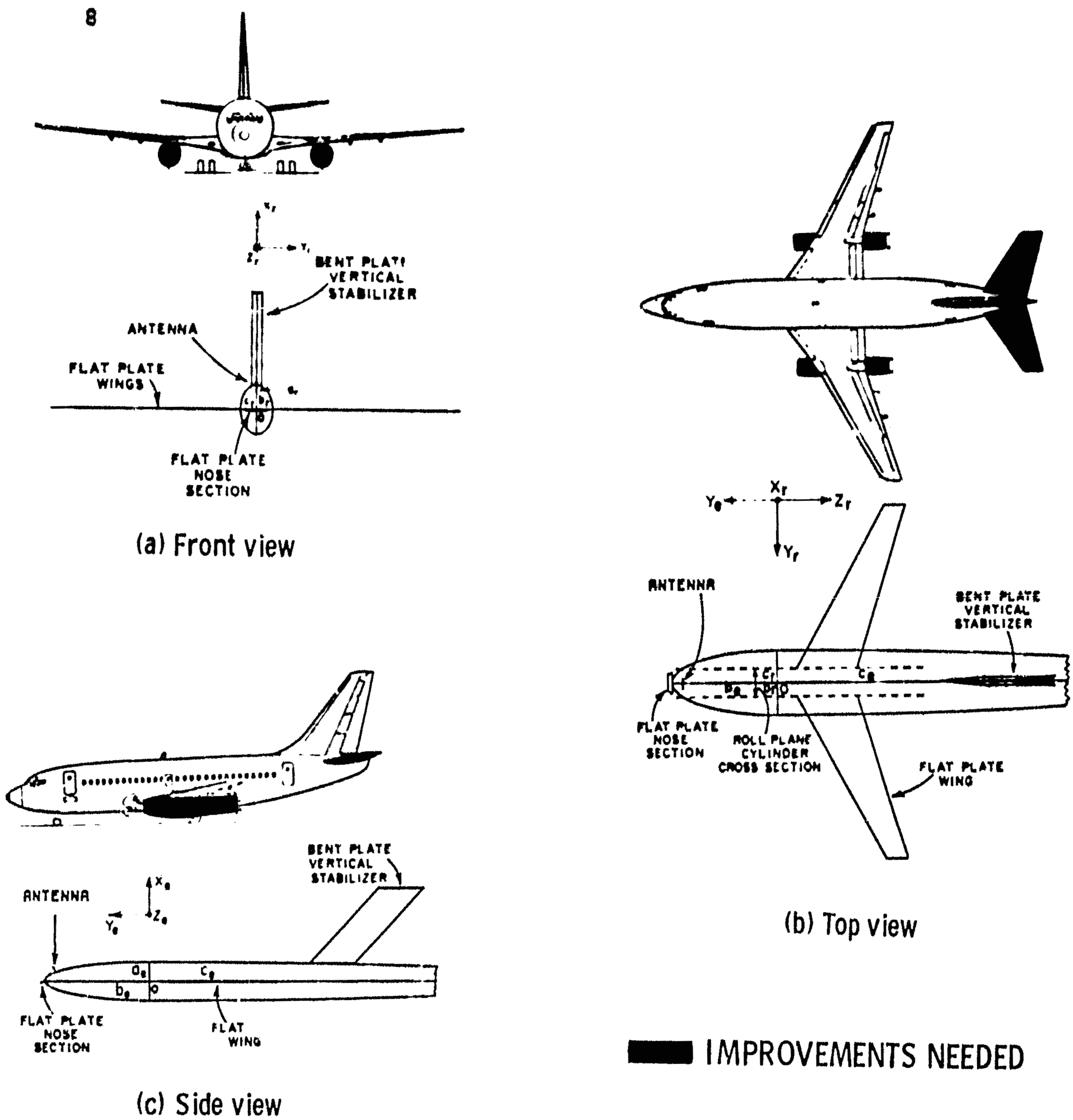
PROBLEM

CURRENT AIRCRAFT ANTENNA DESIGNS ARE DETERMINED EXPERIMENTALLY UTILIZING SECTIONS OR SCALE MODELS OF AIRCRAFT WHICH IS TIME CONSUMING AND EXPENSIVE. NEW ANTENNA SYSTEMS REQUIRE PRECISION AIRBORNE ANTENNA COVERAGE AND PERFORMANCE FOR A WIDE RANGE OF COMMERCIAL AND G/A AIRCRAFT.

APPROACH

DEVELOP ANALYTICAL TECHNIQUES AND COMPUTER PROGRAMS FOR ANTENNA SITING AND PERFORMANCE PREDICTION. USE SCALE MODEL AIRCRAFT TO OBTAIN EXPERIMENTAL DATA FOR VERIFICATION OF ANALYTICAL RESULTS.

Figure 6-1



COMPUTER SIMULATION MODEL OF A BOEING 737 AIRCRAFT WITH MONOPOLE LOCATED AT STATION 220 ON TOP OF THE FUSELAGE

Figure 6-2

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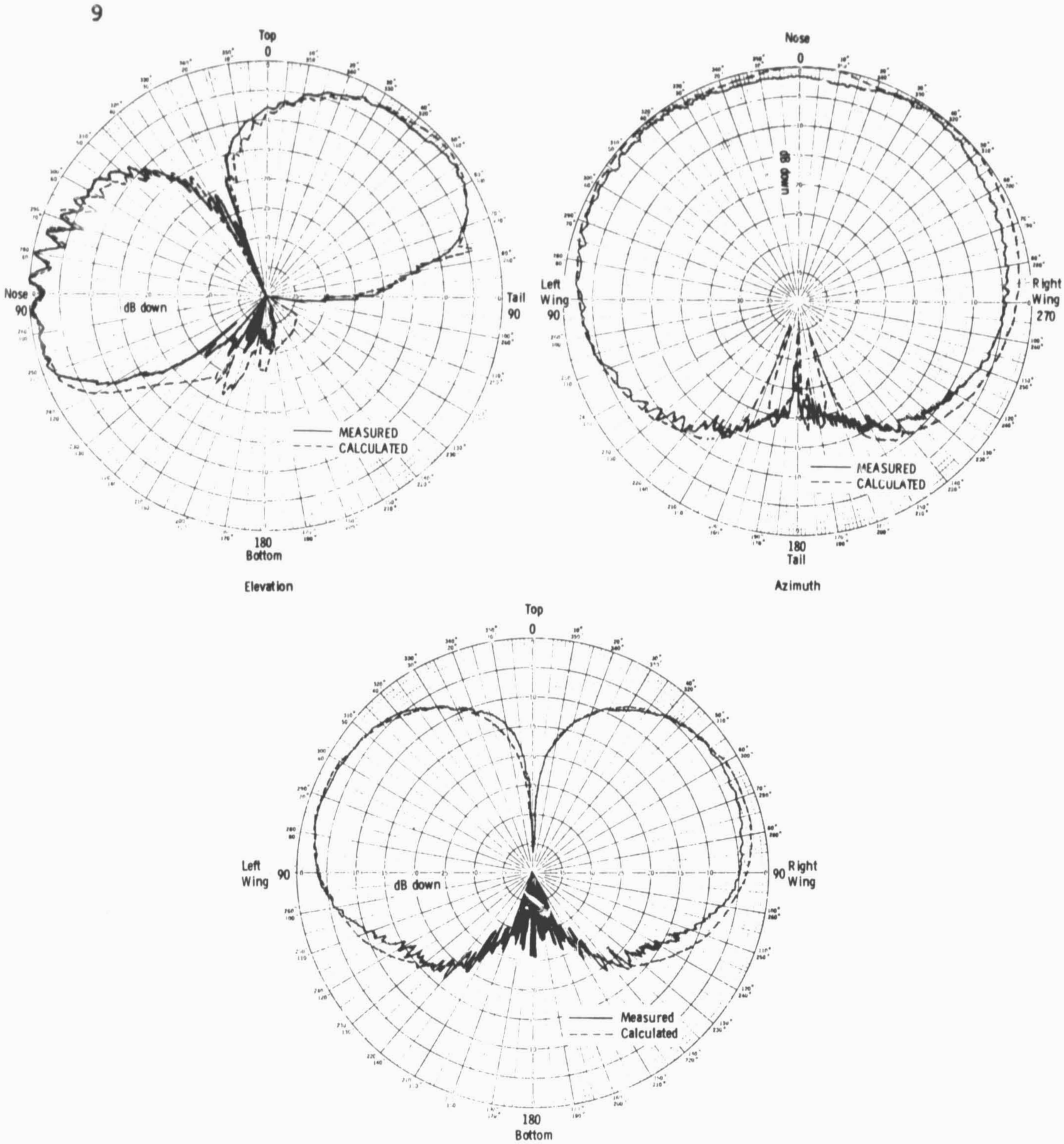

MEASURED AND CALCULATED PATTERNS FOR A MONOPOLE AT STATION 220 ON THE TOP FUSELAGE OF A ONE-ELEVENTH SCALE BOEING 737 MODEL

Figure 6-3

C-2

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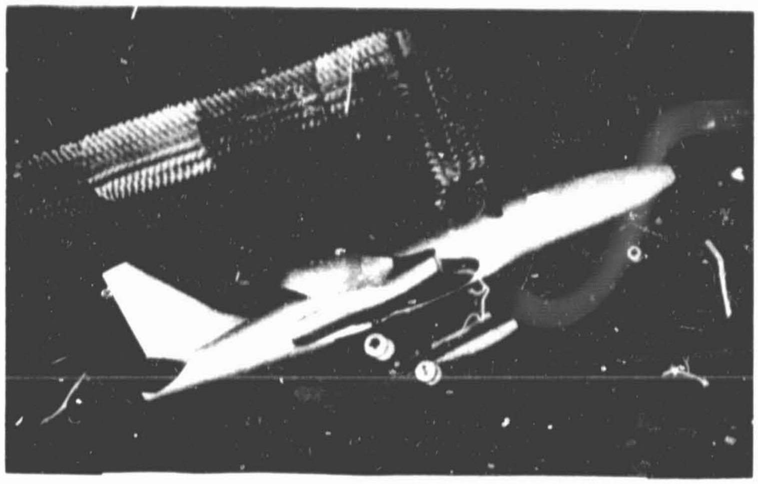
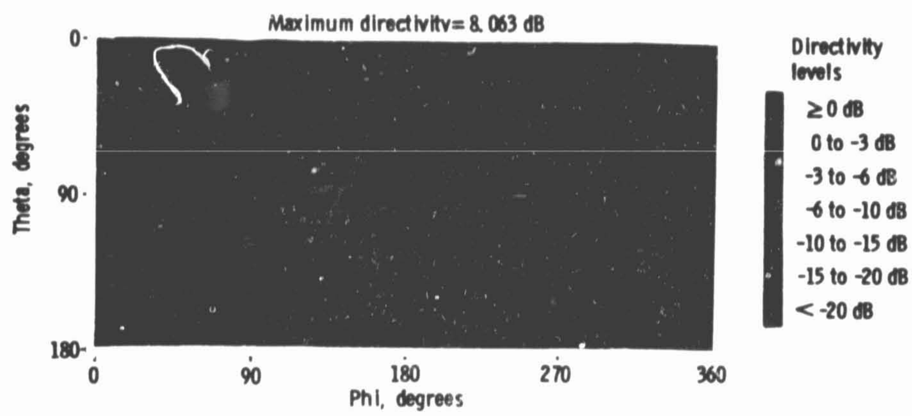
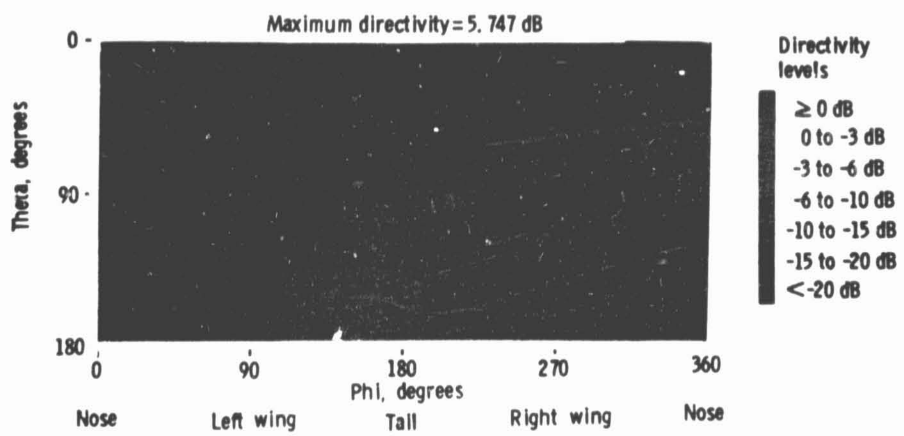


(a) One-eleventh scale model of a Boeing 737



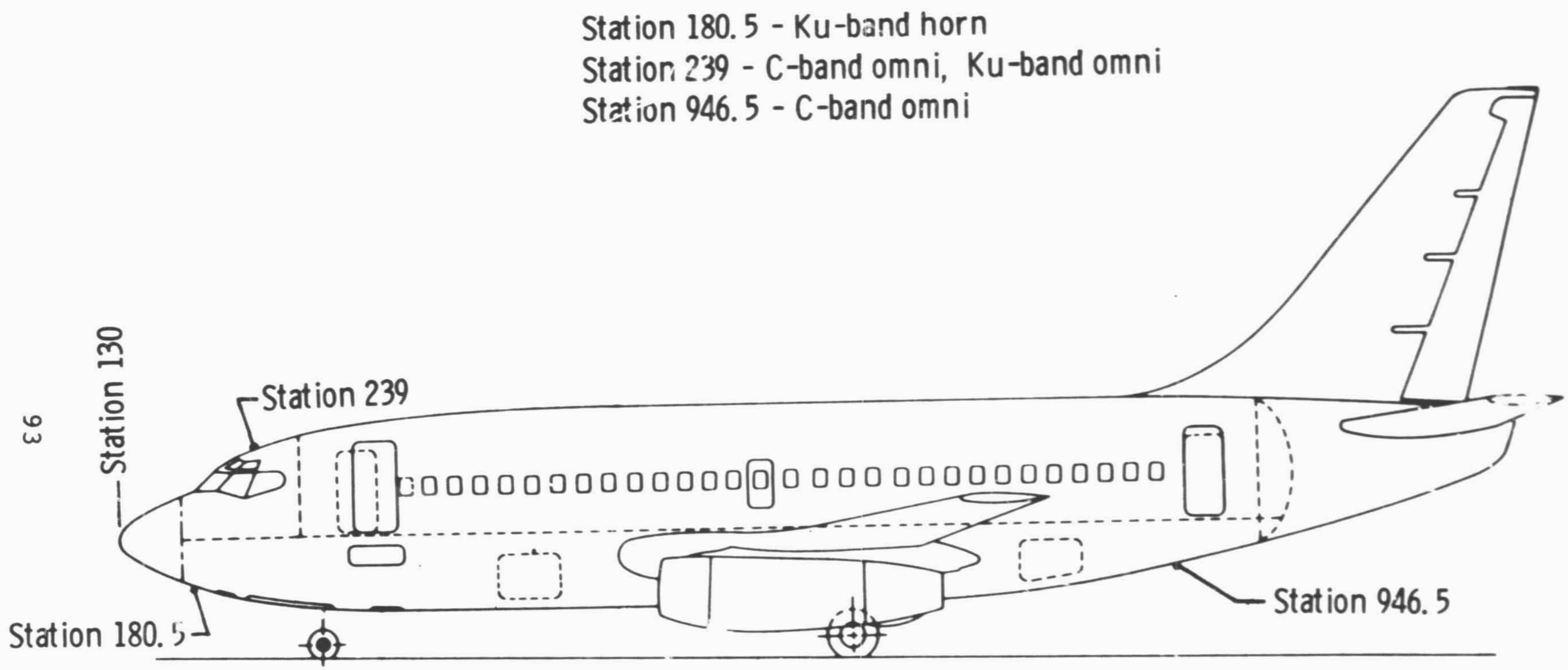
(b) Measured volumetric directive gain pattern of a monopole at station 220



Nose location - Theta = 90°, Phi = 0°

(c) Calculated volumetric directive gain pattern of a monopole at station 220

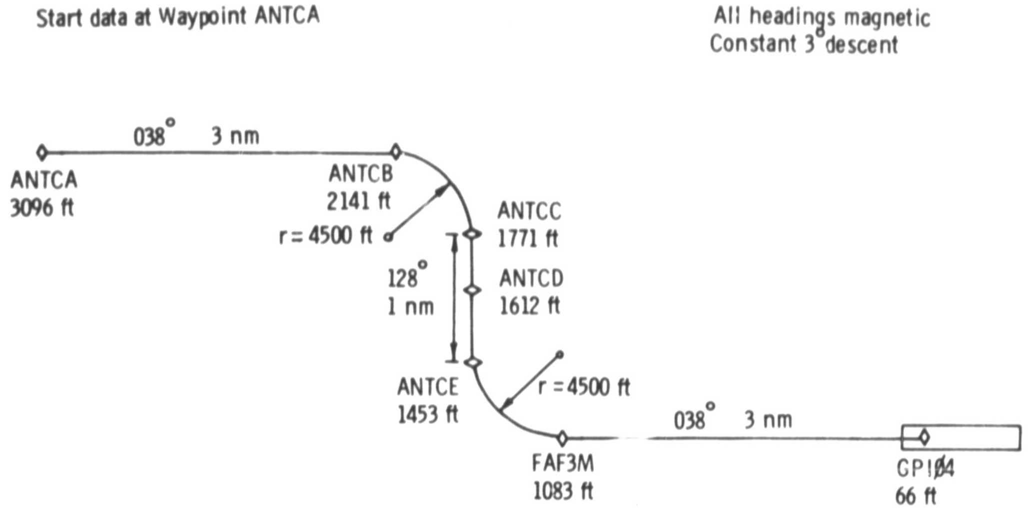
Figure 6-4



ANTENNA LOCATIONS USED FOR FLIGHT EXPERIMENT

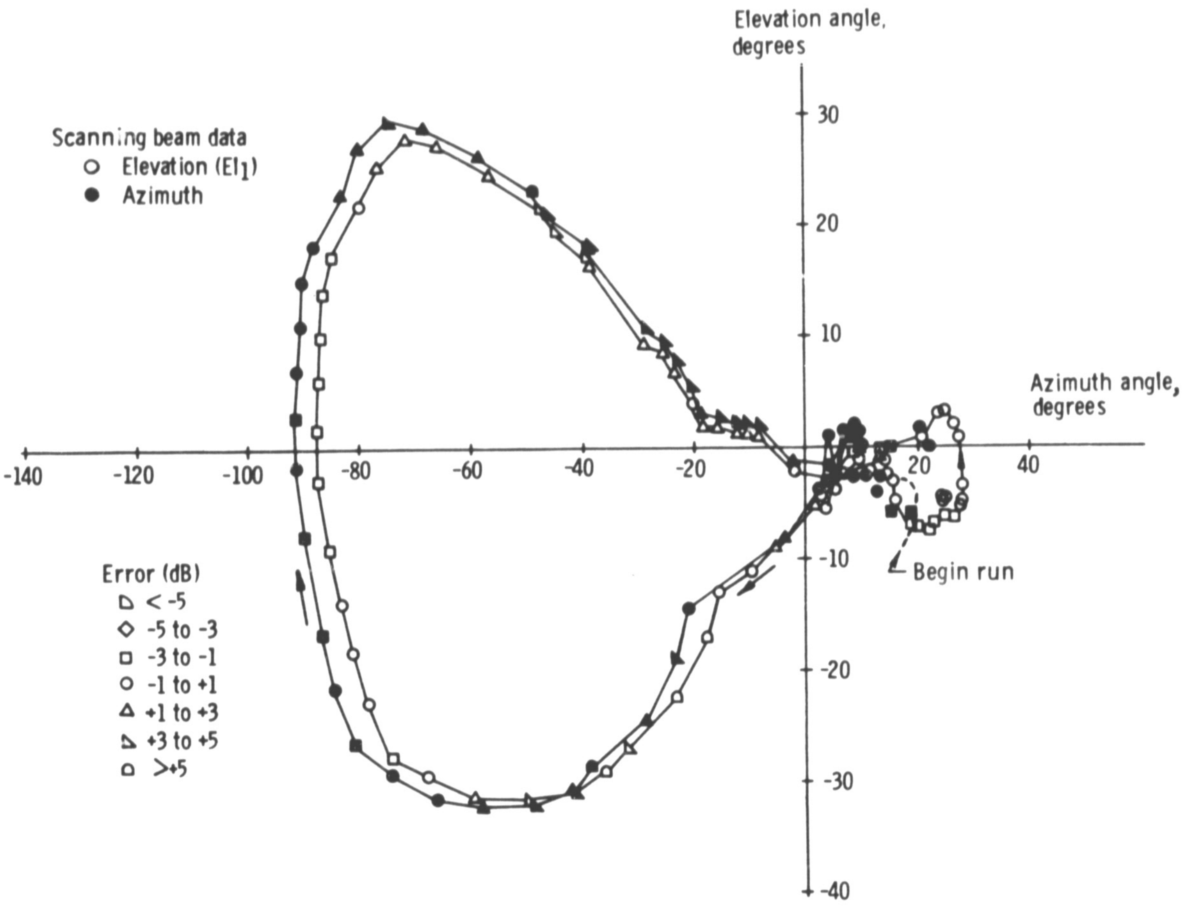
Figure 6-5

12



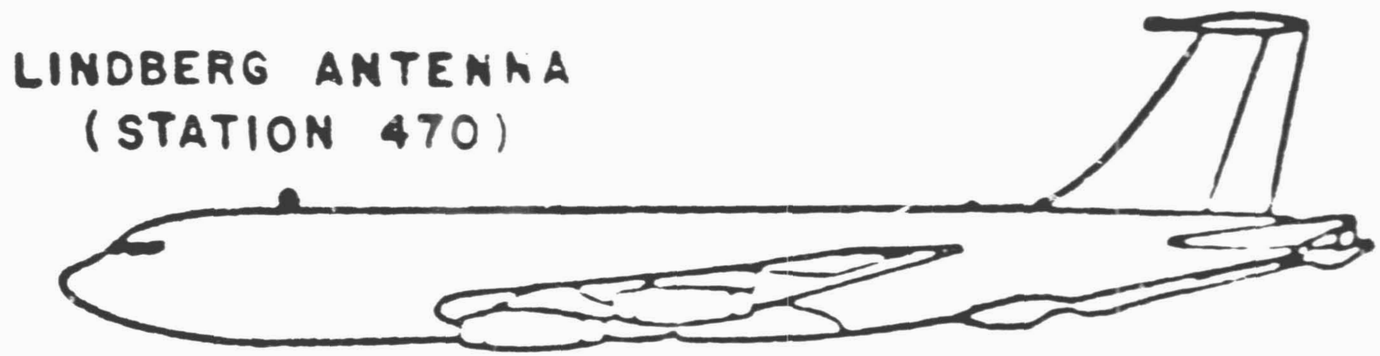
STAR ACØ49

ANTENNA FLIGHT TEST PROFILE



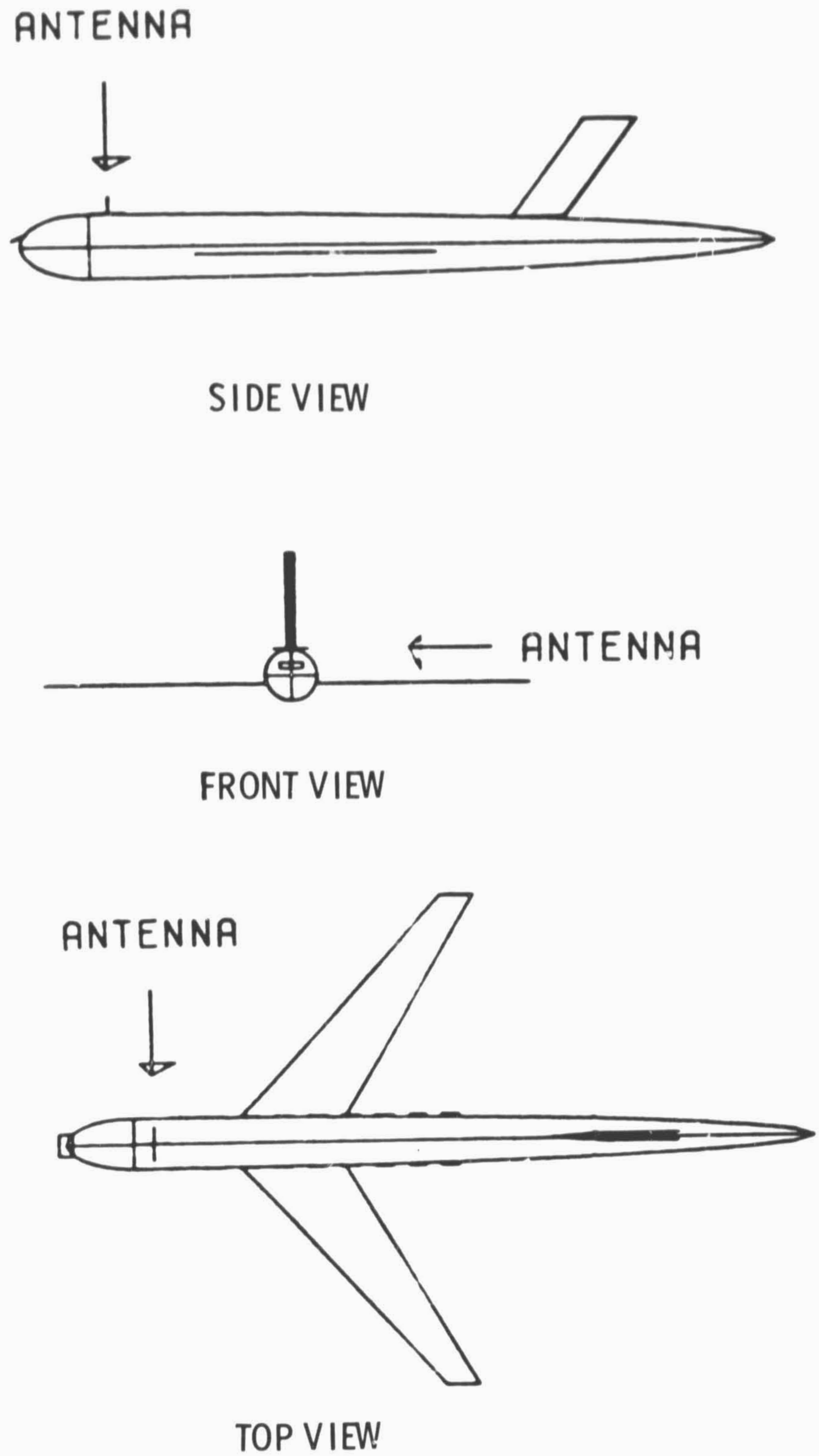
ERRORS BETWEEN PREDICTED AND MEASURED SIGNALS AS A FUNCTION OF AIRCRAFT LOOK ANGLES

 Figure 6-6



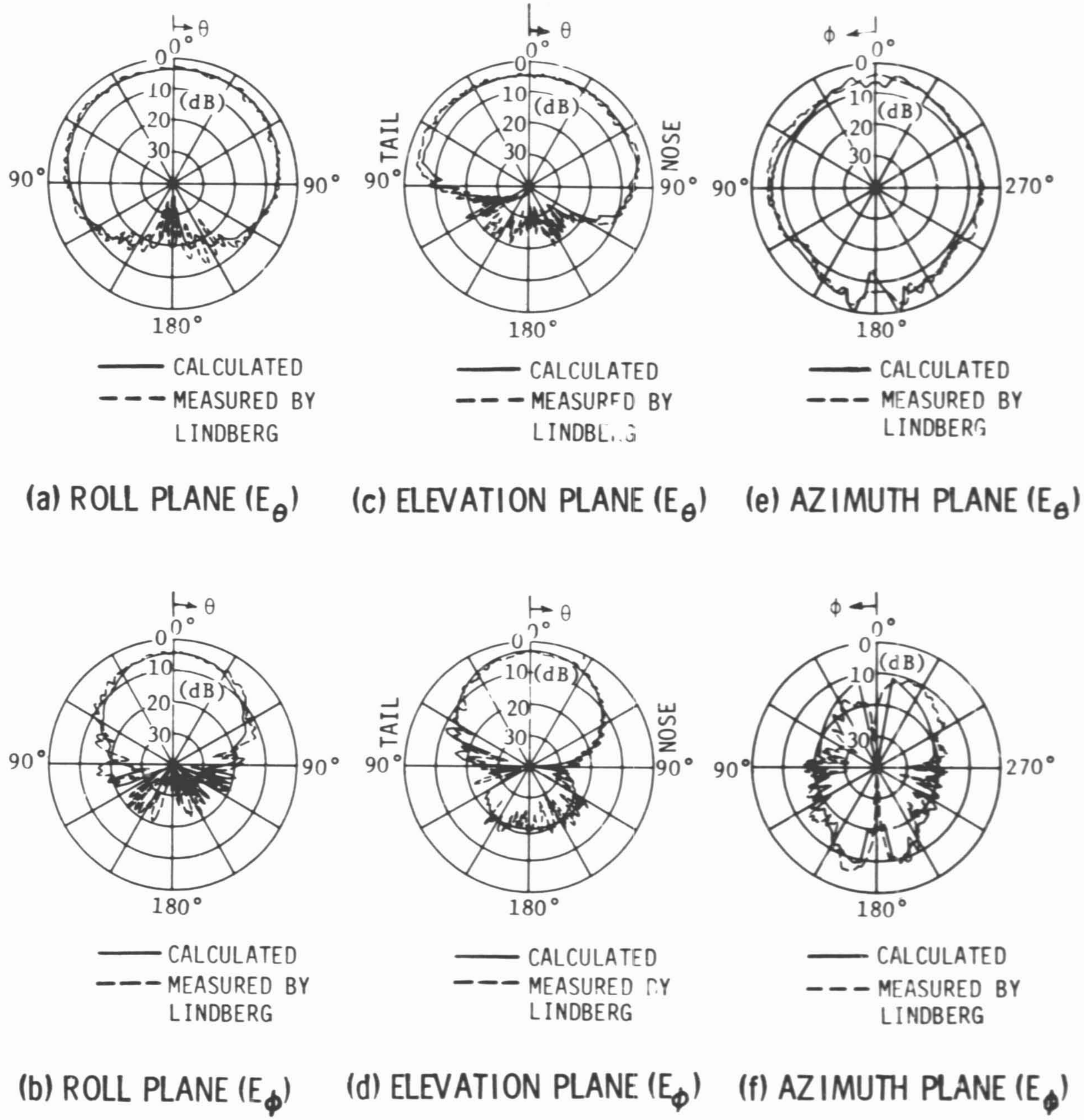
LINDBERG CROSSED-SLOT ANTENNA ON KC-135

Figure 6-7



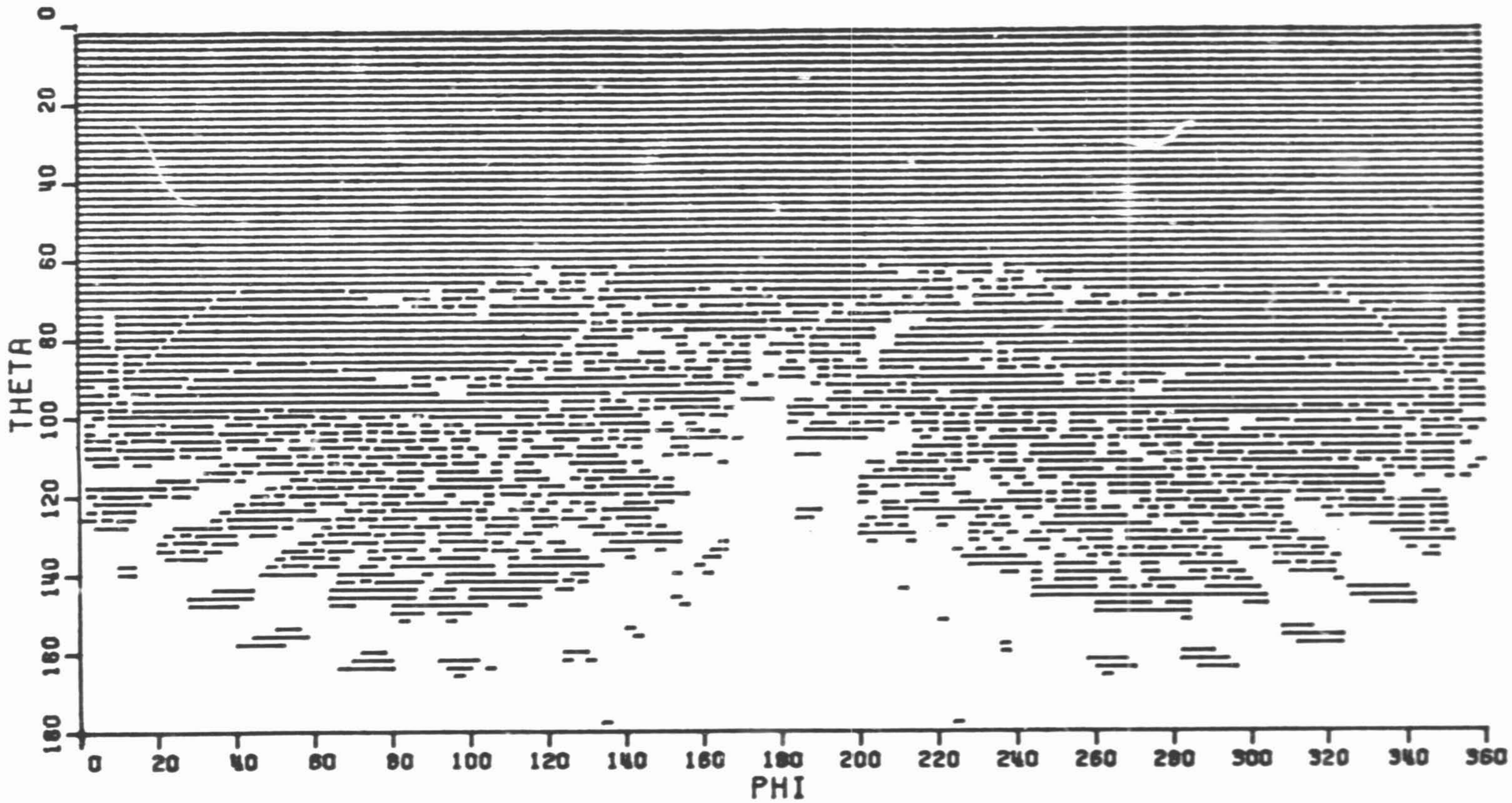
COMPUTER GENERATED MODEL OF KC-135

 Figure 6-8



RADIATION PATTERNS OF LINDBERG CROSSED-SLOT ANTENNA
MOUNTED AT STATION 470 ON KC-135 AIRCRAFT.

Figure 6-9



GAIN= 0.0 GAIN= -3.0 GAIN= -6.0 GAIN= -9.0 GAIN= -12.0
GAIN= -15.0

VOLUMETRIC PATTERN OF LINDBERG RHCP CROSSED-SLOT ON KC-135 AIRCRAFT WITH VARIOUS GAIN LEVELS INDICATED BY COLORS.

Figure 6-10

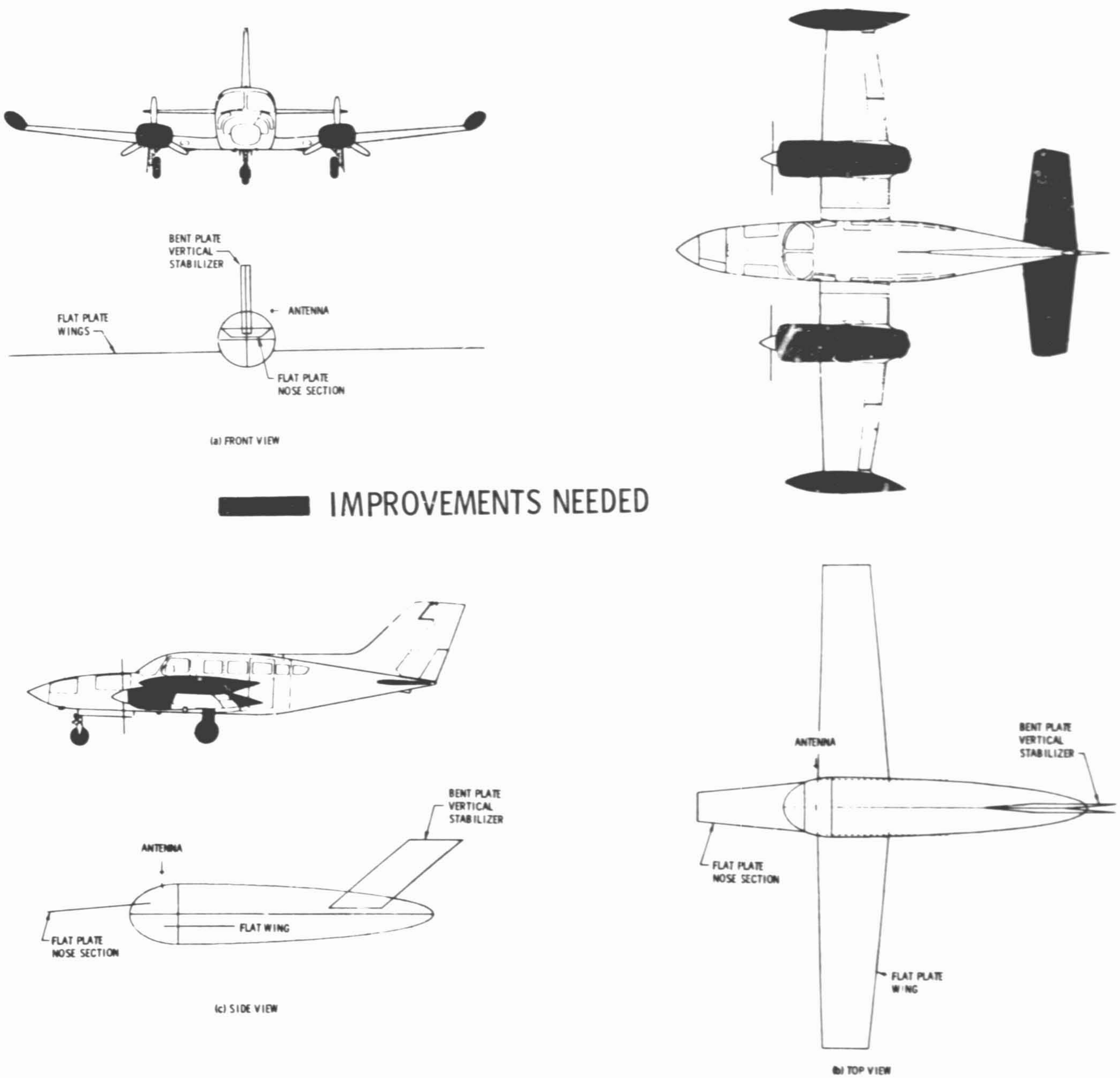
SCALE MODELS OF G/A AIRCRAFT

AIRCRAFT	DESCRIPTION
CESSNA 150*	SINGLE ENGINE-HIGH WING
CESSNA 402B	TWIN ENGINE-LOW WING
BEECHCRAFT BARON*	TWIN ENGINE-LOW WING
BEECHCRAFT B99	TWIN ENGINE-LOW WING
HELIO 295	SINGLE ENGINE-HIGH WING
LEAR JET	SMALL JET
PIPER CHEROKEE ARROW	SINGLE ENGINE-LOW WING
GRUMMAN GULFSTREAM II*	JET

PLANNED FOR CONSTRUCTION	
AERO-COMMANDER	TWIN ENGINE-HIGH WING
DEHAVILLAND DHC-6	TWIN ENGINE-HIGH WING

*EXPERIMENTAL DATA AVAILABLE

Figure 6-11



COMPUTER SIMULATION MODEL OF A CESSNA 402B AIRCRAFT WITH MONOPOLE LOCATED ABOVE COCKPIT

Figure 6-12

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OF POOR QUALITY

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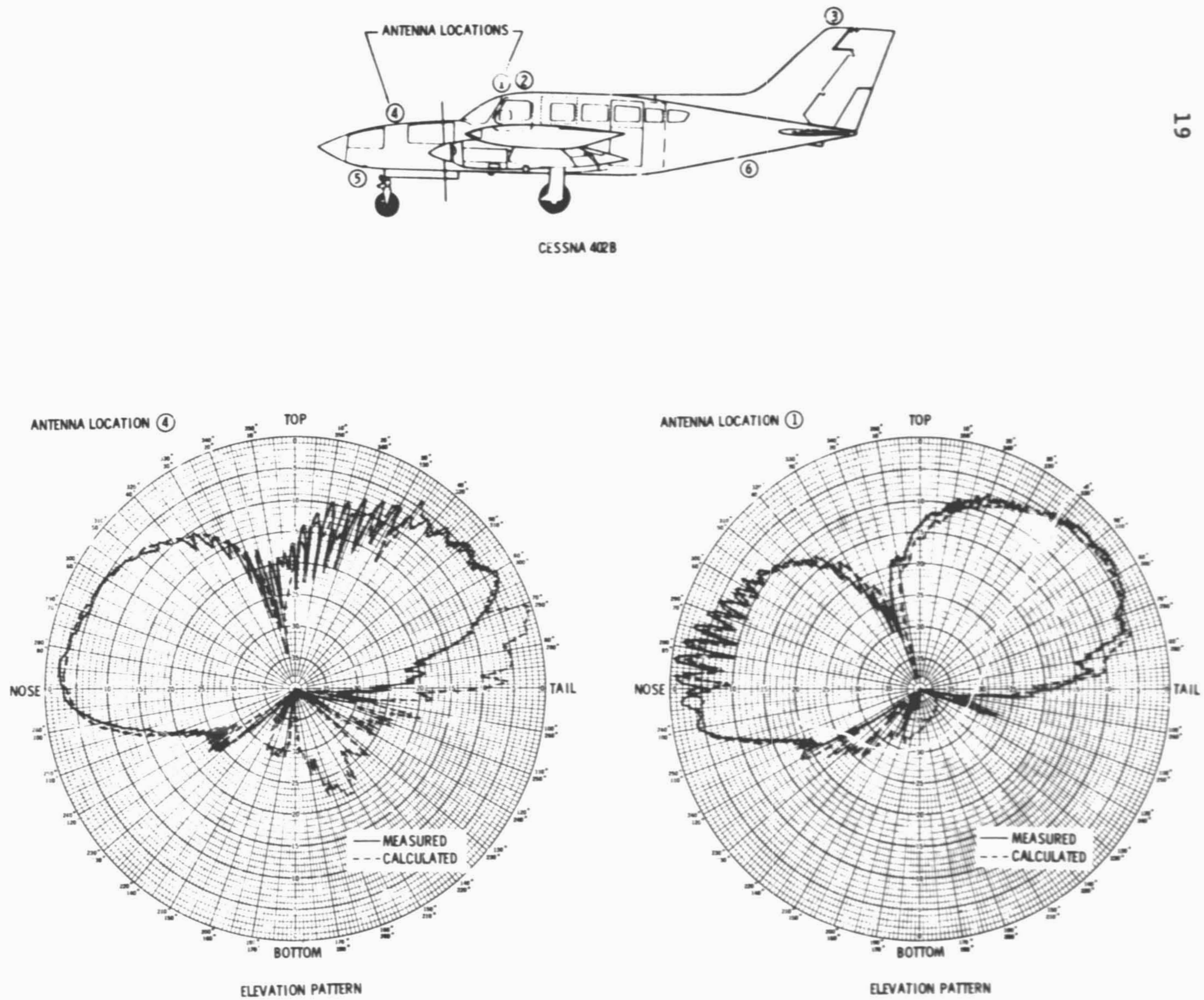
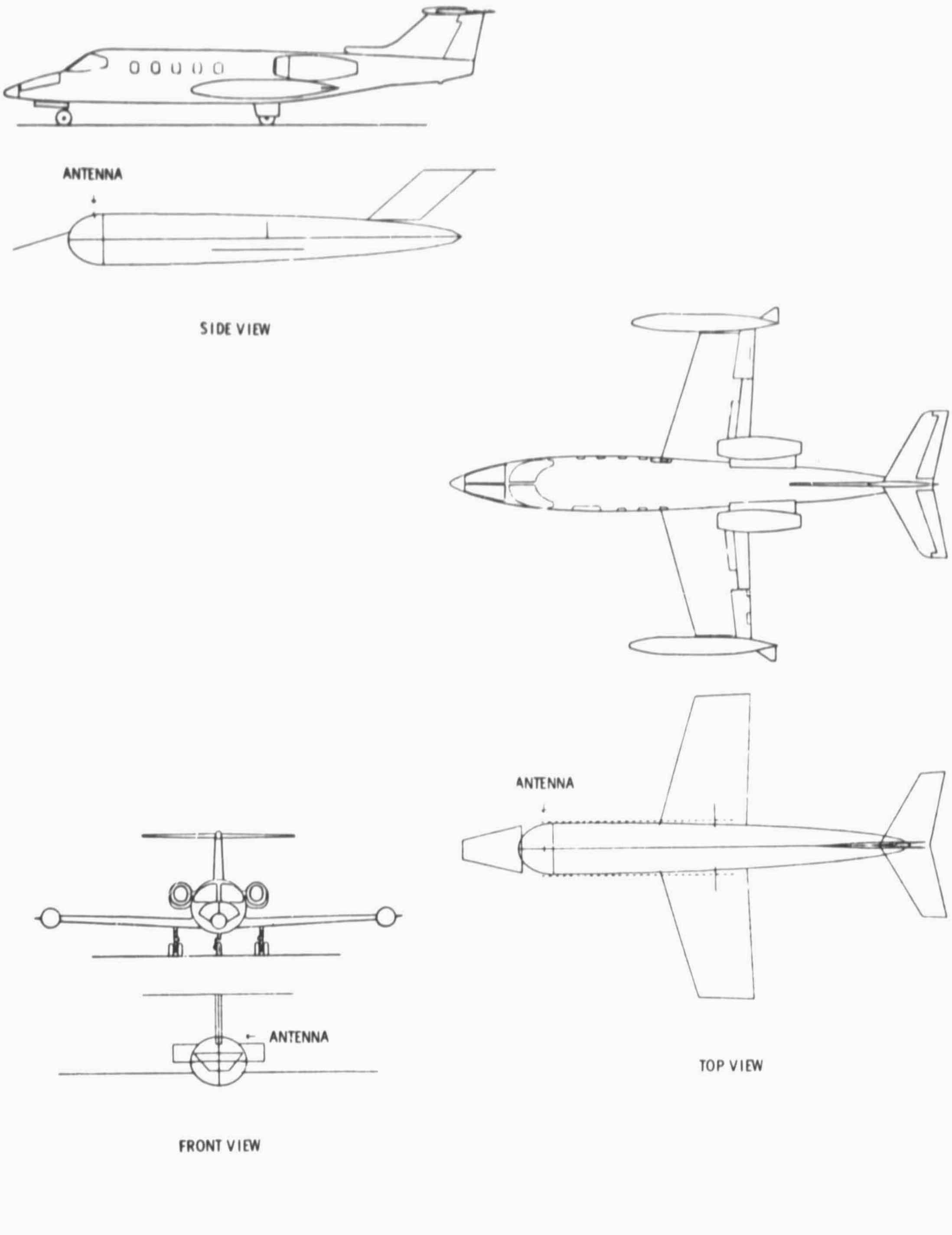


ELEVATION PLANE PATTERNS FOR A MONOPOLE AT DIFFERENT LOCATIONS ON A ONE-SEVENTH SCALE CESSNA 402B

Figure 6-13

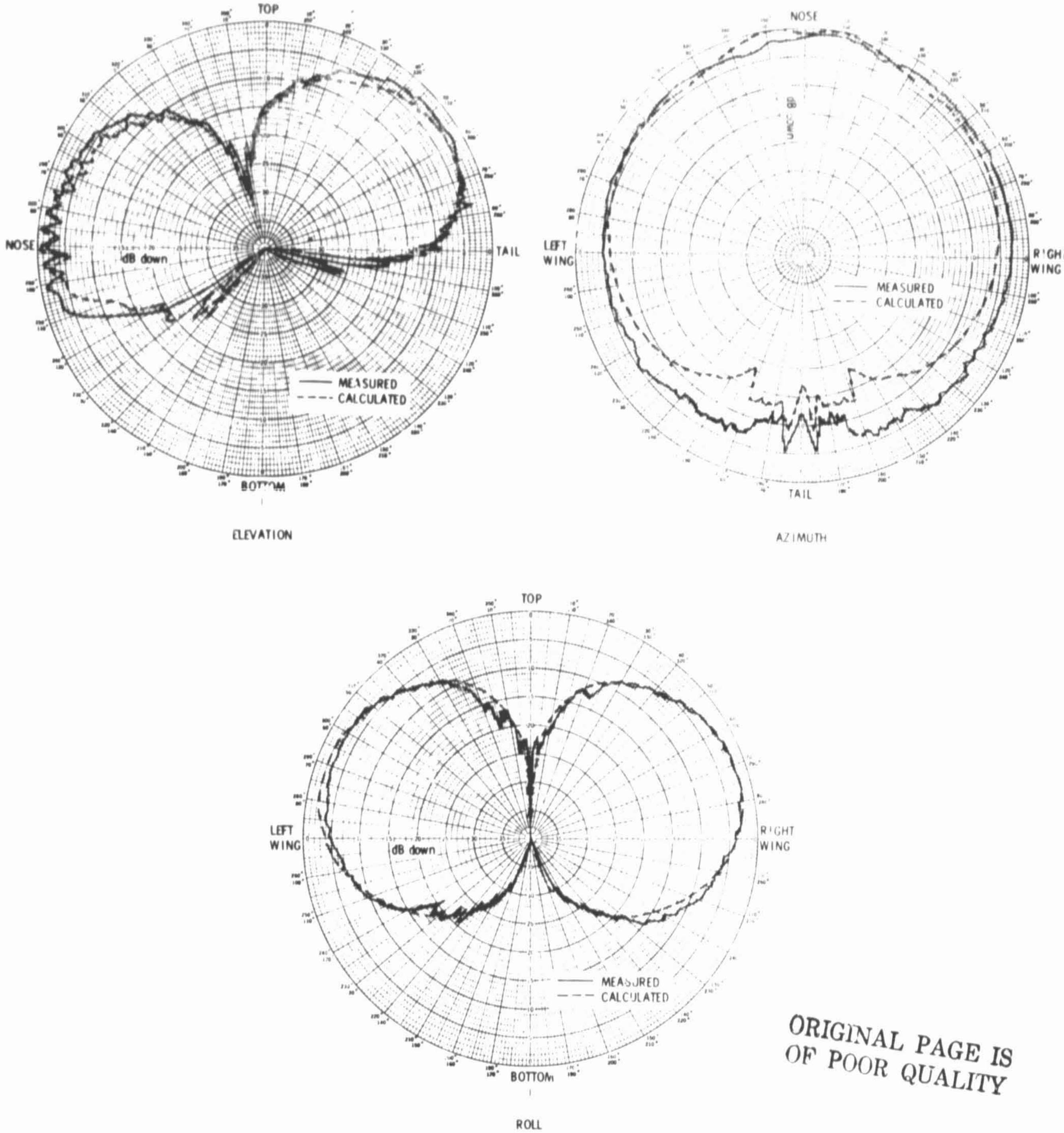
20



COMPUTER SIMULATED MODEL OF GATES LEAR JET WITH MONOPOLE LOCATED ON THE TOP FORWARD FUSELAGE.

Figure 6-14

21



MEASURED AND CALCULATED PATTERNS FOR A MONOPOLE ON THE TOP FUSELAGE OF A ONE-SEVENTH SCALE GATES LEAR JET.

Figure 6-15

ACCOMPLISHMENTS

- COMPUTER PROGRAM AVAILABLE FOR PREDICTING VOLUMETRIC PATTERNS OF FUSELAGE MOUNTED ANTENNAS ON COMMERCIAL AIRCRAFT. PROGRAM SUPPLIED TO THE FOLLOWING -

MARTIN-MARIETTA
LOCKHEED-GEORGIA
ROCKWELL INTERNATIONAL
HUGHES AIRCRAFT
E-SYSTEMS
SINGER AEROSPACE
R. C. HANSEN, INC.

BELL AEROSPACE
GENERAL DYNAMICS
CALIFORNIA STATE
TRW, INC.
AIL
HARRIS CORPORATION
BOEING COMMERCIAL AIRPLANE CO.

- COMPUTER STUDY OF MLS ANTENNA LOCATIONS ON COMMERCIAL AIRCRAFT COMPLETED (REPORT AVAILABLE)

BOEING 707
BOEING 727
BOEING 737
BOEING 747
BOEING YC-14
JETSTAR II

LOCKHEED C130E
LOCKHEED L100-20
LOCKHEED L-1011
MCDONNELL DOUGLAS DC-9
MCDONNELL DOUGLAS DC-10
MCDONNELL DOUGLAS YC-15

- FLIGHT TEST EVALUATION OF MLS ANTENNAS ON TCV AIRCRAFT COMPLETED

Figure 6-16

CURRENT ACTIVITY

- IMPROVING COMPUTER PROGRAM CAPABILITY FOR ANALYZING MORE COMPLEX AIRCRAFT (ADDITION OF ENGINES, MAIN LANDING GEAR, WING TANKS, HORIZONTAL STABILIZER, COCKPIT)
- DEVELOPING COMPUTER PROGRAM FOR ANALYZING LOW FREQUENCY EMERGENCY LOCATOR TRANSMITTER ANTENNAS ON G/A AIRCRAFT
- CONDUCTING EXPERIMENTAL STUDIES OF MLS AND ELT ANTENNA LOCATIONS ON SCALE MODEL G/A AIRCRAFT
- CONDUCTING COMPUTERIZED STUDY OF MLS ANTENNA LOCATIONS ON G/A AIRCRAFT
- GPS
  - DEVELOPING ANTENNA DESIGN FOR UPPER HEMISPERICAL COVERAGE
  - MEASURE ANTENNA PERFORMANCE ON SCALE MODEL AIRCRAFT
  - COMPUTERIZED STUDY TO DETERMINE ANTENNA PERFORMANCE ON OTHER G/A AIRCRAFT

Figure 6-17

N80-21307

Dr. Francis D. Natali
(Title)
Stanford Telecommunications, Inc.

We can say some problems are winners and some problems are losers. The problems you get a solution to are winners, and they are nice to work on.

Some problems are very difficult, and I stay away from them. Conceptually, designing a low-cost receiver today is a winner, while building a low-cost receiver today is a loser because it is not 5 years from now. Maybe it doesn't have to be that low-cost today; but all I can do is try to come up with a configuration that maybe I can build tomorrow, and it is a little less expensive than what is being built today, without having it all in LSI. Then if we put it in LSI, maybe it will be cheaper than that original complex block diagram. Maybe. I don't know, but this is the only way I can approach the problem.

What I would like to come up with is a design for a low-cost GPS receiver that has some flexibility in it, so if we have some good ideas for simplifying the thing, we can work on those today and see where it is going.

The objectives of our study are to investigate the design of a low-cost receiver for general aviation users which meets all IFR requirements for 2D RNAV; to evaluate the potential positioning capability of the receiver design; and to define experiments for validating the performance characteristics of the receiver design during Phases I and II. So, if we are going to design experiments, we are talking about some equipment.

Figure 7-1 shows what are understood to be the navigation accuracy requirements. The main thing to notice is, as shown in the last column of this figure, we are talking about a couple of thousand feet as the end accuracy. Now maybe we can do better, but we aren't talking about 10 meters. Maybe you can do 10 meters, but we aren't talking about that right now.

The assumptions that have been made so they can work on the problem are: Operate with an L_1 C/A signal only; minimum received power available is 160 dBW; the dynamic environment for the typical user is low (200 knot speed and .5G acceleration); there is no intentional jamming; and unintentional RFI may be present.

Our approach is to design a low-cost receiver based on today's technology and using a minimum of specialized LSI; design a receiver of minimum circuit complexity; and minimize the use of critical components. This last item is thought to be really important. A reference oscillator today costs $600. Maybe that same oscillator in quantity in 5 years is going to cost less. I'm sure it will. I'm sure it costs less today in quantity, but wouldn't it be nice if we didn't need a 10^{-9} oscillator? That is something to think about.

Other approaches are to emphasize microprocessor technology as opposed to special-purpose LSI--which seems to make a lot of sense at this point in the game just because of the flexibility involved and the way the microprocessor technology is going.

Consider special analog/digital chip fabrication where appropriate, and consider the tradeoff between analog and digital circuitry. We all like it. I like it, but there are many things that are made a lot more cheaply in analog form. You have to, if you are using analog components, have a circuit that can tolerate variations associated with that analog component, so we will see what happens there.

Figure 7-2 shows a low-cost GPS receiver configuration. Basically, we are talking about a single sequencing tracking channel. This is sequenced at 200 milliseconds per satellite, so it is sequencing much more rapidly than most of the receivers that have been built in the past.

The reason for this is because that means a much less critical or much less accurate master oscillator can be used. If you look into that, it turns out that this receiver is compatible with a 10^{-7} oscillator. If you have a slower sequencing time, the master oscillator accuracy has to go up, so that is one of the main points about this sequencing receiver.

Now we also consider tracking more than four satellites, like five or six satellites because of the banking problem, and we can do that in 1 or 1.2 seconds, depending on how many

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satellites we are tracking. Separate data channels are shown in Figure 7-2.

Our idea for minimizing circuit complexity is first of all to have a single conversion down converter with one phase-locked multiplier. We strip the code directly at 70 megaHertz; and the tracking channel is a noncoherent tracker, which uses a single correlator. Now this is both in the data and in the tracking channel. Most receivers have one correlator for tracking and another for signal processing and data stripping, and what I am doing is using one correlator for doing the Tau-dether, plus taking data. I sacrifice signal strength and throw away one correlator.

Our other ideas to minimize circuit complexity include single correlator tracking and data collection; one sequencing, noncoherent tracking channel; one data channel; and data detection and some tracking functions performed by the microprocessor.

What I have tried to do to minimize critical components is baseband correlation filtering; 10^{-7} master oscillator; use of a microprocessor rather than LSI wherever possible; trade off analog-versus-digital circuit implementations; and one VCO per channel--which is used in a lot of receivers. The receiver has continuous phase tracking. You use the frequency reference from the carrier tracking loop divided down and then have a continuously operating digital phase shifter.

The receiver that is described in our final report is designed to be able to tolerate a fairly cheap analog VCO. That doesn't mean that is the way you do it. With any luck at all, you go to a digital VCO, which we build all the time; but this thing is designed to be able to handle a much less expensive VCO.

The microprocessor receiver functions that we are counting on now are just the very slow ones--noncoherent and Costas baseband detectors, tracking loop filters, and all the data detection technology.

Figure 7-3 gives a bit of an idea of how the receiver is configured.

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I guess we learned some lessons in the early GPS receiver development work about microprocessor throughput. That is why this one is only handling low-speed functions at the moment.

Shown in Figure 7-4 are some of our receiver accuracy estimates. These are just the pseudoranging accuracies. Briefly, we assign 50-foot, 1 sigma error due to receiver tracking error; quantization error, 15 feet; and clock drift, 40 feet for a 200 millisecond dwell interval. The composite accuracy that we estimate is about 100 feet RSS due to the receiver.

Some of the study areas that we are continuing to look at are analog/digital circuit implementations; what functions should go in the microprocessor; a hybrid baseband correlator chip, including the A/D conversion function; single-channel versus two-channel implementation; and the antenna design.

QUESTION (Dr. John M. Painter, TAMU) - Is someone developing the hybrid baseband correlator chip?

ANSWER - Our company is looking at the possibility of developing it.

QUESTION (Dr. Painter) - Do you have that kind of capability out there?

ANSWER - Not in-house. We may have the consultants. We are looking at what function should be in it, but we wouldn't develop it ourselves.

QUESTION (Dr. Anil Joglekar, MITRE) - Do you assume that you will have an encoding altimeter to be interfaced?

ANSWER - It is not interfaced. What we assume is that we only have to give the 2D position. If the operator is in an airplane and he needs altitude, he gets that himself. We don't use it.

QUESTION (Dr. Joglekar) - For your solution?

ANSWER - We don't use the altimeter. We don't output altitude, but we don't use the altimeter.

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QUESTION (Dr. Joglekar) - Your design assumes no intentional jamming. There might be other RFI at that band.

ANSWER - That's right.

QUESTION (Dr. Joglekar) - And then the whole design would not work.

ANSWER - It depends entirely upon the levels of the RFI. That's absolutely right. If you don't have enough signal, I can't do it. That's true.

QUESTION (Mr. James Van Cleave, American Electronics Laboratories) - You went from a 10^{-9} to a 10^{-7} oscillator, which is a hundred to one, and you rationalize this on the basis of going from 1 second to 200 milliseconds.

ANSWER - I didn't. In my design, I did not start with the 10^{-9} oscillator. I did the design to the 10^{-7}. All I am saying is that I believe the other receivers use about a 10^{-9} oscillator. I don't have anything to do with that oscillator.

QUESTION (Mr. Edward F. Prozeller, Applied Physics Laboratory Division, Johns Hopkins University) - In your error budget, you did not include an error term for the presence of the C/A signals from satellites other than the one you are trying to track. It appears to me that could be a large term.

ANSWER - You're telling me! I am presently very, very concerned about this problem. Of course, since I ran the original signal design study, I have been concerned about that problem for many years. I don't feel that problem has been looked at in enough depth.

Now, if you look at it, in most cases, I don't think it is a problem, but there are some cases where I suspect that it may very well be; and I am presently writing up a task description trying to get an effort started to look at this problem. I think it is a really good point, and you're right. It is not up there. We haven't done the problem sufficiently. I don't think anyone has.

<u>QUESTION</u> (Mr. Lawrence Kennedy, Canadian Transport) - Did you mention whether a steerable array antenna was used for this type of receiver?

<u>ANSWER</u> - We are thinking about various antennas. I don't need a steerable array.

<u>QUESTION</u> (Mr. Kennedy) - It is not required in this case?

<u>ANSWER</u> - Not for these satellites.

<u>QUESTION</u> (Mr. Kennedy) - Is there a separate code for each of the satellites?

<u>ANSWER</u> - Each satellite has a different code, but there might be reasons for using a steered array. One of them might be the multiple access problem.

<u>QUESTION</u> (Mr. Joseph Koyne, Transportation Systems Center) - What about the problems of multipath in your design? Have you considered that, and how will it work in the present multipath?

<u>ANSWER</u> - I don't know what to say. The multipath problem is present for everyone; and we can estimate how it is. Everyone is trying to take data to find out exactly what it is. That is being taken into account in the simulations and so forth.

We know the multipath problem. For a given amount of multipath, we know how much error it causes. Exactly how much we are seeing. People are taking data all the time, and they are trying to estimate what those errors will be. That doesn't enter into the receiver design because the receiver can't do much about it.

It does enter into the antenna design, but I can't tell you right now how much of a problem this is going to be, under what conditions. We don't have enough data, or I certainly don't; but that is certainly a problem that is being looked at for everyone.

<u>QUESTION</u> (Mr. Kennedy) - There are some who believe the large time/bandwidth product of the signal is such that multipath is not a problem.

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<u>ANSWER</u> - It sure helps. On the P signal, it helps especially because the time/bandwidth product is quite large; and so for path differentials greater than 150 feet, it is no problem.

In most receivers, you don't see any multipath.

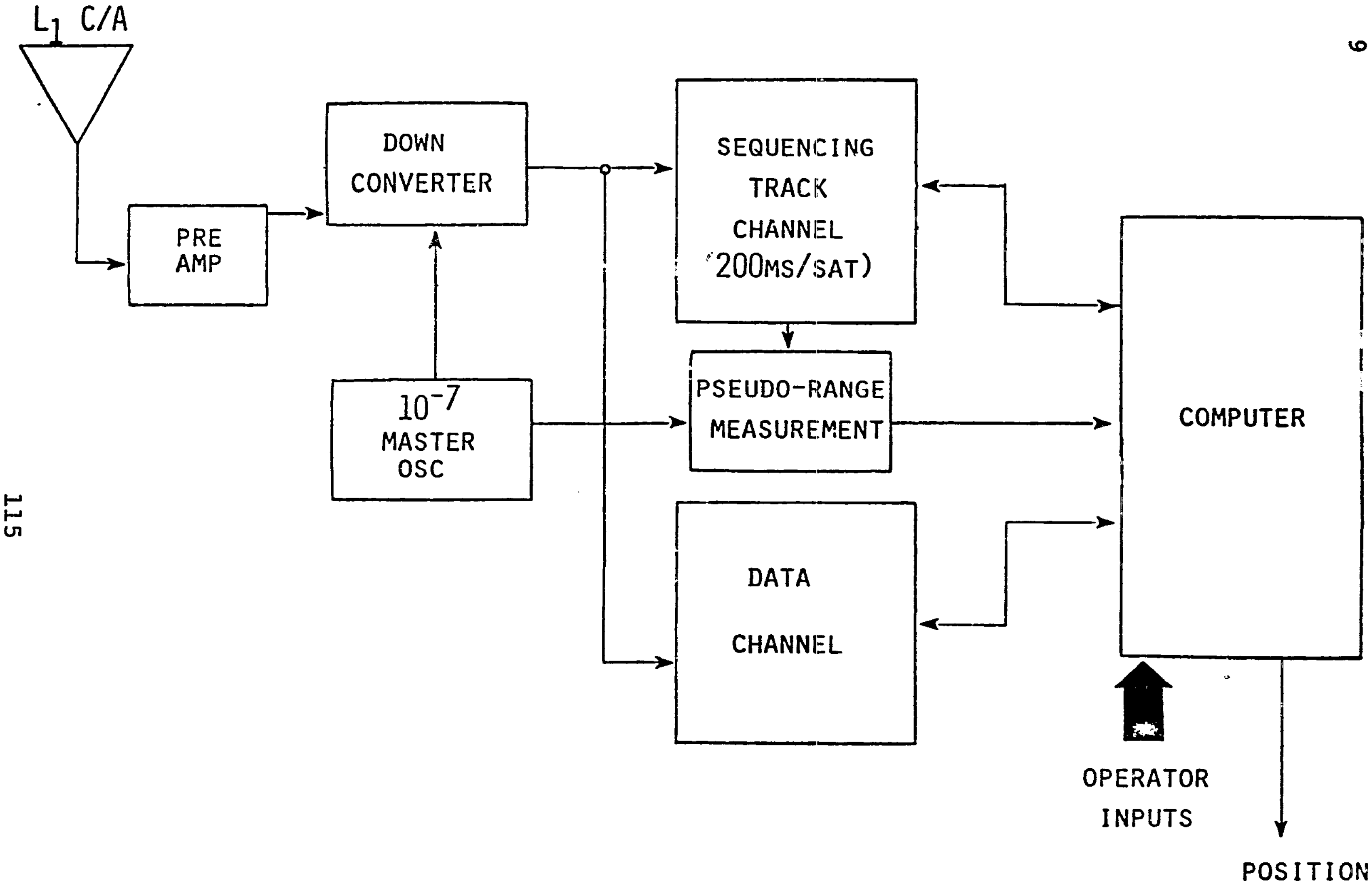
That is one of the objectives of the P signal design. The C/A signal design rejects path differentials that are greater than about 1,500 feet. It doesn't have nearly the multipath rejection that the P signal does, so it can be more of a problem. But yes, the product certainly helps. The larger, the better. The C/A signal isn't terribly large. It is sure better than a side tone ranging signal.

NAVIGATION ACCURACY REQUIREMENTS

APPLICATION	ERROR CATEGORY		TOTAL SYSTEM ERROR*	FLIGHT TECHNICAL ERROR*	USER EQUIPMENT ERROR
2D RNAV (2σ)	CROSS TRACK	EN ROUTE	2.5 NM	2.0	1.5 NM (9000')
		TERMINAL	1.5	1.0	1.2 (7200')
		APPROACH	0.6	0.5	0.5 (3000')
	ALONG TRACK	EN ROUTE	1.5	NOT SPECIFIED	1.5 (9000')
		TERMINAL	1.1		1.1 (6600')
		APPROACH	0.3		0.3 (1800')

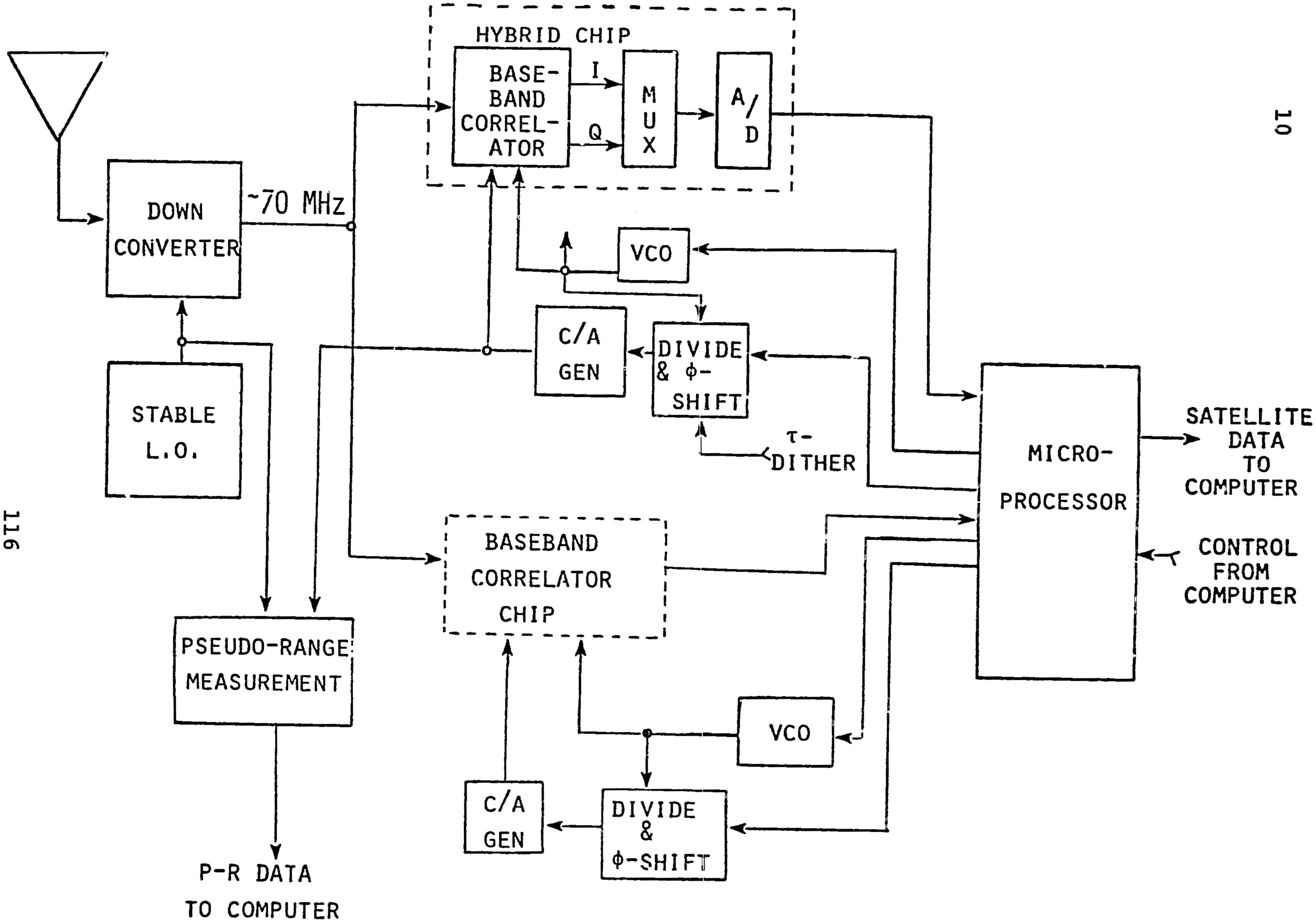
*REFERENCE: FAA ADVISORY CIRCULAR 90-45A "APPROVAL OF AREA NAVIGATION SYSTEMS FOR USE IN THE NATIONAL AIRSPACE SYSTEM" 21 FEBRUARY 1975

Figure 7-1



LOW-COST GPS RECEIVER CONFIGURATION

Figure 7-2



TRACKING AND DATA LOOP CONFIGURATION

Figure 7-3

RANGING ERROR BUDGET

ERROR CONTRIBUTORS		VALUE (1σ)	REMARKS
RECEIVER	PSEUDO-RANGE NOISE	50 FT	
	PSEUDO-RANGE QUANTIZATION	15 FT	50 NS COUNTER QUANTIZATION
	CLOCK DRIFT	40 FT	OSC. $\Delta f/f = 10^{-7}$; 200 MS/SAT SEQUENCING
	COMPUTATIONAL	T B D	ACCURACY vs SPEED TRADEOFF
SPACE SEGMENT	EPHEMERIS UNCERTAINTY	5 - 20 FT	EQUIVALENT UERE (HIGHER FIGURE ONLY FOR UPDATES EVERY 2 - 3 HOURS)
	SAT. CLOCK BIAS & GROUP DELAY	3 FT	
PROPAGATION EFFECTS	IONOSPHERIC DELAY UNCERTAINTY	10 - 30 FT	WITH CRUDE MODEL
	TROPOSHERIC DELAY UNCERTAINTY	< 10 FT	WITH CRUDE MODEL
	MULTIPATH	0 - 50 FT	ENVIRONMENT DEPENDENT
MOTIONAL EFFECTS	AIRCRAFT	< 10 FT	1 SEC UPDATE RATE; 200 MPH A/C
	SATELLITES	< 3 FT	200 MS/SAT SEQ.;
COMPOSITE		~100 FT	(RSS)

Figure 7-4

N80-21308

Robert V. Nino
Teledyne Systems Company

Some of the topics I would like to cover are the need for GPS in general aviation, a little bit about design philosophy, and some design approaches. I will suggest some goals; we will see the $2,000/set goal which everybody is striving for; and then we will show a little bit of our supporting experience that we have done something like that in a less complex system. I will try to draw a few conclusions.

The need for better navigation is apparent in the FAA forecast (as reported in the Los Angeles Times on March 5, 1978) for the area around southern California which shows that the number of commercial passenger departures is going to about double between now and 1990, and the number of general aviation landings and touchdowns is going to do about the same thing. Also, it is known that the airspace density of aircraft is expanding very rapidly; and as time goes on, the private pilot is going to need to know his position and flight path with more and more precision. I contend that time-correlated position tends to minimize collision problems and help him along.

Let's discuss design philosophy. Figure 8-1 shows some of the design approaches to a low-cost GPS receiver/processor. The first objective is to minimize the functions and the amount of hardware--motherhood. That will reduce the complexity and drive down the cost. We are looking at a single-code tracker, C/A. It could possibly be a P code, if you can figure out some effective way of initializing it.

We are talking about putting some of the complexity on the ground. In the military set, we initialized through an X set, which is also carried along with the mother aircraft. We are also talking about things like possible monitor stations on the ground which might initialize you for takeoff or give you some update information. You are expected to get better accuracy than C/A, and this may be a way to do that.

In Figure 8-1, we are talking about a single-channel multiplexed receiver; eliminating or reducing avionic interfaces; and use of present-day technology. Of course, we

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want to simplify the antenna coupler into one unit. Maybe we can do this by imposing more modest requirements, possibly five or so times less accurate than the ultimate. We can also do this by backing off on the vehicle dynamics, limiting the navigation accuracy, and relaxing some of the requirements that are more important in the military area: acquisition time and recovery time.

Of course, more motherhood would be to promote standardization and competition. The goal is to provide significant improvement to many users rather than to give the ultimate performance to just a few.

In our design approach, Figure 8-2 gives a number of accuracy considerations. If you look at TACAN, as we know it, something in the order of half a mile and bearing around 3 degrees is achievable; we can provide .6 of a mile position error at 10 miles.

You can't get airspeed unless you develop it with some sort of an aid, inertial or otherwise, in which case you get 2 percent in GPS; and here, for the sake of argument, we have put in the P code.

The 10.23 megahertz chipping rate, 100 feet per chip, could give you .01 of a nautical mile worldwide; but you are trading .3 of a foot per second velocity. This would afford you some fuel saving.

Figure 8-3 illustrates the same sort of thing, simplification. The block diagram at the left is a typical four-channel set today; and if you go to a single-channel set, you eliminate the first three blocks on the right and go to either P code or a C/A code tracker, but not both.

Simplifying further, we want to do things like eliminating the Costas loop or phase-lock loop and perhaps use an AFC carrier loop. The tradeoff here is an accuracy of 3 to 5 feet per second versus an increase in complexity. Another tradeoff is tolerance to signal dynamics versus cycle slips.

Another technique is to eliminate the rate aiding for high dynamics and use the wide-bandwidth tracking. Here the tradeoff is cost versus increased noise sensitivity and

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decreased vehicle dynamics capability. A reduction from two antenna configurations into one single antenna, polarized or some combination that will give you the characteristic, is another simplification area being studied. In trying to tackle the oscillator problem, if you can get away with something cheaper than an ovenized clock, that would certainly work in your favor.

Some other aspects of the design are the stand-alone receiver, which is similar to commercial receivers, in contrast to an integrated receiver that is tied into other systems. The problems here concern such things like antenna shadowing, transmitter interference. You don't want the GPS antenna to look directly at some other antennas on the vehicle. The integrated receiver would provide a more complete aid to navigation, but at increased cost. You trade off this with a feasibility study. There are other problems because of the need to standardize.

A civil GPS possibly could use a P code instead of a C/A code. The problems would be complexity (although this would not be so bad if you could use only one L channel) and in initialization.

Figure 8-4 contains a diagram of the replaceable module sets of the basic GPS receiver-processor. This is not too different from the other sets (shown in Figure 8-3) that we are pursuing in low-cost receivers.

Figure 8-5 gives a brief sketch of how we would derive and utilize the airspeed, heading, and VOR information and in a GPS-aided navigation system.

The most controversial part of our design approach is the need for independent FAA/NASA monitoring, if you feel that general aviation needs some real-time availability data. Possibly FAA has a comfortable feeling of leaving it all to the Air Force, not knowing what is happening in the satellites. But, I think there is probably a need for some monitor stations, not so much to duplicate the job the Air Force is doing, but to be able to react in real time and give some advisory information as to what can be done in the event certain satellites become unavailable. So we see that the FAA may want to install a network of monitor

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receivers at various airports and centers and provide weather, hazard warnings, and so forth, along with some initialization information which could be handled through the surface channels.

Our suggested goals are set forth in Figure 8-6. Included is the popular cost of $2,000. Of course, we are blue-skying here. If the units were of the size shown, they might be dissipating 80 watts, or even less. GPS would give you 60-meter position worldwide and day of week, hour, minute, and second. I'm not quite sure what the pilot would do with .2 of a microsecond time, but it will be there if needed.

There is supportive data (which was shown at the conference and centered around the TDL 711 LORAN experience) to show that there is some substantiation for the fact that we can drive cost down and come up with equipment that general aviation will be able to afford and utilize.

So in conclusion, I believe everybody agrees that GPS is coming, and we believe there is a definite place for GPS in general aviation. We think that suitable designs are achievable, and we would like to urge civil aviation to continue to monitor DOD programs and FAA and NASA to continue their planning to prepare for the GPS.

QUESTION (Mr. Joseph Gutwein, Transportation Systems Center) - Do you ever see the GPS receiver costs dipping below the cost of the LORAN-C receiver?

ANSWER - I don't see it, not right now. It depends on what time period you are talking about, but I don't see it right now.

DESIGN APPROACH TO LOW COST GPS RCVR/PROCESSOR

DESIGN PHILOSOPHY

MINIMIZE FUNCTION AND HARDWARE (REDUCE PARTS COUNT AND COMPLEXITY)

- SINGLE CODE TRACKING, P-CODE ONLY
- SINGLE CHANNEL MULTIPLEXED RCVR
- REDUCE OR ELIMINATE AVIONIC INTERFACES
- UTILIZE STANDARD MICRO PROCESSOR TECHNOLOGY
- SIMPLIFY ANTENNA/COUPLER

IMPOSE MODEST REQUIREMENTS (5X TACAN ACCURACY)

- MODERATE VEHICLE DYNAMICS
- LIMIT NAV ACCURACY
- RELAX REACTION TIME
- RELAX RECOVERY TIME

PROMOTE STANDARDIZATION AND COMPETITION

- STANDARD EXTERNAL CONFIGURATION
- MODULAR INTERNAL DESIGN (MFR's OPTION)
- ENCOURAGE COMPETITIVE SOURCES

GOAL: PROVIDE SIGNIFICANT IMPROVEMENT TO MANY USERS INSTEAD OF ULTIMATE PERFORMANCE TO FEW

Figure 8-1

T122267

ACCURACY CONSIDERATIONS
DESIGN APPROACH

SYSTEM	CHARACTERISTICS	POSITION ERROR	GROUND VELOCITY
TACAN	RANGE ACC ≈ 0.5 NM BEARING ACC ≈ 3^{0}	0.6 NM @ 10M	AIRSPEED 2% (NOT DEVELOPED EXCEPT WITH INERTIAL OR DOPPLER-NAV SYSTEMS)
GPS	10.23 MHZ CHIPPING RATE* (100 FT/CHIP)	<.01 NM WORLDWIDE	.3 TO .5 FPS (PERMITS COURSE-TO-FLY FOR FUEL SAVING)
	IONOSPHERIC ERROR 50 FT	(≈10 NS TIME)	
	GDOP** = 6 (WORSE CASE)	[PERMITS TIME-CORRELATED POSITION]	

* CHIPPING RATE OF P-CODE IN BPS
** GDOP IS GEOMETRIC DILUTION OF PRECISION

Figure 8-2

TI22268

GPS EQUIPMENT SIMPLIFICATION FOR GENERAL AVIATION

DESIGN APPROACH (CONT)

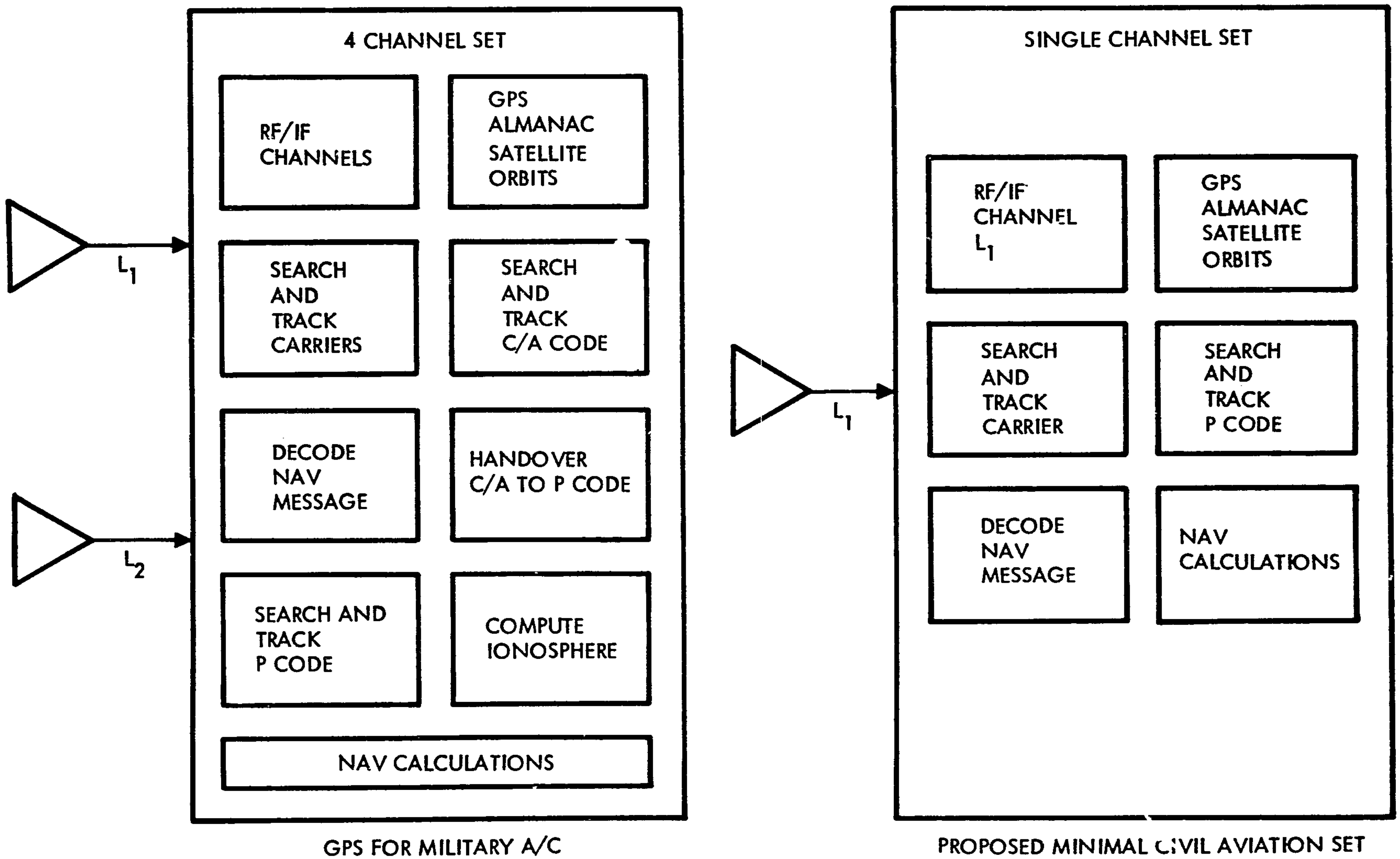


Figure 8-3

T118153

THE REPLACEABLE MODULE SETS OF THE BASIC GPS RECEIVER-PROCESSOR

DESIGN APPROACH (CONT)

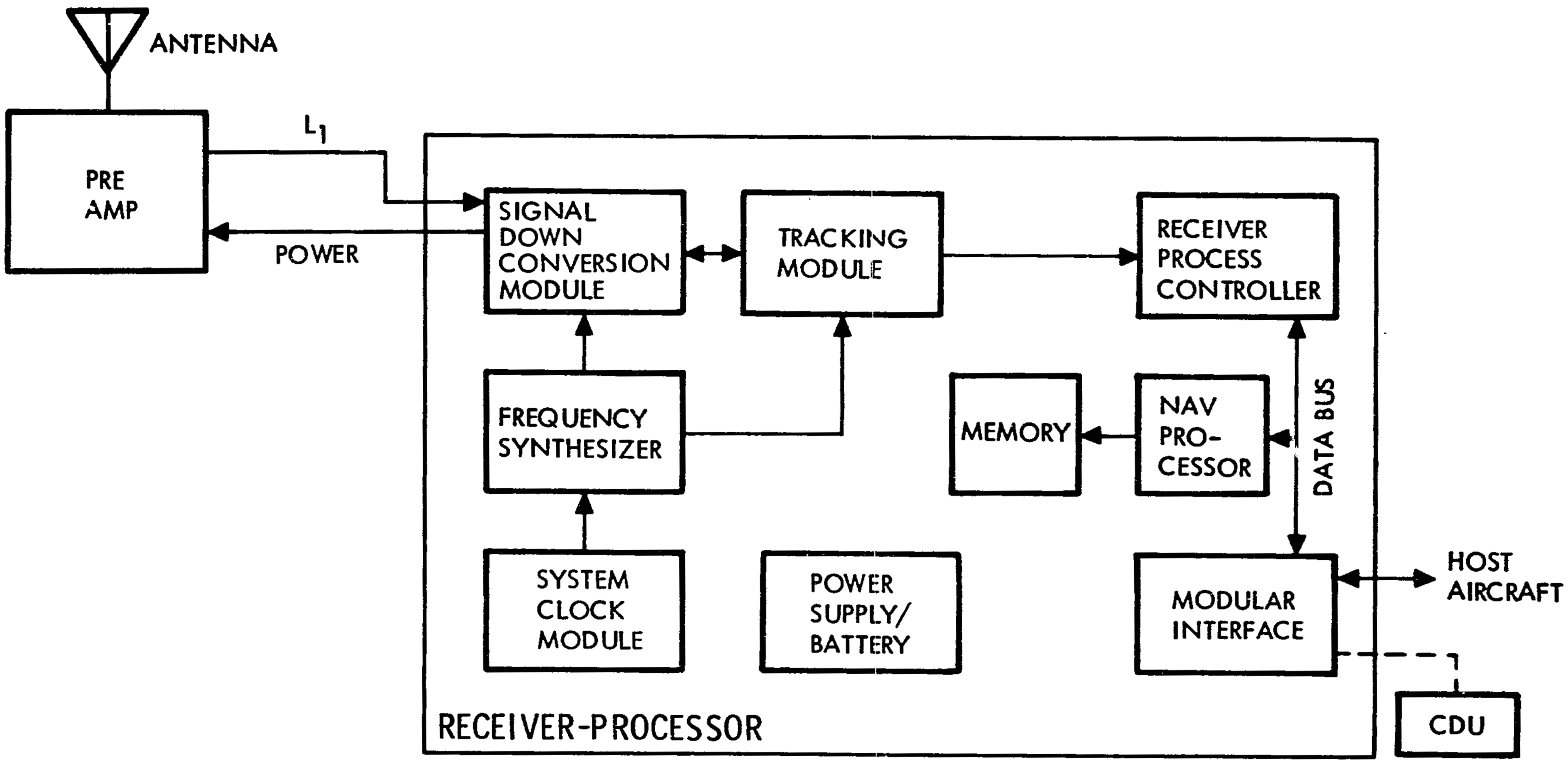
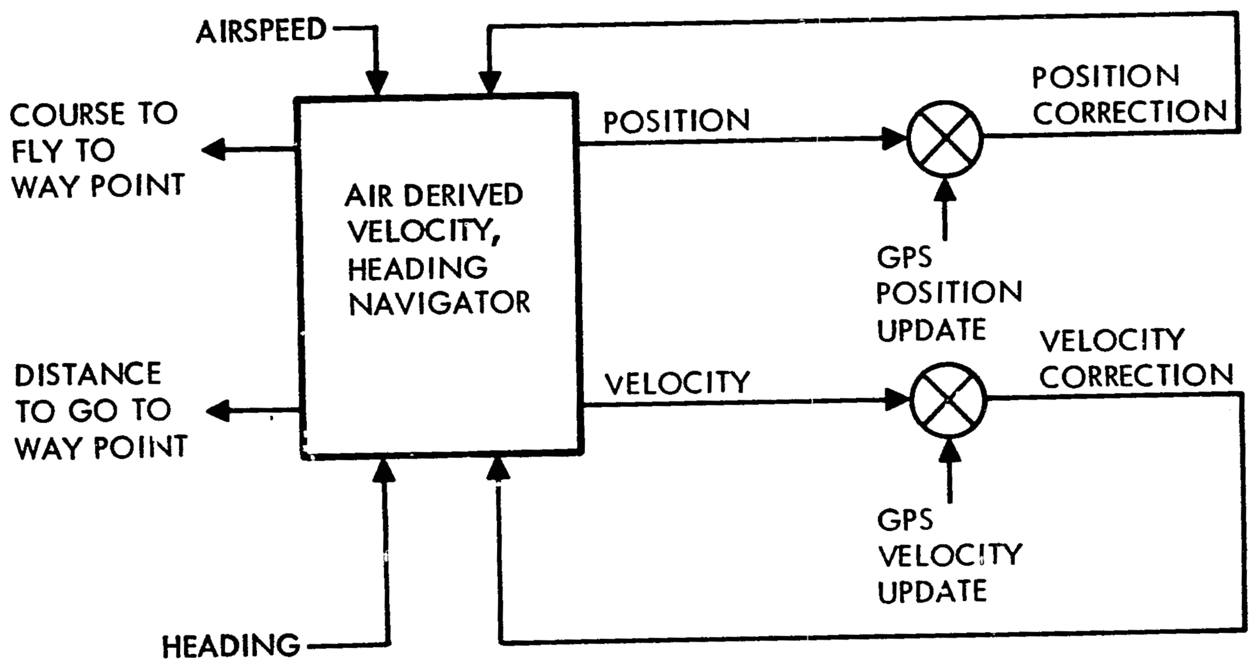


Figure 8-4

TI14623B

NAVIGATION UPDATE CONFIGURATION FOR GENERAL AVIATION NAVIGATION

DESIGN APPROACH (CONT)



- SINGLE CHANNEL GPS – UPDATE EVERY 40 TO 120 SECONDS

Figure 8-5

TI15269A

SUGGESTED GOALS

COST: LESS THAN $2,000

RELIABILITY: 3,000 HOURS MTBF OR MORE

MECHANICAL:	SIZE (CM)	WEIGHT (KGM)
1. ANTENNA/COUPLER UNIT (ACU)	6H X 6W X 9W	0.3
2. CONTROL AND DISPLAY UNIT (CDU)	11H X 11W X 16W	2.0
3. RECEIVER/PROCESSOR (RPU)	19H X 19W X 30W	10.0
4. STEERING DISPLAY INDICATOR (SDI)	7.6D X 14.5L	0.2

POWER:

18 TO 32 VAC OR 115V 400 HZ, 3ϕ, 80 WATTS

ENVIRONMENT:

OPERATING TEMPERATURE: -15^{0}C TO $+55^{0}$C ($+70^{0}$C SHORT TIME)

ALTITUDE - (UNPRESSURIZED): 6,000 METERS

GPS DATA:

PRESENT POSITION (LAT/LONG/ALT): 60 METERS (WORLDWIDE)

TIME: (GMT) DAY OF WEEK, HOUR, MIN, SEC; 0.2 MICROSECOND

Figure 8-6

TI22272

N80-21309

Dr. Philip Noe
Texas A&M University

As was pointed out, a GPS truly is a very complex system if you consider it across its broad aspects of the space vehicles and the launching systems that are involved and the receivers as well. You might say it is about as complex as any system of this type that I have ever been involved in, being a digital system type primarily.

I first got a feeling about this area and decided that I really wanted to look into it more and see if I could get a little bit better understanding of the communications systems that were involved here. So I picked up R. C. Dixon's book on Spread Spectrum Systems and I read it through once; and I said, "Well, I still don't know anything about it."

As a concerted effort thereafter from that time on, in 1975 I made it an effort to learn more about it; and my friend, Mr. Thomas Rhyne, said, "You know, GPS really is a complicated system. It is almost in some ways as complicated as it was for the Egyptians to build the pyramids." He said, "No, no, it is more like the U.S. problem when we put a man on the moon"; and then he said, "No, no, it is really like the Egyptians trying to put a man on the moon."

You know, sometimes it is like, again like Dr. Francis Natali said, maybe we should ask them to give us a simpler problem; and sometimes the answer may not be to build a better mousetrap, but to find an easy rat.

Enough of the introduction. I brought two of my teammates with me so if I can't answer your questions, perhaps they can. We are from the Digital Systems Laboratory and Telecommunications Control Laboratory at Texas A&M University. The TAMU GPS program has been an interdisciplinary team involving Dr. John Painter, Dr. Tom Rhyne, and me, who bring together diverse specialties in terms of the various things that are necessary to solve the GPS program.

Since we have gotten into GPS, we have had some support from a NASA grant from the Langley Research Center and some Air Force grants from the Air Force Office of Scientific Research (AFOSR); and we have been involved with the Space Shuttle GPS panel and various private operations with industry. Our total effort goes hand in glove with what we are

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trying to accomplish here, namely, it is truly a low-cost GPS effort, much in the way that our funding has been a low-cost GPS effort.

The approach to low-cost GPS at TAMU has included the recognition of the fact that low cost is the controlling factor for widespread GPS use. In order to make GPS widely available across the world, it has been pointed out, as was addressed by Mr. Buige in his introduction, that we really would like to have a $2,000 GPS receiver available to the general public to make it competitive with other navigation systems.

I have been a visionary from that aspect. When I first got on board this problem, I saw it as a hand-held calculator type receiver that I could carry around for $500. If you stop and think about it, if you are going to build one and put it on the market for $2,000, that is what you are going to have to build it for, right around $500, because there is a hundred percent markup to the middleman, and again from there to the actual installation. Consequently, that is a pretty sizable chore and a goal to try to meet.

We have various factors that we are considering, much as many of the other designers have considered who got into GPS. The Stanford [STI] idea does pretty much parallel a lot of the things that we have done over the last 3 years. You have a cost-versus-position error tradeoff, cost-versus-fix rate tradeoffs, et cetera, et cetera; and the main thing that we have tried to look at to cut down costs, some factors that would be involved, would be no required coupling to other navigation systems, with a possible add-on feature of coupling for a VHF, UHF, or beacon transponder system for use in collision avoidance.

The keys that we feel are necessary for low-cost GPS implementation are minimum navigational accuracy requirements; minimum complexity positioning and navigation algorithms, which is one of the major areas that I have been involved in; analog and digital partitioning of the receiver processor in order to come up with the best possible cost configuration for the front end; microprocessor architecture for navigation and receiver control; careful organization of this portion of your receiver so that you can make maximum use of the power

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of multiprocessors or single micro computer architecture configurations; and last, but not least, the minimization of special-purpose digital hardware.

As a consequence of the importance of these keys to a low-cost implementation, minimum complexity satellite selection algorithms have been studied in detail. This is a major part of the problem as far as what takes up your computation time. Also efficient, accurate, minimum complexity positioning and navigation algorithms are necessary in order to maintain an accurate and efficient high rate of positioning. Also, a detailed study of integrated receiver processor architecture, fast PN ranging algorithms, and improved Costas loop techniques has been made.

As far as the minimum complexity satellite selection algorithms are concerned, most of our studies were made with a 600-mile-per-hour aircraft simulation of flight from California to Hawaii. I grant you that this is not a uniformly distributed user, but it gave us a good data base to use as simulation for the system. My first efforts along this line were made in June of 1975 at Wright-Patterson with Dr. Thomas Wu and Dr. (Major) Ken Myers at the Avionics Laboratory. We developed a set of optimal and suboptimal GDOP techniques for selecting satellites. In August of 1975, we compared the suboptimal technique against the standard GDOP computation that is shown in Figure 9-1. These results are for a four-channel receiver.

The major advantage here is what you have to do in terms of computation and a computational sense in order to find the optimal set of satellites for which selection is made to do your navigation process. If you have N satellites in view and you are going to select four satellites optimally, you have to consider N things taken four at a time in order to look at GDOP and make a selection. Just, for example, with N equal to 10, there are 210 matrix inversions you are going to have to do to obtain optimal GDOP solutions. The corresponding result with a clear channel receiver is a position error of the user of about 120 meters.

In the suboptimal computation, we made a discovery that we could produce almost as good a result by arbitrarily selecting, in a quadrature framework, satellites that were in the general direction of north, east, overhead, and then select the remaining fourth satellite by computing GDOP on all the rest of the satellites in view, after you have selected three in quadrature. As a consequence, you only require N minus 3 matrix inversions. That is only seven operations, when N is equal to 10 or roughly a 30-to-1 improvement of the computational efficiency.

I realize this gets boring, but it gets into the kinds of details of the sort of work we have been doing. This is what is necessary to do efficient algorithms: to look at this kind of detail, pick these kinds of things to pieces and see what kinds of improvements you can make as a result thereof. How do you cut down the amount of computation that is involved? How do you cut down the amount of software that is involved to store this computation when it turns out that maybe 50 percent (someone earlier quoted 21 percent) of your cost for the low-cost receiver is going to be involved with microprocessor and microprocessor memory? So if you can cut this back and cut it down by hook or crook or whatever technique it takes, then it is a very necessary part of the business.

As the next step in navigation algorithm development, instead of looking at a four-channel receiver, we looked at what would happen if you started taking range measurements sequentially in time. As a consequence of taking these range measurements sequentially in time, I decided what is the worst case in this situation, and that would be if you did no velocity aiding to those range measurements at all. If you took the four measurements, sequentially, but assumed that they were all taken simultaneously, what kind of fix would that give you? That is the worst case of the effect of the velocity on you, and that is what the March 1978 result in Figure 9-1 does with a new algorithm. As a consequence, a quadrature algorithm that relates instead of to north, east, overhead, and optimal GDOP, to on track, cross-track, overhead, and optimal GDOP will produce better results in an unaided velocity relationship.

Figure 9-2 shows the areas we have been considering with regard to minimum complexity navigation algorithms. For example, the Hotelling algorithm that I developed in 1975, which has robust convergence characteristics, will converge with accurate timing if you are even 6,000 miles off on your estimate of where you think you are. That's pretty good. We think we can accomplish the desired results, that reasonably

5

simple filtering will do the job. We will require a floating point processor, and we have done a considerable study of word length-versus-accuracy tradeoffs. In other words, what kind of word lengths do you have to have in order to come up with this hundred meter accuracy?

Figure 9-3 shows the results that we obtained after we had included velocity, moving our range measurements up in time to a common point in time much as an old-fashioned human navigator does with these shots, moving them to common LOP's (Lines of Position) in time. We do this sequentially, and the top curve in Figure 9-3 is navigation without a filter. It shows you that with up to 40 meters of range error, which I feel is the dominant error factor for this order of navigational accuracy, all the others are lumped into the system also. Consequently, the curve does not go to zero when range error is zero. With the complete other system errors in the solution, we allow Sigma R to go to zero, then increase Sigma R to see the effect of it.

It is necessary to determine and thus use the effect of range error to help you find out what your quantization level should be in measuring range within the receiver. As can be seen from Figure 9-3, 100 meters navigation error crosses the curve at a point where Sigma R is about 18 meters. To maintain a 100-meter position error, you would be out beyond 40 meters range error if you have the simple linear so-called "Alpha-Beta" filter that is well known in radar systems, or it is just a simple linear filter.

As a consequence, we concluded that we will be able to get this kind of accuracy and be able to obtain the 100-meter capability with a single-channel receiver as long as we do IQ ranging detecting, that is, in-phase and quadrature measurement. I guess everybody recognized that fact by now, and approximately a sixth of a bit PN quantization for our system.

In other words, at about sixth-bit intervals, you have a 300-meter bit length for the clear access channel code. Divide that by 6, which gives you 50 meters for the Sigma R. Then we divide that by the square root of 3 to give a uniform distribution. This results in a 100-meter position error with single-channel sequential ranging system.

6

I think these results emphasize the fact that the receiver processor will be necessarily microcomputer-controlled and will be capable of aiding the front end and doing the reacquisition of any satellite once acquisition has been achieved. Thus, if you do have a single channel, you are going to have to do this reacquisition and have some aiding in order to maintain a one-second fix rate, which is possible with this system.

Part of the research that we have also been involved in as a result of Dr. Painter's work with our NASA grant has been an improved Costas loop. He has developed a new type of Costas loop that is a tangent Costas loop that tracks on the tangent error function. The loop is switched to tangent configuration for tracking, after acquiring as a sine error loop. The loop pulls into lock in the sine loop configuration because it has better characteristics in that configuration, and it is switched into a tangent configuration for tracking purposes because the tangent loop definitely does hold the lock much better than the sine loop does, particularly in terms that it does not lose lock. We have demonstrated that a sine loop will lose track in those conditions, and it has a higher tolerance to tracking error and inherent automatic gain control. It also has the capability of using digital loop filters for adaptive bandwidth as indicated in Figure 9-4.

The final conclusion that we have in this area is that the key to widespread GPS usage is low-cost implementation. That is an obvious fact.

Today's GPS computations are complex and expensive, and we can minimize that by using only what is absolutely necessary in order to meet the requirements of a 100-meter accuracy system; and clearly not all receivers need even that kind of complexity. Algorithm simplification will provide greater reduction in the cost simply because of the fact that that is where a higher percentage of your cost is. A low-cost GPS receiver will contain a microprocessor and the memory associated with it.

MINIMUM COMPLEXITY SATELLITE SELECTION ALGORITHMS

*600 mph
1 Sat./Sec.

June 1975 Standard GDOP Computation, 4-Channel Receiver

- $\binom{N}{4}$ matrix inversions (210 for n=10)
- σ_E = 120 meters, 6-hour simulated flight

August 1975 Sub-optimal Computation (E/N/OH/GDOP)

- n - 3 matrix inversions (7 for n=10)
- σ_E = 120 meters

November 1977 Sub-optimal Computation, 1-Channel Receiver

- σ_E = 600 meters (No velocity prediction)

March 1978 Improved Computation (OT/CT/OH/GDOP)

- σ_E = 400 meters (No velocity prediction)
- σ_E should reduce to 100 meters with velocity prediction

*Velocity prediction only required for higher speed aircraft (200 mph <V)

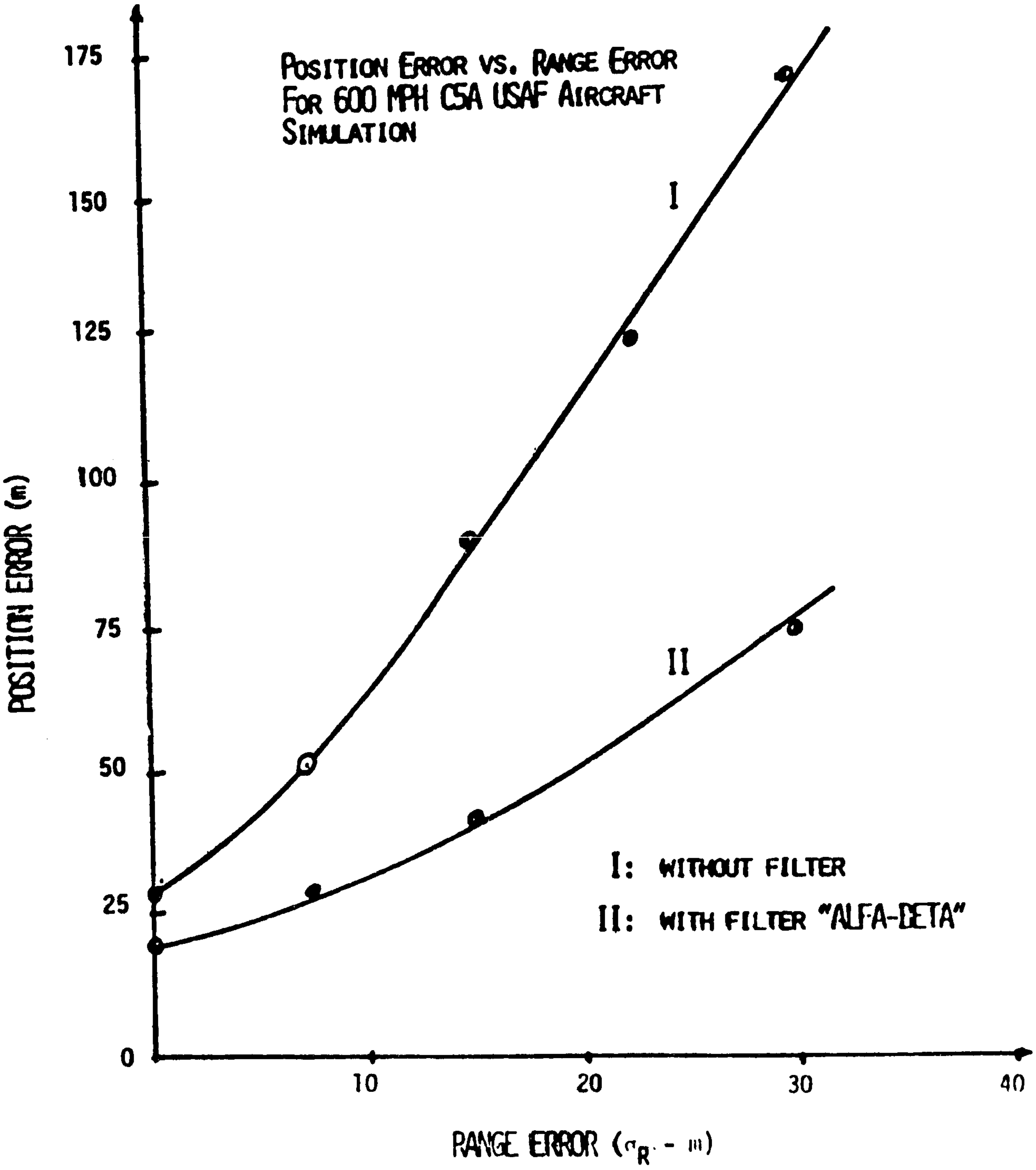
Figure 9-1

MINIMUM COMPLEXITY POSITIONING/NAVIGATION ALGORITHMS

600 mph
1 Sat./Sec.

- o Microprocessor Implementation of Navigation Computations
  - Linearized Navigation Equations
  - Robust Convergence (Hotelling Algorithm - 1975)
  - No Kalman Filter (Possible Simple Smoothing)
  - Floating Point Processor
  - Word Length Versus 100-Meter Accuracy Trade-off
- o Probable TAMU Low-Cost GPS Recommendation
  - 16-bit Microprocessor(s) with Hardware Mult./Divide

Figure 9-2



POSITION ERROR VS. RANGE ERROR
FOR 600 MPH C5A USAF AIRCRAFT
SIMULATION
175
150
125
100
75
50
25
0
10
20
30
40
I
II
I: WITHOUT FILTER
II: WITH FILTER "ALFA-BETA"
POSITION ERROR (m)
RANGE ERROR (σ_R - m)

Figure 9-3

IMPROVED COSTAS LOOP

- Option for Sine or Tangent Tracking Error Function
- Loop Pulls into Lock in the Sine Loop Configuration
- Loop is Switched to Tangent Configuration for Tracking
  - Higher Tolerance to Large Tracking Error ($\sim 40^{\circ}$)
  - Provides Inherent Automatic Gain Control
- Digital Loop Filters for Adaptive Bandwidth

Figure 9-4

N80-21310

Walter H. Riley
Texas Instruments

When Mr. Mike Lockerd (Texas Instruments) asked me to fill in for him today, I looked at the agenda and realized I was going to be the next to the last speaker, and I felt that most of the subjects would be covered by the time I got up here. So I thought I would try to take a little different approach and not be too repetitive.

Texas Instruments started with two contracts with the GPS Joint Program Office in June 1975. One was for a MANPACK or slow-moving vehicle configuration, and the other was for a high dynamic set to go on high-performance aircraft. Figure 10-1 shows the MANPACK and High Dynamic User Equipment.

We had designed cost goals for both of those programs, but the dollars are quite a bit larger than the $2,000 that has been thrown around today.

As part of our contractual requirements, we were to look at all the user classes that were defined at that time. Figure 10-2 shows the various user classes. I realize this chart is obsolete now, but this was part of our contract requirement back then where the classes were broken down by potential application and by function; and you will note you go from high accuracy, high dynamics to high accuracy, low dynamics and finally low cost.

Now, not shown on this class chart is another class for a missile, an ICBM missile test program which was a contract we received in 1976. The M missile class shown in Figure 10-2 was for a tactical missile. Not only did we have design to cost imposed on us on the contracts, but we also had to look at all the classes and try to maximize the commonality across the classes.

One of the bad aspects of doing business with DOD is that most of the procurements don't have enough volume where you can make an investment in tooling or LSI (Large-Scale Integration). All you have is the basic learning curve phenomenon and nothing else, as shown in Figure 10-3.

Now there are a few contracts like the PAVEWAY contract that have enough volume where you can do some tooling, but

2

you are still, because of the limited quantity, limited in the amount of LSI that you can afford.

One of the ways to get your cost down is to get the volume up enough to where you can get a very steep product improvement curve by going to highly integrated components, like LSI.

The approach that we took was to use technology to solve our problems, and Figure 10-4 shows the various types of technologies. The problems were the many classes of user equipments and the requirements imposed by the program office, and included in the requirements is, of course, cost.

Figure 10-5 shows that the approach we took was to look at the requirements of each class and to break the requirements down until we finally had a set of common modules that had design-to-cost goals and the various user requirements imposed by the contracts.

Figure 10-6 is another way to draw GPS user equipment where you have your application-sensitive components such as your antennas, depending on whether you want a high anti-jam phased array antenna or simple MANPACK, and the power supply with 400 cycles, 28 volts, and then the various man-machine interface units.

On the right side of Figure 10-6, we have the application nonsensitive portion of the system, which was broken down into the receiver and the processor. With respect to the processor, looking at the data processing considerations as shown in Figure 10-7, there were a lot of applications. At the low end we had the MANPACK. We also had the high-performance aircraft and the missile with very high velocity, and we were going to try to encompass all those requirements in one set of hardware.

There were a multitude of computation tasks. There was, of course, the need for things to be done in real time. We weren't sure when we started the program how many bits we really needed, and extended precision was required for accuracy. You might need up to 64 bits in the environment that we were looking at, plus the full mil temperature range with potential for some radiation hardness.

3

As shown in Figure 10-8, the design emphasis for the near term was to look at the requirements and break the requirements down into the common functions, and then break the functions apart--whether hardware or software functions--always, of course, looking at design to cost as one of the drivers and using technology.

Our basic strategy was to use technology for power, speed, cost, weight, and size benefits. In the long term, though, we didn't want to design a system that was going to become obsolete while we were designing it, so we tried to design a system where we could achieve incremental growth using common modules so that we didn't have the abrupt startup costs every time we received a new contract or new application. We tried to accommodate all possible applications that we could foresee, at least for DOD. We wanted to permit an evolutionary type system over a multiyear life cycle, where we were looking at family-oriented LSI parts. By that, I mean a part that was not going to be obsolete but would be generically part of a family, a part that would be around for a few years. And we needed hardware support tools and software support tools.

We came up with a set of modules as shown in Figure 10-9. The basic configuration for a single channel was what we had for the MANPACK. It consisted of the microprocessor module, ROM and RAM modules; and we had an interface that allowed us to get to our CDU, and they all talked to each other on the local bus.

For the high-dynamic system, we used this same configuration for our receiver control, but we also needed two more microprocessors. One we used for our navigation filter, and the other we used for our basic controller.

We have a floating point unit that could be accessed by either the navigation or the control processor. More shared memory was needed, so we came out on an I-bus and had some global memory. We also had to interface with the outside world. We then received a contract for an ICBM test program, and we had to have a fourth channel for a fourth processor, so we just added another one as shown here; but all the modules are the same. It is the same basic configuration and same structure.

4

Figure 10-10 is a pictorial of our microprocessor module. It is the heart of our system. It contains a 16-bit microprocessor. It uses I^2L technology. We chose that technology because it was fairly new technology at the time, and we could see the speed would increase with time; and so far, it has done that rather well.

Also, one of the nice features about it is you can change the speed with your current drive; and so, if you have a low-power, low-speed system, you just lower the current drive and you will have a lower speed system.

One of the nice features about the system is that you can interface to an external test panel, which allows you to do a lot of troubleshooting on the system. Another nice feature is an oscillator that is on the card that can be the clock, or we can use an external clock, however we decide to configure the system.

Figure 10-11 shows the hardware that we built.

The name of the game today in DOD, just like it is in the civil and commercial world, is cost, and so the reason we did the common modules was to get the cost down. It wasn't to get the best performance system, but it was to get a system that would meet the requirements at the minimum cost; and we think we have done that.

We are currently building a few of these processor modules, and they are priced at $4,100 for the microprocessor module in very small quantities, and Figure 10-12 shows two learning curves. There is no real significance to the numbers other than the fact that typically, for just the simple learning curve, you look at a number somewhere around 95 percent, and then if you start talking about tooling and LSI, you can start coming down toward the 70 range. Our design-to-cost goal for Phase I was $710 for this module, so we feel that is certainly achievable.

One of the nice things about using the same module for both systems is that if you were to get a quantity buy of each type of system, say a thousand MANPACK's and a thousand High Dynamic Sets, then assuming you did the tooling and LSI, instead of costing $454, it could cost $256; so that is a significant saving.

5

Now these are goals, and we haven't done them yet, other than the fact that we could sell you one for $4,100; so I guess there is some question of credibility.

The last subject I would like to discuss is a LORAN-C navigator that Texas Instruments builds. It sells for a little over $2,000, in quantities of one.

Now, these are sold through marine dealers, so there is a markup, and the numbers are comparable to the numbers being discussed. The $2,000 includes the markup.

Within this unit, we have a timing and control board, and I have one to give you a feel for the size of the board. You will notice that at the end of this board, there are two little connectors. They have 24 pins on them, and you can replace this board with a 24-pin dual in line package (DIP), which we have done.

This new chip costs less than the material costs on this board, but you also eliminate the cost of the PC board, which is minor, but nevertheless, it is a cost; and you don't have the cost of the assembly labor that goes in to making this board with the components on it, so we are getting about a 10-to-1 ratio cost reduction because you have this 24-pin pack versus this board. We are taking the same approach on GPS.

QUESTION (Mr. Allan E. Greenberg, Cardion Electronics) - Is that particular integrated circuit available for anybody or for only in-house?

ANSWER - That is being done by a different group. I can't answer that, but I could find out and let you know if you would like to give me your name. That is being done by a Marine organization.

Figure 10-1

GPS USER EQUIPMENT

BY CLASS	A	B	C	D	E	F	M
BY POTENTIAL APPLICATION	AIR FORCE STRATEGIC RECON	ARMY HELICOPTER USMC CAS A/C HELICOPTER NAVY CAS A/C SURFACE FIGHTERS AIR FORCE CAS FIGHTERS	ARMY SUPPORT A/C NAVY SUPPORT A/C ASW A/C AIR FORCE AIRLIFT SEARCH/ RESCUE	ARMY VEHICLES NAVY SURFACE	ARMY BACKPACK USMC BACKPACK	NAVY SUBS	MISSILE GUIDANCE
BY FUNCTION	HIGH ACC MEDIUM DYNAMICS A/J (HIGH)	HIGH ACC HIGH DYNAMICS A/J (MED)	MED ACC MEDIUM DYNAMICS EMI LOW COST	HIGH ACC LOW DYNAMICS A/J (HIGH)	HIGH ACC LOW DYNAMICS A/J (HIGH) LOW WT LOW COST	HIGH ACC LOW DYNAMICS	HIGH DYNAMICS LOW COST SMALL A/J

Figure 10-2

8

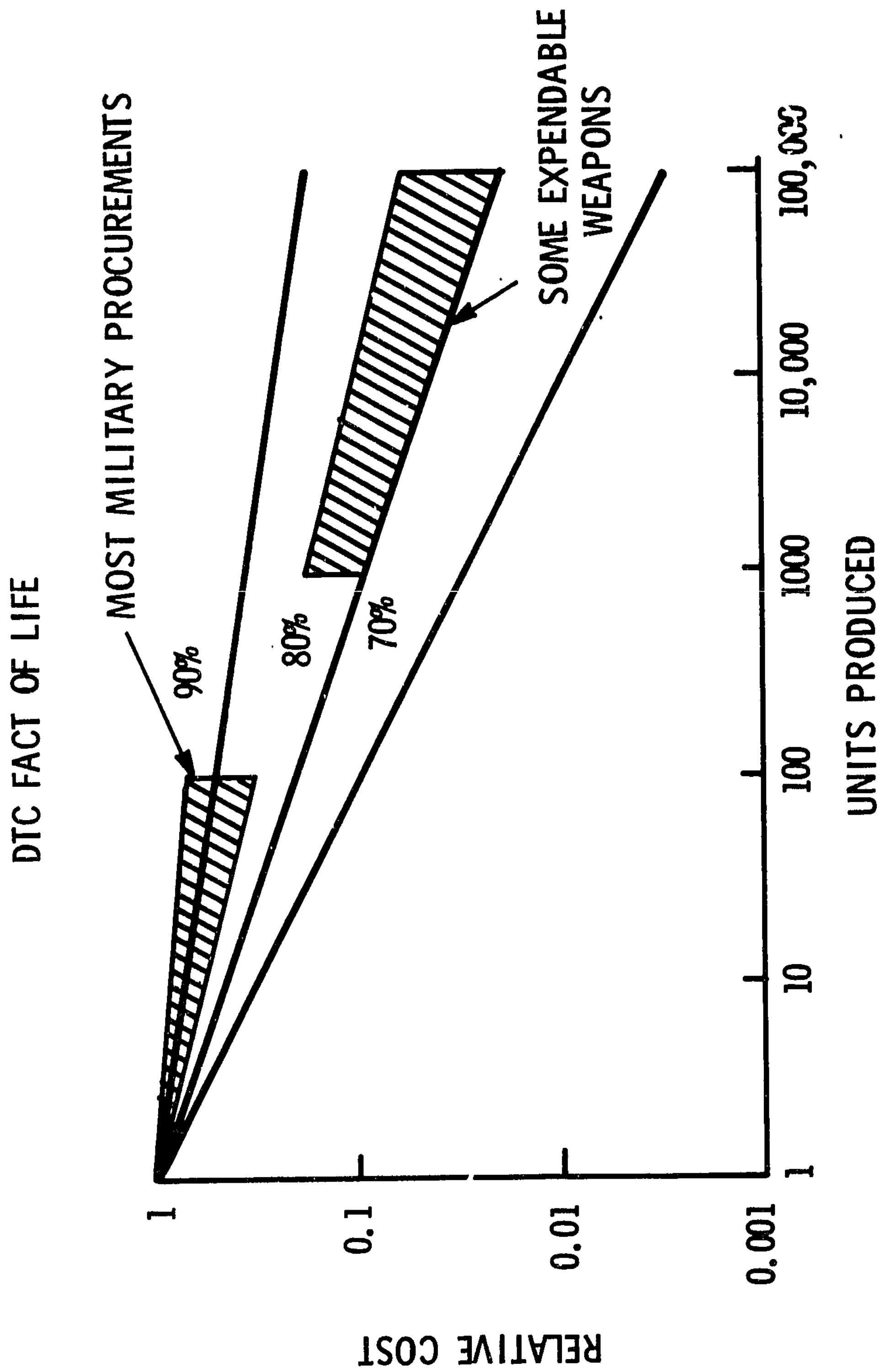

DTC FACT OF LIFE
MOST MILITARY PROCUREMENTS
90%
80%
70%
SOME EXPENDABLE WEAPONS
RELATIVE COST
1
0.1
0.01
0.001
1
10
100
1000
10,000
UNITS PRODUCED

Figure 10-3

DESIGN PHILOSOPHY

TECHNOLOGY

- INTEGRATED CIRCUIT
- I^2L
- SURFACE WAVE DEVICE
- MICROWAVE
- DIGITAL
- SOFTWARE

PROBLEM

- USER EQUIPMENT
- REQUIREMENTS
- SCHEDULE

PHILOSOPHY

- CONFIGURE MODULES TO SATISFY MINIMUM SIZE AND WEIGHT CLASS USER EQUIPMENT
- OPTIMIZE LIFE CYCLE COST WITH TRADE OFFS OF UNIT PRODUCT COST AND RELIABILITY/MAINTAINABILITY
- MINIMIZE RISK BY UTILIZING PROVEN TECHNIQUES
- SATISFY VARIOUS PERFORMANCE REQUIREMENTS THROUGH INNOVATIVE DESIGN

Figure 10-4

TEXAS INSTRUMENTS APPROACH TO USER EQUIPMENT

REQUIREMENTS OF EACH CLASS

- DEFINE FUNCTIONAL ELEMENTS OF EACH CLASS
- IDENTIFY APPLICATION SENSITIVE ELEMENTS
- SUB DIVIDE FUNCTIONAL ELEMENTS
- GROUP SUB ELEMENTS FOR MAXIMUM COMMONALITY BETWEEN CLASSES
- PARTITION SUB ELEMENTS INTO MODULES

COMMON MODULES

- DESIGN-TO-COST GOALS
- SIZE AND WEIGHT
- PERFORMANCE
- RELIABILITY/MAINTAINABILITY

Figure 10-5

SYSTEM FUNCTIONAL DIAGRAM

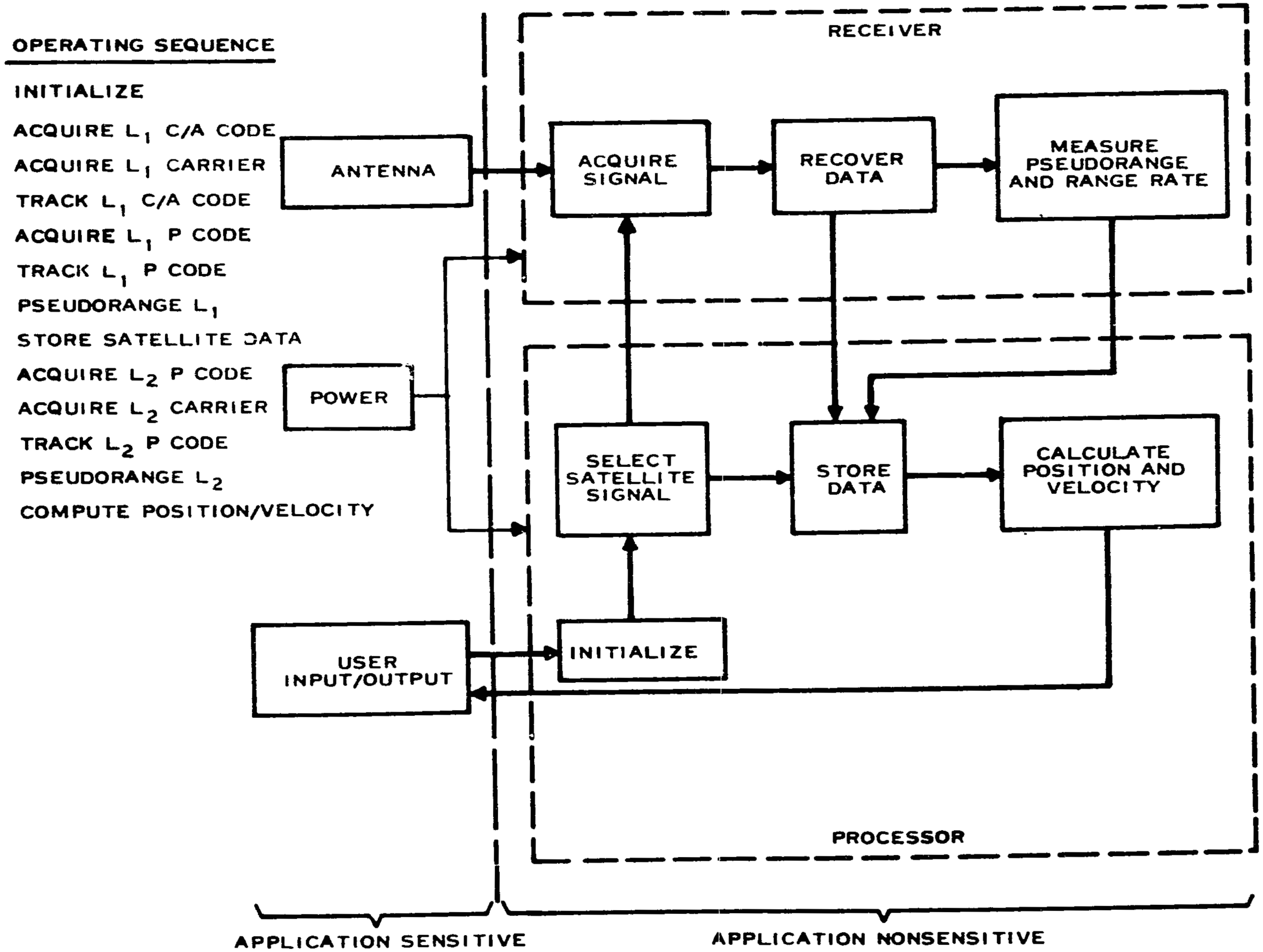


Figure 10-6

DATA PROCESSING CONSIDERATIONS

MULTIPLE APPLICATIONS

- LOW PERFORMANCE MANPACK/VEHICULAR
- MEDIUM/HIGH PERFORMANCE AIRCRAFT
- MISSILEBORNE NAVIGATION AND TELEMETRY

VARIED COMPUTATIONAL TASKS

- REAL-TIME HARDWARE INTERACTION
- PROCESS-CONTROL ORIENTED INPUT/OUTPUT
- N-BIT ORIENTED ARITHMETIC WITH EXTENDED PRECISION

MILITARY ENVIRONMENT EMPHASIS

- WIDE TEMPERATURE RANGE
- HIGH RELIABILITY
- MINIMUM POWER
- POTENTIAL FOR RADIATION HARDNESS

Figure 10-7

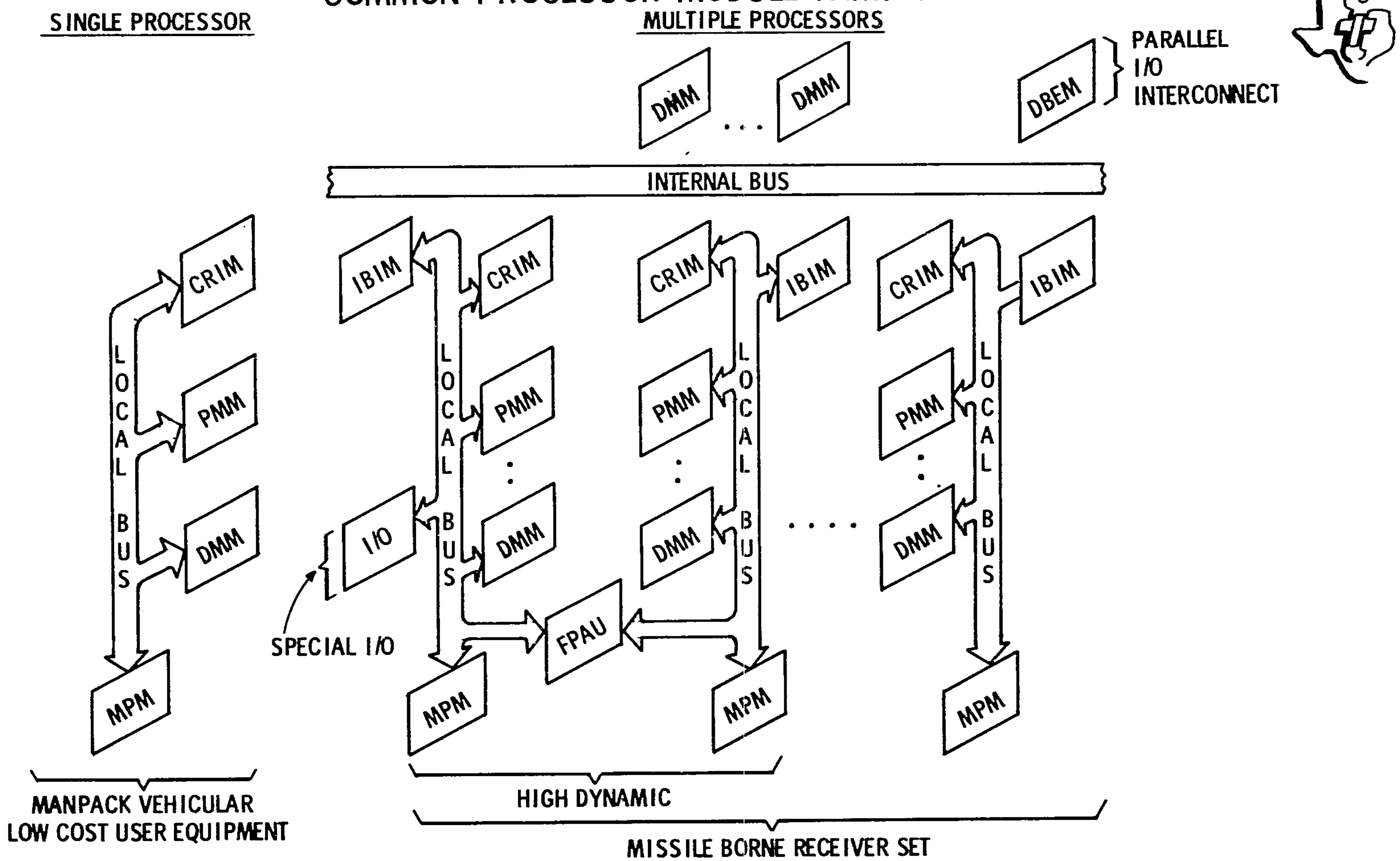
PROCESSOR SYSTEM DESIGN EMPHASIS

- **NEAR TERM**
  - COLLECT REQUIREMENTS FOR USER CLASSES
  - PARTITION COMMON FUNCTIONS
  - ALLOCATE FUNCTIONS TO HARDWARE AND SOFTWARE MODULES
  - FOLLOW DTC/LCC DISCIPLINE IN MODULE FAMILY DEVELOPMENT
  - USE TECHNOLOGY FOR POWER/SPEED/COST BENEFITS

- **LONG TERM**
  - ACHIEVE INCREMENTAL GROWTH VIA COMMON MODULES
    - MINIMIZE COST/SCHEDULE IMPACT
    - ACCOMODATE NEW APPLICATIONS
  - PERMIT DESIGN EVOLUTION OVER MULTI-YEAR LIFE CYCLE
    - FAMILY ORIENTED LSI PARTS
    - HARDWARE SUPPORT TOOLS
    - SOFTWARE SUPPORT TOOLS

Figure 10-8

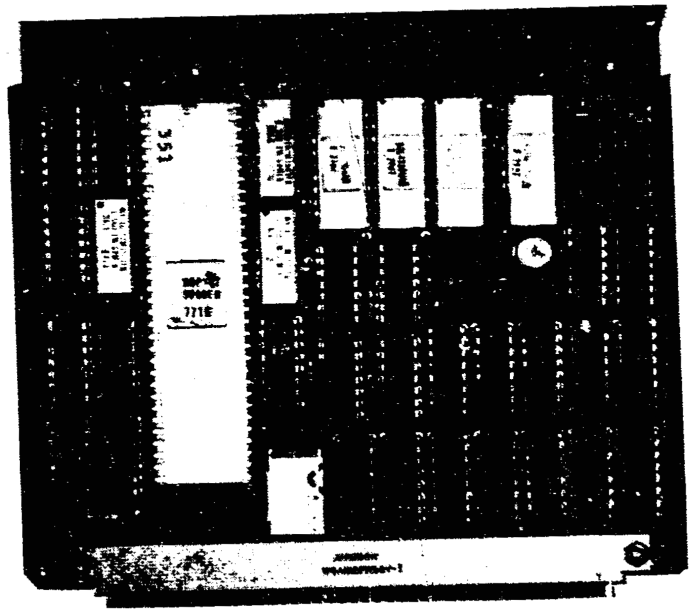
COMMON PROCESSOR MODULE FAMILY

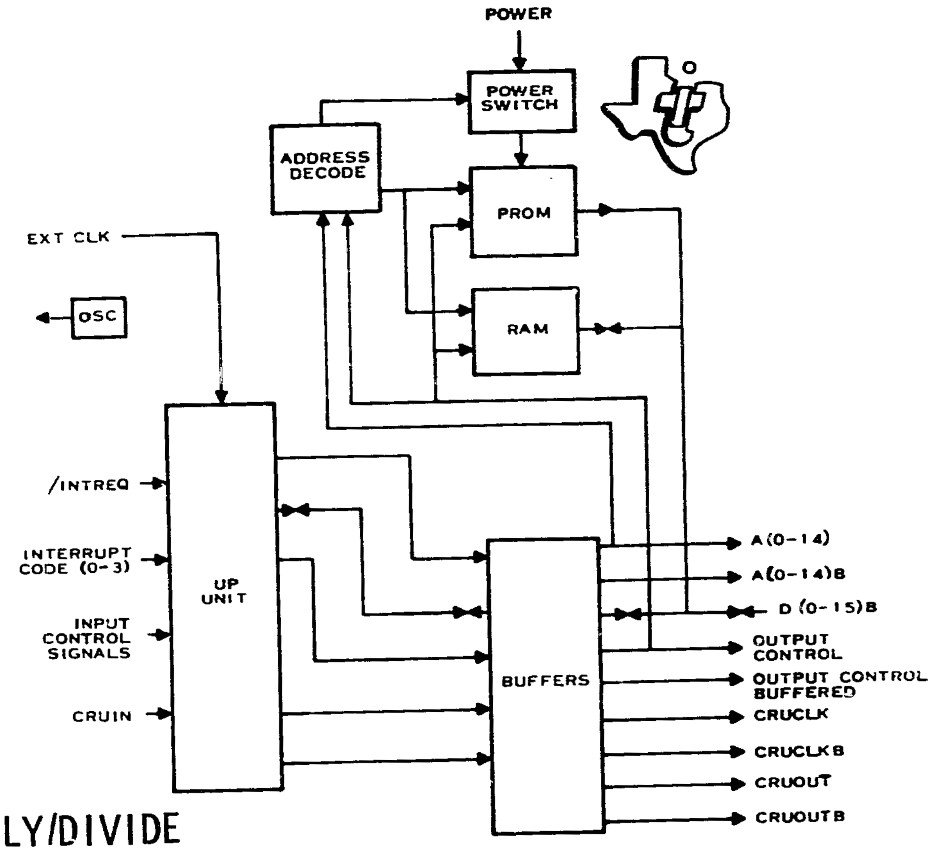


MODULE	FUNCTION	MODULE	FUNCTION
MPM	MICROPROCESSOR MODULE	CRIM	COMMUNICATION REGISTER INTERFACE
DMM	DATA MEMORY MODULE	IBIM	I-BUS INTERFACE MODULE
PMM	PROGRAM MEMORY MODULE	DBEM	DATA BUS EXTENDER MODULE
		FPAU	FLOATING POINT ARITHMETIC UNIT

Figure 10-5

MICROPROCESSOR MODULE





- 16 - BIT SBP9900 I^2L MICROPROCESSOR
  - 64 PIN DIP
  - 69 INSTRUCTIONS INCLUDING MULTIPLY/DIVIDE
  - 16 PRIORITY INTERUPTS
- LOCAL DATA MEMORY
- LOCAL PROGRAM MEMORY
- MAINTENANCE PANEL INTERFACE

ORIGINAL PAGE IS OF POOR QUALITY

Figure 10-10

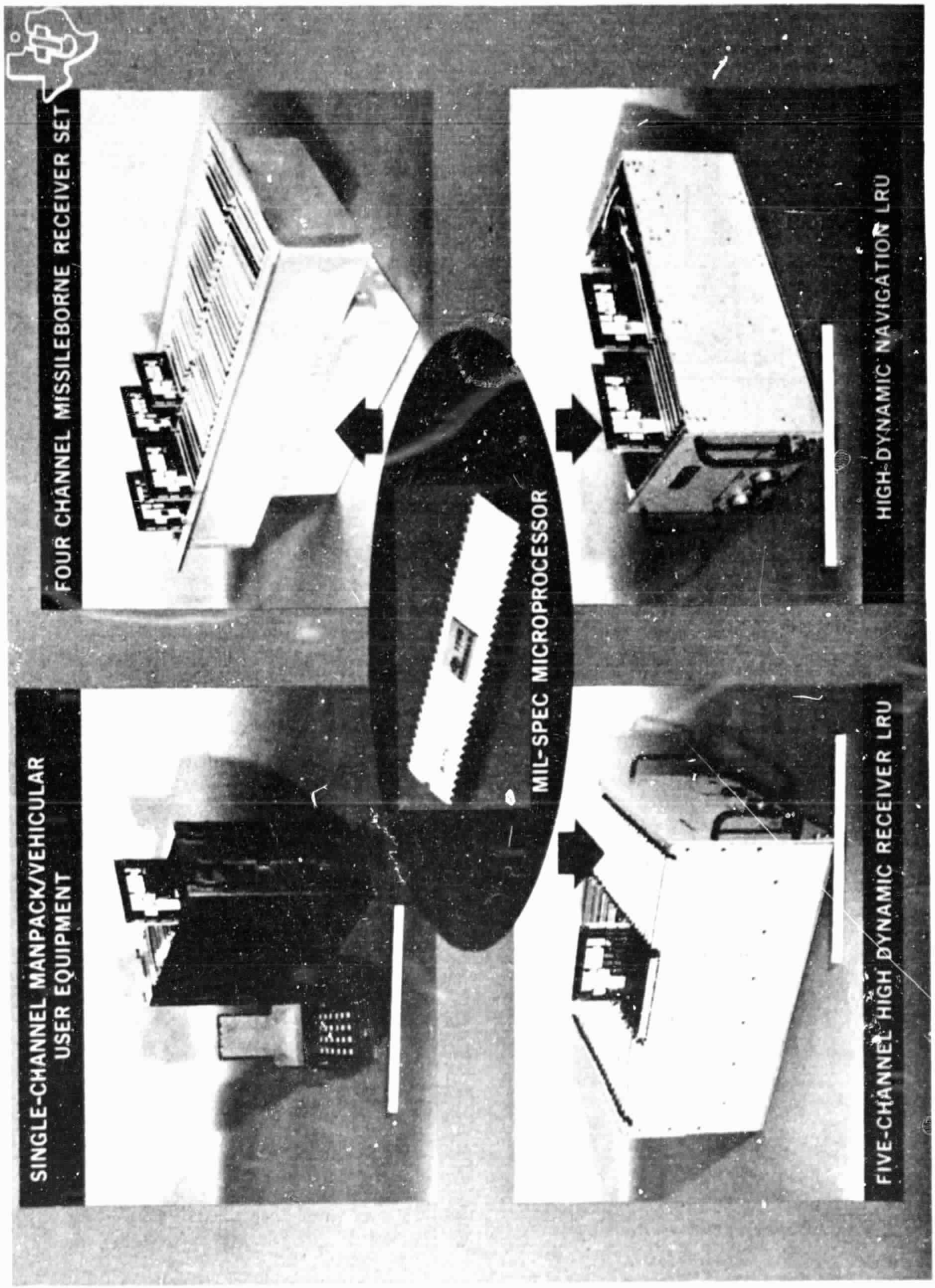

SINGLE-CHANNEL MANPACK/VEHICULAR
USER EQUIPMENT
FOUR CHANNEL MISSILEBORNE RECEIVER SET
MIL-SPEC MICROPROCESSOR
FIVE-CHANNEL HIGH DYNAMIC RECEIVER LRU
HIGH-DYNAMIC NAVIGATION LRU

Figure 10-11

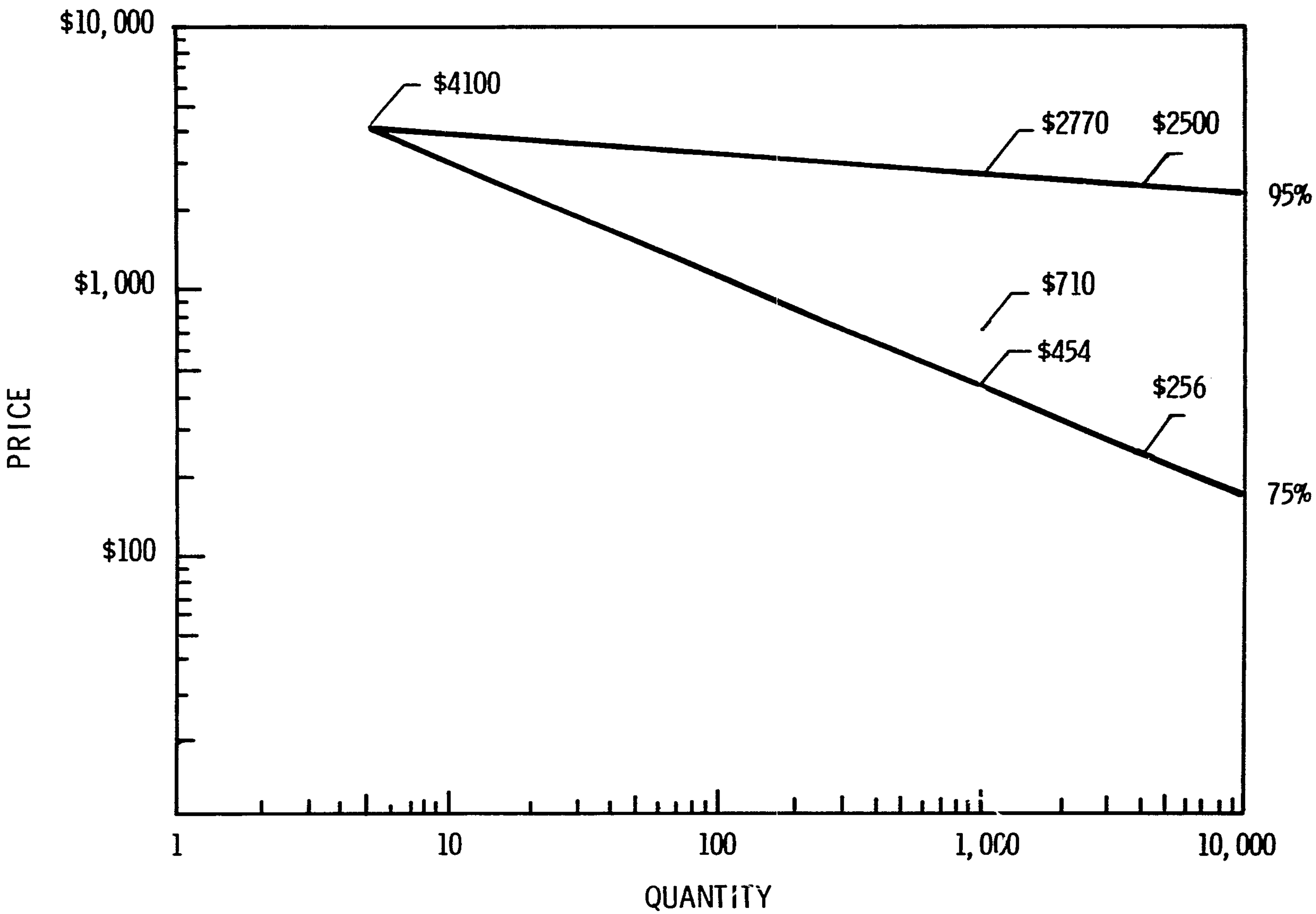

$10,000
$1,000
$100
PRICE
$4100
$2770
$2500
95%
$710
$454
$256
75%
1
10
100
1,000
10,000
QUANTITY

Figure 10-12

Eugene Hoo
TRW
Defense and Space Systems Group

My initial discussion will be directed at the 50 percent that was referred to earlier, that part that one of my colleagues referred to as "...maybe we shouldn't spend time customizing." My only comment is it provides me a living.

I should point out that our involvement in GPS was somewhat through a back door. I say this with respect to the TRW in-house research on methods for improving the cost, reliability, size, and power for so-called RF analog-type circuits. Much has been done in the area of digital LSI, but very little has been done in the realm of analog-type circuits; and when I speak of analog, I am speaking of circuits that operate up to about 2 gigahertz, so let me then set that as a stage for this discussion.

This study is titled "Architectural Design of an Improved GPS Receiver using RF Analog LSI Circuits." We chose the words "improved GPS receiver" so that it would not be controversial. We didn't use the words "low-cost" because the design is not low-cost in the sense of a general aviation receiver. The receiver was intended for military applications, so as such it was called an improved receiver.

I will try to cover quickly some of the background of our LSI work at TRW, the architectural study itself, and the study results; and then I will close by giving some of the progress of that contract, where we are, and where we hope to be.

The technology base that we have used for this work is the oxide aligned transistor technology. Using this technology, we have developed transistors that have an f_t in the range of 4 to 5 gigahertz.

The advantage of this technology is that it allows us to use on-chip precision resistors and metal-on-metal type capacitors. The devices exhibit typical gate delays of 250 picoseconds, very low power (20 milliwatts per gate), and extremely high density (2,000 to 10,000 devices per die).

2

In utilizing these devices then, we require low parasitic interconnections; that is the key to this technology. The benefits that one can derive from this technology are given in the lower five or six lines of Figure 11-1.

Recognizing these potential benefits, TRW embarked about 3 years ago, starting about 1975-1976, on some in-house developments to prove to ourselves that this technology indeed would be and could be implemented outside of a laboratory environment.

Figure 11-2 shows an example of the development work we did. We built two Costas loop demodulators. In the upper left-hand corner is one that operates at an input frequency of 500 megahertz, and next to it is one that operates at about a thousand megahertz.

The package in the lower left of Figure 11-2 shows the chip mounted inside a hermetically sealed package which can be mounted on a PC board for use as part of a receiver.

The first unit was tested at data rates up to a maximum of about 1 megabit and the second unit, to about 10 megabits.

Accompanying the development of the Costas loop demodulators is an RF receiver on a chip (See Figure 11-3), much as was described by our colleague from Stanford Telecommunication, Inc., except that this receiver was designed on the RF frequency.

In a GPS application, the bottom oscillator can be replaced by a code generator so that we can actually despread the signal at RF and go directly into a phase demodulator. Ahead of this receiver we are assuming that a preamplifier conditions the signal to a reasonable level.

This receiver was tested at an input power of between -100 to -70 dBm.

As a result of this in-house technology work, the Naval Electronic Systems Command (NAVELEX) became interested in a possible application of this technology. The application was the development of a family of universal RF LSI circuit building blocks which could be configured for various types of equipment in this RF range.

3

In particular, the types of circuits were low-noise amplifiers, mixers, modulators, demodulators, IF amplifiers, oscillators, phase-lock loops--the types of circuits that would be used in RF receivers.

The Navy, in typical fashion, said, That's great, universal blocks; how about applying it to a specific application? The application chosen was a GPS receiver. Figure 11-4 gives an overview of the contract with the Naval Ocean Systems Laboratory that has as one of its objectives the development of a family of universal RF LSI circuits. Another objective is to demonstrate the applicability of some of these building blocks to a GPS receiver.

The schedule called for a receiver architectural study in 3 months, the objective of which was to define the inputs and outputs and the specifications of some of the RF LSI chips; followed then by the demonstration circuit in 15 months and other building blocks in 21 to 27 months; and finally a demonstration breadboard in 36 months.

Figure 11-5 is a list of some of the building blocks that we will be developing under this contract. Figure 11-6 shows how the circuit designs would be used in practice. One of the features of this program is to generate the basic specifications for these different blocks that I talked about and enter these into a computer-aided design library. Then, depending upon the particular application of the circuit, the circuit can be customized by calling out specific resistor, capacitor, and transistor parameter values.

What we did in that 3-month study was primarily directed at the technology so that we could design a circuit that would be applicable to something specific rather than just a general universal-type application.

Figure 11-7 summarizes the study objectives. The architectural study was under the direction of Mr. Chuck West at Naval Ocean Systems. The three tasks were: (1) Analyze the existing GPS system and user requirements (I might point out that this task was not intended to be on an exhaustive requirements analysis but only intended to pick out those things that were critical to the design of this receiver); (2) Design a GPS receiver which incorporates RF analog circuits; and (3) Estimate the production cost of the receiver.

4

This study was not intended as an exhaustive tradeoff study to cover everything under the sun but was to optimize the receiver for RF LSI; and then, to give it some credence, we were asked to estimate the production costs of the receiver.

The key results are shown in Figure 11-8. Most of these numbers were lifted out of US 200 so they should not be new to anyone.

This design functioned satisfactorily in a nonhostile environment; however, in the GPS jamming environment the receiver design was deficient. The additional noise overloaded the detector circuits.

Figure 11-9 is a very simplified block diagram of the receiver. What we were concerned with was primarily the RF structure of the receiver and not the digital aspect of the receiver. As I go through the block diagram, I will point out some of the assumptions that were made. One of the major constraints was to design the receiver on a card so that a multichannel receiver could be made up of N types of identical channel cards, much like the approach that was taken in the previous speaker's microprocessor.

I might point out that we have included in the design a preamplifier that could be incorporated either at the antenna or on the channel card itself.

L-2 is up converted to the L-1 frequency. A switch and power splitter allows, under the process or control, to process either the L-1 or the L-2.

Figure 11-10 shows a little more detail. Note how the receiver has been partitioned into the five chips. The input circuit is called the RF chip or the RF receiver chip and is the chip under development; another chip, the demodulator chip, and the RF chip use the RF LSI technology.

The other three chips shown in Figure 11-10 are digital in nature. The code generator was specified by direction. It is a set of chips that RCA has developed for the Naval Research Laboratory.

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The code clock divider chip is a digital chip, as is the frequency generator.

Figure 11-11 shows a little more detail of the GPS receiver chip, or the RF chip. It is comprised primarily of amplifiers and mixers; the amplifier gain is about 30 dB. An off-chip filter is required for rejection of the LO frequencies and undesired jamming products.

As part of the study, we did a power tradeoff to see just how much power would be required by the chips and what a typical five-channel configuration would entail. Figure 11-12 summarizes the results.

The RF chip takes a little over a watt. The second chip that is talked about takes about six-tenths of a watt; the divider chip, about half a watt; the code generator, about a quarter of a watt; and the VCO, about two-tenths of a watt, for a total of two and a half watts.

The two and a half watts includes the preamplifier. For a five-channel set, the prime power requirement is about 47 watts.

I might point out that this is probably conservative because the microprocessor that was used was an existing microprocessor; it was not one that we tried to optimize. This was not the intent of the study; but you can certainly see that if a more efficient microprocessor were used, the power would be reduced drastically.

Figure 11-13 is a picture of what that five-channel set would look like. As can be seen, the microprocessor was estimated at about six modules. These modules, incidentally, are a half ATR, or approximately four and a half by six inches in area. The channel cards occupy five slots, with the power supply, filter, and oscillator occupying the rear of the box.

Figure 11-14 summarizes the production cost of a five-channel GPS receiver in 1978 dollars for a typical west coast company to manufacture. For the five-channel receiver, in quantities of a thousand, we estimate a cost, not including markup and fee, of about $14,000; for a single channel, about

$7,500; and the cost per channel, about $1,500. You can see if you were to talk about a single-channel receiver, you are talking roughly $6,000 in what we call common equipment to do a single-channel function.

We feel that this cost estimate is probably conservative based on our assuming a 10 percent yield for these RF LSI circuits. More typically, I think if you are producing LSI circuits, a 30 percent yield is generally a better number; but we picked a 10 percent yield because we don't have that much experience with these circuits.

This design incorporates an RCA ATMAC microprocessor. Again if we were to use the TI microprocessor that is tailored for this particular application, the cost is likely to come down.

We also estimated manual testing of both the modules and at the system level primarily because we couldn't supply the factory cost estimators with enough detail for estimating automatic testing.

In summary then, TRW believes that there is a high potential for RF LSI application to GPS. We are probably 2 years, maybe 3 years from seeing the problems worked out. However, the first RF LSI chip, the front-end chip, which we feel is the most difficult, is scheduled for testing and characterization by the end of December 1978. I hope that next year (1979), if we have another seminar, I can report good results.

QUESTION (A Participant) - Would the cost figures you mentioned also apply to a receiver designed for use by civil aircraft?

ANSWER - The receiver described is a full mil spec receiver. We did use mil standard parts, level B in fact; and these cost numbers are directed at a mil type, military application receiver. So you can see from the work that we did that if you extrapolate to a general aviation type application, the cost would come down drastically.

QUESTION (Mr. Edward F. Prozeller, Applied Physics Laboratory/Johns Hopkins University) - You mentioned that

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the fourth part of your program was the demonstration of a full receiver. When do you expect that to happen?

ANSWER - This program is about 3 years in duration, of which we have gone through about one; so it will be in about another 2 years.

FEATURES OF RF-LSI

TECHNOLOGY APPROACH

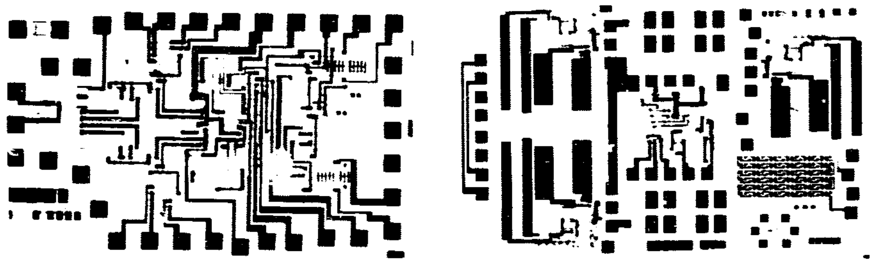
- OXIDE ALIGNED TRANSISTOR (OAT) MONOLITHIC LSI TECHNOLOGY
  - TRANSISTOR F_T = 4 - 5 GHz
  - ON-CHIP PRECISION THIN FILM RESISTORS AND METAL OXIDE METAL CAPACITORS.
  - GATE DELAYS 250 PICO SEC.
  - GATE POWER 20 MW
  - HIGH DENSITY 3000 - 10,000 DEVICES PER DIE
  - LOW PARASITIC INTERCONNECT

BENEFITS

- SYSTEM IMPACT
  - SUBSYSTEM SIZE REDUCTIONS BY FACTORS OF 10 TO 20
  - DC POWER SAVINGS OF 2 TO 4
  - INCREASED CIRCUIT COMPLEXITY OFFERS MORE POWERFUL ANALOG SIGNAL PROCESSING
  - MOST ANALOG CIRCUITS CAN BE FULLY MONOLITHIC GREATLY REDUCING PARTS COUNT
  - RECURRING COST REDUCED BY 50 TO 90% DEPENDING ON QUANTITY

Figure 11-1

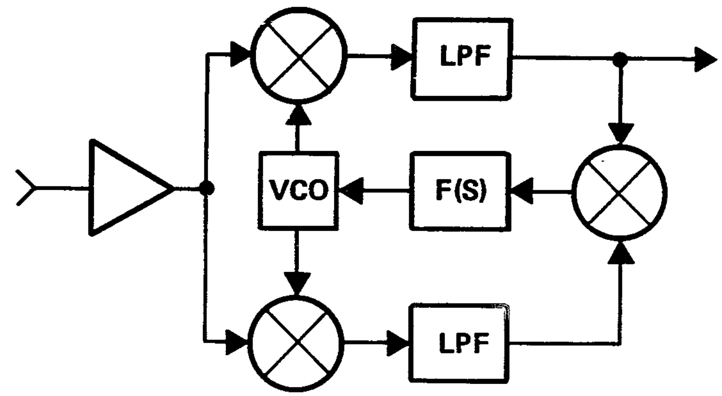
COSTAS LOOP DEMODULATORS

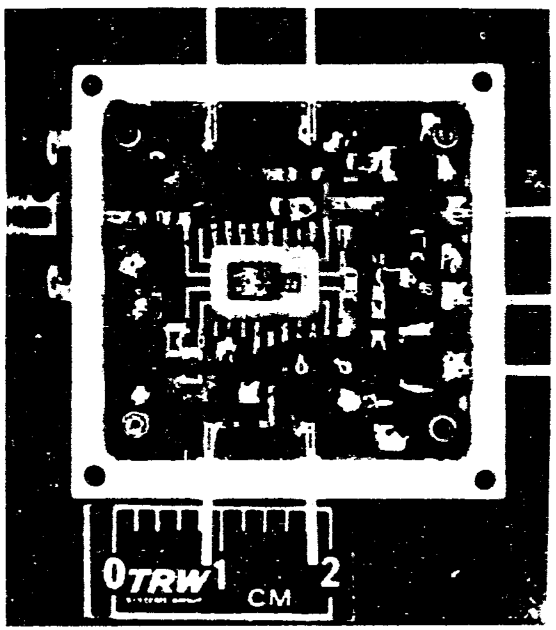


500 MHZ 1000 MHZ

COSTAS LOOP DEMODULATOR CHIPS
(SIZE ~ 70 X 100 MILS)

- CARRIER RECOVERY LOOP BIPHASE DEMOD
- RF LSI VERSIONS ARE ONE TWENTIETH THE SIZE OF BEST CONVENTIONAL





PACKAGED COSTAS DEMODULATOR

PERFORMANCE

PARAMETER	500 MHZ DEMOD	1000 MHZ DEMOD
FREQUENCY RANGE	350 TO 550 MHZ	850 TO 1050 MHZ
DATA RATE	0 TO 1 MBPS	0 TO 10 MBPS
BER DEGRADATION	0.8 DB	TBD
TEST FIXTURE SIZE	1.4 X 1.4 X 0.5 INCHES	1.4 X 1.4 X 0.5 INCHES
DC POWER	0.85 W	0.94 W

Figure 11-2

ORIGINAL PAGE IS
OF POOR QUALITY

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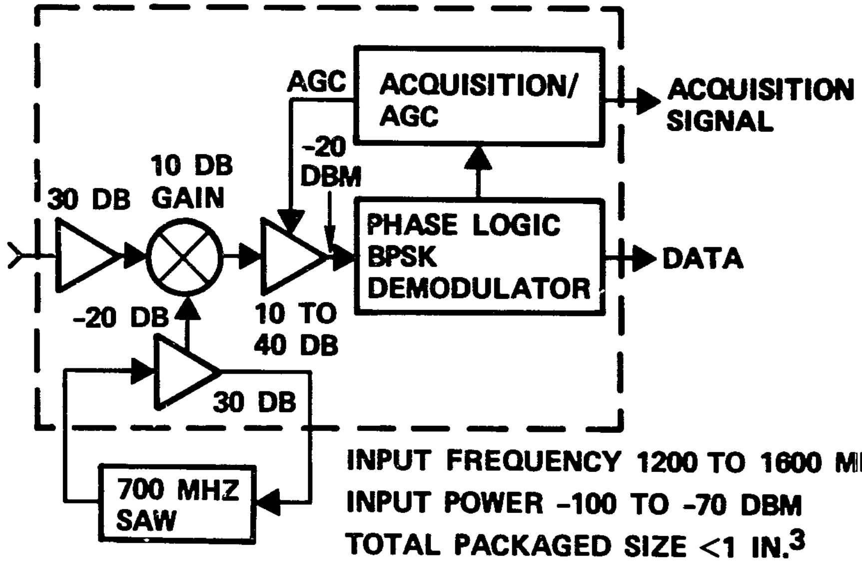
RF LSI L-BAND RECEIVER



INPUT FREQUENCY 1200 TO 1600 MHZ
INPUT POWER -100 TO -70 DBM
TOTAL PACKAGED SIZE <1 IN.^{3}
TOTAL DC POWER <750 MW

- ALL COMPONENTS ON SINGLE CHIP EXCEPT SAW FILTER
- REPRESENTS CURRENT SILICON ANALOG TECHNOLOGY STATE OF THE ART BOTH IN LEVEL OF INTEGRATION AND OPERATING FREQUENCY
- DESIGNED FOR GPS USER RECEIVER TO ACHIEVE SUBSTANTIAL COST REDUCTION

L-BAND RECEIVER CHIP (140 X 60 MILS)

Figure 11-3

PROGRAM OVERVIEW

DEVELOPMENT OBJECTIVES

- DEVELOP A FAMILY OF UNIVERSAL RF-LSI CIRCUIT BUILDING BLOCKS (LOW NOISE AMPLIFIERS, MIXERS, MODULATORS, DEMODULATORS, IF AMPLIFIERS, OSCILLATORS, PHASED LOCK LOOPS).
- DEMONSTRATE APPLICABILITY OF CIRCUITS TO TYPICAL NAVY EQUIPMENT SUCH AS A GPS RECEIVER.

SCHEDULE

• GPS RECEIVER ARCHITECTURAL STUDY	3 MO
• GPS DEMONSTRATION CIRCUIT	15 MO
• BUILDING BLOCK CIRCUITS	21, 27 MO
• DEMONSTRATION BREADBOARD	36 MO

Figure 11-4

PROPOSED BUILDING BLOCK FUNCTIONS

(30-1600 MHz)

- LOW NOISE PREAMP
- AGC AMPLIFIER GAIN BLOCKS
- VCO (GENERAL PURPOSE)
- PHASE DETECTOR, BALANCED MIXER, MULTIPLIER
- LOW PASS ACTIVE FILTERS
- COSTAS DEMODULATOR
- PHASE LOGIC DEMODULATOR
- PROGRAMMABLE DIVIDER
- PN CODE GENERATOR
- NARROW BAND COMB FILTER (SAW + RF • LSI)
- STABLE FREQUENCY SOURCE AND VCO (SAW + • LSI)

Figure 11-5

BUILDING BLOCK CONCEPT
LSI DEVELOPMENT SEQUENCE

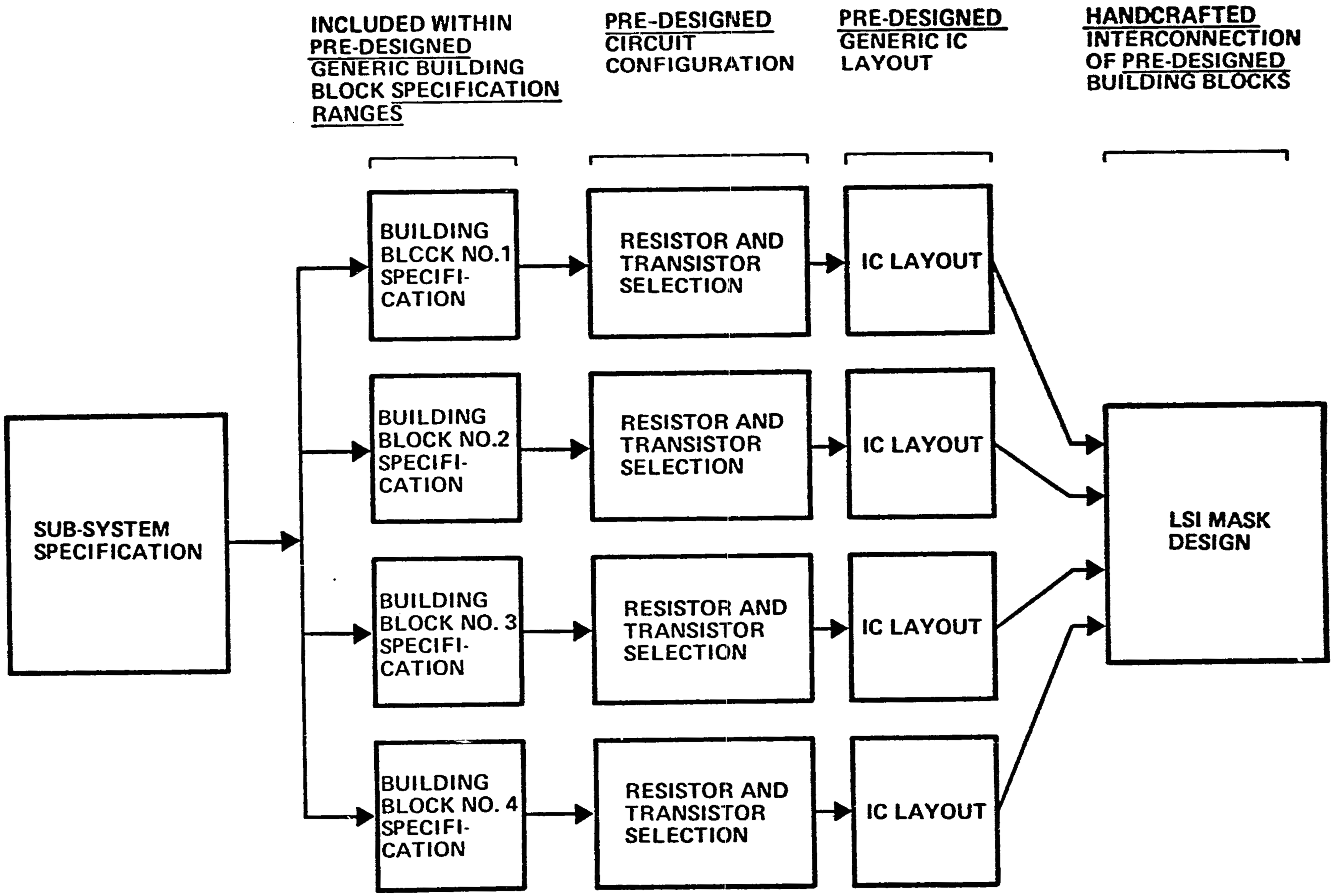


Figure 11-6

DESCRIPTION OF THE STUDY

- SPONSORING AGENCY: NAVAL OCEAN SYSTEMS CENTER AT SAN DIEGO, CALIFORNIA
- NOSC TECHNICAL MONITOR: MR. CHUCK WEST (CODE 9234)
- ARCHITECTURAL STUDY OBJECTIVES
  - ANALYZE EXISTING GPS SYSTEM AND USER REQUIREMENTS
  - DESIGN A GPS RECEIVER WHICH INCORPORATES RF ANALOG LSI CIRCUITS, I.E., DEVELOP RECEIVER FUNCTIONAL SPECS, ARCHITECTURE, AND DETAILED LSI CIRCUIT SPECS.
  - ESTIMATE PRODUCTION COST OF THE RECEIVER.

Figure 11-7

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GPS RECEIVER REQUIREMENTS

	P-CODE	C/A CODE
• RECEIVER SIGNAL LEVELS		
L1	-133 dBm	-133 dBm
L2	-136 dBm	-136 dBm
S_{MAX}	-100 dBm	-100 dBm
J/S	40 dB	30 dB
S_{MAX} + J	-60 dBm	-70 dBm
• DYNAMIC RANGE		
L1	73 dB	63 dB
L2	76 dB	66 dB
• P/NO		
L1 (J/S = 40 dB)	36.0 dB-Hz	36.0 dB-Hz
L2 (J/S = 40 dB)	33.0 dB-Hz	
L1 (J/S = 30 dB)	36.0 dB-Hz	36 dB-Hz
L2 (J/S = 30 dB)	33.0 dB-Hz	33 dB-Hz
• DYNAMIC REQUIREMENTS		
VELOCITY, M/SEC	1200	
ACCELERATION M/SEC^2	90	
JERK, M/SEC^3	180	
YAW RATES	$\pm$ 1 RAD/SEC,	$\pm$ 2 RAD/SEC^2
PITCH RATES	$\pm$ 1 RAD/SEC,	$\pm$ 2 RAD/SEC^2
ROLL RATES	$\pm$ 2 RAD/SEC,	$\pm$ 4 RAD/SEC^2

Figure 11-8

GPS RECEIVER SYSTEM BLOCK DIAGRAM

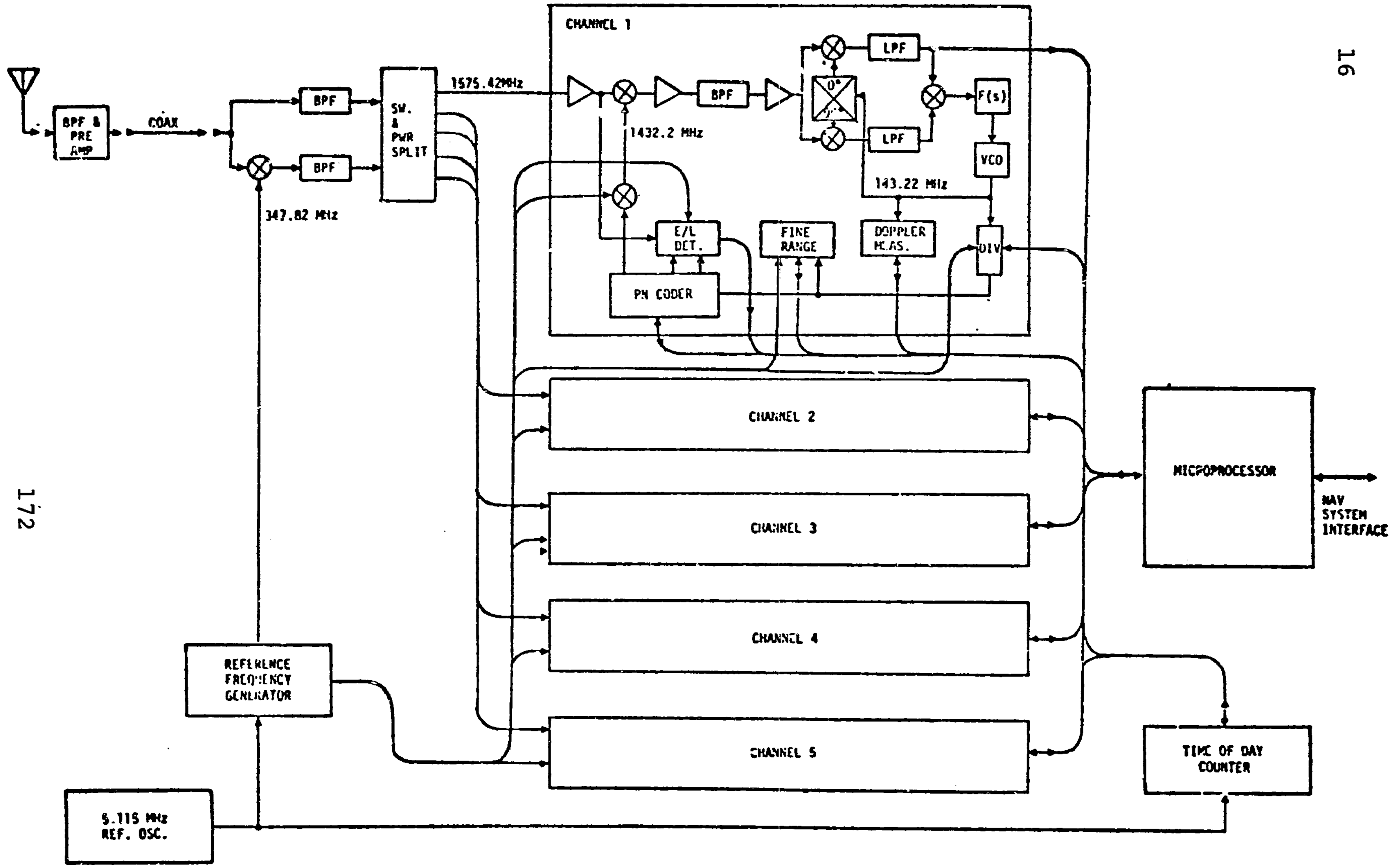
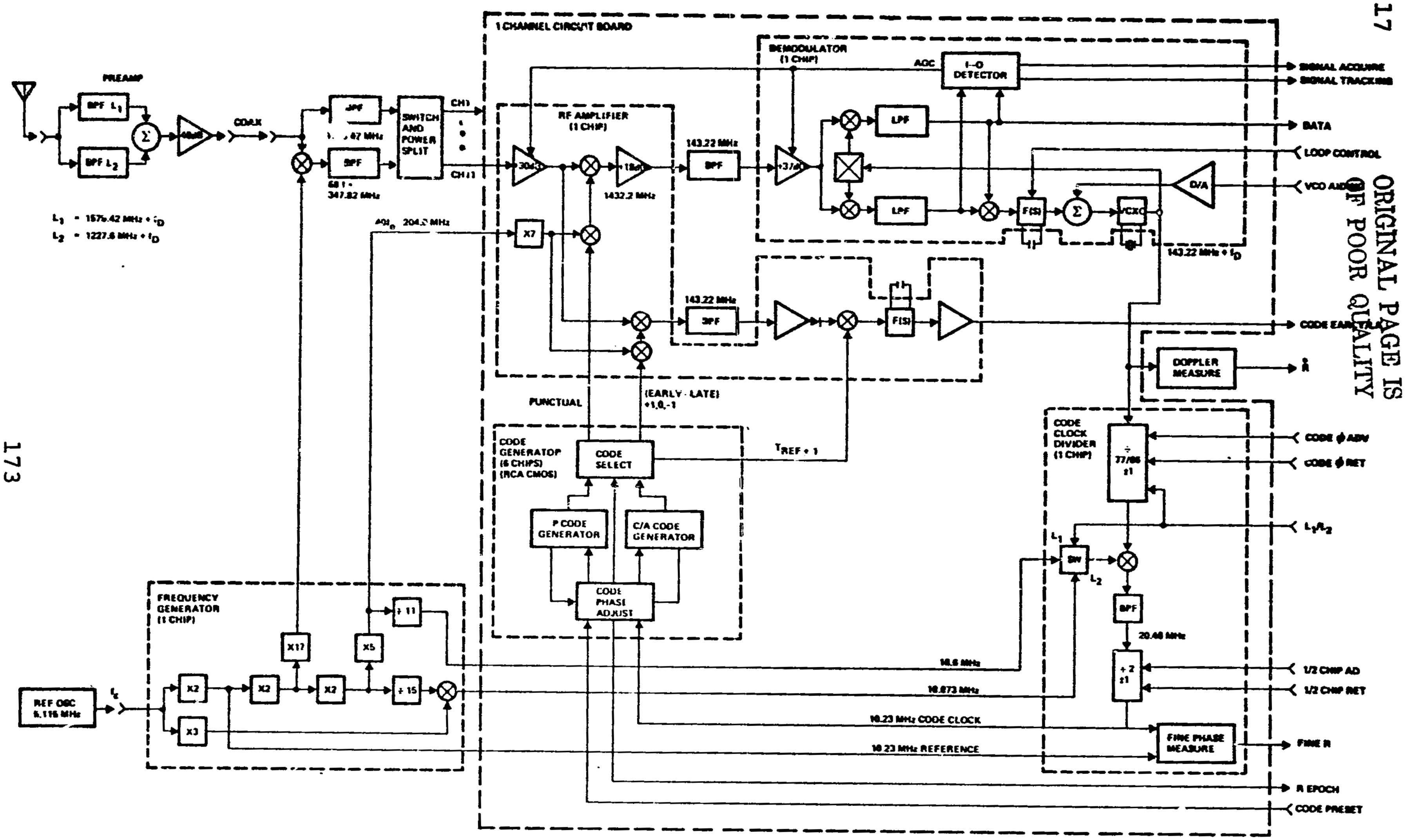


Figure 11-9



GPS RECEIVER FUNCTIONAL BLOCK DIAGRAM

Figure 11-10

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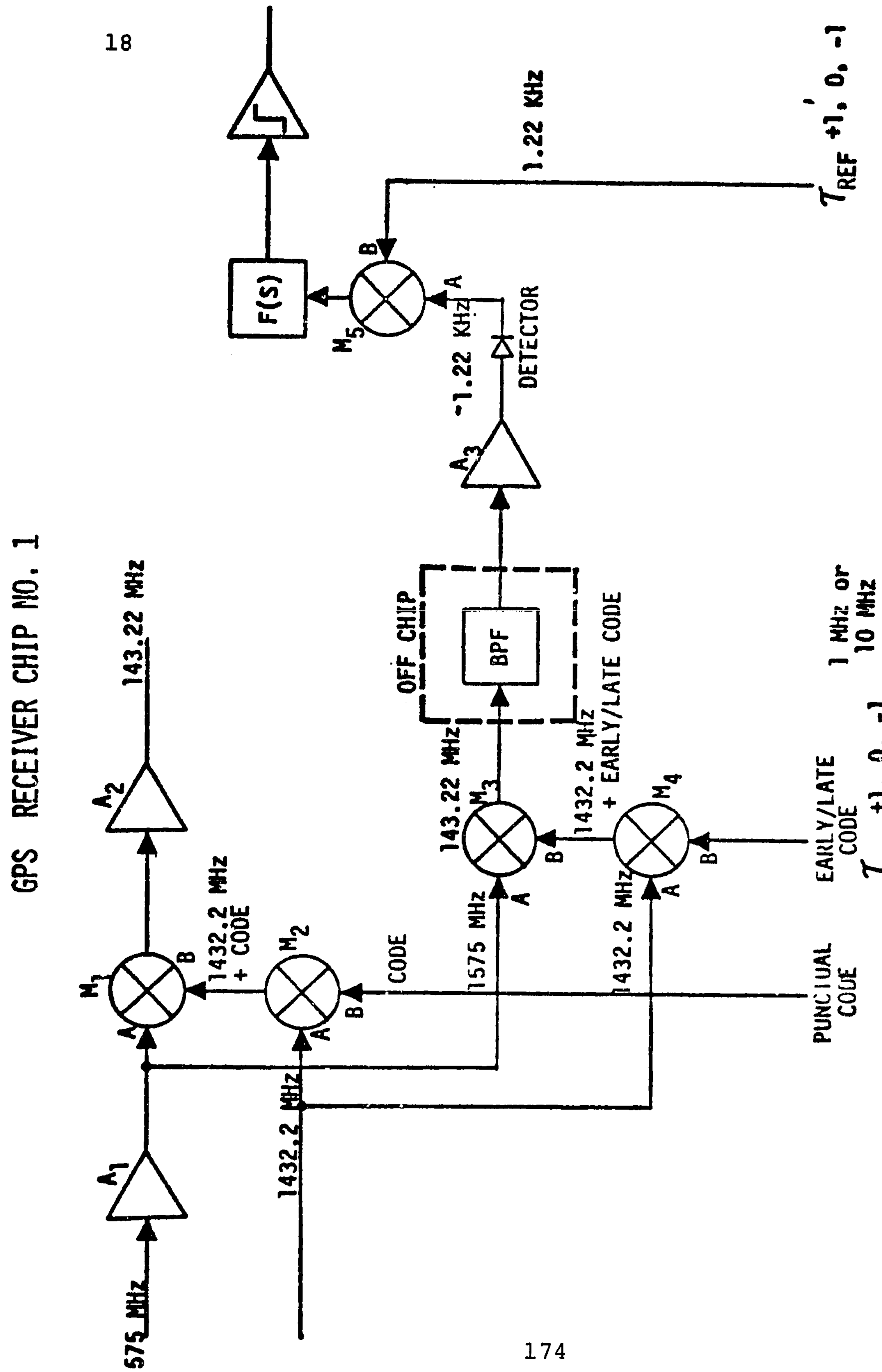

Figure 11-11

RF LSI GPS RECEIVER POWER

MODULE		+5V	±12V	Σ
PREAMP			1.5W	1.5W
FRONT END AND FREQUENCY GENERATOR			0.975W	0.975W
CHANNEL MODULE:	RF AMP (CHIP NO. 1)		1.075W	1.075W
	DEMOD. (CHIP NO. 2)		0.605W	0.605W
	CODE CLOCK DIVIDER (CHIP NO. 3)		0.475W	0.475W
	CODE GENERATOR		0.250W	0.250W
	VCO		0.180W	0.180W
SUBTOTAL:				2.585W
DOPPLER MEASURE		2.5W	0.15W	2.65W
MICROPROCESSOR		16.5W		16.5W
REFERENCE OSCILLATOR			0.5W	0.5W
TOTAL FOR SINGLE CHANNEL RECEIVER:				24.71W
SINGLE CHANNEL PRIME POWER				33W
FIVE CHANNEL PRIME POWER				47W

Figure 11-1[illegible]

MULTICHANNEL GPS RECEIVER

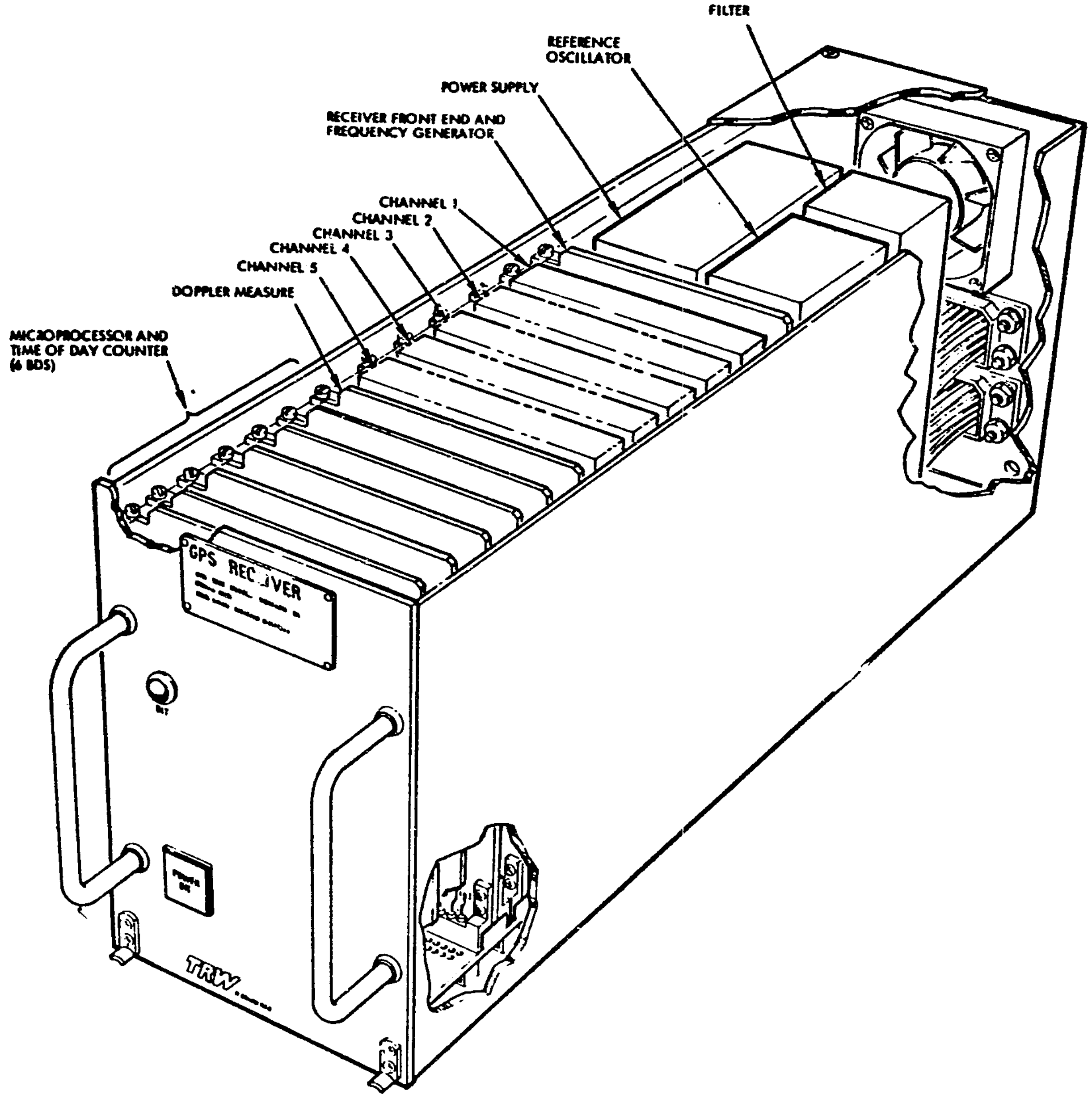

Figure 11-13

PRODUCTION COST ESTIMATES VERSUS QUANTITY FOR VARIOUS RECEIVER CONFIGURATIONS

RECEIVER CONFIGURATION	LOT SIZE 10	100	500	1000
FIVE CHANNEL	$47,446	$25,487	$17,336	$13,937
ONE CHANNEL	$25,826	$13,811	$ 9,396	$ 7,585
INCREMENTAL COST PER CHANNEL (5 CHANNEL MAXIMUM)	$ 5,405	$ 2,919	$ 1,985	$ 1,588

- COST ESTIMATE CONSIDERED CONSERVATIVE:
  - 10% YIELD FOR RF-LSI CIRCUITS
  - INCORPORATES RCA ATMAC MICROPROCESSOR
  - MANUAL MODULE AND SYSTEM LEVEL TESTING

Figure 11-14

OMIT TO END

PANEL DISCUSSION ON USER VIEWS

Moderator: Mr. Anthony Buige, FAA

Panel Members: Mr. William W. Edmunds
Air Line Pilots Association

Mr. Frederick B. McIntosh
National Business Aircraft Association, Inc.

Mr. Glen A. Gilbert
Helicopter Association of America

Mr. Victor J. Kayne
Aircraft Owners and Pilots Association

Mr. Donald W. Beach
National Pilots Association

Mr. Frank C. White
Air Transport Association of America

William W. Edmunds
Air Line Pilots Association

The ALPA position in regard to the NAVSTAR/GPS system is that it appears to have great potential as a navigational system, and we would like to see it receive a thorough evaluation by the FAA to examine its possibilities for civilian use. From the airline pilots' point of view, we feel that its greatest potential is in allowing greater navigational accuracy in oceanic airspace and in the underdeveloped countries and other areas of the world where the U.S. airlines fly. We feel the GPS should be evaluated in light of those navigational systems that are in current use today and projected for the next 15 years.

Frederick B. McIntosh
Director, Operational Services
National Business Aircraft Association

As a user group, we are very glad to see NASA and FAA have joined hands in this type of a meeting, particularly because this area of navigation and traffic control is historically a very touchy thing beaucratically between the two organizations and needs to be complimented.

I must admit that I came to this meeting with a great deal of reservation. Simply put, I wondered if we were looking at another MLS program that is just about to be launched--a program where all progress stops on everything else while we invent a new wheelbarrow.

Now, these feelings are not particularly out of line when you consider that OMB sent to Congress a GAO report on the GPS. This is a report you are all familiar with pointing out its accuracies and the fact that it will do everything for everybody.

They neglected to send the second report that GAO also passed out, namely showing some of the technical problems, things that have to be solved, long-term policy decisions.

I might add industry made up for that deficiency by sending a copy of the second report to the same Congress.

We visited with a Congressional Committee holding hearings of which the GPS was high on the order of discussion. Almost unanimously, all of the groups represented here, to some degree or another, expressed concern about the GPS program and decisions being made prematurely.

When the Congressional Committee report was published, if you read that, you would believe we all wholeheartedly endorsed GPS and get on with it as soon as possible.

Thirdly, RTCA recently established SC-137 for the purpose of developing minimum operation performance standards for RNAV.

At the RTCA meeting at which that was established, the representative from the FAA said that if GPS was included in that committee work, FAA would have to withdraw support from the committee.

And last, but far from least, while we were discussing Omega and all of these navigation systems that were outlined to us yesterday, the Coast Guard quietly started installing three or four new LORAN-C chains.

When you consider the fact that the Coast Guard, at least on paper, works for the Department of Transportation as does the FAA, it makes you wonder how much meat is, in fact, in the National Navigation Plan.

So, when I said that we came to this meeting with slight misgivings, it is based on actions taking place in Washington.

There are some very positive things that have already come out of this meeting, and I would like to endorse them because I don't want you to go home and say, "I have listened to the friendly undertaker."

We are happy to see FAA speak to the total navigation needs of the civil air fleet, not just the one system. It is true we are here talking about GPS, but we were very pleased to see in the briefing yesterday where they put it in its proper context, we think.

They also (FAA), by doing that, endorsed the concept of RNAV. This is the first real major step forward in a long, long time; and I would remind you that if we are to handle the forecast traffic of the future, we have finite airspace and the world's greatest ATC system, and the only way we are going to be able to handle this traffic is to be able to use an RNAV system of navigation, be it Omega or GPS or what.

Now, you are wondering what these policy remarks have to do at an E&D meeting. I would point out to you, at least from our point of view, of late, E&D in FAA tends to set a great deal of policy as witnessed by the five E&D initiative meetings that have been going on for a period of some months and hopefully will be completed within the next couple of months.

There are some interesting problems that were brought up yesterday, and I would like to point out what some of them are because they did not surface as such.

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You recall in the FAA briefing they talked about the need of the offshore helicopter operations. In reality, I would remind you what they are talking about really is not navigation so much as it is FAA control, which is the other side of the coin.

The offshore people have been using Omega and other systems quite satisfactorily on the gulf coast and the Gulf of Alaska and in Norway where they have an Omega station. They did point out the approach problem, which will be addressed later and which we endorse, after you get to the oil rig, how do you get from that path?

I just wanted you to know that there are innuendos to this meeting that involve command and control, if you will, as well as navigation.

We strongly support the helicopter work that is going on at the present time, both offshore and onshore domestically. The helicopter fleet is growing beyond any expectations, in both executive and industrial travel.

There is no denying, however, that an RNAV concept is needed. In summary then, it is the policy of the National Business Aircraft Association that the domestic navigation system must be a common system, usable by the greatest numbers of aircraft; and this common system must be capable of using an RNAV technology. It must provide, if possible, approach guidance to reasonable meteorological conditions, hopefully Category I, and must be compatible with the air traffic control systems for ontrack accuracies and other navigational systems which include the GPS. Although capable of meeting some or all of the criteria, GPS must be considered as supportive or supplemental to a common system; and absent a better alternative, we believe that the present VHF system should be retained as a common U.S. navigation system.

The VORTAC system should be modernized and the beacon locations reviewed for location and maximum approach effectiveness.

We believe the use of every conceived system--LORAN, Omega, and others--as well as self-contained systems should be authorized where the accuracy is obtainable or where the ATC requirements for specific operations and where flight operations are conducted within the coverage of the VORTAC system.

Use of other than the VORTAC equipment must be compatible, including accuracies with the ATC system. We think the ATC system should encourage the increased use of RNAV knowledge; and any new navigation system--and GPS is one of these--must provide an RNAV capability. Although I noticed yesterday the old bugaboo, we have to have routes, we have to have airways. God forbid! I hope that day is soon past.

Satellite technology, we believe, gives considerable promise and may have the potential to provide a common navigation system; and, in our opinion, a knowledgeable decision may not be possible until 1987 with implementation anywhere from 10 to 15 years later. We also believe, very strongly, that no decision on replacing the existing common aviation navigation system, namely VORTAC, should be made until the candidate system--any system, including GPS--is thoroughly developed, engineered, and flight tested and a mutually agreeable implementation plan is in existence.

Remember, it is the users who ultimately pay the bill.

Glen A. Gilbert
Helicopter Association of America

I have a fairly lengthy statement which I will submit for the record. A copy can be obtained from FAA if anyone wants one*. I will attempt to summarize it and highlight some of the comments which are particularly pertinent.

I have been doing some work in writing in the GPS field recently, the most recent being the completion of a very detailed analysis of the potential use of GPS for civil applications. We covered land, sea, and air. This will be published by AGARD, NATO, perhaps in the next two or three months and will be generally available, completely unclassified.

What I would like to do at this seminar is take one segment of that kind of analysis of the potential civil applications of GPS and apply it to an important segment of our civil aviation system--helicopters.

Today, we have something in the order of 6,000 helicopters in the U.S. civil fleet. Of this number, 55 percent currently are engaged in commercial operations; 30 percent, in business/corporate activities; and 15 percent, in government-type work.

Civil helicopter production now has a 12 percent annual growth rate. By the mid-1980's, we expect about 10,000 helicopters, of which some 5,000 will be IFR-capable or virtually all-weather capable. I might just point out that that number by the mid-1980's is almost twice as many IFR-type vehicles as the airlines have in our domestic fleet.

Some people have asked why we should go IFR in helicopters when you can fly low and slow and mainly stay in contact from the surface. I recently made an analysis of helicopter accidents caused by weather. They include such reasons as attempting to continue under VFR into adverse IFR weather conditions, initiating VFR flight in the face of existing IFR weather conditions, flying at night with no horizon, spatial disorientation, and white-outs in snow-covered landscape. In those

* For copy, write to: Federal Aviation Administration, Attention: ASP-10, 800 Independence Avenue, S.W., Washington, D.C. 20591.

accidents, of course, none of the helicopters had IFR equipment. Why should we go off IFR? Well, I will just briefly enumerate three principal reasons.

One is increasing vehicle productivity. My friend Mr. McIntosh certainly knows that a corporate aircraft has to be kept busy because it is an extremely expensive vehicle. The same is the case with helicopters, especially when they cost more than a couple of bucks. They have to be kept busy so we need to have increased vehicle productivity, and we need more expanding air service. Because of the small landing/takeoff area needed by a helicopter, the potential for developing helicopter service virtually is unlimited.

Where surface locations are not available, heliports may be elevated, such as on rooftops, over railroad yards, above warehouse areas, and so on, as well as, of course, on offshore platforms. However, to provide really reliable helicopter service to the many potentially desired landing/takeoff areas, all-weather or IFR capability is essential. To have this kind of operation, and to look a little bit into the future, I have enumerated some helicopter navigation goals that I think may be of interest.

First, a fundamental goal is to have a high-accuracy navigation system with global coverage, capable of providing area navigation (RNAV), without the need for point reference navigation aids. Signal coverage should be down to the surface without the constraints of line-of-sight, radio horizon limitations.

The navigation system should be capable of providing narrow, discrete helicopter routings to facilitate segregation of helicopters and conventional takeoff and landing, CTOL, aircraft.

Similarly needed are discrete instrument approach and missed approach procedures to heliports, helipads at CTOL airports, and points-in-space, requiring a minimum of airspace.

Thus, it should be possible to operate helicopters without interference to or from airlines and other conventional aircraft, in many cases sharing the same landing areas but not the same runway.

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The increasing use of IFR helicopter operations has focused sharp attention on the deficiencies of the present VOR/DME navigation system. This may sound like heresy, but I am saying this in the context of operation, not performance, as it exists in the RNAV environment. These basically are the lack of precision navigation guidance, line-of-sight limitations for low-altitude flight, and unavailability of stations offshore and in remote areas.

Of the 13,000 aircraft landing facilities in the United States and its possessions, we have about 3,500 heliports, some 300 of which are elevated. We only have less than 500 airports having ILS facilities for precision approaches.

We need to open up the capability for making approaches to some of these same 13,000 airports, as well as to unpredictable locations in the case of helicopters for emergency work and operations along pipelines. Also, certainly thousands of oil production platforms may require instrument approach capability in some areas.

The ideal helicopter navigational and positioning concept would be one which would have all of the following capabilities in an integrated system:

- Highly accurate airborne area navigation or RNAV capability, so that airway or route widths could be no greater than 0.5 nautical mile either side of centerline. This does not mean that we should continue with RNAV structure. I don't think we should go that way forever; but when we do lay out a track, I think it should be such that the pilot can follow it within very narrow usage of the airspace.

- Sufficiently accurate approach and landing guidance by the airborne RNAV system so that minimums approaching precision instrument approaches could be achieved to any pilot-selected point on the surface or on space without the need necessarily to have an electronic landing aid at that location.

- Ability to function without line-of-sight radio horizon limitations. This is a new subject which we will be getting into more and more with advanced helicopter models of flying.

C-3

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- Vertical velocity measurement accuracy in the order of 0.1 foot per second; horizontal velocity measurement accuracy in the order of 0.1 of a knot. These are goals; whether they are achievable or not remains to be seen. They are still ideal goals.

- Three-dimensional, lateral, longitudinal, vertical, 3D navigational guidance sufficiently accurate to supplement or supplant barometric altimetry. We make an approach today and can't do it beyond 5 miles from where an altimeter point is available. Hopefully, some day we can have some independence from this kind of restraint.

- Four-dimensional or 4D guidance, adding time-referenced navigational capability to 3D guidance with extremely high time-positioning accuracy.

- Impervious to atmospheric conditions.

- Nonsaturable capacity.

- Service availability to all classes of airspace users on a worldwide basis.

- System outputs capable of advanced multifunction cockpit displays, including display of navigational and traffic situation information.

- An operational item, but I think in some cases we need to come on a decentralized IFR operation.

- Data link capability to transmit x-y-z coordinates for automatic position reporting and air-to-air separation assurance.

- Be cost-effective based on life-cycle cost analyses, with the system design such that it can have various levels of sophistication and thus will be affordable to all classes of airspace users.

I would say from the foregoing that I am going to make four broad assumptions that the desired navigation and positioning requirements can be met most effectively by a satellite-based system and that the satellite-based system most likely

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to achieve these requirements in a realistic time frame is the DOD NAVSTAR Global Positioning System.

I agree with the time frame that Mr. McIntosh mentioned. The earliest we can expect it would be in the mid-1980's or thereabouts. After NAVSTAR systems have been deployed and the system is operational, as we all know, 10 to 15 years is required, so we are talking about maintaining a current system well into the 1990's.

One other thing that has not been talked about very much is that the DOD under any circumstances would not deny use of or degrade precision P signal accuracy of the GPS for civil aviation. My idea of saying that GPS is the most logical candidate in the future to perform these navigation goals which I have enumerated is on the basis of P signal availability. I have grave doubts about cost-effectiveness for transitioning to GPS signals if we have to rely on C/A signals. That is my personal opinion.

Finally, no charges must be levied against civil aviation for the use of GPS.

I have gone into the paper. Now, in conclusion, helicopters have become, and are becoming more and more, a vital element in the Nation's total air transportation system. Due to the unique characteristics of helicopters and future VTOL's, discrete routes and approach procedures are needed in many instances to provide segregation of this type of air traffic from CTOL traffic. We all know of the San Diego accident, and there certainly is some question on how to segregate different performance categories of aircraft in the interest of safety. We might want to consider this more and more.

Area navigation is a must for successful helicopter IFR operations. Current RNAV systems do not fully meet helicopter navigation goals, and GPS appears to be the most logical candidate for a fully satisfactory helicopter RNAV system.

If certain problems of GPS implementation which I have mentioned can be worked out, GPS implementation by helicopters may very well lead GPS implementation by other segments of civil aviation.

Victor J. Kayne
Senior Vice President
Aircraft Owners and Pilots Association

Responding to the technical presentations at this seminar, I would say that VOR/DME very nicely fills the needs of the majority of general aviation users. General aviation is a broad term and includes business jets and most of the helicopter operations.

We see that a supplementary system might fill needs that currently are not filled by VOR/DME, provided that it is a system that is both feasible and practical. There are many general aviation operations at low altitudes where VOR coverage is not available--not only helicopter operations, but also other operations such as those behind mountains, in remote areas, and in undeveloped areas where no VOR/DME coverage exists. It is in these areas that we have a current navigation deficiency.

The general aviation investment in VOR avionics is very large, and I don't think there is going to be any great enthusiastic rush to discard this system overnight by the people who are part of that investment. As an example of the investment, AOPA recently conducted a survey of its 216,000 members and asked them questions on the equipment they have, the planes they fly, and their occupation. The results of the survey showed that they owned aircraft in whole, in part through a partnership or a club, or in some cases there was multiple ownership of one individual in more than one airplane. We found AOPA members owned about 30,000 aircraft with single omni installations and about 86,000 with dual omni receivers. This adds up to 116,000 aircraft with VOR; and if you add the ones with dual installation, this comes to over 202,000 omni receivers just from our members alone, and that doesn't count the rest of general aviation.

If you price these units at $1,000 each, you have a total investment of $202 million. To replace these with a low-cost GPS unit of $2,500 would cost a total of $811 million.

With regard to LORAN-C, general aviation has no requirement for this system other than for specialized users, such as support of oil exploration.

We have looked at GPS with great interest because of its ability to provide worldwide coverage including at low altitudes, over oceans, and in undeveloped areas. Internationally, it is in undeveloped areas where general aviation is providing a large variety of essential services. In those areas, we must now use dead reckoning as there is very little in the way of navigational guidance. From GPS we would want precision comparable to that now required for a nonprecision approach to an airport.

On the Omega front, we see no indication of a breakthrough in avionics which would make it suitable for the general aviation population; and on the other side of the coin, we are optimistic about GPS avionics being suitable for general aviation. If GPS does come into service for civil aviation, it will be in a supplementary role initially, and certainly any change to make it the major system must be evolutionary in nature. We have the same concern that Mr. Gilbert has about the matter of someone in the Pentagon pushing a red button and all of our navigation goes off the air.

I can't leave the subject without noting with some humor that our old friends the economists have gotten into the act. They were talking about their favorite subject, user charges for GPS, and I haven't quite figured out how we are going to get the Russians to pay for their use of GPS. I hope the economists stay out of the picture and not further muddy up the water.

Finally, general aviation is a great user of RNAV. We support it, and we have many thousands of sets in use in general aviation that go all the way from the simple RNAV inexpensive type to the most sophisticated. I agree completely with what Mr. McIntosh said on the RNAV subject.

We do not want its flexibility destroyed by constraining the RNAV use to routes. The ability to follow a course is one thing, but trying to constrain RNAV to use routes is just completely out of the picture.

We think we have a common goal on that one with NBAA and others.

Donald W. Beach
Director of Operations
National Pilots Association

We have heard a variety of experts at this seminar present information as to the current state-of-the-art in this field. Their presentations appeared to provide more questions than answers as to the general aviation application.

We are still a long way from being able to employ this type of technology to meet the needs of that segment of the aviation industry which is loosely grouped together as general aviation. General aviation has many pressing needs; but in my estimation, GPS is not one of them.

I do recognize that special interest groups--such as the helicopter operators and certain transoceanic flights of business and industry--have a need for such a navigation system. In my estimation, the monies available for navigational systems should be spent to upgrade the current system to a second or possibly third generation system. Money should also be spent to upgrade other existing navigational capabilities--such as Omega. If there is money left, research should then be continued to the civilian application of the NAVSTAR GPS program.

I am glad to see that the FAA and NASA have approached the future navigational problems head on, and the fact that we are meeting in a situation like this is heartening.

I would like to close by making just a few suggestions. The first is that Congress spend its time pursuing areas in which it has some expertise--possibly campaigning. The second is that OMB and GAO should concentrate on the GSA, not GPS.

In closing, I look forward to research continuing into areas such as we are discussing at this seminar so that possibly by the year 2000 you will be in a position to tell us how we will get from point A to point B.

Frank C. White
Air Transport Association of America

For the foreseeable future, the airlines are satisfied with the navigation service provided by the ICAO worldwide standard VOR/DME and ILS systems. We anticipate the orderly introduction of the new ICAO MLS and the phasing out of ILS when timely as envisioned by ICAO and specific requirements.

The airlines are beginning to learn about Omega, which we were obligated to put into service before the system was totally developed as a result of our Government's desire to phase down LORAN-A early. In spite of that, we have been able to introduce and use Omega and believe that it will fulfill our overocean navigation requirement, together with doppler and inertial, for many, many years to come. We like Omega because it provides worldwide coverage with only eight stations and a handful of monitoring locations. There seems little potential for the cost of maintaining it to rise above the value of the service it provides. Its accuracy appears to be adequate for at least a decade.

Summarizing, the airlines are not looking for a worldwide-coverage, high-precision, high-cost, early replacement for VOR/DME/ILS/MLS and Omega. Having been shotgunned into accepting Omega, we are not very pleased with the apparent action of some elements of Government to phase out a family of VOR/DME navigation systems which we have found totally acceptable in favor of something they believe will be better for us.

We will continue to state publicly at every opportunity that is offered the desire of the airlines to continue VOR/DME, ILS and MLS, and Omega into the foreseeable future. We will continue to advocate the over $100 million expenditure to update and modernize the U.S. VOR/DME system, which certainly is a fully justified, cost-effective program.

Having stated as clearly as possible the airline view with regard to the navigation systems we now employ and their possible replacement in the next 5 to 7 years, we have a word about NAVSTAR/GPS.

The airlines have followed the development of GPS for about 5 years, beginning from the time its advocates testified before Congress that it would solve the air traffic control, landing guidance, collision avoidance, and many other problems of civil aviation. The record shows, without equivocation, that the airlines are always among the first to look at and try out new technology. We are extremely interested in looking at the potential of satellite technology for satisfying worldwide communications, navigation, and surveillance requirements. We are not at all convinced, at this early point in its development, that NAVSTAR/GPS is the single optimum system to provide the navigation portion of these services. I hesitate to mention communications and surveillance satellites as having an earlier, brighter future than navigation satellites such as GPS, since the last time we did that a number of governments developed a monster Aerosat program that forced us to disown ourselves from it as being too much, too early, something we couldn't afford.

Those of you here today who know the airline industry, and I speak now of FAA as the best-informed in the Government, and many others--manufacturers, universities, researchers, and others--all of you know that we will carefully work with you to investigate the possible future potential of GPS toward solving future airline navigation requirements on a cost-effective basis.

As it appears at this time, we would expect that by the mid-1980's, NAVSTAR/GPS, if it continues in development as some forecast, should be to a point where enough will be known about the system, particularly reasonably priced receivers for the masses of U.S. civil aviation aircraft, to determine if it has any future at all for serving the requirements for the over 100,000 aircraft which now use VOR. We all know that a decision to move toward the possible use of NAVSTAR/GPS for serving civil aviation will be determined primarily by its ability to serve general aviation in the United States. It seems to me, recognizing that situation, that the airlines will probably not encourage or discourage the development of NAVSTAR/GPS but will participate and be of whatever assistance they can be toward achieving good answers for civil aviation users, primarily general aviation, in the next 5 years.

We have carefully read the economic studies that have been produced by FAA contractors, particularly that of Systems Control, Inc. (Vt.) ("Economic Requirements Analysis of Civil Air Navigation Alternatives), and find they are reasonable, satisfactory assessments of the likely cost for introducing NAVSTAR/GPS into the civil fleet. Frankly, these data are not very encouraging.

We are satisfied with the present level of FAA/NASA funding for developing low-cost receivers for civil aviation use of NAVSTAR/GPS. We do not believe that funding level should be increased at this time.

Thank you for the opportunity given to a representative of the scheduled airline industry for presenting the views of that segment of users.

DISCUSSION

Mr. White - I feel the development of GPS receivers is in good hands, and we look forward to seeing how it moves ahead. It is interesting, though, that in our various discussions with representatives of the manufacturers and universities and with other users involved in FAA's New Engineering and Development Initiatives effort, GPS has not been brought up for discussion. There is not that much interest in GPS at this time. We are much more interested in much more pressing problems--and that is the way it is.

If GPS is really going to be satisfactory for civil aviation, the primary need is to develop a low-cost receiver. This is not of primary concern to the airlines--although we like low-cost receivers, too--but is of course a primary concern to general aviation.

I would like to add one other thing. I have heard some Government representatives say that the FAA is dominating this and is forcing the users to take their stated position. If there was anything that the FAA was doing that we didn't like, we would sure let them know privately, publicly, and at every opportunity. You will find that whatever was stated here about GPS in the past as far as I am aware has been a reasonable reflection of my view.

Mr. McIntosh - I have been thinking about a light-twin delivery flight recently in Africa where the pilot had all the navaids turned off and the only thing that saved him was Omega. I think there is a lesson to be learned from all of this. I was also reminiscing about having first heard of this wonderful system when I was in the service over 20 years ago. So, if that is indicative of any time frame, many of us on this panel will be long retired as this battle is ultimately fought out.

I would also like to point out the inertia of our system. Even those of us who work in the industry are amazed at the amount of traffic that is moved in the airspace, and it took a long time before I was convinced that when you make a small change in Seattle, there is a ripple effect right back in LaGuardia. We usually talk about ICAO and international requirements as well as other requirements. You are dealing with one hell of a big steamroller when you start making changes. And we have some major changes already in the works. We are going to MLS technology. General aviation continues to grow. How high it can grow I have no idea, but they are turning airplanes out in Wichita like they are going out of style.

You simply are going to have to get more people who are concerned with designing the method and the means by which these airplanes get from place to place.

I know you are tired of hearing the term RNAV; but the days of the blue and the green are, for all practical purposes, done, and the sooner we all recognize it, the better off we are going to be. The point now is going to have to be separation assurance, so that two people can go in the same direction and fly at a reasonably safe distance apart. It may well be that GPS can help us with that. I don't know, but the point is we can no longer afford five, six, or ten different systems. So, if some of us do not wax particularly enthusiastic about the GPS, the fact that we are trying to make it work for the diversity of aviation in the largest and the safest air traffic control system in the world is a challenge; and it is a privilege to be a part of it.

Mr. Gilbert - My first impression is that this panel represents a good cross-section of the user community's views on GPS. These views range on a scale of zero to ten, with ATA being number one; myself, number nine; and the others, in between. I think it is a healthy sign that the industry has different criteria and reasons for determining navigational requirements.

When I speak in the more or less optimistic tone about the future of the GPS--and I use GPS because that is the only satellite system we have at the moment that seems to be reasonably far enough along to use for some of the things I have in mind--I am not thinking of doing this tomorrow, and I know the system is not going to be in place tomorrow. But, I think in the aviation industry we have traditionally had to have it waiting for some crisis or catastrophe to occur or some great bind to take place; and all of a sudden somebody says we ought to do something about it. So, when I am outlining the applications to be used for GPS, it is for the purpose of its being in place some time in the future when we need it and can use it more effectively--perhaps on a broader scale throughout the industry that might not be apparent to us now.

In the meantime, notwithstanding Mr. White's remarks, I still maintain confidence that GPS has a good future.

Mr. White - I think it might be helpful to relate a little history about the development and implementation of LORAN-A during World War II as we may learn from it. I was on the staff of the Chief of Naval Operations and worked with Mr. Paul Goldsborough (who is now deceased), who gave us this very fine navigation system that is still surviving. As the war was coming to an end, my office began to look at what to do with the systems which had been developed during the war. We tried to envision their introduction and acceptance into civil use. Both Mr. Goldsborough and I felt that if LORAN-A was operated by the Navy, it would not be accepted by civil aviation. So we came up with the idea of having the Coast Guard be the operating agency. We had a tough time selling that idea, but we did; and it is obvious that we did the right thing.

Now, I think it would be extremely difficult to successfully convince ICAO that GPS is a proper system for ICAO to endorse. One of the things I find particularly embarrassing is the role of those satellites since, as almost everyone knows, there are other things in these satellites besides GPS. The United States has one vote in ICAO. Many nations do not think we are the "Great White Father." In fact, they think we are the ogre. We dominate too many things in the world.

My personal view is that long before the United States considers introducing GPS for possible civil use, we will have to divorce the total GPS program from the military. Otherwise, we will likely find it absolutely unacceptable.

Mr. Peter S.P. Hui, NASA/Goddard Space Flight Center - Mr. White, do you consider the current polar navigation service adequate for the airlines?

Mr. White - I believe I can say yes, unequivocally. Traffic density at the poles is extremely low. There is practically no traffic across the South Pole, and across the North Pole it is extremely light. The INS, the Doppler, and Omega currently do a good job, and to my knowledge we are not experiencing any problems.

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Mr. W. W. Bailey, U.S. General Accounting Office - I would like to comment first that GAO does not work for OMB. We work for the Congress, and all of our reports go to Congress, including the one mentioned by Mr. McIntosh. Also, on frequent occasions, we send copies to the affected agencies.

I would also like to make a short comment on LORAN-A and the transferring from a military to a civil system. I think it is probably true that virtually every navigation system in use today began as a military system. It is interesting to note, however, that as of this year there are approximately 4,000 users of Transit, which is still a Navy system, of which I am told 80 percent are non-Government users.

Obviously Transit is not suitable for aviation, so these are all maritime users, but that is still a pretty impressive number.

Dr. B. W. Parkinson, Colorado State University - I would like to summarize my views on the NAVSTAR/GPS. First, I think GPS is coming--the Department of Defense by and large has endorsed it and feels that it is an absolutely necessary thing. So that part is almost a fact of life.

I think, also, in listening to various people that there are genuine civil needs. They are not universal civil needs and certainly not universal needs now at the projected cost--which is probably optimistic for today and perhaps somewhat pessimistic for 1990.

I contend that the overall responsibility on us is to allow the system to be certified and let the users vote with their billfolds on whether they individually feel that the user equipment costs justify its potential use.

I also have a few challenges that I would like to offer. First, I would like the Department of Defense to provide the P channel to all users. I think this is a logical and rational approach to what should be done.

I think the staff of NASA is exactly right in exploring some possibly wild schemes because I think their whole purpose is to push the frontiers of technology and see where they lead us. There are great potentials there.

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I think FAA should agree to certify GPS, assuming that GPS meets whatever constraints they have as an RNAV system. Furthermore, I think they should ask the Congress to provide additional dollars to underwrite low-cost equipment developments, particularly in those key developments of LSI technology that make sense.

I think the burden of proof is really on the manufacturers, because if this is going to come to pass as a universally used civilian system, the manufacturer has to provide the low-cost equipment to support that.

I think GAO should support a prudent approach, and I am not certain they are not. I think we are all perceiving things a little differently here today; but I think the GAO is simply saying, "Look, it's coming, it offers great potential, it is unproven, but let's give it a try." I think that is a very reasonable approach. Personally, I think it is still unproven, and I have a lot of my life tied up in the system.

Lastly, I think the challenge that I offer to the users is to keep an open mind. GPS is not something that should be crammed down our throats. I think certain users, and even certain segments within each of the organizations that are represented here, feel there are genuine uses for GPS. In some cases, users would pay $100,000 if they could have a set that provided them with a GPS capability, whereas other users would not pay $100 today for GPS. But I think the opportunity is coming, and I think it is incumbent upon all of us to simply take advantage of it and to exploit it for the civilian community if we can.

Mr. McIntosh - You will recall our long negotiations with the Navy over the use of VLF for navigational purposes. It came into use only after the Navy granted certain assurances, but then it was integrated in most boxes with Omega--in a dual box. Pilots don't know whether their equipment is monitoring a VLF station or an Omega system. This equipment is now certified for certain types of operations, but it would never have been certified for Minimum Navigation Performance Standards across the Atlantic if it had not been for the availability of Omega. I agree with Professor Parkinson that anything that could be made available should be made available for those who need it on an optional basis, much the way VLF was used in the first place.

Mr. Buige - I would like to make one comment on Dr. Parkinson's comment. The FAA has publicly stated in any number of forums, and I will repeat it here today, that with regard to GPS, if a piece of equipment can be certified to meet the specific navigation requirements, we will certify it and the user will be able to use it. There is no question about that.

A Participant - Mr. White, relative to your feeling that ICAO would be reluctant to consider the new GPS system, do you feel that it would be considered if the system were designed to complement the VORTAC system as opposed to competing against it? Or do you feel that the approach is not the issue? The thought here is, navigating to VOR facilities, a facility doesn't really care how I get there as long as I get there. If I receive signals from some other source that gets me there, I am still operating within the system and the airway. It is a question of whether or not the ICAO people would believe the system would allow me to operate within the airway.

Mr. White - I am satisfied with VOR/DME. I don't want GPS or any other system in the domestic United States unless it is obviously a better, lower cost way of doing the job.

As I understand it, the Government is currently looking for a reduction in the number of facilities. Therefore, if, for example, I endorse GPS as a better domestic solution, I would expect in time to have VOR/DME phased out--and that is a long way off.

Mr. Kayne - ICAO is not an enforcement agency. Collectively, the 143 contracting States of ICAO establish Standards and Recommended Practices, and the States implement those or adhere to them as the case may be.

Talking about flying down the centerline of an airway, you can be cleared from here to there with certain equipment on board, and nothing prevents you from using any or all of that equipment to fly that centerline to where air traffic control has cleared you.

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In the United States, the military have been flying certain airways and jet routes, where they exist, for many years now; and they aren't necessarily using the same equipment that other people are using. But they navigate just like everyone else right down the centerline, make position reports, and everything else. In international airspace, you can be in a mix of traffic using two or three different navigational systems. Nothing says you have to use one system to follow that airway.

Mr. Buige - We should point out that you can actually fly the airways with no navigation system at all. You can get a radar vector clearance. It is pretty hard, but every once in a while they will do it.

Mr. Gilbert - I would like to expand on the remarks made by Professor Parkinson with regard to the GPS/RNAV system.

If the constellation of 24 satellites is put in place by the DOD and the manufacturers come out with an acceptably packaged GPS/RNAV system for aircraft, and if the FAA goes forward and runs through the routine necessary to conform GPS/RNAV system to a C-90-45A for all three modes in the terminal area and approach, I would believe in my own mind that the helicopter industry would start in selected cases to put this equipment on board aircraft as soon as the total system is in place--and that very well could be in the late 1980's.

Mr. R. Alfred Whiting, National Research Council - You must be well aware that Proposition 13 fever is at hand; and in the days and years to come, the taxpayer is going to be looking more closely at what he gets for his money. He does get some services from navigational aids when he flies on airlines and in general aviation or when he is a recipient of some service (such as freight or other services) that the aviation community provides.

He is still going to ask, What am I getting for my money? I think in the next 10 years or so there is going to be a serious question of how many systems we are going to have and at what cost. Can the GPS provide this at lower cost? And if so, you can rest assured that you will get that system.

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I think we ought to consider, also, that we are talking about a GPS system and not necessarily the GPS system. It may be that some private company may see a lucrative possibility here and may launch the system on its own instead of a COMSAT or NAVSAT.

I haven't heard said at this seminar that the P signal is really necessary. But if it is necessary for general aviation, I think there is probably no reason why we won't get it.

Mention was made of the use of Omega, LORAN, and so on. These services require the use of a host country, and you know what happens when the host country decides to deny us that availability.

I would like also to say to Mr. Kayne that I was a little disappointed in his statement about the cost of VOR sets because he neglected to take into account the cost of the DME, the RNAV, etc.

Mr. Poberezny and Mr. Baker recently agreed to work together to bring down the general aviation costs of flying to the public, and I think what Mr. Kayne said is inconsistent with that.

Mr. Kayne - I was using, first, the investments that general aviation has in omni navigational equipment. I didn't throw in the figures for DME, ADF, RNAV equipment, or anything else we might have because I don't think from what I have heard about the way the military is heading, for example, that we would be so optimistic to think that we are going to get something out of this so accurate that we could throw all the rest of the equipment away.

I also said as far as we are concerned, it looked like the accuracy of GPS will be something in the order of what we need for a nonprecision approach. For precision approaches, we would need whatever the system happened to be for precision approaches--ILS, MLS, and ISMLS.

With regard to ADF and NDB's, which have been with us practically since aviation started flying across country, I don't think you will ever get that one out of the picture--internationally. It is a simple, low-cost device for the airplane, and you can operate against a variety of ground sources. The NDB provides not only for aviation, but also the marine and broadcast stations. I guess the ADF probably gets more use around the world than any other piece of navigation equipment, and I can't even foresee if they come up with the GPS and we get the so-called "low-cost" piece of equipment that it would replace something like the ADF in the airplane. I think that is going to be with us for a long time.

I didn't overlook these other costs, but I left them out. I was just trying to deal with replacement of the VOR/DME with NAVSTAR, and I just stuck to the VOR end of it because the bulk of the general aviation airplanes depend just upon VOR. They don't have DME in them.

Mr. McIntosh - I think DME in one form or another is going to have to be with us because I can just see a controller telling you with the GPS, You hold on a 320-degree radial, 20 miles east of so and so. Without this equipment, what is the pilot supposed to do?

I assume that it has been pointed out at this seminar that the current ATC computers all deal in latitude/longitude, and we have the anachronism of having our RNAV today in Rho-Theta, bearing in mind that the computer has to change into a language it can compute with and put it back in terms that the pilot can understand on his equipment.

We have to take a look at ATC, the environment that we are going to be operating in, the terminology, the controller, the pilot, and the instrumentation he is going to have to use.

These are not insurmountable problems--I appreciate that--but it is something that your marker beacon will always be in there with some description. You have to have some idea where you are from the end of concrete, and I think DME is going to be an integral part of whatever navigation system you have. It might not be called DME.

A Participant - There seems to be some discussion and confusion about this business about the interface of the GPS receiver with the aircrew.

I guess from the point of view of some of us who manufacture the software that drives those interfaces, we would like a coherent statement of exactly what sort of interface is wanted. It would be pernicious for somebody to go ahead and design that sort of software and put out latitude/ longitude indications if that is not what the pilots are going to use. I don't think this is a big problem provided those of us who are not normal members of the civil aviation community understand exactly what is wanted when the time comes. This is not a technical problem.

Mr. Edmunds - I agree with you that the interface is not really a technical problem. That is not what we are really looking into now. I think the Omega system works pretty well using the input and the interface that it has, and it could be very easily adapted in the GPS when the time comes.

Mr. White - The biggest problem we have with inertial and Omega today is pilot entry. The word the mathematicians use in defining it is "blunder."

I can't respond to the question about what I want. I know that we have a problem, and I am sure ALPA will know that kind of a problem better than I do.

It is a problem we are not able to solve. We have aircraft going the wrong way on one-way airways across the North Atlantic simply because the improper entry was made by the pilot, and we find them on the other side of the ocean arriving at the place where radar coverage occurs exactly one degree off course, on the airway going in the wrong direction. This is an extreme case, but it happens.

Again, the biggest problem we have today is pilot blunders. I am not encouraged by the kinds of problems that the NAVSTAR GPS introduced in this regard. They are the same problems, however, that are apparent with regard to any other form of RNAV coverage systems, such as VOR/DME, RNAV, and so on.

I don't pretend to know the answers, and you didn't see anybody jump up to answer these questions. Incidentally, it appears that the New R&D Initiatives groups are emphasizing the need to understand better and to give guidance to those who are trying to provide us a better interface with the humans we expect so much of who are flying our airplanes.

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Whereas we know the airline pilots are highly trained and very competent, we know that in many cases there are tens of thousands of general aviation pilots who are probably not as well-trained or as competent as airline pilots. It is a tough problem. We all know it, and I don't know that any of us can give you a better answer at this time.

We are all encouraging investigation into this problem, and we need better answers than we are getting today. Unfortunately, we can't give them today.

A Participant - I have done work on interface with complicated navigation systems and am sensitive to the problem identified as "blunders."

In the case of a GPS user equipment set, we do have as an intrinsic part of it a data process which has software for a variety of purposes beyond just navigation.

Any display which comes out must be dealt with by that software and format. From the software designers' view, it then becomes a question of what format is wanted. In the form that the data is in the processor, it is unsuitable for use by human beings. Something has to be done with it. The question is, What? If we can get together and figure out what should be done, I will make a conjecture that it is not going to cost any more to put it in whatever traditional or accepted format is wanted provided we know about that in advance.

Mr. McIntosh - I think we are addressing a problem here that is not unique to GPS. As Mr. White pointed out, it is common to any RNAV concept in which latitude/longitude, or coordinates, would be a basic problem. I can see downstream perhaps LORAN-C or Omega getting into this. At least one manufacturer has solved the pilots' intelligence quotient by having a taped set so that the pilot can actually punch in the identifier. The fact that this is 36.5/122.7 West, the computer knows this; but the pilot is not expected to know it. All he has to do is remember three letters. That is one solution.

I, for one, can see downstream as we attempt to move RNAV in. Let's say that we go to the route structure people are talking about and you put an intersection in. We have already run into this in the low-level dedicated helicopter routes from Boston to Washington. How do you tell the pilot where that intersection is? You can do it on a chart. You can give him latitude/longitude. You can give him an identifier. You can give him several things, but think of it in terms of the controller. He calls you up and says, November One, you are cleared. What is he going to say? 36.5/122.7? Not domestically!

So, when they start talking about route structure, they are probably going to end up picking a space between Salinas and Manhattan, and that will become an intersection. At that point, he will convert that and identify it to something phonetic that an air controller can say to a pilot. This is not unique to GPS. I think we are going to find this in all kinds of the generic family known as RNAV.

Mr. Van Cleave - If you you want range and variance instead of latitude/longitude, that is a trivial calculation. If you want to replace DME, that is extremely easy. I think the panel should comment on that if you do eliminate DME with GPS, because I think GPS can eliminate DME and VOR and ADF. I think that might just reverse some of their prior statements.

Mr. Kayne - First you have to identify the waypoint, which I think was Mr. McIntosh's point. The thing that ran through my mind when the gentleman was talking about interface was that I think we are way premature. This whole conference may be premature. In effect, we are talking about a system that is unproven. There has been no practical operational experience with it, at least as far as the public is concerned; and yet we are trying to say here that it is going to replace DME, ADF, and everything else.

As far as I am concerned, it is not going to replace anything for a long time until we know a lot more about it. We have to go a lot further down the road before it replaces anything.

As presently described, we can see that this might be a supplementary navigation system to provide service in areas where we don't have it for those who need it. And there are people flying in those areas right now who say they don't need it. There is no great crying need for it.

We will see it first as a supplementary type thing. Further downstream if it proves itself and we solve all of these things about somebody sitting in the Pentagon shutting the thing off, there may not be any need for it at all. We may not even accept it if it was offered.

I think we are getting premature on this type of thing, like the interface and saying it is going to replace DME and ADF and so on. In my book, it is not going to replace anything for a while.

A Participant - You have alluded to something that I didn't quite understand about the DOD's commitment to not turning this system off and towards supplying precision code and not degrading it. Are you aware of any such statement by DOD concerning these things?

Mr. Gilbert - I said there was a question--a problem. I didn't say DOD committed themselves at this stage of the game.

The only thing I can add to my statement is that Executive Order 11165 provides for the DOD to take over all navigation aids under certain circumstances as prescribed by the President. That can include VOR's, VORTAC's, etc.

If the DOD, an Executive order, or an Act of Congress, however, were to classify GPS as a navigation system under the same terms and circumstances as are applicable under Executive Order 11165, then at least GPS has been put into the equivalent position with regard to our other navigational systems. That has not been done, and I raised this question and pointed out in my assumptions how we would be able to use the GPS most effectively in the helicopter industry. Specifically, one of the assumptions was the DOD would not deny the use of GPS in most circumstances, and only in the event that DOD takes over the whole national navigation system.

A Participant - Relative to the conference being premature, I think that in looking at the time schedule we are discussing, a potential system that might be of use even in the year 2000, for a system to come into general use, it is going to take 10 to 15 years. If we get started in 1985, considering very sizable and technical problems to integrate the system into the air traffic control system as well as the low-cost problem, the 6 or 7 years that we have left to solve these problems is still a relatively short time.

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Mr. Thomas Rhyne, Texas A&M University - I am a general aviation pilot, and I got interested in this because I was a young navigator and was excited about it.

I don't know if it is fair to characterize your positions, representing your organizations, as being a little bit defensive about GPS; but I guess it is fair for me to say that I come away with a little bit of that feeling. I have been speculating in my own mind. I feel as if somebody is a little bit concerned, and there must be valid reasons for it.

I know, having read some of your reports and from the presentations, that occasionally those of us in general aviation have had a little bit of problem with the FAA.

Let me just say that if the FAA could clearly assure all of us that GPS would never become the newly enforced hardware requirement on those of us in general aviation--the little guys in the 182's, 172's--if they could give us a system that was GPS-based and was really a complement to the present system, it might mean a VOR-type head that gave you the same kind of guidance except it drew its basic intelligence from GPS signals instead of VOR; and maybe it would do everything the VOR system did, except it would give me coverage at lower altitudes.

Certainly there are a lot of technical problems, and that is not what I feel is being addressed. If we could get a policy statement that said the FAA or the DOD wouldn't try to justify the massive expenditure based on the fact that it is going to be a good deal. If they could just say some day there might be a GPS-based system that cooperatively permitted you to fly in the existing environment. If you could be sure that the limited research dollars that are available were not going to be unfairly distributed in favor of GPS as opposed to some of the other pressing needs that have been defined. If you could be sure there were not going to be some kind of user charge.

I guess it's unreasonable to expect your organizations to be proponents; but would this bring you to, at least, the level of neutrality?

Mr. White - I can only answer that with a no. I have been around Washington too long. I have had all kinds of assurances.

There is no way that anybody can give any assurance at all that GPS will not have to be paid for by those who use it.

It is only realistic to look at the total system cost--the ground elements, the airborne elements, the system costs, and the users' costs in toto--and then take a look at what my share is going to be. There is no other way to look at it. I follow very closely how the Government is trending towards making users pay for the services they receive, and a milestone was passed in the hurried efforts of our last Congress in this regard (with respect to waterways).

Mr. Kayne - We are not saying opposition. As far as I am concerned, this is great. If the Defense Department has a need for this kind of thing, put it up and let's have it.

We will all pay for it, as taxpayers. This is part of our national defense system.

The question before us is GPS for general aviation, and that is where I say we want to see the thing. We could see it right now if we had it today and could buy a receiver for some reasonable sum--for special application, $2,500 and up. There would be some general aviation use of it.

General aviation is building some 14,000 airplanes a year and is exporting about at least a quarter of them. Most of those exports are flyaways. A lot of them fly across the oceans. Right now, with their navigation, they are having a difficult time of it. There are a lot of things that they are flying across that you can't stick an Omega receiver in. So, we are going across the oceans by a variety of substitute things.

It would be great for that. It would be great out in these low-level places--maybe for the helicopter operations out to the platforms and other helicopter operations and low-level general aviation operations.

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But, at the moment, it is a supplementary system; but I don't think we could convince our members anywhere, our constituency, that they ought to throw all the VFR receivers away and start buying GPS. It is a pig in the poke at the moment.

We are not opposing the Defense Department's getting the thing up. Let's get it up and let's take a look at it. That is why I said we are premature.

Let's see what we are into as far as civil use of it is concerned. Let's consider all of the ramifications. Do we have the accuracy? Do we have the access? What is it going to cost us? Not only for the equipment, but we have to settle this user charge thing. There are a lot of things we have to settle before we get around to the practical applications of its use.

We certainly cannot settle it here because at this point we don't have enough information.

Mr. Beach - Is there anyone here who doubts that if all of us had said, No, we are not interested at all, the project would not proceed?

I doubt anyone said no. I think that we expressed some concern.

Secondly, I would not think that we are on the defensive.

I wasn't on the defensive. I was on the offensive. On my desk is a toll-free number that our members are free to pick up and dial at will. I am the guy at the end of the line; and believe me, none of them are expressing concerns over navigation. They are expressing concerns over weather, airport access, availability, and a long laundry list of what has been identified for years as general aviation needs.

So, I would like to say that I have been here, not defensively, but offensively. I need assistance in other areas, and I know full well that the Department of Defense has a need. It is a justifiable need, and the program will go on; and sometime downstream possibly there will be some answers that we can publish to our membership which will be helpful to them.

PANEL DISCUSSION ON INDUSTRY VIEWS

Moderator: Mr. Roger Winblade, NASA

Panel Members: Mr. Norman Messinger
NARCO Avionics

Mr. Joseph Sawicki
Bendix Avionics Division

Mr. Jerry Schmitt
King Radio Corporation

Dr. Norbert Hemesath
Collins Avicnics Group

Mr. James Van Cleave
American Electronics Laboratories (AEL)

Dr. Clark M. Neily, Jr.
Intermetrics

Mr. Paul Gralnick
Aircraft Radio and Control

INTRODUCTORY STATEMENTS

Roger Winblade
Manager, General Aviation Technology Office
National Aeronautics and Space Administration
Washington, D.C.

The purpose of this panel is to solicit the views of the civil aviation avionics manufacturers tha. will supply the devices should GPS move into the civil sector. As evidenced by the previous discussions at this seminar, it is genrally agreed that there is no common need perceived at present. It was acknowledged, though, that there were special uses that might benefit from such a system; but there is not exactly a clamoring at the door for a new piece of equipment.

My own perception is that if GPS, LORAN-C, or any other system were to be used only as a different source of signals, it will find little accommodation in the industry. The new introduction will have to be because it does more--cheaper and better. It lets you do something that you can't do now. So unless we see capabilities being generated by the new system that are beyond what we have now, then there is little reason to change.

There is a difference between the civil aviation sector and the other part of aerospace, where the Government--NASA and DOD--is the customer. In civil aviation, the customer has to work through the free enterprise system. We have set a series of questions for the panel to attempt to solicit their viewpoints as to what it would take to make that happen. These questions are:

- What are your views of the viability of GPS NAVSTAR as a civil aviation navigation system?

- What factors do you view as having to be in place in order to trigger the commercial development?

- What do you view as the potential for low cost?

Norman Messinger
Vice President, Research and Engineering
NARCO Avionics

Of the three questions the Moderator has posed to the panel, I find it a very difficult charge at this point in time to respond to his request for my view of GPS as a navigation system for general aviation. This is because of the diverse opinions that have been expressed thus far at this meeting and the fact that I don't yet know enough about the system to form an opinion of my own.

It would appear, however, that this very fascinating and advanced concept of navigation could hold some significant advantages and benefits to the entire aviation community.

I would, at this time, leave the critical decision of the applicability of GPS as regards general aviation to those able persons and organizations best equipped and staffed to make such a judgment. Should the decision be in favor of some form of GPS, we would certainly evaluate the situation from a product development standpoint and what returns would be forthcoming from such an investment.

The advisability of a near-future development effort would be questionable in light of MLS implementation progress. We are currently midway through a major navigation system transition which has been underway for some time. MLS was in the GPS stages in the late sixties; and as of the late seventies, we are now looking forward to just a reasonable implementation in something less than 10 years. Suffice to say that we would proceed with great caution as regards internal development of GPS equipment.

I do believe, however, that significant contributions are achievable by a design team operating in a cost-versus-performance arena of a profit-minded and competitive situation.

Estimates of up to $5,000 in large quantities for a general aviation GPS would hardly compete in today's VOR/DME nonprecision approach world and wouldn't even raise an eyebrow without the threat of some present system obsolescence.

General aviation, of course, covers the whole gamut from privately-owned Boeing-700 series airplanes down to the very smallest and poorly equipped airplanes, not to mention the

20,000 or 25,000 airplanes in our fleet which don't even have batteries.

Now, what is an expensive piece of equipment to one person is obviously not expensive to another; and the corporate supportive aircraft seeking some advantages or different form of navigation or significant improvement probably wouldn't sneeze at many thousands of dollars as far as a piece of equipment is concerned, whereas the person at the other end of the line has been having nightmares for the last week trying to figure out how to tell his wife that his annual cost is 500 bucks.

Given the right incentive circumstances, I believe commercial design effort will make significant price/performance advances with competition being the driving force. We have seen it happen with present-day systems, and it may happen again with the satellite-based navigation systems.

Joseph Sawicki
Bendix Avionics Division

An evolutionary implementation of the GPS system for the civil aviation community would offer certain benefits to the user and the avionics manufacturer with minimum disruption to the present airway system. A simplified baseline GPS system using a custom microprocessor and new memory technology would form the basis of a panel-mounted GPS receiver/processor. A simplified four-digit code would be entered by the pilot to correlate with a code designation of the VOR. This code tuning with a defined, range-limiting feature would minimize system blunders and allow instant acceptance of its operation since the course deviation indicator's usage would remain the same as presently utilized.

The FAA would be required to identify existing VOR's with code designators, project future airways where VOR's are presently not usable, and coordinate similar planning/projections with ICAO Members. This activity would expedite a GPS minimum performance standard and allow manufacturers to assess the magnitude of the internal memory requirements.

Moving on into the way we view the marketplace, in the business jet marketplace because of the high certification costs of systems in this marketplace and the importance of long-term planning, it appears GPS will have a long, uphill struggle primarily against the Omega system. The certification factor, the benefits of similar technologies, and years of Omega experience will indeed make it difficult for any new global navigation system to successfully compete in this marketplace.

In the general aviation middle market (light twins to turboprops), GPS must compete head-on with the VOR/DME sensors. In addition, the VOR receiver becomes a localizer receiver for defining the lateral displacement during a precision approach. Therefore, a localizer receiver and tuning head would still be required in addition to the GPS system. On the other hand, the present ILS system is nonexistent for the majority of general aviation airports, which makes the nonprecision approach aspects of GPS extremely attractive and potentially useful.

In the general aviation low market (trainers to heavy singles), minimum complexity and low cost are required, especially for trainer aircraft. The GPS must perform the basic

VOR function and can be penalized if it costs more just because it does more.

Digressing a moment to consider how a general aviation product is successfully marketed, consider the following:

1. You can legislate it into the marketplace, e.g., a ground proximity device makes flying safer. We don't know how to legislate GPS at this point.

2. You can bury a portion of its expense through integration, e.g., King Nav System (KNS 80) and the Bendix BX-2000 system represent this type of technology. On a long-term basis, integration offers some cost reduction for GPS.

3. You can have the customer or OEM demand the product because it makes flying easier and safer and increases sales appeal and resale value of aircraft.

Because of the controversial aspects of 1 and 2, let's consider what might be required toward satisfying item 3. You could begin by defining a baseline system compatible with the existing VOR/DME route structures. This then could be a panel-mounted unit with code selections similar to the ATC transponder. These codes, along with the VHF frequencies, would identify the existing VOR facilities. The pilot would simply enter the appropriate four-digit code and fly the course deviation indicator as usual. Programmed within the unit's internal memory would be latitude, longitude, and magnetic deviation of the existing VOR's, which would correlate with the selected codes. This approach would allow implementing an inexpensive inputting scheme, achieving minimum pilot workload, reducing blunder error, and conserving panel space. Further reduction in blunder errors would be attained by limiting the range to the VOR, therefore automatically excluding all codes except those satisfying the range criterion. This concept is termed evolutionary in that it attempts to improve upon and complement the existing VOR's and preserve the present airway structure. It further allows expansion of the VOR-type airway system into airspace not presently served because of terrain and economic factors, being careful to note that only GPS- or equivalent equipped aircraft could use these expanded airways. A system thus defined would allow for the future elimination of present ground facilities when the civil community is GPS-equipped and allow an orderly transition to occur consistent with an agreed-upon phaseout date. This approach would require further consideration of ATIS and other VOR voice transmissions.

As a manufacturer, we would prefer the option of offering additional outputs of range, groundspeed, time of station, and elevation consistent with the desires of the marketplace to buy features. If one chooses an RNAV version of GPS, provisions consistent with the marketplace would allow latitude and longitude to be entered similar to present Omega systems. It is further conceivable to identify published RNAV routes with additional codes. Again, an expanded internal memory would contain the equivalent latitude, longitude, and magnetic deviation of the codes.

At this point of the discussion, it appears appropriate to address the issues of "How big?" and "How much?" The Bendix Avionics Division is and continues to be involved in moving high technology into the marketplace. We designed the first low-cost general aviation transponder using LSI technology and continue to introduce products into the marketplace using LSI's designed at our Fort Lauderdale facility. We recently developed our first custom microcomputer on a chip for use in our general aviation color radar. We've learned from experience that a custom implementation of any system will always yield the greatest efficiency because both the hardware and software are optimized for a particular application. Therefore, instead of a computer consisting of a CPU, ROM, RAM, clock generator, I/O ports, special peripheral devices, and maybe a custom chip, it can now end up as only one chip. In the GPS design, we see at least this level of technology required in addition to a breakthrough in nonvolatile memories. The magnetic bubble memory (MBB) scheduled for 1980 production promises to become one of the major nonvolatile memory technologies of the future and will provide mass memories for computing systems. It is conceivable that this form of mass memory may become a GPS system candidate with further improvements in operating temperature range.

In closing then, we the manufacturers need more information such as, What is it? and How do I use it? This then is clearly what the FAA and industry must come to grips with in the near future.

Jerry Schmitt
King Radio Corporation

This afternoon we are to discuss the industry view of potential general aviation use of the Global Positioning System. It isn't a new subject. It seems to me that we went through this same thought process about 10 years ago when RNAV was first being implemented.

During the implementation of RNAV, there was a tremendous amount of effort devoted to establishing specifications and discussing an RNAV route structure that would provide the economic justification. Once equipments were on the marketplace, however, we found that this concept had virtually nothing to do with the RNAV business--that is, the manufacture, sale, and use of RNAV. In hindsight, the user bought RNAV because it was a convenient way to navigate from one place to another, and this seldom involved established routes, RNAV or otherwise.

I think the same will be true of GPS. The market (that is, user) will define the use of GPS. The proper role of Government organizations is to see that the satellites are in place and then, once they are in place, provide any necessary structure for the use of GPS. The proper role for industry is to develop the GPS equipment. The proper role of the user is nothing more than to use GPS where it represents an economic or convenience advantage.

Let me elaborate on these points. There are numerous companies with adequate financing, engineers, and the desire to do battle for the GPS marketplace. Many will be failures, but there is no more powerful system for fulfilling the market needs than competition. The shape of the market is not up to us--it already exists. Our job is to find it. I don't believe Government or industry can create the market or substantially change it. In fact, it would be a mistake to attempt or even seriously discuss substituting GPS for VOR/DME. If GPS makes economic sense, the discussion won't be necessary; and if GPS doesn't make economic sense, the discussion still won't be necessary. Therefore, King's position is: When we perceive that GPS is (1) solidly defined, (2) on the verge of being available, (3) useful, and (4) economic for general aviation, we will become active in the design, manufacture, and marketing of the equipment.

Our major reservation is not the existence of the GPS market or our ability to design reasonably priced equipment. Our primary concern is the loss of low-cost ILS as well as backup voice communications if VOR/DME is replaced with GPS. At some future date, MLS will be available to fill this void, but it will cost far more than ILS and will probably be a more severe economic impact than GPS.

Much has been said about the equipment cost impacting the implementation of GPS. Those of you who design equipment are well aware of the rapid evolution of semiconductor technology. I believe GPS techniques are ideally suited to take advantage of these technological advances. The advances that will be used in GPS are probably little more than a glimmer in someone's eyes at this time, primarily because the GPS implementation time seems to exceed the time it takes for a new technology to develop and mature. In fact, the evolution of technology makes it very difficult to time the equipment development. Start too soon and the slower competitor will seriously undercut your product. Start too late and your technological advantage may be too small to overcome an established position.

Last, there are recurring proposals for simplifying the GPS signal format to make it easier on the equipment designer. Many of these proposals are obviously lacking in thought, and their presence leads one to believe that a lot of dollars exist for studying alternative signal formats. My study of the problem leads me to believe the Air Force has done an excellent job of establishing a signal format. The proposals for change represent a distraction and, if anything, will delay implementation.

What we do need is a clear Government policy that the GPS will be fully deployed by a stated date and will be available to the public. Then put up the satellites and stand back.

Dr. Norbert Hemesath
Collins Avionics Group

I believe we have all learned quite a bit in the last day and a half about where we, as individuals or groups, "are coming from" with respect to GPS. However, while we may understand where we are coming from, it is not at all obvious that we do or don't agree on where we are heading. There is apparently a lot of disagreement in that area. So, I would suggest that perhaps in the theme of the conference we come up with some "low-cost" heading reference for this whole activity.

Collins' position on GPS is that the system has a lot of potential. However, I emphasize that it is potential only at this time. GPS cannot be considered reality for the civil aviation community at the present time. There are many problems that have to be addressed before that can be true.

But on the other hand, because it takes many years to get a system of this kind implemented and in place so that users can turn on the radio and watch it play, it is also appropriate at this time that work go on to address those problems.

Collins sees a substantial role eventually for GPS in civil aviation, but it is one of an evolutionary nature--not a revolutionary one. The kind of thing we can see happening is that initially when the satellites are up and user equipment becomes available, we will find the system filling in with supplementary roles of one kind or another. A good example might be the helicopter service to Baltimore Canyon, as LORAN-C is used for these days. And there are many others. We will let the users determine what those are. But it will find a niche there, probably first.

It strikes us also that there is a very substantial potential for the system in oceanic service, where Omega and inertial are today filling the need. Now that doesn't mean that either Omega or inertial will go away. As a matter of fact, unless GPS can offer some cost advantages, which is very doubtful, I don't think that Omega will go away. What we might see happening there, though, is that in certain classes of aircraft, because of the truly global nature of GPS and the accuracy that is available from it, it would fill the oceanic role as well as the domestic role for certain kinds of operators.

Another place that we can see GPS filling in fairly quickly is in the underdeveloped areas of the world. A large amount of equipment and aircraft go out of this country internationally every year; and when you get outside of the United States and Europe, the existing radio navaids become relatively few and far between. So, in underdeveloped parts of the world, then, it would seem clear to us that there will be some role for GPS. The obvious competition there again is Omega, and it is a question of what the exact requirements are. Omega can't provide the accuracy; it can provide the continuity and global nature of service. Again, the issue will be decided by the marketplace.

In the CONUS ultimately, we see GPS coming on as a supplement to VOR/DME, at least initially. It clearly can do a job, when implemented, of filling in where there are poor coverage areas now--like mountainous regions and Alaska. GPS has capabilities that cannot be matched by the existing VOR/DME system today, and these are particularly prominent in the general aviation sector where I would think the key capability that would be exploited is the accuracy that it can deliver for nonprecision approaches.

Ultimately, and I emphasize ultimately, we can see GPS coming on as a replacement for VOR/DME. My personal opinion, though, is that there is very much work that needs to be done addressing the cost issue because, unless cost can really be beaten down, even ultimately, there will be some residual VOR/DME in this country to support the bottom tier of general aviation. Unless the cost battle can be won, VOR receiver vis-a-vis GPS, VOR will stay there. It's just that simple. Look at NDB's, look at LORAN-A, and all the past history.

One of the questions we were asked to address is, What are the factors that must happen in the GPS world before our organizations would make a commitment to lay dollars on the line, develop a product, try to market it? Well, a short answer to that is if there is an identifiable market there, we will go do it and others will do the same. I believe that what must happen is an environment would have to be created that would encourage the potential users to have the confidence in the system that they would be willing to go out and buy equipment.

What are the ingredients? First of all, the DOD program must be a full go. That is, everybody must know that the 24 satellites are going to go up and they are going to be operational. That is an absolute essential.

Secondly, I firmly believe that there must be a relatively early resolution of this denial of access question in a manner that will satisfy civil use. I am not prepared to offer any suggestion as to what I think that is, but it must be resolved and in a way that isn't going to put a tremendous cost burden on those civil users. It is already a tough enough job to get the cost down. One possibility, certainly, with regard to that problem would be if the CA signal were not tampered with. I personally believe that that would meet virtually all civil requirements, including nonprecision approaches. It clearly would be nicer to have P for a variety of reasons, but I think CA would do a pretty good job.

Another issue is the resolution of system control. I really believe, again, that before you find any serious civil interest in use, there will have to be a resolution of the matter of who controls the system: a civil agency, a military, a combination of the two--something that people know and understand and have confidence in.

Perhaps not absolutely necessary, but desirable as an ingredient in helping us get on toward the decision, would be some progress in the ICAO arena. Ultimately, if GPS is going to have a very large place in the firmament, so to speak, it must have ICAO approval. It is just that simple. Now, that doesn't mean there couldn't be some preliminary usage in this country, but I am sure all of us would feel a lot better if there were a pretty good indication that ICAO is going to go along with the gag.

User charges will also have to be addressed. If someone stands up in Congress and says, It looks like we are going to have a bunch of civil users there, let's tax the living daylights out of them for this equipment, there is nothing that will more quickly kill any interest in GPS. Now, I don't know how that gets resolved, but people are concerned about it.

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Last on my list and one that I personally think is a very key issue is that there will have to be created a national airspace environment that permits users to take maximum advantage of the equipment if they buy it--maximum advantage of the GPS system capabilities. Now, what that means is that there will have to be a hard look at the system and a greater move in the direction of RNAV-based procedures.

What should the FAA, DOD, NASA, and all the relevant Government agencies do? On top of the list is address and solve the access denial question. It must be done--work out a policy on system control and operation--get out there and start working for ICAO acceptance. That isn't totally a Government problem, but it can't be done without the Government doing some work.

For the FAA specifically, I think a lot of effort must be expended to work out ATC procedures, communication methods, and so on. I want to stress that that is not a GPS problem. Anything that is put into the airspace to replace VOR/DME as the basic signal source--be it LORAN-C or Omega or anything else you can dream up in the way of a radio navaid--has got the same problem. Anything which is basically global in nature creates this problem of, How are procedures set up? How is the airspace operated? and, How do pilots and controllers communicate? And the answer is surely not, Latitude/longitude. We all know that.

With respect to the question: Is low cost achievable? If I look at the marketplaces that we serve in the commercial world, depending on which one I look at, the answer is easy--certainly low cost is achievable in the context of what the air transport industry would be used to. I am very confident of that. It is also achievable in the context of the business jet community, where Collins does a lot of business. When you get down to the Microline (which is the Collins general aviation line that competes with King's Silver Crown), it is problematical, in my opinion, with regard to whether low cost is achievable; that is, if by low cost we use a workable definition that says this set must more or less compete with the cost of a single VOR.

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I was interested to listen to Mr. Victor Kayne, AOPA, who indicated that in their pilot survey--to indicate the magnitude of this problem--they found that there are 30,000 aircraft among their owners that have one single VOR--just a single VOR, not even dual. That is a major problem. So, if the low-cost issue is how we replace those single VOR receivers in those 30,000 airplanes, I am not optimistic.

In summary, then, we like GPS. Our position at Collins is bullish with respect to GPS. We think there is a good future for it, and not just because we happen to be involved in the DOD program. We are anxious to see it move into the civil marketplace if, in fact, it does find a niche.

We suppr[illegible] much the Government working the problem. By the Gover[illegible] mean the non-DOD part of the Government getting in[illegible] these problems can be addressed.

One last [illegible] is, again, that it is not a technology problem in my opinion. There isn't any significant technology that absolutely needs to be developed here. The technology is coming along rapidly enough. That will take care of itself.

The Government doesn't have to go off creating a bunch of special gizwigets for GPS receivers. That will happen naturally in the competitive environment that we all work in. What the Government should work is the large policy issues and the electro-political issues associated with this whole thing because none of us here can attack those. There is nothing we can do about those. You people in Government can.

Finally, I would like to echo the comments of both Mr. Messinger and Mr. Schmitt here with regard to the role of GPS; that is, if there is a place for it in civil aviation, it will find its place very naturally by virtue of users seeking it out. And when we talk about low cost, let the competitive thing among all of us take care of that problem. It will. It always has in the past.

One last point I would like to make: The thousand dollar VOR receiver that you can buy today and the $2,200 DME that you can buy today were not the result of the Government going

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out and spending a bunch of money on technology. They were purely and simply the result of competitive forces working in the marketplace.

James Van Cleave
American Electronics Laboratories (AEL)

The American Electronics Laboratories' (AEL) general view of the feasibility of GPS is that we are pretty "bullish" on it. We agree that GPS can provide several operational advantages such as worldwide, trouble-free, precise navigation; simpler course planning with minimum flight time; and minimum fuel. And ultimately, GPS will provide lower cost for FAA support due to the phasing out of VORTAC ground systems.

We also feel that 20 years from now, an airplane cockpit may look like the following: a GPS receiver, which will replace the DME, VOR, and ADF; the MLS receiver for precision landings; communications gear; and the basic IFF or ATC transponder. We see that kind of a configuration. Also, we like to entertain the thoughts of position encoding, using the GPS, such that air traffic control, collision avoidance, and things like that can be effected. And I believe that 20 years from now, we are going to see a lot more processing in the cockpit of all the information available. There should certainly be enough available from GPS, MLS, et cetera, at that time to make a lot of navigation decisions.

With respect to the issue of what is the principal factor now missing that has to exist for private corporations to decide to develop the gear, this is a difficult question. Number one in importance is that it is absolutely necessary for DOD to commit to the implementation. It has to be a go program. There has to be a commitment that, except in the event of national disaster or whatever, they are not going to perturb the code and they are not going to deny access.

All we want is the CA code. We understand why the P code is necessary, but we really don't want it. The CA code is fine for the particular application that we have in mind.

Because of the costs involved, it will probably be 10 years before avionics companies decide to invest in GPS. It would be absolutely stupid for a company to invest their own money right now in a low-cost GPS receiver for general aviation. They couldn't possibly sell it until all 24 satellites are operational, and that is several years away. In addition, those 4 or 5 years are probably going to become big years for more advanced microprocessors, LSI, and things like that. As an example, just in the MLS program there is a world of difference between the first microprocessors available 4 or 5 years ago and what is available today.

So, we don't believe that now is the time to develop low-cost GPS avionics--not on your own money. It is quite possible that the Government may want to fund it for other reasons, primarily to prove that it can be done. Frankly, I think that we are in an interesting quandary here--a Catch-22 situation. DOD would be very happy if someone were to develop a low-cost receiver and prove that it can be done for $3,000. Then, they could justify the implementation somewhat more by saying it is indeed a national resource since right now it is not a national resource for non-DOD users.

So that is the Catch-22 phase. Industry isn't going to develop it on their own money until the thing is operational; and it would be easier to get it operational if, for example, the need for general aviation is proven.

Of course, there are other uses for GPS besides general aviation. The most important, I think, is a commitment from DOD; and again, I haven't heard of any such commitment yet, but I sure would like to see one.

The prospects for low-cost GPS avionics, I think, are very good. In the process of their MLS receiver development, AEL has gone through a lot of exercises and looked at a lot of avionics manufacturers, especially NARCO (our subcontractor for the low-cost MLS receiver), on what their procedures are and what their costing techniques are. Also, we have looked at the technique of utilizing very commercial parts--that is, the extremely low-cost stuff that comes out of TV sets, calculators, and other such parts.

Frankly, from everything that I have seen at this seminar, it just didn't look low-cost enough. And I am tossing out $3,000 although the figure has fluctuated from $2,000 to $3,000 on a daily basis, depending on what kinds of operator interfaces there are.

These are installed costs I am talking about. You have to be very careful about the installation price because the actual cost is a lot lower than that. You have to really look at the cost that the distributor and the installer have

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and the gross margin, if you will, of the company that manufactures it.

In order to sell a $3,000 receiver to the average pilot, you are really going to have to build it for around $750--loaded labor and material. That is just one of the facts of life in this industry.

In conclusion, we feel that a GPS receiver can be developed for production in lot quantities of 2,000 for under $3,000 by 1985.

Clark M. Neily, Jr.
Intermetrics

As background, Intermetrics is not a hardware provider and, for that reason, our concerns tend to reflect the point of view of a company which is likely to sell services to the people who will make that hardware. Our role in the GPS program principally involves selling navigation performance analysis services and user software, for both user equipment and simulation software. As a result, our answers to the questions raised by the Moderator will be given from that somewhat more narrow and restrictive point of view.

From a technical point of view, GPS is an excellent, robust answer to the navigation problem. It has high accuracy, design flexibility, and global availability. The question of whether this is appropriate in any sense at this point in time is not something we are prepared to authoritatively address. We are concerned, though, about the navigation performance, guaranteed access, and some signal strength problems.

With respect to private sector development, Intermetrics, as a software vendor, would like to see the following preconditions before civil software starts being built:

- Engineering (simulation) studies to define the basic functional and performance requirements for the fewest designs for the largest user community
- Software/hardware tradeoff analysis to minimize recurring hardware costs
- Standardization of control and data interfaces to minimize software redevelopment costs
- Stable, detailed, but not constrictive software development specifications prior to development
- Recognition of the software/processor component as a significant development cost center (which is different from the traditional types of navigation equipment that have been put in place to date on aircraft)

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Development of test and certification standards for software components of civil aviation navigation aids

With respect to the recommended simulation studies, GPS is highly amenable to simulation. It is not necessary to go out and spend a great deal of money on a brass board and fly that around on an airplane in order to get a very good idea of where you stand with any particular equipment design. If there are questions relative to implementability, EMI, or antenna coverage zones, they can be resolved by standard techniques of putting an antenna on an electromagnetic mockup and making the measurements. I don't know whether anybody actually plans to do this, but simulation in general is a lot cheaper than hardware development.

The development of test and certification standards for software components is thought to be very important, especially if there are going to be any uses in which that is flight critical. I don't know that at this point in time anybody knows how to certify software as safe. We can tell if it meets specifications and we can tell if it meets a given level of performance in a variety of different situations, but the whole business of safe software is really a new one--and somebody has got to think about that.

Again from the software point of view, Intermetrics thinks that the prospects for low-cost software are excellent, provided the previously described conditions are met, the costs can be made almost nonrecurring, and the original development cost can be held down to a very much smaller fraction than it has today. I have some raw numbers which I don't want taken seriously, but these are kind of midway between our actual experience to date and what we think our experience should have been. It has been our experience that the cost of provided software is primarily in the design, debugging, validation, and documentation and not the algorithm development or coding. As an example, the basic specification and program for a typical modest GPS complete set of user navigation software, including receiver control, satellite selection, and other miscellaneous software, would presently run about $100,000. The cost to get it debugged and working would be about $250,000, while the cost to get it validated and documented (that is, to take it through some kind of a formal review and certification that it meets a certain set of specification requirements, interface requirements, etc.) would be about $500,000 to meet civil requirements and on the order of $1 million to meet military requirements. These costs are expected to come down in the future.

The final two comments I would make are first, that documentation, which can be awfully expensive, ought to be limited to that which the customer actually needs to understand what product he has got and how to maintain it, and no more; secondly, low-cost software comes from good specifications and good design--We think that we can effect cost reductions in future builds by standardizing certain of the generic GPS software functions.

We feel absolutely certain that if the civilian Government agencies that are concerned do nothing, this will happen of its own accord over the next few years; there is quite enough incentive to do this; and it will be done.

And we are not concerned about getting it done. In summary, from the software point of view, our conclusions are: software can be expensive, but it doesn't have to be.

Paul Gralnick
Aircraft Radio and Control

In response to the Moderator's question about the GPS as a civil aviation navigation system, the basic question that comes to my mind is, What user benefit is there? There has to be that for the civil sector to use it. The present systems for general aviation and air transport seem to be adequate. We have the route structures, ILS, VOR, DME. And they work, so what are we going to get out of GPS?

If GPS had been formulated 30 years ago, maybe there wouldn't be VOR/DME and the rest because GPS seems to have it all. It has what the military needs, and I think the military will go ahead with it. There is, however, an enormous dollar commitment to VOR/DME in the civil sector. The FAA has that commitment. The whole general aviation fleet is equipped with it. And I don't think it is rational to think that that is going to change in a big hurry, even if GPS were available today. Thus, it will be the user who will decide.

If we can produce the equipment and it can do the thing for the user, then I think it will fly.

Also, I think what manufacturers such as ourselves will do is look at GPS; see what the results of the military experience have been; cautiously invest; and, if there is good benefit, then produce the products.

There are some key points, though, worth reechoing. The first is, What will the legislative environment be for i? Will there be routings, procedures, and ATC problems sorted out by the FAA? And they are not unique to GPS.

We are going to a global base system, and it is going to change the way the pilot interfaces with the system. There has to be very clear-cut availability. That has to be settled. Possibly the system will tie into other things and produce other results that we don't see today, and I couldn't begin to guess what they might be.

My feeling at this point in terms of investment on the part of the Government and the civil sector is to take a "wait and see" attitude and to upgrade the current VOR/DME system for more precision approaches and better nonprecision

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approaches. This is because VOR/DME is here today, and GPS is a long way off.

With regard to the costing, in my opinion the competitive marketplace will settle the costing. During the past 2 days, we have heard a wide spectrum of insurmountable problems to get the price down to $3,000. They are not insurmountable, and some of the problems that have been brought up as things that would have to be addressed by general aviation already are addressed by general aviation.

We don't know what the technology is going to be 5 years from now. Experience is a teacher. Our $3,000 transponder is going to cost $600, and our $5,000 GPS receiver might cost $600. We don't know. But if there is a marketplace and there seems to be a need for it, when the legislative and the availability situations are settled, then we will manufacture.

I will not go into the details of what our marketplaces look like; but for the corporate operator who operates a G-2 or $6 million jet, if he is going to fly transoceanic, $100,000 is not expensive. For someone with a $35,000 airplane, $1,000 is expensive; and he is going to place his priorities where he feels they best serve his needs.

My own personal feeling on GPS is it is a very good system, if it works. I don't know the details of how much accuracy we can achieve, but I think some of that will come out in the testing we will see. I think it is a good overlay system. However, if it fails, it fails hard--50 pilots on an approach simultaneously can lose what they need. That is not a problem when our current system fails soft. There is one advantage to having a diversified system: it comes down a little bit at a time. You don't lose everybody in the system.

DISCUSSION

Mr. Schmitt - Based on what I have heard at this and other meetings, I don't think you have to stretch a point a great deal in order to perceive that maybe some people are really thinking of GPS as an ILS. It seems that everybody is trying to do everything with the system, and half the battle is to make your system the dominant one and wipe out all the others.

Mr. Winblade - I have heard comments to that effect.

Mr. Ralph E. Taylor, NASA/Goddard Space Flight Center - NASA/Goddard has taken a look at the land/sea applications--but not the airborne application--of the NAVSTAR GPS. One of our thoughts was to take the present system and add another satellite in the geostationary orbit in order to, primarily, cut the cost of the user terminal as well as to help the user on the ground. The results looked quite encouraging.

Dr. Hemesath - I would first point out that there will be a very substantial difference between the land/sea requirements and the airborne requirements. Secondly, I assume when you say 2,500 bytes of memory--that is, 1,250 16-bit words--that is the complete GPS solution, navigation algorithms and all.

Some of us missed the boat.

Mr. Schmitt - When we talk about the geostationary satellite, it should be remembered that a great portion of the general aviation equipment produced in this country is exported. If you want GPS to occur here, you had better address the international market and international coverage with geostationary satellites.

Also, I would believe from your numbers that GPS has suddenly become less costly than LORAN-C. I don't believe that is ever going to happen.

I am frankly not impressed with costs until you get down to making the equipment. These costs are all based on gross assumptions. For example, it is a gross assumption that everybody is going to need that high-stability oscillator. From what I have seen studying the system, there is a lot more going on and a lot more to come out than people will let you know about.

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We heard discussions today about knocking the high-stability oscillators down from a part in 10^{-9} to a part in 10^{-7}. We are 7, 8, 9 years away from having equipment on the market. At that rate, we won't even need an oscillator.

Dr. Hemesath - One last comment about the geostationary satellite concept. It was pointed out there are some problems in a global sense there. But apart from that, this would imply that each aircraft, to get the initialization data that you refer to, would have a fairly sophisticated receiver or data link system on board because you need to transfer data and time with great accuracy.

I would be surprised if that receiver itself weren't equal in cost to the GPS set, or very close to it.

Mr. Schmitt - I would like to make a real strong point here. We have an RNAV system on the market. It has an all solid-state DME in it, a VOR, complete ILS, an RNAV computer, and the display, the whole works. It only requires three inches of panel height--and it sells for $5,000 list, which is a very attractive price.

If one is to believe the GPS cost that we hear bandied around, VOR/DME is twice as complex as GPS since dollars and complexity are quite the same thing. I don't believe it.

Mr. T. K. Vickers, The Journal of Air Traffic Control - When we are listening to satellites, don't we need a very high gain antenna and, if so, is it feasible to install such things, aerodynamically, on our lighter aircraft?

Dr. Hemesath - You do not need a high-gain antenna. The ideal antenna would be one with upper hemispheric coverage. How achievable that is is something else, although there are some designs that have been used in the Phase I Program that come surprisingly close to that.

With respect to the aerodynamics of installation, there is no reason why an antenna of that kind couldn't be conformal.

Mr. Hui - I would like for Mr. Gralnick to clarify his comments about the nature of the current VOR failures being soft, where he envisioned that the GPS system would be hard failures; and I don't quite unde stand that because, if anything, I think the current GPS system in the Phase III configuration with a lot of redundancy should not have a hard failure.

Mr. Gralnick - What I was referring to was that the total airspace system doesn't go down. If a VOR or a glide slope goes off the air, the effect of a failure of that nature is localized. I do not suggest that there is necessarily a hard failure mode for the GPS system; but if there were, global coverage, if that were the only system, would be lost, and it could affect a very wide area.

If several satellites, for whatever reason, became unavailable, perhaps a large portion of coverage would go down, whereas today in our current system with its distributive nature, a failure is a very localized thing. It is still important to somebody involved in an approach at that time, but it may not affect several thousand aircraft.

Mr. Neily - There are some individuals and organizations that do intend at some point in the near future to use GPS in a way which will make it absolutely flight-critical and where it would be exceedingly embarrassing to have an outage over a considerable portion of the globe.

As far as we can tell, the only type of failure that we are vulnerable to that we would expect to affect the system as a whole is a failure in the control segment that tracks and updates the satellites.

If such a failure were to occur, it would be some hours before the satellites began to become severely unusable for most users, and the fact would be obvious.

Now, it might be a continuing inconvenience to somebody who wanted to go somewhere and needed this system and couldn't go. But I don't think you would have a situation where somebody would get caught in midstride and be embarrassed severely right at that moment.

A Participant - I would just like to make a comment on that. Several months ago, Newsweek Magazine did a special on "Soviet Satellite Killer Technology." The satellites being shot out of the sky were GPS's.

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Mr. Richard E. Leslie, Aerospace Corporation - I would like to talk a little bit about the vulnerability of the GPS system itself. Mr. Neily mentioned something about the autonomy of the satellite system relative to the ground control segment.

We fully intend by Phase III to have a soft-failure mode within the GPS system in that if the Master Control Station or the National Control Center is somehow incapacitated, the satellites will maintain good clock data for a period of up to a week, with degraded accuracy, perhaps 20 meters in three dimensions.

The second point relative to outages of the satellites themselves due to failures of redundant components is that before the Master Control Station can effect a transfer of the redundant unit into operation, we have computed for the 24-satellite configuration in Phase III with a 50 percent glit rate--that is, 50 percent of the time there is one satellite that is incapacitated for one reason or another, we will achieve 100 percent coverage of the entire globe.

If there are two satellites out at any given time, there will be what we call a GDOP hole that will occur at the North Pole.

It will not ever move from the North Pole, and that GDOP hole will be there over the North Pole for as long as there are two satellites out.

Our trigger point for replenishing the satellite system is when one satellite is out, two satellites will go up on the space shuttle. We are assuming anywhere between a 2-1/2 to 6-1/2 month period of time for replenishment once we get down to 23 satellites.

The other point is that, let's say there are three satellites out and there is a GDOP hole somewhere else in the world other than the North Pole or the South Pole.

Depending on the satellite that is out, you will know, predictably, as a function of time during the day, where the GDOP hole exists; and I would think that this information could be disseminated to people who are attempting flight-critical items using GPS.

Mr. Neily - With respect to "killer satellites," a substantial number of the 24 satellites must become nonoperational to really seriously begin to interfere with operations.

I am personally a little skeptical of how close the Russians are to an operational system. That is, of course, tantamount to an act of war; and if that happens, we have other problems as well.

Mr. Joseph Gutwein, Transportation Systems Center - (Department of Transportation) - Yesterday we heard some comments by Mr. Rogers relative to the fact that the GPS system is a system designed to meet military requirements. I believe he was asking the question, Why aren't we looking at techniques, methodologies, and processes by which we can optimize GPS for civil uses?

I would like to comment on what the Department of Transportation is doing in this regard. One of our current activities is to assemble a GPS R&D plan and activity. Some of the areas we are looking at are low-cost GPS receiver designs, propagation RFI, and many other critical areas of technology. We are also examining alternate GPS signal structures in the hope of reducing cost to the civil user. Mr. Schmitt made the comment that he did not feel that this was a fruitful area of endeavor.

I would like to have him address this comment.

Mr. Schmitt - I have heard some of these comments about new signal structures, and I do not have a very high opinion of them. Frankly, from what I have seen in the GPS system, I don't think anybody could have come up with a better system than the Spread Spectrum System.

Frankly, it just inherently bothers me that when the military wants to put up a satellite navigation system and it meets their needs, the next thing that is said is, "The civilians can use the system for free since the military paid for the satellites"; and this leads to, "The satellites are for free, so let's see if we can find a spot to put on a civilian satellite navigation system something that is different."

I am perfectly satisfied with what the military is doing. I think we need to get on with it. If we start developing a new signal structure, we will put the whole program back a minimum of 5 and probably 10 years.

Mr. Gutwein - I believe the next phase of GPS, Phase II, contemplates a system of six more satellites or thereabouts.

The ultimate goal of the Department of Transportation signal structure activity is aimed at a time schedule for the 1984-1985 period for Phase III of GPS when the system progresses into its final phase of implementation and, when possible, design changes can still be made.

The ideas that we are looking at for the civil user are areas that we felt have not been properly considered in the optimization of the system for the military requirement. It is an activity where we would like to keep an open mind and possibly look at other concepts and approaches that might lead to lower costs for the general civil aviation user, the maritime user, and the potential land user of the system.

Mr. Schmitt - Let me add to that a little bit. Given ten engineers and one problem, we usually arrive at at least ten different solutions, five of which are very nearly optimum. In a political sense, it is not too important which one of those you take; furthermore, if you just want to get within 90 percent of optimum, which is probably closer than we ever get in reality, you can probably pick about seven of those ten systems.

You know, the military has thought about this thing pretty carefully. They have much the same problems as we do. They have low-cost equipment needs, too. Of course, low cost to them is not the same as low cost to us; but for years general aviation and the military have used the same navigation systems, and their equipment costs $20,000, while ours costs $2,000. There is nothing new about that.

Although it is a gut feeling, I believe the system we have has been studied a great deal; but it is always vulnerable to systems that have not been studied as carefully.

A Participant - I would like to comment on that signal structure consideration, and I am not sure if I am in total agreement with Mr. Schmitt. I believe that the system could be improved and that there are things that could be done

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to the signal that would make acquisition a lot simpler and would reduce hardware. Of course, it very well may set back the military program if certain things would happen since two satellites are already up there.

But the point is that it could result in a GPS receiver that would sell for well under the numbers that we have previously discussed.

There are a whole list of things that could conceivably be done. We are not saying they can't be done; we are just saying that it would set the military system back.

I think the GPS system was originally designed to be quite difficult to detect and to acquire, and that is not totally consistent with what general aviation wants.

General aviation certainly does not want a signal that is difficult to detect and acquire. They want something that is easy to detect and acquire. There are ways of making it easier, if that were really desired.

Dr. Hemesath - I agree that there are perhaps some changes that could be made to the signal structure that would result in some simplification in the receiver. I think there is little doubt about that, and I don't take issue. However, I would like to try to put this into proper perspective. I referred earlier to the business about the cost of the receiver being 50 percent of the total installed cost in an airplane. So if you get it for nothing, you are still only halfway there on a major problem. I think it ought to be understood that there is a substantial overhead that comes with satellite navigation, regardless of the signal structure. Satellites move, and you have to deal with that problem. This means you need very precise orbital information, and to get that means you need data.

In this system, this data can be obtained from the down link or from an alternate channel. Since the accuracy of the orbital elements decays very rapidly--it is a one-hour proposition--it is a real data transmission problem to support the satellite navigation process if the down link does not supply this data. It is a complex problem. There is this overhead element that must be dealt with, for which there is no counterpart in VOR, DME, LORAN-C, or Omega.

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The other comment I want to make is that there have been a lot of very sharp people over the last 15 years who have been working on signal formats for satellite navigation, and a lot of dollars have been spent on that problem. I agree with Mr. Schmitt that I am satisfied with the signal format that they developed, although it would be nice if the receiver could be simpler.

Finally, there are the realities of this thing. Suppose suddenly a new, very attractive, universally agreed upon signal format were to appear tomorrow. Who would pay the bill this time to put it up in space? Until that issue is addressed, I think it is not very fruitful to talk about alternate signal structures.

Mr. Neily - I have a comment that I would like to make on that, too. As we understand the current development plan, we are now almost at the midpoint of Phase II where the four main GPS vendors are about to be reduced to two. Those two vendors are going to carry into production candidate user equipment designs, one set of which will then be chosen for deployment by the military. While it is true that the Phase II constellation of satellites, of which half are now about to be in place, are not in mechanical design and so on the Phase III operational satellites, there has not, so far as I know, been any talk that for Phase III the military will change its current signal structure over what they have now. All of the very, very costly design decisions on whose equipment to "take forward" are going to be based on designs and field test demonstrations that are based on that signal structure.

It might be possible that somebody could talk the DOD into adding a box or putting an additional modulation on existing signals, when we get to Phase III, which would be for civilian use and which would have better qualities from the point of view of low-cost design. If they do that, the industry, particularly that part of the industry which is not already making GPS equipment and hasn't had the 4 or 5 years' experience, would be essentially starting a new development. They are not going to have available for their use standardized parts and pieces which have grown up as a result of the Phase II and III military designs. They will have to do something a little different, and I find it hard to believe that that is cost-effective.

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Mr. Whiting - Mr. Schmitt, I would like to say that I think perhaps you missed Mr. Rogers' point, and perhaps some other people here did, too. His point is that when you consider a navigation system--or any system--you need to consider the total system.

In the case of the GPS, it was designed with the idea that there would be few--meaning whether that number happens to be 1; 5; 10,000; whatever--GPS receivers; therefore, you could afford to put the complexity in the receiver rather than have it in the satellite.

I think what Mr. Rogers was trying to say was that if you were to stand back and look at the total system and the requirements for the civil market, you might want to put more complexity in the satellites and have less in the receivers. This would be particularly true if you look at the total marketplace which extends beyond that of the general aviation market into the maritime market which is, let's say, several orders of magnitude larger than the general aviation market. There are some land uses, too.

When you examine the system from that standpoint, you find that you could build the satellites and prorate the cost of the satellites over the number of receivers that are produced. Since we are talking about very large numbers, the satellite cost becomes almost insignificant relative to the cost of the total system. If you do that, you may well want to go to a different format for the signal.

Mr. Schmitt - I fully expect those arguments, and I stand by what I said earlier. You can start with the assumption of what the military was thinking; but when you extrapolate it into what the resulting system was, I don't agree. I think the resulting system is very, very good.

Mr. Leslie - I would like to make one comment on signal structure. It appears that people believe that a receiver can be simplified if we go to a different signal structure. Despite the fact that I work with SAMSO and for Aerospace Corporation, I think that probably is true. In one area I can think of, if we expanded the C/A code to a 20-millisecond code, as opposed to being a 1-millisecond code, it would do two things: In the first place, it would improve its antijam capability or resistance to interference; and, secondly, since about 20 percent of the digital logic in some of the digital-implemented receivers is in trying to determine where the bit transitions occur--that is, in data demodulation--you could make its epochs occur exactly where the data bit transfers and could vastly simplify the receiver.

Thus, there are a lot of other areas that we could look at; but the military has kind of said, For Phases I and II, we are going to have the PN C/A codes as they are now, and probably for Phase III as well, unless there is a real driving force to go to an alternate signal structure.

Let me make a comment on what Norb Hemesath said about the need to gather data continuously. The primary need to gather data continuously is one to replenish satellites as they come and go. I think that in Phase III, as I alluded to previously, the orbital and clock parameters will be of such accuracy that data for any given satellite would be good for about a week for precision navigation.

Mr. Schmitt - Won't a 20-millisecond code be a lot more difficult to acquire than a 1-millisecond code since we will have a code that is 20 times longer to search for acquisition?

Mr. Leslie - Yes.

Mr. Schmitt - It doesn't exactly come for free then, does it?

Mr. Leslie - That is true, and that is why it really hasn't been thought of too seriously up until now.

But if we had a programmable matched filter with an SAW device or a charge-coupled device for about a dollar each, a 20-millisecond code would not really be a problem any more in terms of the time to acquire the signal. But with our present serial search, it definitely is.

Mr. Schmitt - It would still be 20 times bigger. We could buy that one-dollar SAW filter for a nickel if it was only a thousand chips long rather than 20,000 chips long.

Mr. Rhyne - I am reminded a little bit of a friend who was getting a divorce, and he kept complaining to me about the unfairness of the decree as it was reflecting his position. I asked him why he didn't go back and renegotiate; and he said every time he did, those two attorneys got together and he came out worse than he was when he started.

I have to agree with Mr. Schmitt. I think that we have hashed this thing around a lot, and certainly there are some very clever ideas about how we can improve the signal structure. I have heard some. I probably haven't heard them all. I think it is probably time to put it on the table. If I could argue for anything that has been said, first it would be to have guaranteed access to the course access channel. If I could just get guaranteed course access, as this has now been defined, I could probably go around with some of my ideas and find an entrepreneur willing to put up some money; and maybe in a few years, we could talk about coming out with a set.

If I could argue for an FAA position that would reflect maybe the general aviation community, I would want a little more power where another dB or two or three could cut expected access time and search time or bandwidths by 50 percent, or double the available bandwidth. I am, frankly, a little bit disappointed to hear that the DOT is supporting one more look at a change in the signal structure. We have something now with which we can work, and the plea from up here was, Just give us certainty; just give us one cornerstone to stand upon; and from there, let these smart guys or the Japanese, or whoever it is that is going to come into this area and do a good job get on with it.

If I could recommend a position to influence decisionmakers, I would say that we should plead first for the simplest of all solutions. That would be more power in the channel. I think that would do us more good than anything. I would maybe appreciate a little reaction to that.

Mr. Buige - I think we have made that point very clear about more power. I recall an informal meeting a month or two ago at SAMSO when other FAA representatives and I discussed this subject with the satellite people. We said that we accept the fact that the system is probably going to be built in this way and that we think we can live with the C/A code; however, if you want to do us a favor, put more dB in there--if you can't get 10 dB, whatever you can. That was our position, which has never been officially stated or officially put out because that was an informal meeting.

Mr. Jerry W. Bradley, FAA Office of Systems Engineering Management - We have gone on record with the Department of Defense that we do not plan to interfere with their implementation of their present signal structure.

The thing that we have talked about is that we might want to add a package to the satellite for a civil signal. This is a very remote possibility. At the same time, we went on record saying that we also would like to have increased power. This is in the minutes of the OMB meeting.

A Participant - We have been struggling with the Phase III satellite for about 6 months now, and I personally have been fighting for 10 dB more power. I can almost guarantee that we are going to get about 7 dB more power in both the clear channel and the P channel on L1 and L2.

With regard to the other point that was made about leaving the signal structure alone, I think the C/A code (a C/A code chip is one-fourth of a P code chip in terms of complexity; if we made it 20 times as long, it wouldn't get 20 times as big) is a very poor choice when it comes to self-jamming. It has about 17 dB of cross-correlation between the family of Gold codes that we use. The idea for lengthening it is to reduce the amount of cross-correlation. This is particularly important when operating in a mixed mode of navigation.

One might say that we are going to operate all the satellites, but that is not necessarily true. Somebody may someday want to put a GPS transmitter at the end of a runway. If this did occur, let's say that as you approach such a GPS transmitter you attempt to acquire a different satellite. The runway transmitter could be drowning you out because the C/A code has poor cross-correlation characteristics. There are other considerations like that. I am not sure how many others there are to be thought about.

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A Participant - Did this seminar meet the objective of identifying if GPS can satisfy the future needs of general aviation?

Mr. Buige - I think the panels have stated clearly that they see a selective role for GPS. There are areas in this country where you can't navigate very well at low altitudes, and it would be a nice filler. There are people who probably want to fly the ocean who would use it. The thing I didn't get out of this panel is whether or not general aviation is going to fly GPS.

If GPS goes up and becomes operational, somebody in general aviation is going to fly GPS. The first guy that purchases a receiver is going to be one of Mr. Fred McIntosh's boys who has a jet; \$2 million, \$3 million in there; and wants to go anywhere at any time. It would be the latest "gold-plated" box; it will be in his airplane, and he will fly it. That is a very select market.

I think, realistically, we have to wait and see where GPS goes, where the technology goes, who wants it, when they want it, and why they want it.

I think that is a much broader issue. We hear that boats may use GPS. There are a large number of boats out there. Maybe they want it, and maybe they will drive the cost down to where it will be attractive to somebody else; but we don't know.

I think the idea here at this meeting was to get the entire community--the technologists, the bureaucrats, the users, and the builders--all together at one time to discuss the issues. No real conclusion to the seminar is anticipated. The seminar was to plant some seeds, perhaps put a challenge out there. There is no specific goal such as to determine that there is a consensus which is either pro GPS or against GPS to solve the problems of general aviation. We are not trying to set policy. We are not trying to make a decision. We are trying to get all of you people together to talk to one another. The reason Aerosat died was because we never did this in Aerosat. Similarly, the reason other projects have died or the reason projects that probably shouldn't be going on go on is because we did not do this.

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This is probably just the first of many of these seminars, and I hope that we have succeeded in g 'ting people to talk and think about this subject and that we will see some interaction--some Government interaction, Government/industry interaction--and, as a result, maybe we all will know where to go from here.

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