NASA CONTRACTOR REPORT 159176

DESIGN STUDY OF A LOW COST CIVIL AVIATION GPS RECEIVER SYSTEM

Magnavox Government & Industrial Electronics Company
Advanced Products Division
2829 Maricopa Street
Torrance, California 90503

CONTRACT NAS-1-15343
DECEMBER 1979

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665
AC 804 827-3966

NASA CONTRACTOR REPORT 159176

DESIGN STUDY OF A LOW COST CIVIL AVIATION GPS RECEIVER SYSTEM

CONTRACT NAS-1-15343
DECEMBER 1979

NASA
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

LANGLEY RESEARCH CENTER
Hampton, Virginia 23665
AC 804 827-3966

Prepared by

Magnavox Government and Industrial Electronics Company
Advanced Product Division
2829 Maricopa Street
Torrance, California 90503

BR5315
December 1979
No. 10028

N80-15062 #

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

SECTION 1
INTRODUCTION

The Global Positioning System (GPS) is a worldwide, satellite-based navigation system being developed by the Department of Defense to be operative in the mid-1980's time period. It has a potential for significant applications and potential increases in performance and safety in the civil aviation field, including general aviation.

This report addresses the basic GPS set requirements for civil uses in light of present objectives and constraints. It evaluates architecture design alternatives and projects an implementation based on applicable component technology available now and in the future. In addition, it makes recommendations for technology research which will lead to a practical low-cost GPS set for civil aviation users in the 1985 time frame.

Section II provides an executive overview of this report. Major issues, alternatives and recommendations are summarized.

Section III contains a scenario for General Aviation over the next decade. Growth projections for major segments of the industry are outlined. Requirements based on present general aviation objectives and constraints are summarized and the potential impact of GPS is assessed.

Section IV presents, in summary, the equipment configurations which are expected to meet the future needs of the major segments of the civil aviation community.

Section V presents a comprehensive review of the Control/Display requirements. Rationale for each entry and display function is described along with appropriate implementation recommendations.

Section VI deals with system processing design. System design trades are presented along with a summary of alternatives. Simulation results are provided for selected processing designs operating within the constraint of the projected GPS satellite constellation and civil aviation operating environment.

Section VII provides a trade analysis on antenna/preamplier performance requirements. Alternatives are evaluated in light of projected technology developments. The section concludes with a detailed design for two alternative antenna/preamplifier designs.

Section VIII describes the performance requirements for a low cost GPS receiver design. The architecture for this receiver design is presented along with recommendations for technology development.

Section IX evaluates the requirements for a computer processor implementation. It identifies processor candidates and makes technology projections based on current design trends.

Section X outlines anticipated power supply requirements and describes a candidate power supply design.

Section XI deals with the packaging requirements and presents several alternative package configurations for a low cost civil aviation set.

SECTION 2
EXECUTIVE SUMMARY

2.1 GENERAL AVIATION SCENARIO

With the need for resource conservation and increasing costs, the main stimulus to general aviation should come from business flying during the forecast interval between 1979 to 1990. The number of itinerant general aviation operations at towered airports is expected to grow from 28.1 million in 1978 to 43.2 million in 1990. Active aircraft in the general aviation fleet should increase from 186,600 to 310,800. Strong growth in air taxi instrument operations (127.6%) attributable to increased commuter traffic and higher utilization of avionics, is expected to complement significant increase (82%) in general aviation instrument operations.

Potential benefits of GPS to certain basic General Aviation constraints is appreciable. Application of GPS in the area of airspace utilization would include the creation of VFR "freeways" and other methods of facilitating separation between VFR and IFR traffic. Because of inherent signal coverage down to the surface, GPS could relieve the current line-of-sight limitation on present enroute VOR navigation systems and provide virtually an infinite number of locations at which an instrument approach could be made without the necessity of having a ground based electronic aid at each location. GPS navigation capability would also reduce the incidence of "lost" aircraft, facilitate IFR pilot capability and substantially reduce the present "overload" constraint on both the pilot and controller.

2.2 EQUIPMENT CONFIGURATIONS

A low cost NAVSTAR set is configured as a basic receiver/ processor and control/display unit which is usable by a wide range of users outside as well as within the general aviation community. Three other configurations tailored for specific segments of the general aviation community are provided by using the same basic NAVSTAR set with additional electronic modules.

The basic NAVSTAR set is housed in a standard ATI-3 (3-1/4" x 3-1/4" x 9") instrument case. The set functions as a simple position fixer with digital display of 3-dimensional position plus groundspeed, ground track and precise time. Distance and bearing display to nine manually entered way points has been included to add to the general utility of the set. The basic NAVSTAR set can be expanded to interface a standard course deviation indicator (CDI) or horizontal situation indicator (HSI) by adding a plug-in interface module.

A second configuration, the NAVSTAR/COMM Unit combines a basic NAVSTAR set with a solid-state CDI package and a transceiver module in a single 3-1/2" x 6-1/2" x 9" integral package. This unit becomes a direct physical and functional swap-out for many present day VOR-with-Transceiver sets but adds the capability for precise 3-D RNAV and navigation in areas not covered by line-of-sight VOR/DME signals.

Finally, for the sophisticated user, the basic NAVSTAR set can be configured to include an optional digital interface module to allow the set to communicate with a selected RNAV/Cockpit Display subsystem via a standard digital data buss.

2.3 CONTROL AND DISPLAYS

Two underlying assumptions for this study are: 1) air routes devised for air traffic control (ATC) purposes will continue to be defined in terms of magnetic north reference and 2) all aeronautical charts will be based upon a common map datum such as WGS-84.

As an area navigator, a GPS set must contain, in its memory, the latitude and longitude of geographic points (waypoints) that define the route of flight. This is a complication (shared by other RNAV sensors such as LORAN and OMEGA) in the view of the general aviation user who has become accustomed to using VOR stations as waypoints and selecting them by means of frequency change.

With due considerations for its strengths and weaknesses, a keyboard was selected for alphanumeric data entry. Three lines of twelve, 16-segment, liquid crystal displays (LCD's) were selected for data display. A relatively simple panel configuration was achieved to a large extent by software within the set for 1) data formatting and 2) logic to minimize human error.

2.4 SYSTEM PROCESSING

The design of an unaided, low-cost, moderate accuracy GPS receiver for general civil aviation users is shown to be completely feasible using a one channel, one frequency receiver attached to a single antenna/ preamplifier with no aiding devices.

An eleven-state Kalman filter with a satellite switching algorithm and stored ephemerides to provide one hundred meter dynamic performance is implemented in the software. The software also provides control of all other set functions to the extent that an operator need only turn the set on.

2.5 ANTENNA/PREAMPLIFIER

A one channel, one frequency single antenna/preamplifier will meet the requirements for civil aviation users. This antenna-preamplifier is an integrated package consisting of a microstrip or volute antenna and a interconnected microstrip bipolar preamp-amplifier and microstrip bandpass filters. The antenna is one PCB and the preamp and filters another. This design offers a 5-10:1 reduction in size and weight compared to current GPS antenna preamplifiers with similar performance.

2.6 RECEIVER

Basic receiver requirements are summarized as follows: The threshold referenced to the preamplifier input would be - 133 dBm for acquisition and -140 dBm for tracking. The receiver would accommodate dynamics for 400 m/sec velocity and 5 m/sec^2 acceleration. The range measurement accuracy would be 50 meters or better and the delta range accuracy would be 0.1 meter. The C/A code search rate would be 50 chips/sec. The most cost effective architecture which meets these requirements is a single channel sequential receiver. The set uses double frequency conversion which is optimized for L1 and C/A code only.

The set incorporates a digital phase sampler at the hard limited final IF output followed by a digital phase comparator, quadrature phase rotators, inphase and quadrature phase accumulators and a single chip microcomputer signal processor. An analysis of the digital portions of the receiver indicates that all of the digital functions including the phase sampler, comparators, rotators, accumulators, microprocessor interfaces, code clock synthesizer, code generator and coder control logic can be implemented or a single CMOS/SOS chip using current technology and can be implemented on a single lower cost NMOS chip by 1985.

It is projected that the entire receiver could be implemented on a single 3 by 8.5 inch circuit board in 1985 using a single custom IC for the synthesizer, a custom chip for the baseband and standard ICs for the downconverter, and IF circuits. To achieve this objective, further research and development on low cost oscillators, gallium arsenide RF/synthesizer ICs, and SAW resonator filters and oscillators, is required.

2.7 COMPUTER PROCESSOR UNIT

The functional requirements for the computer processor of a Civil Aviation GPS set are similar to the GPS Phase I Z-Set computer processor. Forty percent of the throughput is spent executing basic instructions, 35% on single precision and 25% on extended precision floating point instructions. The recommended addressing range is 96K bytes. Minimum memory size requirements for program, data and almanac memory are estimated to be 30K, 5K and 1K words, respectively.

Little additional technology development is required in this area because considerable effort is underway by the semiconductor industry toward increasing function density, improving speed and, at the same time, lowering power dissipation in newly developed integrated circuits. NMOS is expected to offer the most function density per dollar and offer low power and small size as well.

2.8 POWER SUPPLY

An off-line boost regulation is the design approach selected for the power supply. The dual potential power supply is capable of supplying up to 3 watts at 9 volts for the receiver and 5 watts at 5 volts for the processor from a general aviation aircraft 12 volt battery supply. A low current battery is included to "keep alive" critical circuits and to provide non-volatile almanac memory for several months.

2.9 PACKAGING

Three packaging configurations are projected: A conservative packaging approach to the NAVSTAR set has a volume of 126 cubic inches, a weight of 4.5 lbs. and dissipates 8 watts. An alternate packaging configuration for the NAVSTAR set which incorporates a more advanced level of technology, has a volume of only 91 cubic inches, weighs 3 lbs. and dissipates 5 watts. Finally, a fullup NAVSTAR/COMM set configuration has a volume of 186 cubic inches, a weight of 5 lbs. and dissipates 10 watts.

The basic set design will consist of a flex print harnesses containing the required PWB's held in place on spindles. Connectors will be molded into the harness and removal of the dust cover will allow complete access for testing.

SECTION 3
GENERAL AVIATION SCENARIO

3.1 PROJECTIONS

3.1.1 GENERAL*

With emphasis on conservation of resources, coupled with operating costs that are expected to rise more rapidly than the rise in prices attributable to inflation, private flying for pleasure is not expected to increase rapidly as in the past. The main stimulus to general aviation should come from business flying. Many companies, particularly those located at the edge of urban areas or in the country, may find that flying managerial staff and engineering and marketing personnel in company planes makes economic sense.

During the 1980s, a number of new general aviation airports are expected to open. Typically, these airports will be located at the edge of urban areas and many will serve as reliever airports, thus reducing traffic at the major hubs. They will also tend to serve as major maintenance and training facilities for geographic regions. The number of general aviation airports with towers and instrument landing systems should grow to match the availability of avionics equipment and increased traffic volumes.

In its efforts to improve the safety of the National Aviation System, the Federal Aviation Administration can be expected to encourage general aviation pilots to upgrade their use of avionics equipment. This, coupled with intensified training and educational programs, should result in a reduction of the general aviation fatality rate.

During the forecast period, the growth in the pilot population, business flying and the number of towered airports will combine to increase the number of itinerant general aviation operations at towered airports from 28.1 million in 1978 to 43.2 million in 1990. General aviation local operations are expected to increase from 22.5 million operations in 1978 to 33.2 million in 1990. A current General Aviation Scenario along with projected growth over the next decade is shown in Table 3-1.

---

*References: FAA Data (Forecast period 1978 - 1990)

Table 3-1. General Aviation Scenario

Topic	1978	1990
Fleet Size	186,600	310,800
Airports	14,117	~20,000
Heliports	3,500	
Total Aircraft Operations	60,700,000	~100,000,000
Instrument Operations	--	59% Increase
IFR Aircraft Handled	28,100,000	~40,000,000
Flight Services	65,800,000	>130,000,000

3.1.2 FLEET SIZE

3.1.2.1 Status

There were 186,000 active aircraft in the general aviation fleet as of January 1, 1978, up 4.7 percent from the preceding year.

3.1.2.2 Forecast

General aviation airframe manufacturers will continue producing aircraft at a steady pace. Based on the past relationships between employment, expenditures in the aircraft industry, and the number of active GA aircraft, the fleet is forecast to rise from 186,000 in 1978 to 310,800 in 1990. This represents a 66.6 percent increase during the 1978-1990 forecast period or an annual average increase of 4.3 percent. By comparison, the average growth rate was 5.2 percent during the 1973-78 period. In conjunction with the continued increase in the fleet during the 1978-1990 period, there should be gradual product improvements encouraging more people to fly, particularly in smaller aircraft that will continue to dominate the market.

3.1.3 FLEET COMPOSITION

3.1.3.1 Status

Single-engine piston aircraft totaled 151,200 on January 1, 1978, representing approximately 81 percent of the general aviation fleet. The remaining 19 percent was distributed among multiengine piston aircraft (22,400), turbine aircraft (4,900), rotorcraft (6,000), and balloons, dirigibles and gliders (3,400).

3.1.3.2 Forecast

Based on past trends and relative market shares, the number of single-engine piston aircraft is expected to increase to 245,000 by 1990 and to account for 78.8 percent of the fleet. In 1990, multi-engine piston aircraft will represent 12.5 percent of the fleet as compared to 12.0 percent in 1978. The higher relative growth rate in multiengine piston and turbine aircraft, compared with single-engine piston aircraft, points to increased sophistication among general aviation pilots.

3.1.4 HOURS FLOWN

3.1.4.1 Status

Based on preliminary data, hours flown in general aviation aircraft reached 38.6 million in 1978, up from 36.7 million in 1977. The 5.2 percent increase for 1978 was higher than the 4.6 percent growth in 1977.

3.1.4.2 Forecast

The number of hours flown is forecast to increase to 67.4 million by 1990, which is 74.6 percent higher than the 1978 total. This translates to a 4.8 percent average annual growth rate, down sharply from historical values (the average annual increase was 6.3 percent from 1973 through 1978). The lower growth forecast is due primarily to higher anticipated fuel costs to general aviation and is consistent with recent trends in aircraft utilization rate.

3.1.5 ACTIVE PILOTS

3.1.5.1 Status

On January 1, 1978, there were 783,900 active pilots, up 5.3 percent from the 744,200 reported one year earlier. The number of instrument-rated pilots totaled 226,300, an increase of 14,900 over the previous year.

3.1.5.2 Forecast

The number of general aviation pilots is expected to increase to 1,155,800 by 1990. This represents a 47.0 percent increase during the forecast period. The number of private pilots is forecast to increase as interest in flying grows among a populace that will be slightly older, will have fewer children and will have a steadily rising disposable personal income. The number of student pilots is forecast to rise slowly from approximately 203,500 in 1978 to a peak of 321,800 in 1985, and to decline steadily thereafter, going back to 225,000 in 1990. Since the number of pilots who will give up their license are fewer than the number of new pilots trained, the private pilot population will increase steadily during the forecast period, rising from 327,400 in 1978 to 529,600 in 1990. Despite this increase in the number of pilots, pleasure flights by individuals are expected to diminish in importance as costs continue to increase and as conditions become more and more crowded at those urban GA airports that continue operations.

3.1.6 AIRPORTS

3.1.6.1 Status

Currently there are 14,117 airports in the United States, plus about 3,500 heliports including some 300 which are elevated. 418 of these airports are served by FAA Towers, plus 27 served by non-Federal Towers and 45 by military towers. There are 660 runways served by an ILS on some 500 air carrier airports. Lighted runways total 4,483 and paved runways 5,313. It is obvious that, with few exceptions, general aviation airports do not have "precision" (ILS) instrument approach capability; none of the heliports are served by an ILS.

3.1.6.2 Forecast

General aviation airports will continue to increase at a gradual rate, probably in the order of 20,000 by 1990. The number of ILS/MLS installations for general aviation will probably be modest, leaving the great proportion (±95%) of general aviation airports with "non-precision" or no instrument approach facilities.

3.1.7 TOTAL AIRCRAFT OPERATIONS

3.1.7.1 Status

FY 1978 total aircraft operations (takeoffs and landings) at airports with FAA air traffic control towers will remain at the FY 1977 level of 66.7 million, according to preliminary FY 1978 data.

3.1.7.2 Forecast

Total aircraft operations at towered airports are forecast to increase at an average annual rate of 3.5 percent or by a total of 50.2 percent by 1990. Long-term activity forecasts are quite similar to those published last year by the FAA, with slightly higher forecasts of itinerant operations being offset by lower growth in general aviation local operations. The forecast for air carriers and military aviation are essentially the same as last year, while the forecast for air taxi operations is higher as a result of anticipated regulatory changes that will encourage the use of commuters for short haul travel.

3.1.8 INSTRUMENT OPERATIONS

3.1.8.1 Status

A 3.8 percent increase in instrument operations was recorded between FY 1977 and 1978. This growth reflects the increased use of avionics by the general aviation fleet, as well as strong growth in air taxi and air carrier instrument operations. Military operations declined slightly from the 1977 level.

3.1.8.2 Forecast

Instrument operations at FAA towered airports are forecast to rise an average of 3.9 percent, or a total of 59 percent by 1990. These forecasts are slightly higher than last year's FAA forecast. Strong growth in air taxi instrument operations (127.6 percent by 1990) attributable to increased commuter traffic and higher utilization of avionics, is expected to complement a significant increase (82 percent) in general aviation instrument operations.

3.1.9 IFR AIRCRAFT HANDLED

3.1.9.1 Status

In FY 1978, it is estimated that FAA Air Route Traffic Control Centers (ARTCCs) handled 28.1 million IFR aircraft, an 8.1 percent increase over the 26.0 million recorded in FY 1977. Air carrier IFR aircraft handled increased 4.6 percent, while the number handled for general aviation rose 18.8 percent over the same period. Air carrier traffic accounts for about 48 percent of the current IFR volume, followed by general aviation (29 percent), the military (16 percent), and air taxis (7 percent).

3.1.9.2 Forecast

The forecast for workloads at ARTCC's through 1990 run higher than last year, primarily because the number of IFR-rated general aviation pilots is expected to increase. General aviation IFR-aircraft handled are expected to grow at a 6.8 percent annual rate from 1978 through 1990. Complementing this will be an expected 9.8 percent annual growth in air taxi IFR aircraft that are handled. Air carrier IFR operations should grow at a 2.1 percent annual rate. Zero growth if projected for military IFR activity.

3.1.10 FLIGHT SERVICES

3.1.10.1 Status

FAA flight services include pilot briefings, the filing of flight plans and the contacting of aircraft. Historically, general aviation has generated the primary demand for flight services, and this trend is expected to continue. Between 1977 and 1978, total flight services provided by flight service stations and combined station/towers rose by 7.3 percent from 61.3 million to 65.8 million. In 1978, pilot briefs rose 7.7 percent, aircraft contacted 3.9 percent, and flight plans 8 percent.

3.1.10.2 Forecast

By FY 1981, flight services are forecast to increase 31.3 percent over the 1978 level, reflecting continuation of the general economic recovery and an increase in IFR flying by general aviation. A slower growth rate in overall general aviation activity, after FY 1983 will temper this growth somewhat. Yet, total flight services in FY 1990 are forecast to be more than double the current level. Over the forecast period, pilot briefs are expected to increase 132.4 percent and flight plans by 105.3 percent. In contrast, the number of aircraft contacted are expected to remain relatively unchanged throughout the forecast period.

3.2 OBJECTIVES OF GENERAL AVIATION USERS

General aviation is comprised of several distinct categories covering the following:

- Personal flying, including flights performed for pleasure and non-business purposes.
- Business flying, including flights carried out by companies and individuals in the course of conducting their particular business.
- Commercial flying, including such activities as air taxis, aerial application of insecticides, pipeline patrol, aerial surveys, aerial photography, and police surveillance.
- Instructional flying, including flights performed in the course of training pilots.

In all of the above categories of general aviation may be included both CTOL and VTOL aircraft.

Aircraft have been used for personal flying all over the world ever since man learned to fly. On a worldwide basis, it is probably the largest segment of general aviation, and is constantly growing at a rapid pace. The other categories, which could be grouped in a general way as "non-pleasure", also account for a significant portion of general aviation's total activity.

In some countries, as for example in the United States, general aviation has made swift progress, due, in part, to encouragement and lack of unduly restrictive regulations by the government. In other countries, however, military and airline operations have received priority treatment to the detriment of general aviation's development. While the sheer number of general aviation aircraft reflects a significant demand upon the ATC System, it is also true that many of these aircraft conduct most of their operations outside of the system where no type of air traffic service is needed. The number of general aviation aircraft handled by the ATC System, however, is constantly moving upward, particularly in the substantially increasing volume of such aircraft which are operated under positive air traffic control procedures (IFR).

The nature of the ATC Service provided to the pilots of these aircraft is almost identical to that provided to the other categories. An IFR flight made by a general aviation aircraft is given the same handling by ATC facilities as are the scheduled air carriers, for example. Since many such flights operate into and out of airports not served by the air carriers, slight differences in handling, as well as in formal procedures, do arise occasionally. Such differences result mainly from the different degrees of skill, training, and experience which apply to some classes of the general aviation pilot.

These classes would include naturally those who are still in the training stage, as well as those who fly exclusively for a hobby in good weather. On the other hand, general aviation also includes professional pilots, in the case of business flying for example, who may be part of a highly organized department of a large corporation. Those pilots have the skill and training equal to an air carrier pilot as well as a wealth of experience in all types of aircraft including those used by the air carriers.

In between these two general groups are many thousands of pilots -- with every type of qualification -- which lie between the two extremes. In addition, general aviation pilots fly aircraft of all sizes and varieties which are available. These range from tiny home-built single-place pleasure aircraft with little or no instruments or electronic equipment, to the latest airline-type jet carrying the most modern and sophisticated instrumentation and avionics systems.

3.3 CONSTRAINTS OF GENERAL AVIATION USERS

There are certain basic constraints to General Aviation. These are enumerated below. Some may be reduced or eliminated to one degree or another. Others are of a type which, strictly speaking, are a fact of life and must be recognized as such. The dissertation which follows deals with the various constraints and makes particular reference to the potential impact of GPS on each constraint as applicable.

3.3.1 AIRSPACE UTILIZATION

3.3.1.1 ATC Management

The airspace per se has infinite capacity to handle air traffic. However, management of the airspace by the Air Traffic Control System (ATC) imposes certain constraints on the utilization of the airspace by General Aviation and air traffic in general. These constraints depend to a large extent upon whether a flight is conducted under Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). Certain minimum weather conditions (specified in the Federal Aviation Regulations) must exist in order to fly VFR; otherwise a flight must be cancelled or conducted under IFR.

Under VFR, the pilot generally may follow routings and fly to destinations of his own choosing, subject to airspace restrictions. Since VFR minimum weather conditions frequently do not exist, and many General Aviation pilots and/or aircraft are not qualified to fly under IFR, imposition of the Visual Flight Rules may be considered as constituting a constraint to General Aviation. These rules, however, are necessary in the interests of reducing the possibility of mid-air collisions by limiting such flights to weather which might be considered as "good", thus (at least in theory) permitting pilots to avoid collisions by visual reference to other VFR aircraft ("see and be seen").

Under IFR, such aircraft are under active control of ATC in the interests of preventing mid-air collisions. However, ATC exercises this control only over aircraft flying in accordance with the Instrument Flight Rules and does not necessarily protect IFR traffic from VFR traffic or vice versa. When flying in accordance with IFR, aircraft are subject to many constraints in the use of the airspace, which are described more fully under section 3.3.7 (Separation Assurance).

3.3.1.2 Airspace Restrictions

These constraints take the form of restricting the utilization of certain portions of the airspace. In some cases, these restrictions apply to all types of air traffic (e.g. over the White House). In other cases, they may apply only to civil aircraft (e.g. in the case of military airspace reservations). Another form of airspace restriction is the Terminal Control Area (TCA) concept.

3.3.1.3 GPS Potential Impact

Major contributions of GPS in the area of airspace utilization would include: Permitting the creation of VFR "freeways" and other methods of facilitating separation between VFR and IFR traffic; facilitating reduced route widths for IFR traffic; facilitating avoidance of restricted airspace; facilitating the use of airspace "overpasses" and "underpasses" to help separate air traffic. All of these are examples of GPS advantages which would contribute to increased airspace utilization.

3.3.2 NAVIGATION

3.3.2.1 Enroute

A major constraint to General Aviation with respect to enroute navigation is that the present VOR system (used by virtually all of General Aviation), is line-of-sight (radio horizon) limited. Furthermore, calibration of VOR General Aviation receivers is very loose, and accuracy leaves much to be desired. Finally, the present VOR system does not provide complete signal coverage either on a geographic basis or at low altitudes.

3.3.2.2 Terminal Area

In this type of constraint, General Aviation must conform to precise flight patterns, largely based on radar vectoring by ATC when flying under IFR. This situation may cause delays and undue conflict with larger, higher performance, aircraft.

3.3.2.3 Approach/Landing

In this environment, General Aviation is constrained to two types of approaches, "precision" and "non-precision". Precision approaches at this time can only be made using an ILS (Instrument Landing System) or PAR (Precision Approach Radar). (Note: Microwave Landing Systems (MLS) are not expected to be significantly implemented much before the year 2000). There are approximately 500 civil (mainly airline) airports having precision approach capability today, although the FAA recently has announced that during the next several years a relatively modest number of ILS installations are planned for General Aviation "reliever" airports. Non-precision approaches can be made using VOR, NDB or RNAV (basically using VOR/DME sensors). The number of airports at which such approaches can be made is a small percentage of the more than 14,000 airports in the U.S. today, not counting a virtually unlimited potential for heliport instrument approaches by helicopters. (Note: Helicopters are considered as a part of General Aviation.)

3.3.2.4 GPS Potential Impact

GPS with its high accuracy navigational capability and inherent signal coverage down to the surface would significantly reduce or eliminate the types of navigation constraints discussed above. In addition to improved enroute and terminal area navigational capability, including narrower route widths, discrete routes for separation of different categories of aircraft, and "random" routing capability, GPS would open up to General Aviation virtually an infinite number of locations at which an instrument approach could be made without the necessity of having a ground based electronic aid at that location.

3.3.3 LANDING/TAKEOFF AREAS

3.3.3.1 Airports

As indicated previously there are over 14,000 airports in the U.S. today. Only some 60 of these airports handle about 85% of the scheduled airline service. Many types of General Aviation aircraft (e.g. business/ executive, commuters, helicopters) need to serve these same airports for connections with airlines. Yet, General Aviation is constrained in using these airports through a reservation or quota imposition. Further, General Aviation may be constrained at other airline airports through imposition of high landing fees. On the other hand, up to now, General Aviation (with few exceptions) can practice precision instrument approaches only at airline airports (where the ILS installations are).

Another airport constraint is that auxiliary runways at an airline airport generally are closed to General Aviation in IFR weather, as all of the traffic in such conditions is confined to ILS approaches. (The traffic handling capacity of a given airline airport during VFR conditions may be reduced by 50% in IFR conditions).

In addition, at the some 13,500 non-airline airports in the United States, General Aviation is constrained to VFR operation, or at best, non-precision approaches in IFR weather, at a relatively few such airports.

3.3.3.2 Heliports/Helipads

Heliports and helipads are landing/takeoff areas for helicopters. Heliports, numbering about 3,500 in the U.S. today, generally are reasonably well prepared surfaces and may accommodate several helicopters at one time. Helipads generally are more modest landing/takeoff surfaces, such as on oil rigs/platforms (over 2,000 in the Gulf of Mexico alone), on rooftops, in fields, parking lots; also on some segregated spot on a conventional fixed wing airport. General aviation is constrained in the use of heliports/helipads to VFR or "special" VFR weather conditions due to the absence of navigation capability to make instrument approaches to such landing/takeoff areas.

3.3.3.3 GPS Potential Impact

GPS would greatly increase the productivity of airports/ heliports/ helipads by opening them up to use by General Aviation under IFR conditions independently of any ground navigation aids. For example, auxiliary, parallel, or "General Aviation" runways at airline airports could be used in IFR independently of airline or other high performance traffic; all General Aviation airports would have IFR capability; all heliports/ helipads would have IFR capability.

3.3.4 WEATHER

3.3.4.1 Enroute

Weather constraints to General Aviation enroute generally involve such phenomena as thunderstorms, icing, adverse winds, turbulence. These phenomena may cause detours, delays, accidents, flight cancellations.

3.3.4.2 Approach/Landing/Takeoff

Weather constraints in this environment are essentially as above. However, the consequences to General Aviation may be much more severe. For example, a General Aviation aircraft, with limited (or no) navigation capability may frequently get lost in adverse weather (or sometimes even in good weather); run out of fuel due to winds, have structural failure in thunderstorms, and more frequently, undershoot/overshoot a runway in limited ceiling and/or visibility conditions. The same weather constraints apply to helicopters.

3.3.4.3 Forecasting

Weather forecasts may help General Aviation, but they also can be a constraint when a pilot and/or aircraft are VFR qualified only, and IFR weather conditions may be forecast. A large degree of General Aviation accidents are caused by weather when the pilot thought he could fly VFR but encountered IFR and was not competent to continue the flight.

3.3.4.4 <u>GPS Potential Impact</u>

Weather constraints to General Aviation would be alleviated to a considerable extent by improved navigation capability through the use of GPS. GPS would facilitate planning routes/tracks so as to avoid thunderstorm/ frontal areas; icing; turbulence; and take advantage of "best winds" routes. In addition, GPS navigation capability would reduce the incidence of "lost" aircraft; facilitate IFR pilot capability; and probably most important increase landing/takeoff safety.

3.3.5 OBSTRUCTIONS

3.3.5.1 <u>Enroute</u>

Constraints in this category include natural terrain (e.g. mountains) and man made obstructions (e.g. TV towers). These must be avoided by flying over or around them.

3.3.5.2 <u>Approach/Landing/Takeoff</u>

Obstruction clearance criteria in this category call for the application of sloping planes of varying dimensions to determine obstruction penetration. Clearance of these obstructions within the protected approach/ departure areas must be observed to avoid a collision with an obstruction. Application of these criteria may be considered as a constraint to General Aviation. Instrument approach minimums (ceiling, visibility) will vary based on application of obstruction clearance criteria in different locations, and based upon the type of navigation aid used. Airspace requirements for obstruction clearance in "holding" patterns also will vary as above.

3.3.5.3 <u>Missed Approach</u>

When an instrument approach is made and not completed after reaching approach minimums, a "missed approach" is executed by the pilot. This may be considered as a constraint due to the need to follow a prescribed flight profile, in order to avoid obstructions in the climb-out. (Note: Obstruction clearance criteria for approach and landing, takeoff and missed approach, are set forth in a joint FAA, DOD, Coast Guard "TERPS" Manual.)

3.3.5.4 GPS Potential Impact

As a consequence of the unique navigation capabilities of GPS, enroute obstruction clearance would be facilitated; accurate approach, departure and missed approach flight paths could be followed, thus enhancing obstruction clearance safety; airspace requirements for approach, departure and missed approach obstruction clearance criteria could be reduced; holding pattern airspace requirements could be reduced.

3.3.6 ECONOMICS

3.3.6.1 Avionics

Avionics may be considered to be a constraint to General Aviation from an economic sense. The cost of the avionics in a General Aviation aircraft may vary from zero to something in the order of $100,000, depending upon the degree of sophistication and redundancy desired by the operator. A typical General Aviation aircraft would be equipped with a VOR receiver, possible a DME, a transponder and a communications system totaling something in the order of $5,000.

3.3.6.2 User Charges

General Aviation pays certain user charges such as special taxes on fuel, tires and aircraft (depending on weight). These taxes go into a U.S. Treasury Airport/Airway "trust fund". Other user charges include landing fees and parking/ramp charges. These funds are collected by the airport operator.

3.3.6.3 Capital Investment (Aircraft)

General Aviation aircraft can vary in price from several thousand dollars up to several million dollars. (For a breakdown of the General Aviation fleet composition, see sections 3.1.3.1 and 3.1.3.2). Obviously, the owner of a very low cost General Aviation aircraft can afford to invest very little in avionics, whereas in the higher priced aircraft avionics costs will not be a significant item.

3.3.6.4 Training

Training imposes certain constraints on General Aviation depending upon its nature. Primary and basic training may be restricted to certain airports or areas. Advanced or instrument training may require the use of certain airports/ facilities (see 3.3.3.1).

3.3.6.5 Cost of Operation (Fuel)

The cost of operation of a General Aviation aircraft is largely influenced by the cost of fuel. Contributing cost factors include maintenance, insurance, depreciation, pilot's salaries (when applicable). The cost of operation thus may be considered as a constraint to General Aviation.

3.3.6.6 GPS Potential Impact

GPS would have a significant impact on the economics of General Aviation by being a more cost effective avionics system as a result of providing many more additional capabilities than are provided by today's General Aviation avionics, yet in approximately the same price range; reducing user taxes to some extent by facilitating reduced fuel consumption through improved flight planning capability; permitting more efficient training by providing more accurate observance of training areas and diversifying availability of landing/takeoff areas for instrument practice.

3.3.7 SEPARATION ASSURANCE

3.3.7.1 Surveillance (ATC Radar)

Today's ATC surveillance by radar may cause constraints to General Aviation, particularly when flying under IFR. This may be the result of excessive radar vectoring by the Controller, path stretching and/or speed controls. Also, due to radar's line of sight characteristics and incomplete geographical coverage, great portions of the airspace, especially at lower altitudes, are not under radar surveillance with a resultant higher exposure to mid-air collisions.

3.3.7.2 Air-to-Air

There is no provision in the ATC system today to provide for air-to-air separation assurance by the pilots. Thus, General Aviation, as well as other air traffic, must rely on the ground based ATC System for separation (when under IFR), or on the "see and be seen" principle when under VFR. This lack of air-to-air separation assurance constitutes a constraint to General Aviation in the sense of causing a significant risk of mid-air collisions.

3.3.7.3 Procedures

Separation assurance procedures can cause constraints to General Aviation by requiring the use of large blocks of airspace to reduce collision exposure, especially in airspace not under radar surveillance; delays in landing and/or takeoff to provide separation from other aircraft; distraction from piloting functions in order to look outside the cockpit for other aircraft (especially under VFR).

3.3.7.4 Terminal Control Areas (TCA)

These areas are established around certain high density airports to provide ATC separation of all air traffic flying within the TCA, in all weather conditions, including VFR. This causes a constraint to General Aviation as the operators either must conform to the TCA requirements for certain airborne equipment (not necessarily required for VFR) and comply with ATC separation instructions, or they must fly around the TCA.

3.3.7.5 GPS Potential Impact

GPS could contribute significantly to separation assurance through data link applications which would provide air-to-air separation assurance, simplified separation procedures, and full airspace surveillance coverage by means of automatic position reporting into the ATC system.

3.3.8 COMMUNICATIONS

3.3.8.1 Coverage

Lack of communications coverage in many areas can result in constraints to General Aviation through inability to communicate with ATC facilities when necessary, causing delays or otherwise interfering with desired operations.

3.3.8.2 Efficiency

Today's General Aviation communications in many instances leaves much to be desired in terms of efficiency. Voice communications may be garbled, interference may reduce availability, channels may be jammed.

3.3.8.3 Reliability

General Aviation Communications equipment as such generally is quite reliable today. However, since the VHF (sometimes UHF) signals are radio horizon limited, communications may not always be reliable, especially at lower altitudes.

3.3.8.4 GPS Potential Impact

GPS has the possibility of incorporating a data link communication technique which is based on time division multiplexing, or Time Division Multiple Access (TDMA). TDMA appears to be most fruitful for pursuing to significantly improve General Aviation (and other segments of aviation) communications capability.

3.3.9 HUMAN FACTORS

3.3.9.1 Pilot Workload

This can be a constraint to General Aviation in such areas as aircraft flight technique, communications and navigation. If the pilot workload exceeds the capability of an individual pilot, an accident may result.

3.3.9.2 Controller Workload

Excess controller workload may cause constraints resulting in delays, unsafe control instructions, or failure to monitor and avoid mid-air collision situations.

3.3.9.3 Pilot/Controller Interface

This interface largely depends upon effective communication between the two parties. If the communication is poor or non-existent, unsafe flight situations may result.

3.3.9.4 Man-Machine Interface

The man-machine interface includes such aspects as use of flight controls, flight instruments, navigation equipment, and communications.

3.3.9.5 GPS Potential Impact

GPS could reduce pilot navigation workload by providing flexible, preprogrammed area navigation (RNAV) capability; reduce pilot communications workload through automatic position reporting, air-to-air separation assurance and TDMA; reduce controller workload by reducing controller/pilot communications, radar vectoring, necessity to exercise detailed separation procedures. GPS could improve pilot/controller and man-machine interfaces through improved communications, "unloading" the ground based ATC system through both pilot navigation capability and providing more effective tools for pilot/controller use in separation assurance.

3.3.10 ENVIRONMENTAL

3.3.10.1 Noise

Noise can be a factor which constrains General Aviation by limiting airport use to certain hours, imposing noise abatement procedures during landing and takeoff, restricting areas over which flight may be conducted.

3.3.10.2 Emission

Constraints to General Aviation may result from imposition of emission (pollution) control standards.

3.3.10.3 Community Acceptance

A significant constraint to General Aviation may be community acceptance. This constraint largely is a by-product of where a General Aviation airport is located, noise nuisance impact, emission considerations, value attached to General Aviation by the community.

3.3.10.4 GPS Potential Impact

In the field of environmental constraints, GPS would contribute significantly by: facilitating noise abatement procedures as a result of giving the pilot the navigation ability to follow more precisely minimum noise impact and emission exposure routings; providing navigation capability for reliable service to a community for commuter service, industrial support service, business/executive support service.

3.3.11 VEHICLES

3.3.11.1 Conventional Takeoff and Landing (CTOL)

A constaint to General Aviation inherent to CTOLs is the requirement to have airports with one or more runways, varying in length according to the types of CTOL aircraft using the airport with resultant real estate needs. A constraint at larger airline CTOL airports generally is the lack of separate "General Aviation" runways.

3.3.11.2 Short Takeoff and Landing (STOL)

STOLs (mainly used by commuter/taxi type General Aviation operators) are constrained by the lack of STOL airports and STOL strips at major airline airports, which commuter/taxi operators generally need to serve.

3.3.11.3 Vertical Takeoff and Landing (VTOL) (Includes Helicopters)

General Aviation operators using this type vehicle have minimum constraints insofar as the size of landing/takeoff areas is concerned. However, such operators are constrained at present by the lack of adequate navigation capability for low altitude flight in remote areas or offshore; accurate navigation on discrete, narrow route widths to permit operation independently of CTOL/STOL aircraft; and lack of instrument approach capability to a virtually infinite number of desired heliport/helipads.

3.3.11.4 GPS Potential Impact

GPS would: facilitate use of separate General Aviation runways by General Aviation CTOL aircraft to increase an airline airport's productivity without conflict to the airline and other high performance aircraft using the main runways on the airport; make possible instrument operation on reduced real estate requirements for General Aviation CTOL reliever airports and STOLports as well as facilitating STOL strips at major airports; provide instrument approach capability to virtually an infinite number of heliports/ helipads for VTOL aircraft as well as making possible discrete routings to heliports/helipads without interference to or from CTOL and STOL air traffic.

SECTION IV
EQUIPMENT CONFIGURATIONS

The primary thrust of this study centers on achieving a low cost NAVSTAR set for the general aviation user. Volume production is the most effective means of reducing cost per unit. With this in mind, the study focused on developing a basic receiver/processor and control/display configuration that is useable by a wide range of users outside as well as within the general aviation community. Three other configurations tailored for specific segments of the general aviation community were developed using the same electronic modules as the basic configuration. By spreading the cost of development and production of these core modules among users outside the general aviation community, the unit cost for all users can be reduced.

4.1 BASIC SET

This set forms the core or architectural base for mass production of common set modules. The set functions as a simple position fixer with digital display of 3-dimensional position plus groundspeed, ground track, and precise time. Distance and bearing display to nine manually entered waypoints has been included to add to the general utility of the set. The complete repertoire of control/display inputs and outputs (sixteen different navigational quantities) is described in Section 5. The basic set package is a standard 3.25" by 3.25" by 9" aircraft instrument case. For non-aviation uses, this case is enclosed in a housing appropriate to the specific application. Some examples are shown in Figures 4-1 and 4-2. The greater part of the subsequent sections of this study show how a complete NAVSTAR receiver/processor with integral control/display can be implemented as a set of basic modules that will fit in this relatively small package. The resulting basic set should be appealing to a wide range of users including pleasure boating enthusiasts, fishing fleets, forestry, law enforcement, land survey, wildlife management and others. The basic set would also be useable by some segments of the general aviation community such as aerial applicators and soaring enthusiasts as shown in Figure 4-3.

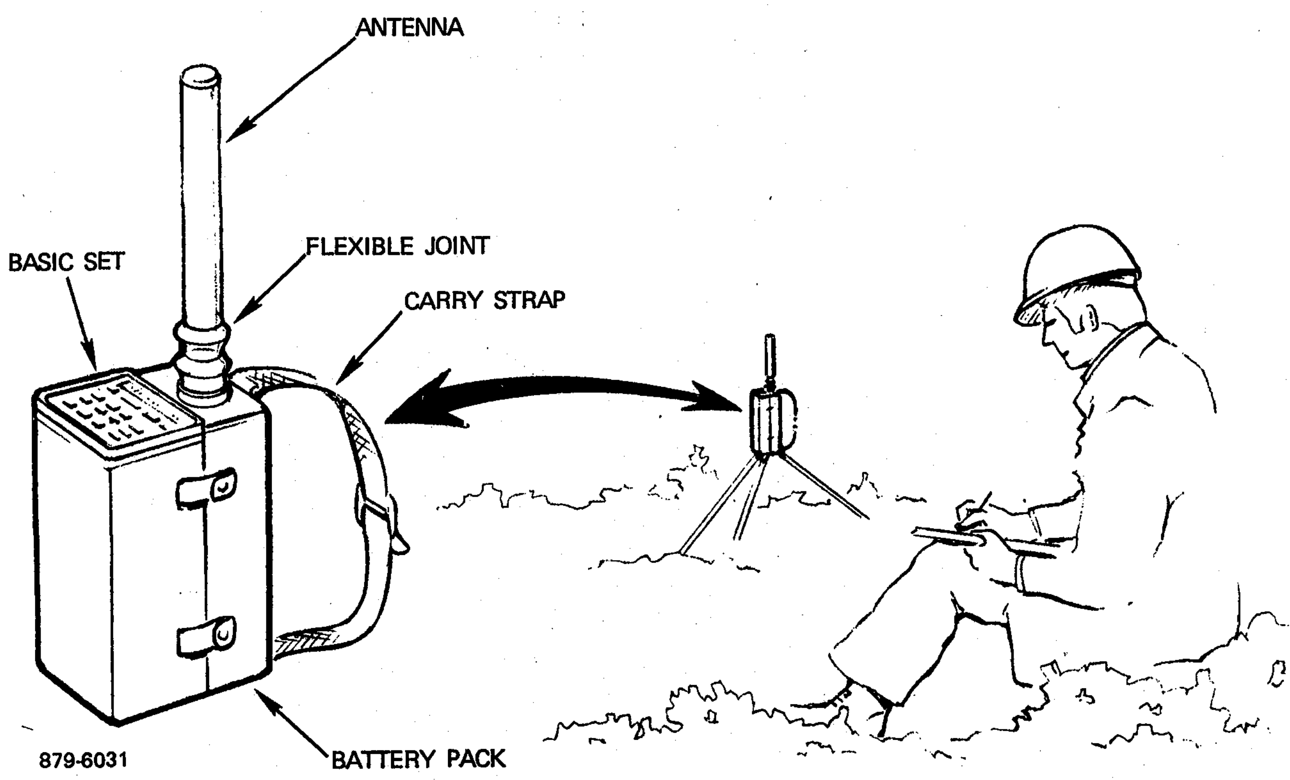


Figure 4-1. Land User Configuration of Basic Set

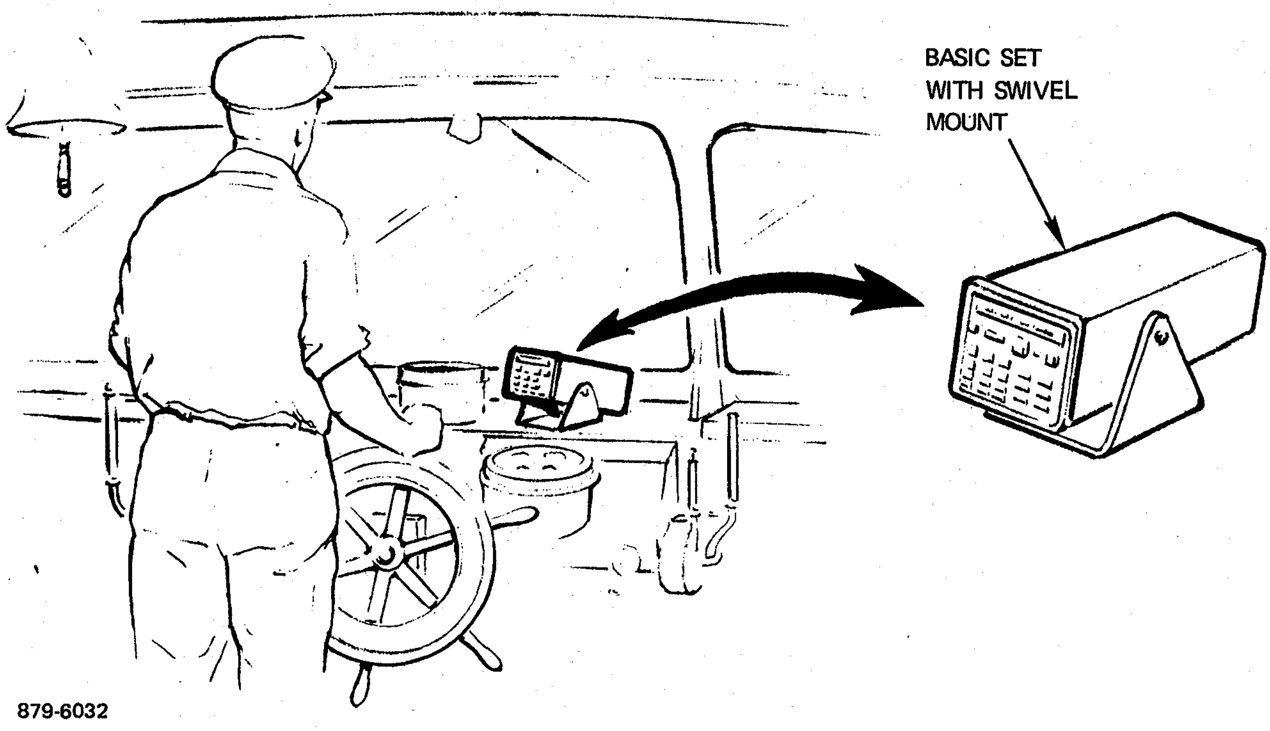


Figure 4-2. Marine Application of Basic Set

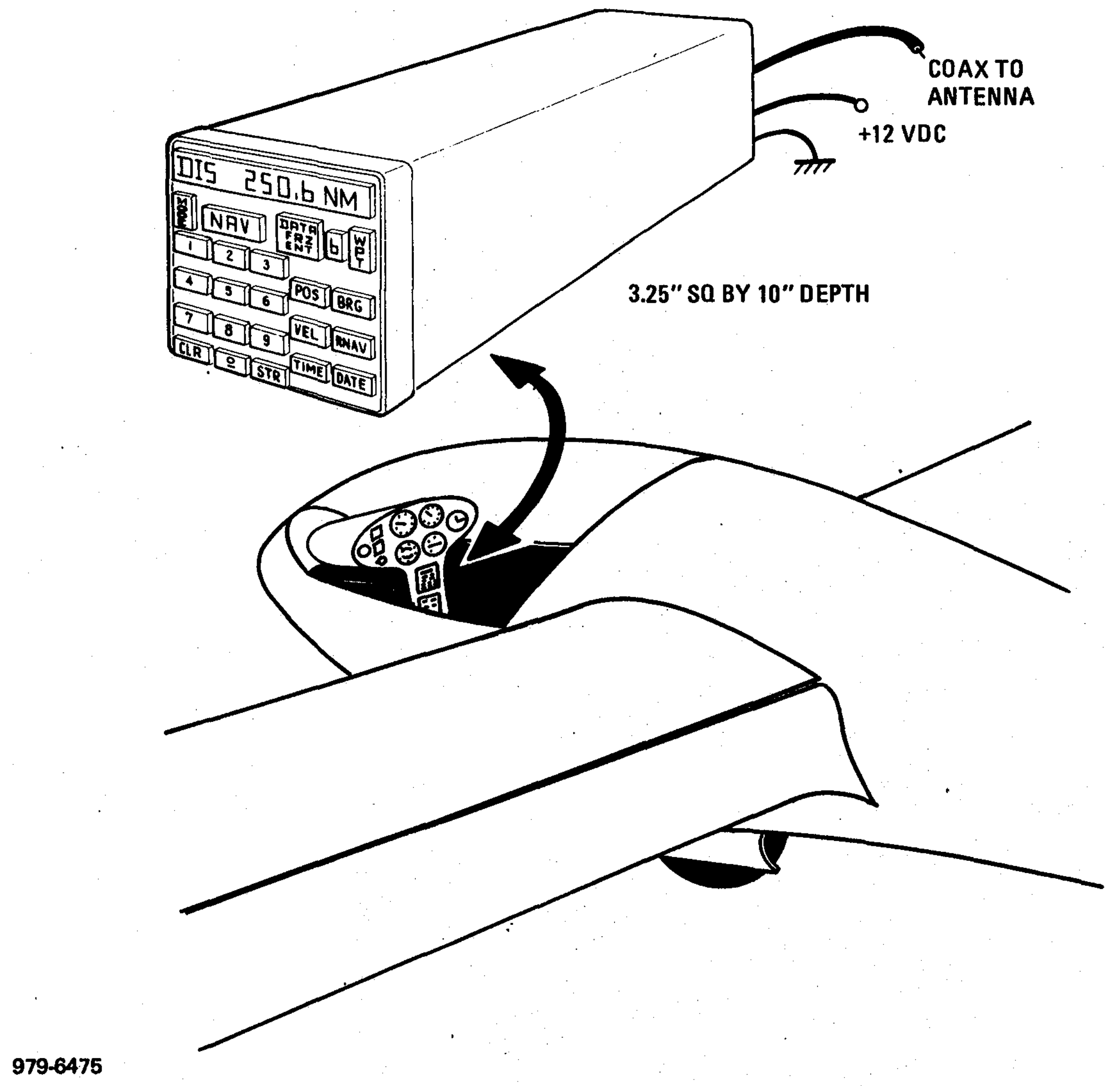


Figure 4-3. Basic Set Configuration and Installation in a High-Performance Sailplane

4.2 SET WITH SEPARATE STEERING DISPLAY

The basic set has sufficient volume to enclose a plug-in D/A, A/D module to allow interfacing with a standard course deviation indicator (CDI) or horizontal situation indicator (HSI). If the user selects a CDI or HSI that does not have integral readouts for Destination Waypoint Number, and Selected Scale Factor, then two small auxiliary switches should be installed adjacent to the CDI or HSI to allow the pilot to control and readout these items. See Figure 4-4. Alternatively, a solid-state CDI package can be provided with all the necessary auxiliary readouts as shown in Figure 4-5. This configuration has ample space behind the CDI for a VHF communication transceiver. These two arrangements provide convenient non-parallax viewing of the CDI or HSI, centerline mounting of the set with its control/display panel, and the functional equivalence of the following present day equipment but greater navigational accuracy:

a) VOR set
b) DME set
c) Loran C or Omega receiver
b) 3-D RNAV computer
c) Precise time clock
d) 720 channel VHF transceiver (if COMM option included)

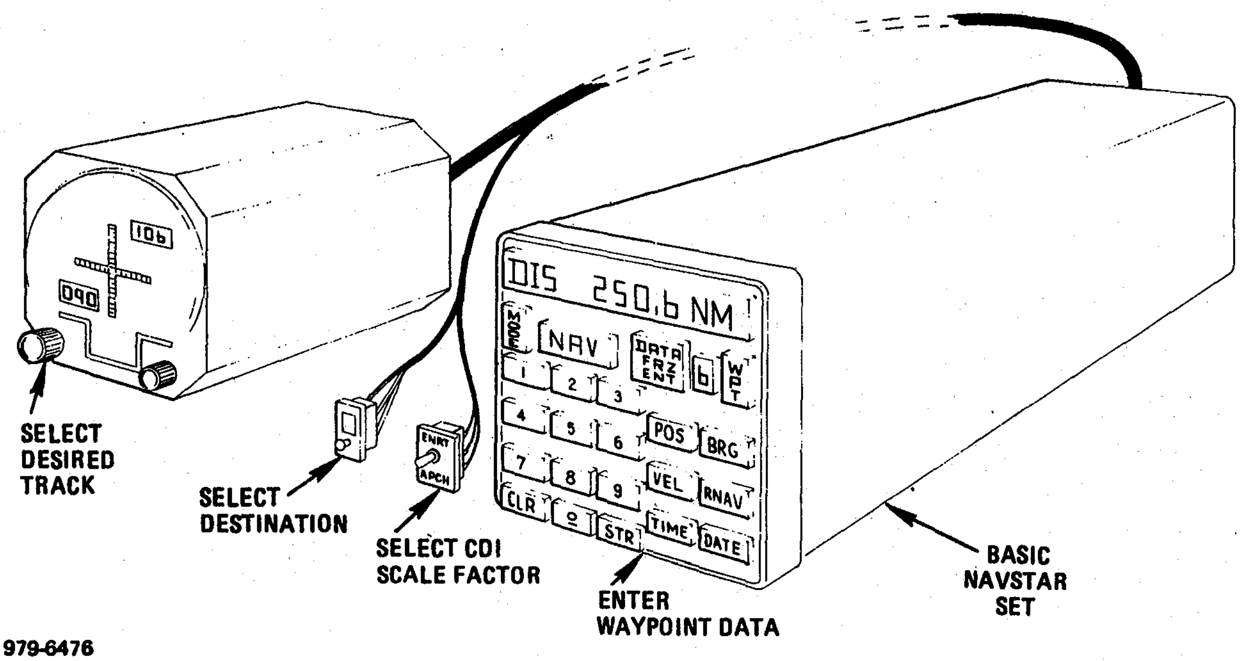


Figure 4-4. Basic Set Driving a Conventional Course Deviation Indicator (CDI)

NOTE: Separate switches may be required for destination waypoint number and CDI scale factor selection. D/A and A/D converters for the CDI are on an optional plug-in module inside the set.

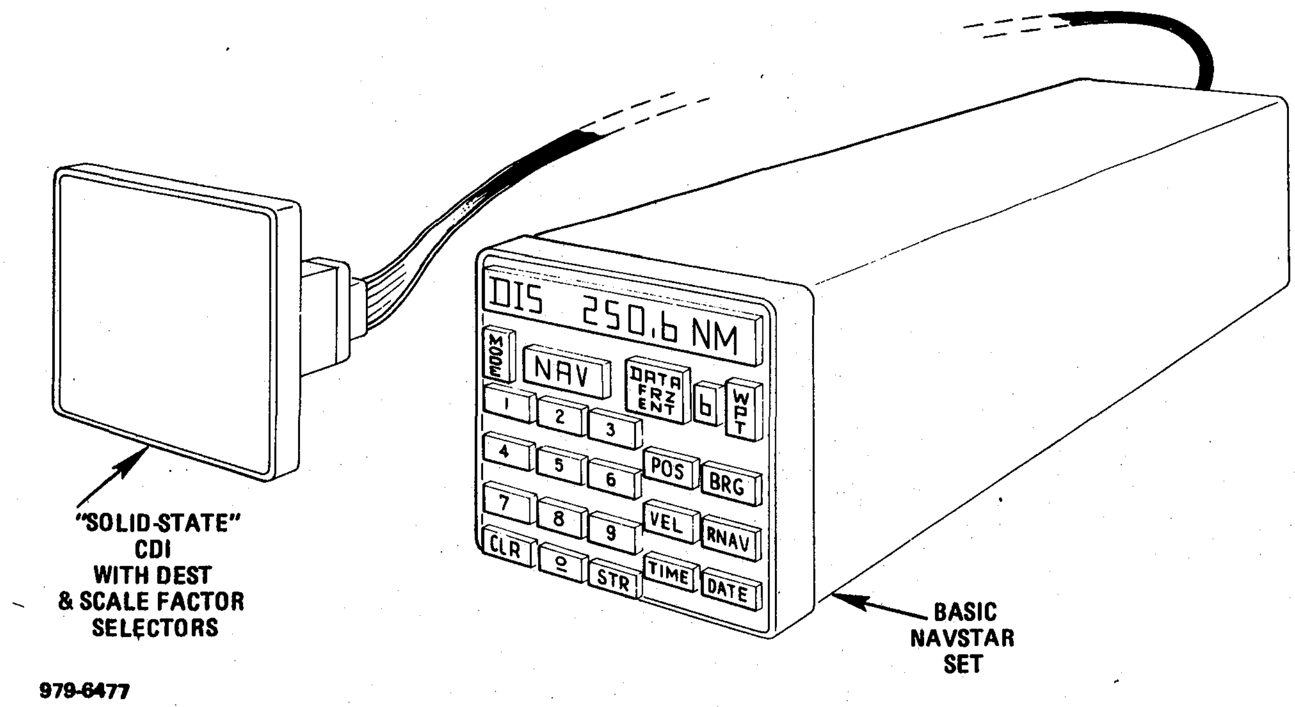


Figure 4-5. Basic Set with Separate Solid-State CDI

NOTE: Showing space available behind the CDI for a VHF COMM transceiver.

4.3 SET WITH INTEGRAL STEERING DISPLAY

This set has the same capability as that described in 4.2 above including the optional communication capability. However, it is packaged as a single unit in the popular 3.25" by 6.5" by 9" form factor common to the majority of NAV/COMM units purchased by general aviation users. This unit becomes a direct physical and functional swap-out for many present day VOR-with-Transceiver sets but adds the capability for precise 3-D RNAV and navigation in areas not covered by line-of-sight VOR/DME signals. A complete description of the operation of this set is provided in the next section of this report. This set is recommended as the set most likely to be purchased by the majority of light-aircraft owners and is the principal focus of this study. See Figure 4-6.

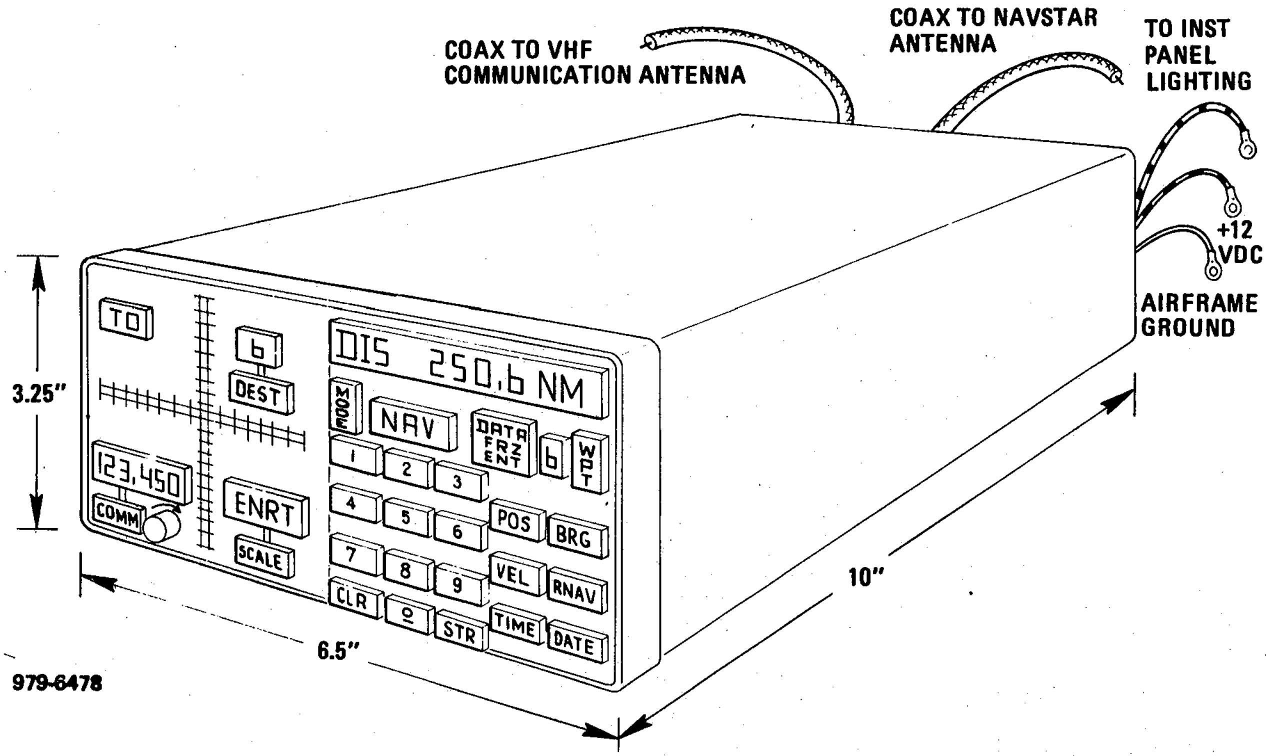


Figure 4-6. General Aviation COMM/NAVSTAR Set

4.4 SETS FOR THE SOPHISTICATED USER

The basic set has the necessary computational data base to allow input/output of the following quantities:*

- Along track distance (ATK)
- Cross track distance (DTK)
- Track angle error (TKE)
- Vertical error (VE)
- Slant range (RNG)
- True airspeed and heading (TAS, HDG)
- Wind velocity and direction (WV, WD)
- North and east velocities (NV, EV)
- Vertical velocity (VV)
- Forward and sideward velocities (FWD, DRIFT)
- Desired time of arrival (DTA)

*Assuming manually entered TAS/HDG or WV/WD.

However, it is not recommended that any of these quantities be implemented as digital displays in a LOW-COST general aviation set. Instead, larger control/display panels can be devised as "optional extras" for the user who demands this added capability. In addition to the displays listed above, the following functional capability is often demanded by many users:

- More than ten waypoints
- Automatic waypoint insertion (mag. tape, punched card, light pen, memory module, etc.)
- Alphabetic waypoint identifier display and entry
- Pseudo-frequency waypoint identifier display and entry
- Rho-theta offset waypoint entry
- Automatic waypoint routing
- TO/TO waypoint track designation
- Null steering along curved flight paths for leg-to-leg and track capture flight paths
- Wind triangle computations
- 4-D RNAV
- Auxiliary sensor inputs
- Extensive built-in-test and fault readout
- World wide magnetic variation computation
- Polar grid navigation
- Map projection displays
- Autopilot and/or hover coupler
- Cruise control computations and displays

The above listed optional extra capabilities are considered to be the purview of specialized display subsystems or integrated cockpit subsystems that may be driven by a NAVSTAR set or any other accurate position fixing or dead reckoning sensor(s). Present day examples of such subsystems include the various commercial RNAV systems produced in accordance with ARINC Characteristic 582, the Canadian

Marconi CMA-720, the J.E.T. 3-D R-NAV System, the Rockwell-Collins AN/ASQ-166, Garrett's AIRNAV-200, and the USAF Digital Avionics Information System (DAIS). If the civil user wants the above listed control/display features, the recommended approach would be to purchase the basic NAVSTAR Set without its Control/Display Unit. Instead of the CDU, his basic NAVSTAR Set should include an optional digital interface module to allow the Set to communicate with its selected RNAV/Cockpit Display subsystem via a standard digital data buss such as ARINC Specification 429. Figure 4-7 shows the use of the low cost basic NAVSTAR Set as a sensor for high capability control/display subsystems.

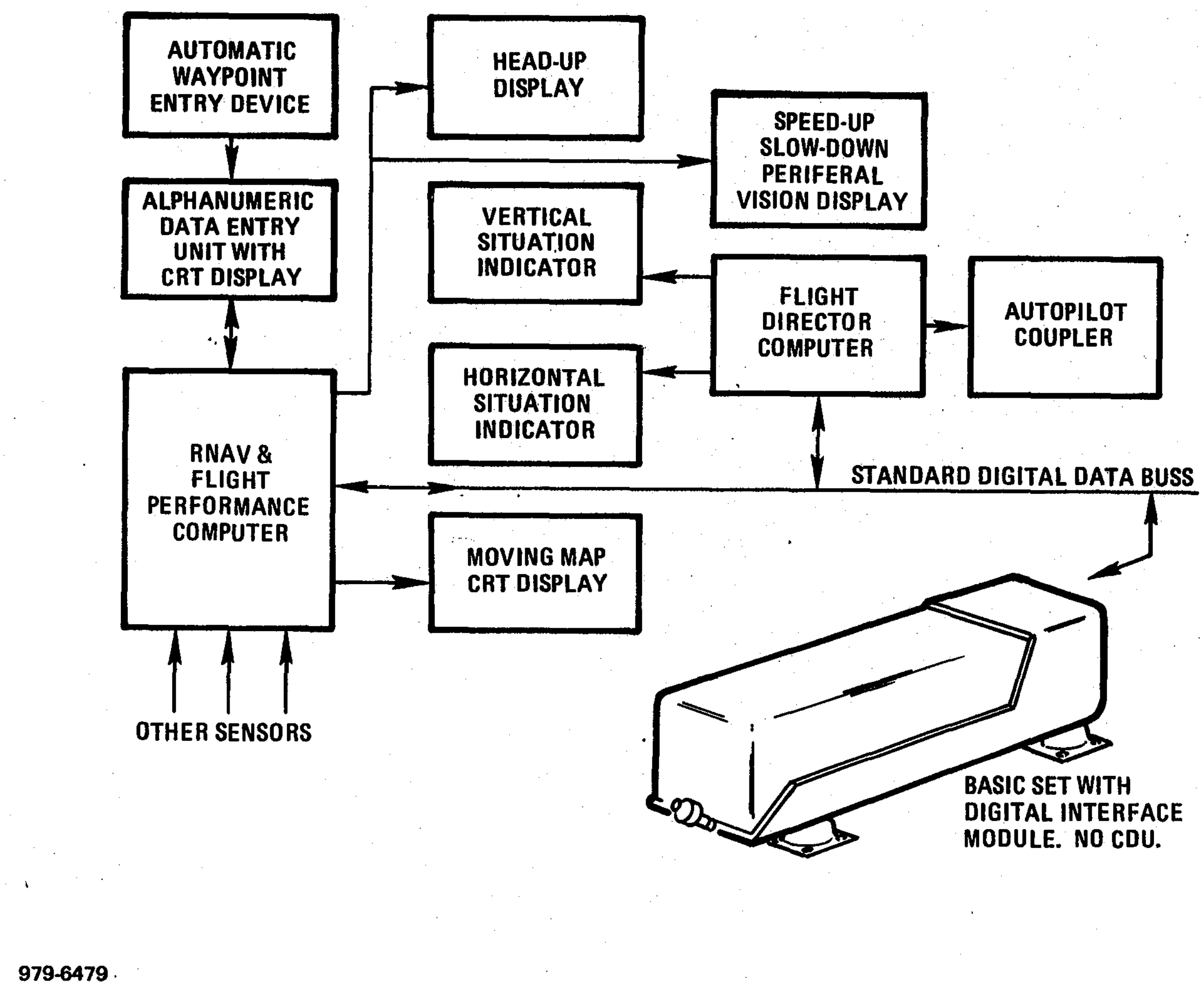


Figure 4-7. Basic NAVSTAR Set

4.5 ABOUT THE OPTIONAL COMMUNICATION (COMM) CAPABILITY

As will be shown in Section 11, the proposed package design for the low-cost, general aviation, NAVSTAR set has adequate internal volume to enclose a VHF communication transceiver. Control and display of the communication frequency is easily accommodated by the proposed NAVSTAR CDU. Thus, a NAVSTAR based NAV/COMM package can be produced that is a direct swap-out for present VOR based NAV/COMM sets utilized by the majority of light aircraft pilots. Assuming that the present aeronautical VHF-COMM spectrum allocation remains in effect during the time of GPS implementation, and that 25 kilo-Hertz channel spacing is used, then 720 COMM channels should be selectable by the operator. If the aeronautical COMM band can eventually be extended to include the present VHF navigation frequencies, then potentially 1111 channels would be available from 108.000 MHz through 135.975 MHz, including guard bands around emergency and VFR frequencies. Some of these channels might be used for direct data link between the NAVSTAR set and various external facilities. Various uses suggest themselves such as automatic position reporting for ATC, collision avoidance, ELT tie-in, ATIS data dump, local area ionospheric correction, etc.

SECTION 5
CONTROLS AND DISPLAYS

This section concentrates on the control/display requirements for the basic set with 3D-RNAV and COMM capability described in Section 4.0 and pictured in Figure 4.6. Two underlying assumptions made throughout this study are:

a. Air routes devised for air traffic control (ATC) purposes will continue to be defined in terms of magnetic north reference.

b. By the time of full scale GPS implementation, all aeronautical charts will be based upon a common map datum such as WGS-84. This will avoid the expense and complication of carrying transformation coefficients for 46 different map data as is presently done in the Phase I, GPS user equipment sets.

5.1 POSITION DATA ENTRY AND DISPLAY

The absence of GPS signals useable for direct homing or bearing measurement with respect to ground radio transmitters dictates that GPS navigators must operate as position fixers (latitude/longitude) or as area navigation (RNAV) systems. As an area navigator, a GPS set must contain, in its memory, the latitude and longitude of geographic points (waypoints) that define the route of flight. This is a complication in the view of the general aviation user who has become accustomed to using VOR stations as waypoints and selecting them by means of frequency change (similar to channel change in a television set). The complication of latitude/longitude waypoint definition is shared by other RNAV sensors such as LORAN and OMEGA. It manifests itself as an inconvenience, at best, and as a further burden on pilot work load, at worst, by requiring manual entry of latitude/longitude position data via some data entry device such as a keyboard. These position data are cumbersome and more conducive to human error than the simple channel selection of VOR. Several schemes have been proposed to mitigate the inconvenience or burden of manual latitude/longitude data entry. Each invariably adds to the complication and cost of the navigation equipment, i.e., hardware replaces operator work. Some of these schemes were listed with the "optional extras" in paragraph 4.4. The reader is warned that even when one or more of these schemes is incorporated, the requirement for manual entry and alteration of latitude/longitude position data remains because:

a. It is necessary for rapid set initialization.

b. It is required by RNAV system specifications (FAA).

c. It adds to the flexibility and general usefulness of the set and its consequent acceptance by users.

The format required for latitude/longitude displays is determined by the resolution of these data which, in turn, should be compatible with the accuracy of the system. Consider the resolution of each of these coordinate display formats:

Equipment	Typical Display	Resolution
Typical INS or OMEGA/VLF system	N 33° 59.9'	608 ft.
GPS Phase I Z-Set	33° 59' 59" N	101 ft.
GPS Phase I Manpack	N 33° 59' 59.9"	10 ft.
All GPS Combat environment sets with Mil. Grid Ref. System Coordinates	WN 1234512345	1 meter

Flight test data from the GPS, Phase I, Z-Set* has shown consistent RMS errors of less than fifty feet (the typical width of a general aviation runway).

This is an order of magnitude better than the resolution of typical present-day inertial navigation displays. Therefore, it would seem appropriate to use the degrees/minutes/seconds/tenths-of-seconds format for the latitude/longitude displays of a general aviation, NAVSTAR set. This will provide the capability to enter high resolution data when required, e.g., landing approaches. When high resolution data are not required, e.g., enroute, the user need not enter the least significant digits of the position data.

---

*The Z-Set uses C/A code only. Flight-test data were obtained directly from the internal digital data buss of the Z-Set and recorded in real-time, while being flown in a C-141 aircraft, for post-flight evaluation.

5.2 VELOCITY DATA DISPLAY AND ENTRY

One of the natural outputs of a GPS set is the host vehicle's 3-dimensional velocity vector. This can easily be resolved into the very useful components of groundspeed (GS), and ground track (GTK), and less useful vertical velocity. Two-sigma accuracy is better than one knot. Of these components, digital display of vertical velocity is probably of little use to the general aviation pilot since he will usually have a static pressure derived vertical speed indicator in his instrument panel already. Therefore, vertical velocity is not recommended for display by the general aviation NAVSTAR set. However, the groundspeed vector components are useful for both VFR and IFR navigation, and are also required as manual inputs for in-flight initialization and for use of the NAVSTAR set as a dead-reckoning computer in event of signal or receiver failure. Therefore, the general aviation NAVSTAR set should be capable of displaying and accepting manual entry of groundspeed with a resolution of one knot. For compatibility with RNAV requirements, the angular component of the groundspeed vector (GTK) should be displayable and enterable with a resolution of one-tenth degree, and be referenceable to magnetic north.

5.3 NORTH REFERENCE

A "natural" north reference for a GPS set is a geodetic reference such as true north. However, nearly all general aviation flying is done with respect to compass headings and bearings, i.e., magnetic north. Therefore, it is highly desirable to have ground track and other north referenced azimuth angles displayable as magnetic north referenced data. This gives rise to requirements for display and entry or automatic computation of magnetic variation (VAR), and a means for manual selection of true or magnetic north reference. Our analysis shows that a look-up table and interpolation computation technique will enable automatic output of magnetic variation within the continental United States with a memory requirement of 2K, 16-bit words and negligible demand on throughput rate. The area of automatic coverage could be extended by means of optional plug-in memory. Alternatively, the operator can manually enter the local magnetic variations of each waypoint. This, in effect, converts each waypoint to a quasi-VOR station (magnetic north orientation) with respect to bearing data. Then GTK and other north referenced data can use the current destination waypoint's magnetic variation for true-to-magnetic conversion.

5.4 TIME DATA DISPLAY AND ENTRY

Highly accurate Universal Time, Coordinated (UTC) as available from various standard time radio signals throughout the world is a natural output of a

NAVSTAR set. UTC is also required for set initialization. A clock readout with one-second resolution is useful for navigation and mandatory for IFR flight. Furthermore, the validity of stored NAVSTAR almanac and ephemeris data is related to date and time. These factors lead to the requirement for entry and display of calendar date and UTC in hours, minutes and seconds. If the set contains a low power, electronic clock module to maintain time during periods when the set is turned off, then it can subsequently acquire satellite signals and begin navigating without any manual initialization by the operator other than turning the set ON. This assumes that the set was operating properly the last time it was turned off, and had not been flown, towed or taxied, in the OFF condition, more than 100 kilometers from the place where it was turned off. Once the requirement for a time display has been established, other useful time outputs such as estimated-time-enroute (ETE) to a waypoint and estimated time of arrival at a waypoint (ETA) are easily implemented with minimum cost.

5.5 FIGURE-OF-MERIT

The set should indicate to the operator, some figure-of-merit to allow him to determine the probable accuracy of the set at any given time. All GPS Phase I sets displayed a quantity called Estimated Position Error (EPE). This quantity is the radius of a circle, centered on the coordinates of the current present position readout, within which the set is estimated to be located with 68 percent probability. It is displayed in nautical miles with resolution of one-onehundredth nautical mile. For general aviation use, it is recommended that this quantity be scaled to represent a 2-sigma value.

5.6 ALTITUDE DISPLAY AND ENTRY

Altitude above mean sea level is a natural output of a GPS navigator. However, the utility of a digital readout of altitude for the general aviation pilot is questionable since he will already have a barometric altimeter installed in his aircraft. Nor is manual altitude input necessary for set initialization since all possible altitudes are within the 100 kilometer sphere of initial position uncertainty mentioned under TIME above. For a basic set in an environment of complete satellite coverage, altitude display and entry are of questionable value. The value of manual altitude entry in the GPS Phase I and II sets lies in its usefulness as a measurement in an environment of partial satellite coverage. However, altitude display is recommended for the general aviation set as part of an optional vertical navigation or 3-D RNAV capability. See paragraph 5.9.5.

5.7 WAYPOINT IDENT., DISTANCE AND BEARING

Distance and bearing to or from a known geographic point are the most useful outputs a navigation set can provide and are more meaningful to navigators than geodetic grid position. Perhaps the greatest defficiency of a VOR set is that it is necessary to supplement it with expensive DME or theta/theta RNAV computer in order to obtain direct readout of distance. However, great circle distance and bearing outputs are easily provided by a GPS set as soon as the coordinates of the waypoint in question have been inserted in the set. If provisions are made for more than one waypoint*, some form of identification for each waypoint is required. For a low cost general aviation set with provisions for nine waypoints, simple numbering from 0 through 9 is recommended with zero representing present position. The numerical waypoint identification can be marked in flight plans and logs next to the waypoint name or alphabetic identification in the spaces formerly reserved for station frequency. Other means of waypoint identification including alphabetic identifiers and psuedo-frequencies were mentioned under Optional Extras, paragraph 4.4. It should be noted here that if the GPS set drives some form of null-steering display, two waypoint identification displays are recommended. The first designates the waypoint currently being used for steering display computations (DESTINATION) while the second is available for digital data display, and the entering and alteration of coordinates without disturbing the first. Distance (DIS) should be displayed with a resolution of one-tenth nautical mile for compatibility with existing systems and procedures. It should be noted that DIS as computed by a GPS set is actual great-circle distance and not slant range. No auxiliary altimeter input is required to produce the DIS display. The set can compute and display any great-circle length but a practical limit would be five figures, i.e., 9999.9 nautical miles. The resolution of the bearing and reciprocal bearing displays should be one-tenth degree for compatibility with other azimuth displays. Bearings should be referenceable to true or magnetic north as selected by the operator. If the set has insufficient magnetic variation data to compute magnetic bearings, a suitable warning should be displayed when the operator selects magnetic north reference. In addition, reciprocal bearing readout is a convenience appreciated highly by many general aviation pilots.

---

*The GPS Phase I Manpack Set has one waypoint, whose coordinates can be inserted/ altered by the operator, and is selectable by a two-position toggle switch labelled SELF (present position) and REMOTE (the waypoint).

5.8 BASIC SET CONTROL AND STATUS DISPLAY

The basic NAVSTAR set can be considered to have ten modes of operation as described below, plus some additional internal receiver modes such as search, acquisition, carrier lock, code lock, etc. All of these modes need not be signalled to, or controlled by the operator. Nor do all have to be displayed as status information to him. The recommended mode control and status display scheme for general aviation sets is included with the description of the more significant modes below.

OFF. No prime power is applied to the set except for a small internal battery that maintains a real-time clock and holds up memory of the last known set position, almanac, and entered waypoint data. If the set is installed in a vehicle with an electrical system, the vehicle's battery can be used to maintain charge on, and thereby extend the life of, the small internal set battery. The recommended control for this mode is a switch controlled by the operator with on/off status indicated by the presence or absence of information in the set's mode display.

IDLE. A power conservation mode in which only the set's local oscillator, clock and critical memory circuits are powered. Enables quicker first fix when set is turned ON. This mode is deemed as having no special value to the general aviation user. It finds utility in military manpack sets.

SEARCH. The set has no stored satellite almanac or an excessively old (over 180 days) almanac. The set will have to search for a satellite and extract almanac data. This may require over an hour to accomplish. Only sets that have just been manufactured or repaired or have been infrequently used will enter this mode. This mode can be eliminated by inserting almanac data derived from another source such as data link from an ATIS or another NAVSTAR Set. See 4.5. This mode should be automatically selected by the set and indicated to the operator. The set is not usable for position fixing while in this mode. However, the set can be used for dead reckoning navigation concurrent with this mode.

COLLECT. The set has dedicated itself to the collection of ephemerides from all visible satellites rather than operation in its normal mode of time sharing the ephemerides collection function with the navigation function. This mode is only of value immediately after set turn-on when it is expected that take-off will not occur for at least five minutes. Use of this mode will allow more precise navigation through such maneuvers as may occur immediately after take-off due to the availability of the freshly updated ephemerides in the set. This mode should be automatically controlled by the set and not controlled by or indicated to the operator.

INITIALIZE. The set has insufficient data to acquire satellite signals in a reasonable amount of time. The operator should enter an estimate of the set's present position coordinates, present time (UTC or "Zulu" time) and, if moving, the current estimated groundspeed and ground track. It is recommended that this mode be automatically selected by the set and indicated to the operator when the set "knows" that it has insufficient data to begin navigation. However, it should also be manually selectable by the operator to enable him to override previously remembered or entered initialization data.

ALIGN. The operator has indicated to the set, via a control input, that the set is not moving. This will allow more rapid and accurate position fixing while stationary. This mode will provide the most accurate position data in geostationary uses of the set such as land survey. Align mode may be concurrent with other modes. The operator should take the set out of Align mode before allowing the set to move, e.g., before taxiing. This mode should be selected and de-selected solely by the operator, and accompanied by a warning indicator while in effect. If the set is moved (specifically the set's antenna) while in ALIGN mode, the position fix solution will be badly degraded.

STANDBY. The set is in the acquisition process or has acquired and is tracking satellites, but the set's estimate of its own position error exceeds some threshold accuracy value chosen by the user.* The operator should hold altitude and not maneuver or complete his present maneuver and then hold straight-and-level until the set automatically reverts to Navigate mode. More rapid changeover to Navigate mode will occur if the operator manually inserts an altitude estimate such as field elevation or barometric altimeter reading. This mode should be automatically entered/exited by the set from/to Init or Navigate modes and indicated to the operator. No direct operator control except by selection of a lower mode.

---

*The Z-Set used 0.25 nautical mile as the basis for change between STBY and NAV modes.

NAVIGATE. The set is providing accurate navigational data*. The operator can select and readout the set's estimated position error in this or any other mode for quantitative verification of the set's present accuracy. This mode should be automatically entered/exited by the set from/to Standby mode and indicated to the operator. No direct operator control except by selection of a lower mode.

DEAD RECKONING. The NAVSTAR receiver has failed but the set's computational and control/display capability is still useable as a dead reckoning computer. The set extrapolates position along the velocity vector that was last known prior to receiver failure or along an operator entered velocity vector. This mode should be automatically entered by the set and indicated to the operator in event of receiver failure. It should also be available concurrent with all ON modes except Standby and Navigate in that operator inputs will override remembered data.

TEST. A special mode for set self-test with a GO/NO-GO indication to the operator. Automatically conducted by the set concurrent with other modes. Indication to the operator only when there is a failure. A special subtask of test concerned only with verifying the health of displays and their driver circuits is recommended as being solely under operator control and concurrent with any other ON mode. Normal display indications will be interrupted during Display Test in favor of a special display that allows visual verification of display device health.

5.9 THREE-DIMENSIONAL AREA NAVIGATION (3D-RNAV)

The essence of present VOR-DME derived area navigation (2D-RNAV) systems lies in their ability to provide guidance to and from, so called, offset waypoints. The principle of the offset waypoint, i.e., one that is not colocated with a ground radio facility, is already embodied in the basic NAVSTAR set since any point on earth, land or sea, can be inserted in the set as a destination or waypoint. If altitude is added to the basic latitude/longitude coordinates of a waypoint, then vertical guidance (3D-RNAV) can be provided by the set. The additional controls and displays necessary to provide 2D and 3D area navigation are described below.

5.9.1 DESIRED TRACK ANGLE (DTK)

This quantity is a manual input that specifies the azimuth angle of the intended flight path through a waypoint position. It is the equivalent of omni-bearing select (OBS) or course-set in a VOR system. The angle must be referenceable to true or magnetic north at the option of the operator and should have a resolution of one-tenth degree.

5.9.2 CROSSTRACK DEVIATION

This quantity becomes the primary RNAV steering display when presented to the pilot as an analog guidance command. It is actually an analog indication of the "leftness" or "rightness" of the aircraft's present position with respect to the intended flight path. It is roughly equivalent to course deviation in a VOR system except that it indicates the linear distance left or right rather than the angular difference between bearing and desired track provided by a VOR. This display allows null steering to or from the waypoint along the intended flight path. The display should be scaled as appropriate for the particular flight phase (see scale factor next).

5.9.3 SCALE FACTOR

Human factors studies have shown that the magnitude or cross track distance should be scaled prior to presentation on a cross track deviation display as appropriate for the flight phase in progress. The pilot should be able to manually select scale factors and have a continuous indication of which scale factor is being applied at all times. The majority of current VOR/DME derived RNAV systems designed for general aviation have two scale factors:

ENROUTE flight phase: Full scale deviation display deflection left and right of center is equivalent to 5 nautical miles right or left cross track distance.

APPROACH flight phase: Full scale deviation equivalent to 1 nautical mile.

For actual cross track distances greater than the 5 nautical miles and 1 nautical mile values, the deviation display remains deflected at its full scale limit. These scale factors should remain in effect for NAVSTAR derived RNAV.

5.9.4 TO/FROM AND VALIDITY

A continuous display should be provided to indicate the present position of the aircraft relative to a great circle that extends through the waypoint position and is orthogonal to the desired track angle. Present positions on the side of this line where bearing to the station is within the limits of desired track ±90° result in a FROM display. Present positions on the opposite side of this line result in a TO display. Unlike VOR, a GPS set will experience no cone of silence or zone of ambiguity over the waypoint. Therefore, no intermediate "barber pole" display between TO and FROM indications is required. However, some form of validity display is required to indicate when the cross track deviation and To/From indications are reliable for accurate navigation.

5.9.5 WAYPOINT ALTITUDE (ALT)

To allow 3-D RNAV, the altitude of the waypoint must be manually inserted. Once a digital altitude display is provided for, the operator can select waypoint zero, and use the display for readout of the aircraft's present altitude, and for manual override of computed altitude to enable more rapid changeover from Standby to Navigate mode. The display should have a resolution of one foot and range from minus three significant figures to plus five significant figures. Practical limits would be -999 to +45000 feet.

5.9.6 DESIRED VERTICAL ANGLE (DVA)

This quantity is a manual input that allows the pilot to specify the ascent/descent angle of the intended flight path. It is roughly equivalent to the glide path angle of an ILS system with the following exceptions: The actual path about which vertical distance deviation is computed should follow the earth's curvature such that the path maintains a constant angle with respect to local vertical at all points along the desired track. Also, the path should continue smoothly through the 3-dimensional waypoint position. Positive as well as negative path angles should be enterable by the pilot. These characteristics will enable the set to provide 3-dimensional guidance along fuel-efficient cruise/climb paths, as well as landing approach and 3-D RNAV flight paths. A practical range of values for DVA would be plus and minus fifteen degrees with resolution of one onehundredth degree for compatibility with present ILS glideslope angles, and the climb/descent capability of high performance light aircraft and VTOL/STOL aircraft.

5.9.7 VERTICAL DISTANCE DEVIATION

This quantity is the vertical equivalent to cross track deviation and enables null steering along a flight path in the vertical plane. The scaling applied to this quantity in conventional ILS displays is related to cross track deviation by the ratio 0.28. If this ratio is used in the NAVSTAR set, when ENROUTE scale factor is selected, vertical deviations of 8500 feet or greater will produce full scale display deflection. When APPROACH scale factor is selected, full scale deflection will represent 1700 feet above or below the desired path.

5.9.8 VERTICAL STEERING DISPLAY

If the operator has not inserted sufficient information to enable vertical steering, or the set detects excessive vertical GDOP, a visual warning should be displayed to indicate unreliability or lack of vertical steering information.

5.10 COMMUNICATION DISPLAYS

The optional COMM capability described in paragraph 4.5 will require a six digit display and entry (first digit fixed numeral one) and an on/off/volume control.

5.11 CONTROL/DISPLAY REQUIREMENTS SUMMARY

Table 5-1 summarizes the general aviation control/display requirements along with typical or worst case display examples and Input/Output usage. Some of the listed quantities must be apportioned among several simultaneous displays in order to conform to RNAV system specifications. The minimum display complement is:

1. Mode, on/off, fail (basic set)
2. Data display waypoint (basic set)
3. One line or three line data display (basic set)
4. Destination waypoint (with RNAV)
5. To/from/fail (with RNAV)
6. Scale factor (with RNAV)
7. Horizontal steering display and fail flag (with RNAV)
8. Vertical steering display and fail flag (if 3-D option included)
9. Communication frequency (if COMM option included)

Table 5-1. Control/Display Requirements Summary

Control	Typical Control	Input/Output Usage
Mode display address	Pushbutton adjacent to display	I
Scale factor address	Pushbutton below display	I
Basic waypoint address	Pushbutton adjacent to display	I
Destination address	Pushbutton below display	I
Data display address	Data category pushbuttons (see Table 5.2) and Freeze/Enter pushbutton	I
Alphanumeric entry	10-key keyboard (see 5.12.1)	I
Store data command	STR key	I
Clear data command	CLR key	I
Display Datum	**Typical or worst-case display**	**Input/Output Usage**
User or waypoint latitude	N089°59'59.9"	I/O
User or waypoint longitude	W179°59'59.9"	I/O
User or waypoint altitude	ALT 45000 FT	I/O
User estimated position error	EPE 0.25 NM	O
Waypoint Distance	DIS 250.6 NM	O
Waypoint bearing	BRG 330.1° TO	O
Reciprocal waypoint bearing	BRG 150.1° FRM	O
Desired track angle	DTK 300.0° MAG	I
Cross track deviation	Analog display with fail flag	O
Desired vertical angle	DVA 03.25° ↘	I
Vertical distance deviation	Analog display with fail flag	O
Ground speed	GS 150 KTS	I/O
Ground track	GTK 300.0° TRU	I/O
Magnetic variation	VAR 10.5° E	O
Universal time, coordinated	UTC 2300+59"	I/O
Estimated time enroute	ETE03+55'59"	O

Table 5-1. Control/Display Requirements Summary (Continued)

Control or display datum	Typical or worst-case display	Input/Output Usage
Estimated time of arrival	ETA02+27'00"	O
Calendar date	MONTH10DAY30	I/O
Scale factor	ENRT or APCH	I
True/magnetic north reference	Entered as suffix to DTK & GTK displays	I
Communication frequency	COMM 123.400	I
Basic waypoint identifier	WPT 0	I
Destination waypoint identifier	DEST 9	I
Set on/off	Mode display illumination	I
Manually selectable modes	INIT,ALN or DR	I
Automatic modes	INIT,SRCH, STBY,NAV or DR	O O
Display test mode	All segments of all displays activate simultaneously	I
Set test readout	123456712 (fault code)	O
To/from	TO, FRM or blank	O

5.12 RECOMMENDED CONTROL MECHANIZATION

5.12.1 ALPHANUMERIC DATA ENTRY

In systems where complicated alphanumeric data must be entered, keyboards have proven to be the most practical control input device. However, there are two problems with keyboards in the low-cost, general aviation application. One arises due to the lack of a pedestal or similar horizontal or sloping panel area for mounting the keyboard in most light aircraft. And, a vertically oriented, instrument panel mounted keyboard is difficult to operate. This difficulty is compounded in turbulence when the pilot's arm is extended horizontally with no support at the hand to mitigate the effects of vertical accelerations encountered. The other problem arises due to the small panel area available if the Set is designed as a swap-out replacement for a present-day VHF-NAV/COMM package. Since low cost is the principle forcing function in the present study, we will pursue this swap-out package approach, even though it is a less-than-optimum solution from a human factors point of view. Obviously, panel area can be increased to allow a larger keyboard, or the keyboard can be remotely located at a more favorable position. The virtue of the present approach is that it results in a common set of modules and packages that are useable by the largest number of users, thereby reducing the cost to all. When the Set is installed in an instrument panel, some form of wrist support adjacent to the keyboard is recommended.

a. Keyboard operation. If the display mechanization to be described in 5.13 is utilized, then a 12-key keyboard plus display line-address button(s) will be sufficient. The keyboard allows entry of numerals zero through nine as well as the following alphabetic/symbolic data:

N	North latitude
S	South latitude
E	East longitude or magnetic variation
W	West longitude or magnetic variation
INIT	Initialization mode
ALIGN	Alignment mode
DR	Dead reckoning mode
TRUE	True north azimuth reference
MAG	Magnetic north azimuth reference
/	Climbing flight path
\	Descending flight path
-	Minus or below sea level altitude

There is no requirement for a shift key or second function key to select between the alphabetic and numeric functions of the keys. Selection is performed automatically by the display cursor in the fixed format displays which also preclude the requirements for manual entry of decimal points and units symbols. The alphabetic arrangement of the keyboard allows easy access to the Mode, Hemisphere, North Reference, and polarity selectors as shown in Figure 5-1.

The keyboard software includes blunderproofing features that cause it to not respond to out-of-limits or otherwise impossible entries, e.g., South Longitude, and to disallow storage of easily detected errors, e.g., minutes and seconds greater than 59, etc. Attempts to store "illegal" entries result in the entire data

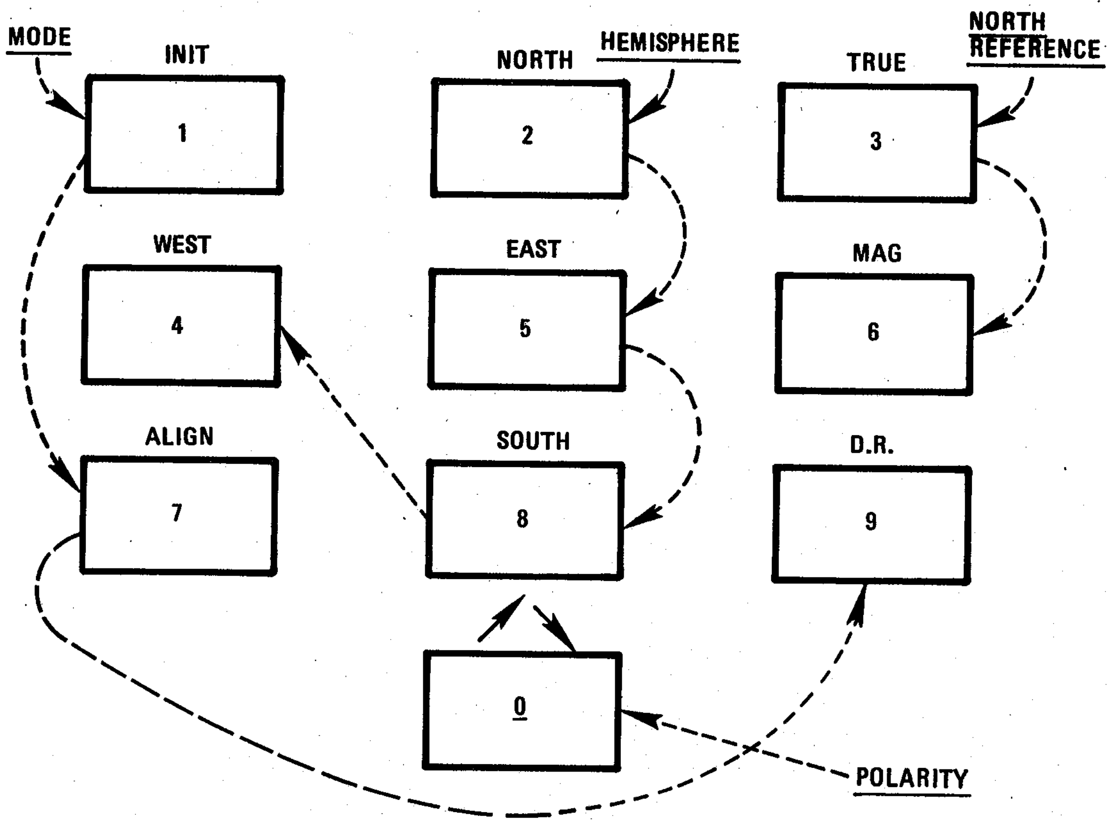


Figure 5-1. Keyboard Alphabetic/Symbolic Arrangement

display blinking continuously until the error is corrected or another datum is selected. While the keyboard arrangement shown is tailored for general aviation use, it embodies features of the GPS Phase I Sets. These sets have proven to be easily operable by a wide range of users including pilots and foot soldiers.

Use of the keyboard including operation of the CLR and STR keys and the various display line-address buttons (MODE, FRZ/ENT, WPT, COMM, DEST, SCALE) is described in paragraph 5.15 and its subparagraphs.

b. Data selection. One method of controlling the data display(s) with a minimum amount of panel space employs data category pushbuttons. Each button controls three display data. If only one line of data display is provided, then sequential pressing of any given data category pushbutton will sequence the display line to the desired datum in that category. If three simultaneous display lines are provided, then only one press of any given button will cause all three data in its category to be displayed simultaneously. In this latter case, an address button or some other form of line address must be provided to enable addressing the keyboard to a specific datum. Table 5-2 lists the data category control buttons along with the blank data formats that would appear in the display for each datum.

Table 5-2. Data Category Control

Data Category Pushbutton	Controlled Data	Display Formats
POS (position)	Latitude* Longitude* Estimated position error	N --°--"--.-" W---°--"--.-" EPE -.-- NM
DIS/BRG	Distance Bearing to# Bearing from#	DIS ----.- NM BRG ---.-° TO BRG ---.-° FRM
RNAV (3-D area navigation)	Desired track# Altitude Desired vertical angle*	DTK ---.-° MAG ALT ----- FT DVA --.--°↘
VEL (velocity)	Groundspeed Ground track# Magnetic Variation*	GS --- KTS GTK ---.-° MAG VAR --.-° E
TIME	"Zulu" time Estimated time enroute Estimated time of arrival	UTC ----+--" ETE--+--'--" ETA--+--'--"
DATE/TEST	Calendar date Display test Set test	MONTH--DAY-- All segments activate Numerical fault code

*Hemisphere or polarity will default to that previously selected.

#All north references will default to MAG unless TRU is selected on any one datum. Then all data will re-reference to TRU.

c. Display line-address buttons. The single keyboard must be selectably addressed to the following simultaneous display lines:

1. Communication frequency
2. Destination number
3. Mode
4. Waypoint number
5. Data display
6. Other data display(s), if more than one

In addition, the scale factor display line needs to be addressed, although it need not require interaction with the keyboard. Simple sequential pressing of this button is sufficient to select any one of the two to three scale factors it can display.

The line-address buttons (1 through 6 above) are respectively labelled COMM, DEST, MODE, WPT, and FRZ-ENT. The scale factor button is labelled SCALE.

d. Freeze data control. The data display line-address button (FRZ-ENT) also functions to "freeze" the navigation data base at the time it was pressed. This allows readout of the values of the various quantities that were in effect at "freeze time" including the freeze time itself. The first enterable character in any given datum will blink off and on while the freeze command is in effect, and will stop blinking when the freeze command is countermanded by either pressing the FRZ-ENT button again, or by pressing the STR key.

5.12.2 RECOMMENDED CONTROL DEVICES

a. Data control. Pressure sensitive stick-on, membrane type keyboards are available from several vendors. Latest improvements in these include raised-above-the-surface keys, snap-action tactile feel, backlighting, and extreme environment compatibility. They have the virtues of zero behind-panel space and very low cost, and are finding wide application in consumer products. It is recommended that the 6 line-address buttons, 12 keys, and 6 data control buttons described above be implemented as twenty-four, 0.25" by 0.5" raised, pressure sensitive areas on a single stick-on label type front panel for the set. This label would incorporate electroluminescent back-lighting for numerals and legends, and would have holes where the various display windows are located. A flex-harness connector would be used to connect the keys to the set. For sets without an integral CDU function, this panel would be disconnected and supplied as an optional spare part.

b. Transceiver on/off/volume control. A rotary switch/potentiometer is recommended to make operation of this control identical to that of nearly all radio sets.

c. Set on/off control. A slide switch is recommended for this control to make it difficult to accidentally turn the set off and thereby preclude the loss of time involved in a re-start.

5.13 RECOMMENDED DISPLAY IMPLEMENTATION

5.13.1 DATA DISPLAY

Rapid learning and low operator error rate are achieved when the name or abbreviation as well as the units-of-measure of each display quantity are displayed with its value in a fixed, consistent display format.

Accordingly, the various display quantities shown in Table 5-1 have been formatted with the abbreviation to the left of the quantity and the units-of-measure to the right. Standardized abbreviations are used as obtained from RNAV specifications and other sources. All quantities are amenable to display on a line consisting of twelve, 16-segment display devices if the following rules are applied (see Figure 5-2).

a. All letters, plus sign, up/down arrows, and prompting dashes occupy the full width of a device.

b. All numerals and minus sign occupy only the right-hand half of a device.

c. The lower left vertical segment is used as a decimal point in the same device as the numeral that trails it.

d. The four upper left segments are used as required to form degree, minute and second symbols.

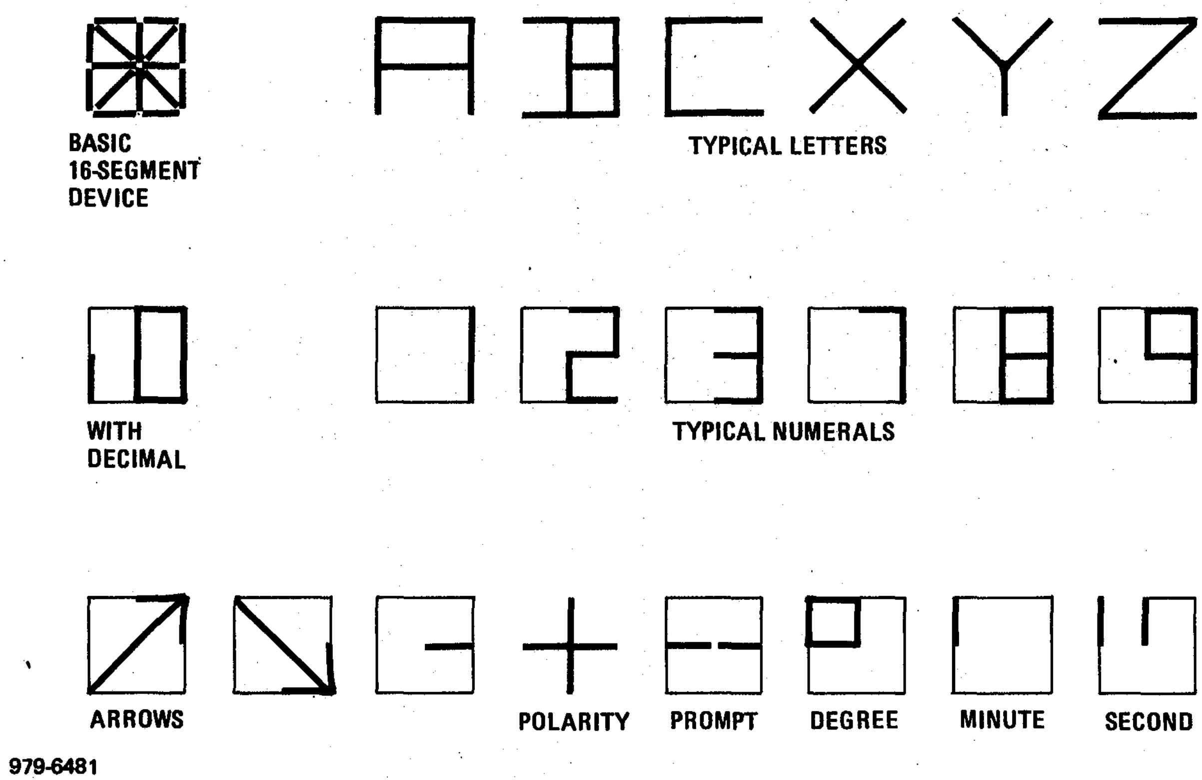


Figure 5-2. Display Character Formation

One-quarter inch character height is ample for the typical viewing distances involved. The displays should be readable in bright sunlight and under dimmed cockpit, night viewing conditions.

5.13.2 ANCILLARY ALPHANUMERIC DISPLAYS

The displays for MODE, WPT, etc., can use the same display devices and character formation rules as described in 5.13.2 above. There may be some economy in combining some of these displays, e.g., TO/FRM with DEST, or MODE with WPT, to allow use of a reduced number of common display components. For example, display "sticks" consisting of six characters per stick can be distributed on the panel as required to form the various displays. Also, since the first numeral in the COMM frequency is always the numeral 1, it can be displayed in the same character space as the second numeral.

5.13.3 FLIGHT PATH DEVIATION DISPLAYS

A "solid-state" bar graph type of presentation is recommended for compatibility with the driver circuitry of the data displays.

5.13.4 RECOMMENDED DISPLAY DEVICE

Liquid crystal displays (LCDs) offer excellent promise for meeting the display requirements set forth above, with low cost. The principle area of development required is the reduction of behind-panel area presently required by these devices for pin-out and connection to their driver circuits. At the present time, the former high temperature unreliability of these devices has been solved while the use of an integral heating element enables operation at extreme low temperatures. At the present time, LCDs offer the following advantages:

a. High contrast ratio, daylight readability.

b. 16-segment or equivalent dot-matrix character formation.

c. Electroluminescent or incandescent back-lighting for night viewing.

d. Negligible behind-panel projection.

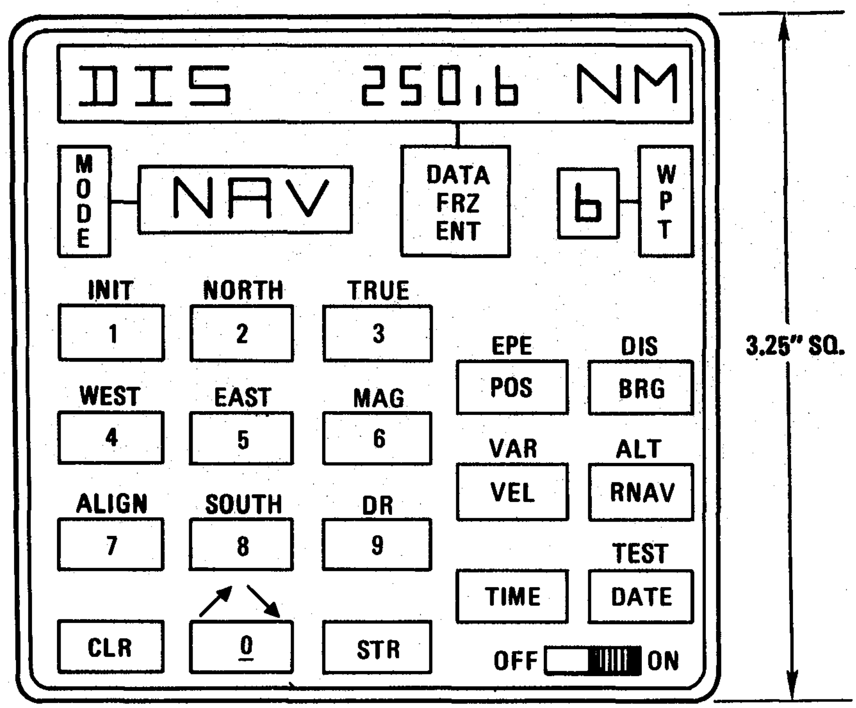
e. Negligible power consumption and heat dissipation.

f. Low cost in common, mass-produced configurations.

However, arrangements of LCDs with the close spacing recommended here are not presently possible due to the blank panel area required around the edges of the present devices due to their pin-out configurations. Some configurations are available with integral driver circuits. These displays would find wider application and greater utility if the unusable panel area they consume could be made usable, even at the expense of greater behind-panel (backward) projection. This is an area for future development.

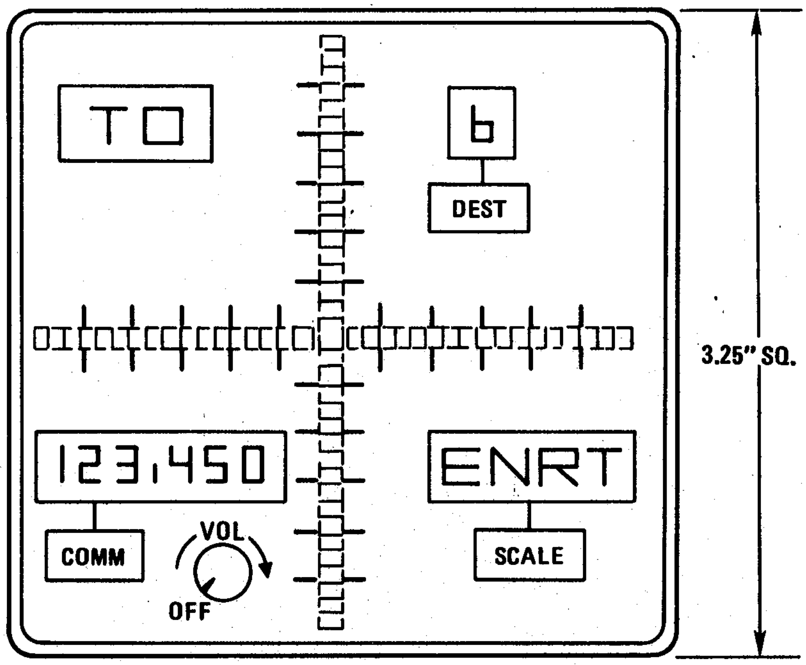
5.14 PANEL CONFIGURATIONS

The control and display elements previously described have been arranged according to human factors guidelines (see references) with some influence from existing general aviation COMM/NAV panel configurations. Three configurations result as shown in Figures 5-3, 5-4 and 5-5. First is the basic position fixing set with waypoint distance and bearing capability. Second is a solid-state CDI with



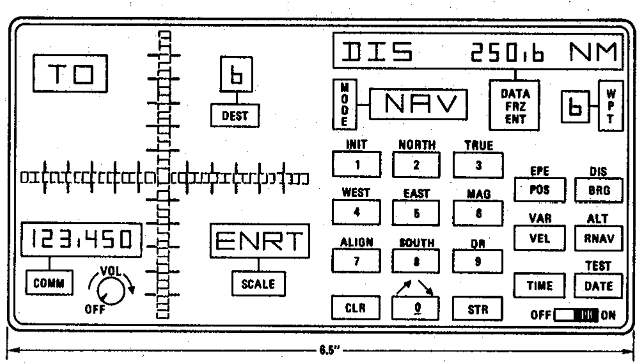
979-6482

Figure 5-3. Basic Set Control/Display Panel



979-6483

Figure 5-4. CDI Adds RNAV and COMM Capability



979-6484

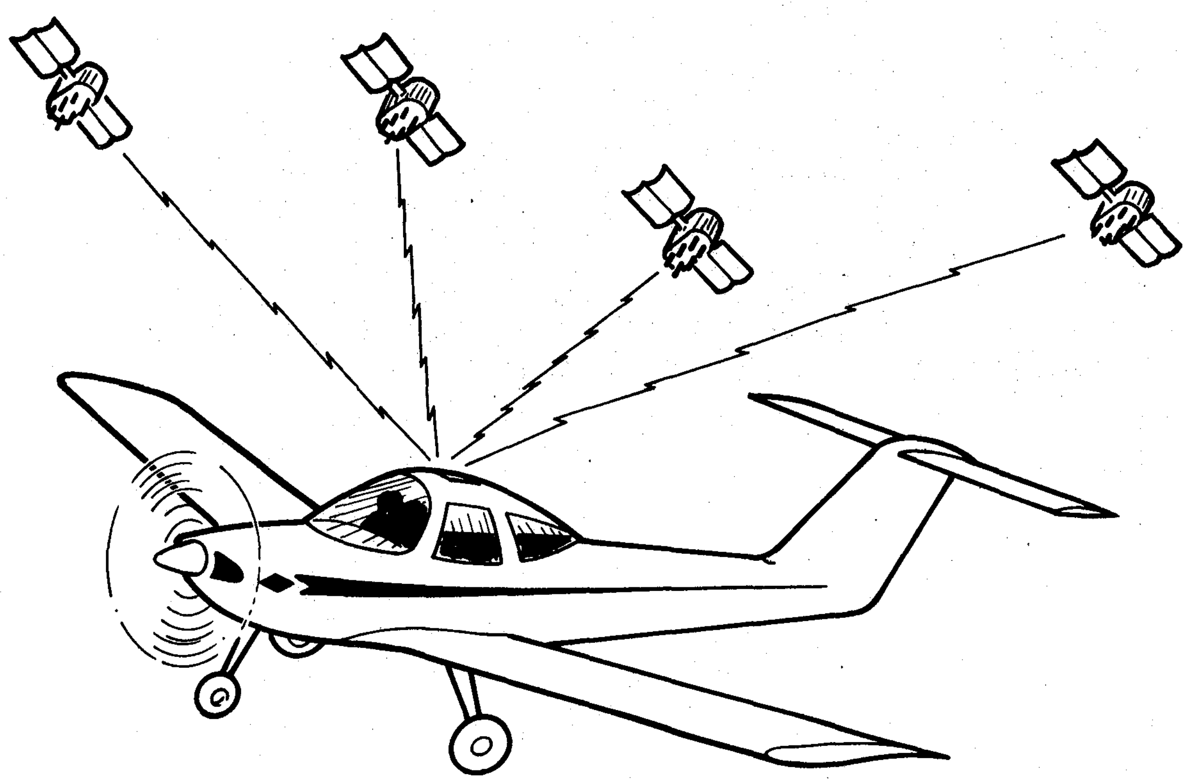
Figure 5-5. Low Cost NAVSTAR/COMM Front Panel integral VHF transceiver. The third configuration combines the first two, to form a NAVSTAR/COMM set. When one compares the quantity of data controlled and displayed (refer to Table 5.1) by these relatively simple panels, it becomes clear that much of the potential operator work load is being accomplished by software within the set. The data formatting and blunderproofing previously described are examples of this. Software is not cheap. However, experience with the NAVSTAR Phase I user equipment has shown that an "up front" expenditure in software produces long term benefits in safe operation and user acceptance of the equipment.

5.15 USING THE LOW COST NAVSTAR/COMM SET

In the following procedural descriptions we will assume that the Set is installed in a light aircraft and has been flown within the last 180 days from its present location so that it need not be reinitialized or required to enter search mode.

5.15.1 PREFLIGHT PROCEDURES

Turn the set on by sliding the ON/OFF switch to the right (Figure 5-6). Observe the WPT display default to zero (present position), the MODE display



979-6485

Figure 5-6. Light-Plane Navigation With NAVSTAR indicate STBY, and the data display show the estimated position error (EPE) format temporarily filled with dashes. As the navigation solution converges to less than 99 miles error, the EPE display will begin showing decreasing values of position error. Typically within five minutes, the value of EPE will proceed below 0.25 nautical mile, and the MODE display will change to read NAV. All displays on the left-hand (CDI) side of the panel will remain blank until manually addressed. While the navigation solution converges, the pilot may select the local ground control or other COMM frequency and enter or verify waypoint data. If the aircraft has been pulled out of a T-hanger and is temporarily parked between two rows of T-hangers or is otherwise blocked from direct view of some of the available satellites, it will typically require an extra minute to converge on a navigation solution with 0.25 nautical mile or better accuracy.

a. Transceiver operation. Turn the transceiver on and adjust volume by rotating the on/off/volume control clockwise. The COMM frequency display will activate and indicate the frequency that was selected prior to last set turn-off. To change the frequency:

1. Press the COMM pushbutton and observe the second character in the display begin blinking on and off as a prompting symbol.

2. Using the keyboard, enter as many digits as are necessary to readout the desired frequency. The digits will enter the display from left to right, as in typing. The first character (one) and the decimal point are fixed in the display and need not be entered. As each digit is entered, the prompting symbol will shift to the right by one character space.

3. If a mistake is made, clear out the wrong digit by pressing the CLR key. The digit will be replaced by a dash. Further pressing of the CLR key will clear out digits from right to left like the back space key of a typewriter. The entire display can be cleared prior to step 3 above, if desired, prior to entering the new frequency. The CLR key will always address the last character entered, or if nothing was entered, it will address the last digit in the display.

4. When the correct frequency has been entered, press the STR key. The entered frequency will blink off and then on again indicating that the new frequency has been stored in the set. The transceiver will now shift to the new channel.

Note: Certain blunder proofing is incorporated in the control/display software to prevent erroneous entries. The set will not store "impossible" frequencies and the display will not respond to certain keyboard entries. For example, the second digit will only respond to 0, 1, 2 or 3, the fifth digit will only respond to 0, 2, 5 or 7, and the last digit will automatically change to 0 when the fourth digit is 0 or 5, or to 5 when the fourth digit is 2 or 7.

b. Selecting a waypoint for data readout, entry or alteration.

1. Press the WPT button and observe the existing waypoint number begin blinking off and on.

2. Press the keyboard key with the desired number and observe it appear in the WPT display. The new waypoint is now stored, and whatever datum had been previously selected in the data display will now change value as appropriate to the newly selected waypoint, unless the selected datum is not waypoint dependent, e.g., UTC, DATE, GS, GTK, and EPE.

c. Entering and altering waypoint data.

1. Press the POS button until the latitude display appears (always prefixed by an N or S). In the absence of entered data, the display will always default to N. The degree, minutes, seconds and decimal are fixed in the display.

2. Press the FRZ/ENT button.

3. If a hemisphere change is required, press the 2 (North) or 8 (South) key. If not, always begin the numerical entry with the zero key. Type in or edit the numerical entry as described for COMM frequency above.

4. Press the STR key and observe the display blink off and then on again.

5. Press the POS button until the longitude display appears (always preceded by an E or W). In the absence of entered data, the display will always default to W.

6. Freeze the data display and enter, edit and store longitude as described for latitude in b, c and d above. If a hemisphere change is required, begin the entry with the 4 (West) or 5 (East) key. If not, type in the numerical entry.

7. If desired, one or more of the RNAV data may be entered or altered at this time rather than in flight. See 5.15.2d.

8. If desired, the first destination waypoint, e.g., the first turn point of an SID, may be selected at this time. Use the DEST enter button and keyboard. When a destination waypoint has been selected, the scale factor display will default to ENRT unless manually changed to APCH by pressing the SCALE pushbutton. If the appropriate RNAV data have been entered for the selected destination, the vertical deviation, horizontal deviation, and TO/FROM displays will begin indicating. If RNAV data have not been entered, these guidance indicators will remain blank.

5.15.2 INFLIGHT PROCEDURES

a. Reading out present position.

1. Press the FRZ/ENT button. This will freeze all navigational data in its state at the time the button was pressed.

2. If desired, the time that the freeze command was put in effect can be readout by selecting UTC for display with the TIME button.

3. Select waypoint zero in the WPT display and then sequentially select and readout latitude and longitude with the POS button. If desired, select and readout own altitude with the RNAV/ALT button.

4. Alternatively, select any other reference waypoint in the WPT display and then sequentially select and readout distance (DIS) and bearing to (BRG TO) or reciprocal bearing (BRG FRM) that waypoint with the DIS/BRG button.

5. If desired, the confidence level of the position readout can be established by selecting and reading out estimated position error (EPE) with the POS button.

6. Press the FRZ/ENT button again to unfreeze the data base and allow the displays to update to the current dynamic situation. Note that while the FRZ/ENT command is in effect, the first character of any given display will be blinking off and on as a prompting symbol for possible operator entry or alteration of data. When the display is unfrozen, the prompting symbol will stop.

b. Reading out pilotage data.

1. Sequentially press the VEL button to sequentially display the present groundspeed (GS) and ground track (GTK), of the aircraft, as well as the magnetic variation (VAR) at whatever waypoint (0 thru 9) is being displayed in the WPT display.

2. Sequentially press the TIME button to sequentially display current time (UTC), the estimated time enroute (ETE) to, and the estimated time of arrival (ETA) at the waypoint currently being displayed in the WPT display, at current groundspeed.

c. Reading out, entering and altering RNAV data.

1. Select the waypoint for which RNAV data are to be entered in the WPT display.

2. Sequentially press the RNAV button until the desired track (DTK) display appears in the data display.

3. Press the FRZ/ENT button, and enter or edit the numerical value in the display. Leading zero(s) must be entered when appropriate for all angular values. Degree marks and decimal points are fixed in the display. If desired, change the north reference by pressing the 3(TRU) or 6(MAG) key after entering the numerical value.

4. Press the STR key.

5. If 3-D RNAV or landing approach is to be done, select ALT with the RNAV button and enter or edit and store the desired crossing altitude at the waypoint position. Altitudes at or below sea level are enterable by beginning the numerical entry with the zero/minus key to cause a minus sign to be entered in the display.

Then enter or edit and store the desired climb or descent path angle (DVA) to the waypoint. If the climb/descent polarity must be changed, sequentially press the zero/minus key after entering the numerical value till the desired up or down arrow is displayed.

d. Performing RNAV.

1. Press the DEST button and then, using the keyboard, enter the number of one of the previously stored waypoints in the DEST display.

2. Sequentially press the SCALE pushbutton until the desired scale factor (either ENRT or APCH) is obtained.

3. Follow the guidance of the vertical and horizontal deviation displays and the TO/FROM display. If data become unreliable, the affected display(s) will go blank.

e. Transceiver operation. Same as described in 5.15.1a.

5.15.3 INITIALIZATION

The difference between an in-flight and a ground initialization is that ground speed will usually be zero during ground initialization and therefore ALIGN mode may be used. It is imperative that the set be taken out of ALIGN mode prior to any motion, since the Set's internal navigation filter must completely reconfigure between non-moving and moving operation.

a. Press the MODE pushbutton and observe the mode display begin blinking off and on.

b. Press the 1(INIT) key and observe the abbreviation INIT appear in the mode display. Also the format for latitude will appear in the data display with the numerical value of the last known latitude, if any.

c. Press the FRZ/ENT button and enter or edit and store the best estimate of present position latitude. If moving, enter data for a dead-reckoning advanced position. Upon storing latitude, the longitude display will appear.

d. Enter or edit and store longitude. Upon storing longitude, the altitude (ALT) display will appear.

e. Enter or edit and store altitude. Upon storing altitude, the groundspeed (GS) display will appear.

f. Enter or edit and store groundspeed. Upon storing groundspeed, the ground track (GTK) display will appear. Note: This step not necessary in ALIGN mode. GS will default to zero. Proceed to step h.

g. Enter or edit and store ground track. Upon storing ground track, the date (MONTH/DAY) display will appear.

h. Enter or edit and store the current month and day at Greenwich (Zulu date). Upon storing the date, the time (UTC) display will appear.

i. Enter or edit and store the current Universal Time, Coordinated as obtained from National Bureau of Standards radio stations WWV, WWVH, a tower time "hack" or other reasonably accurate time source. Upon storing time, the INIT indication in the MODE display will be replaced by the abbreviation STBY, indicating that initialization is complete and the Set has begun satellite signal acquisition and is converging on a navigation solution. Note that if the set has an excessively old almanac, it may enter SRCH mode at this point before it can enter STBY mode.

SECTION VI
SYSTEM PROCESSING DESIGN

6.1 SATELLITE CONSTELLATION

The low cost civil aviation GPS navigation system will use a Phase III GPS satellite constellation consisting of 24 satellites. These satellites are distributed uniformly within three orbit planes, each at a 63 degree inclination to the equator. The current plan to use a 55 degree inclination should improve visibility and accuracy in all but the polar regions of the earth. The enclosed simulation results are therefore valid with the exception that maneuvering accuracy may decrease near the poles. The orbits are circular with a nearly 12 hour inertial period designed to repeat the same earth-fixed ground track with a period of almost 24 hours.

Investigations of satellite visibilities at various latitudes and times show that the visibility geometries range between two patterns herein designated in-plane and mid-plane constellation. The number of satellites visible above a ten degree cutoff are typically six or seven with occasional instances of five or eight. Representatives of the geometries used in many of the simulation studies are shown in Figures 6-1 and 6-2.

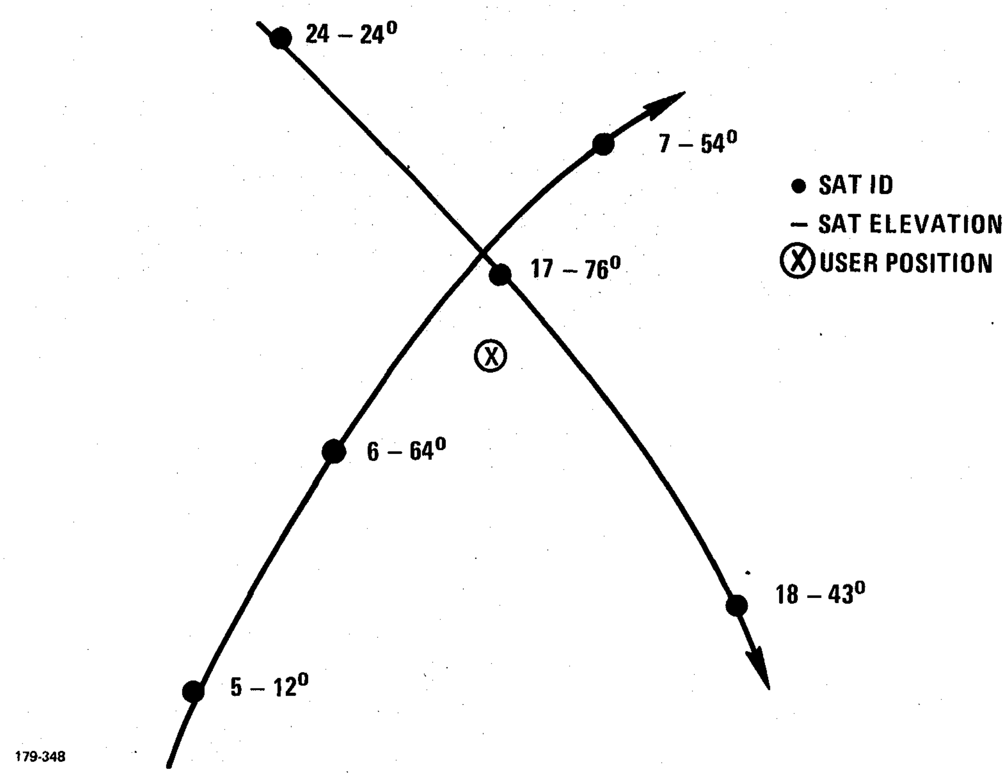


Figure 6-1. Phase III Satellite Inplane Configuration

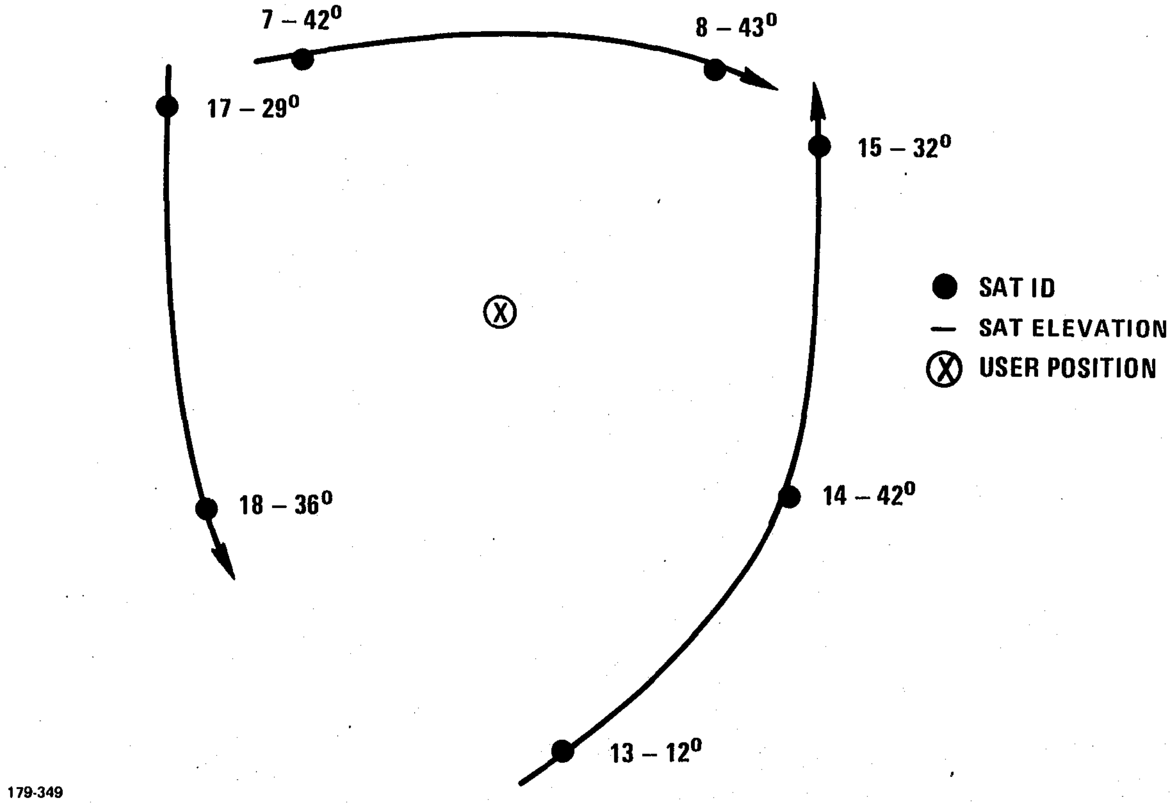


Figure 6-2. Phase III Satellite Mid-Plane Configuration

6.2 USER TRAJECTORIES

The test trajectory used most extensively is a full circle with a one-half g turn rate and with straightaway flight before and after the circle. The turn is modelled as coordinated with lateral acceleration in g's equal to the arc tangent of bank angle. In this case bank angle is 27 degrees. The antenna is modelled as having a sharp cutoff ten degrees above the wing plane and ten degrees above the horizon. The trajectory is chosen to provide a worst case for typical civil aviation maneuvers in terms of shading the antenna from GPS satellites. Every satellite below 37 degrees is shaded for some portion of the turn. In addition, lateral acceleration changes abruptly at the beginning and end of the turn. Other trajectories tested consist of a two g circle and a one-half g racetrack maneuver. All of these trajectories were tested with the in-plane and mid-plane constellations.

6.3 SET ARCHITECTURE

In order to provide a low cost set while maintaining navigation capability, the set will consist of very simple hardware with considerable computational capability within the data processor and with a sizeable amount of navigation software. Specifically, the hardware will consist of a single channel, single frequency receiver and with a single antenna and pre-amp. The data processor will be a computer with about 32K-48K words of memory and with floating point and extended precision arithmetic. Figure 6-3 shows a block diagram of the set hardware.

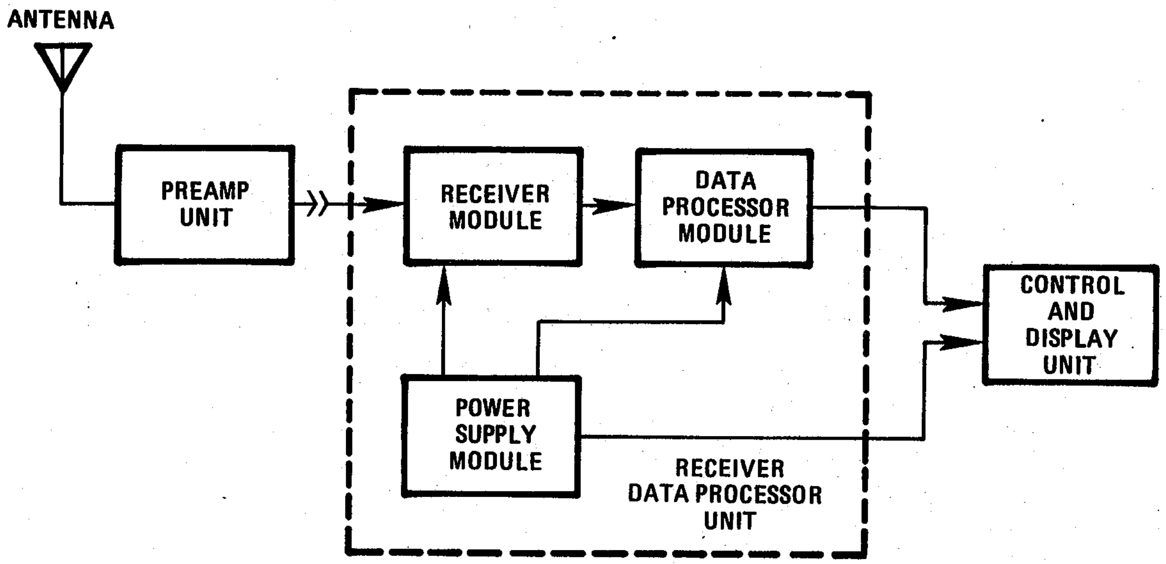
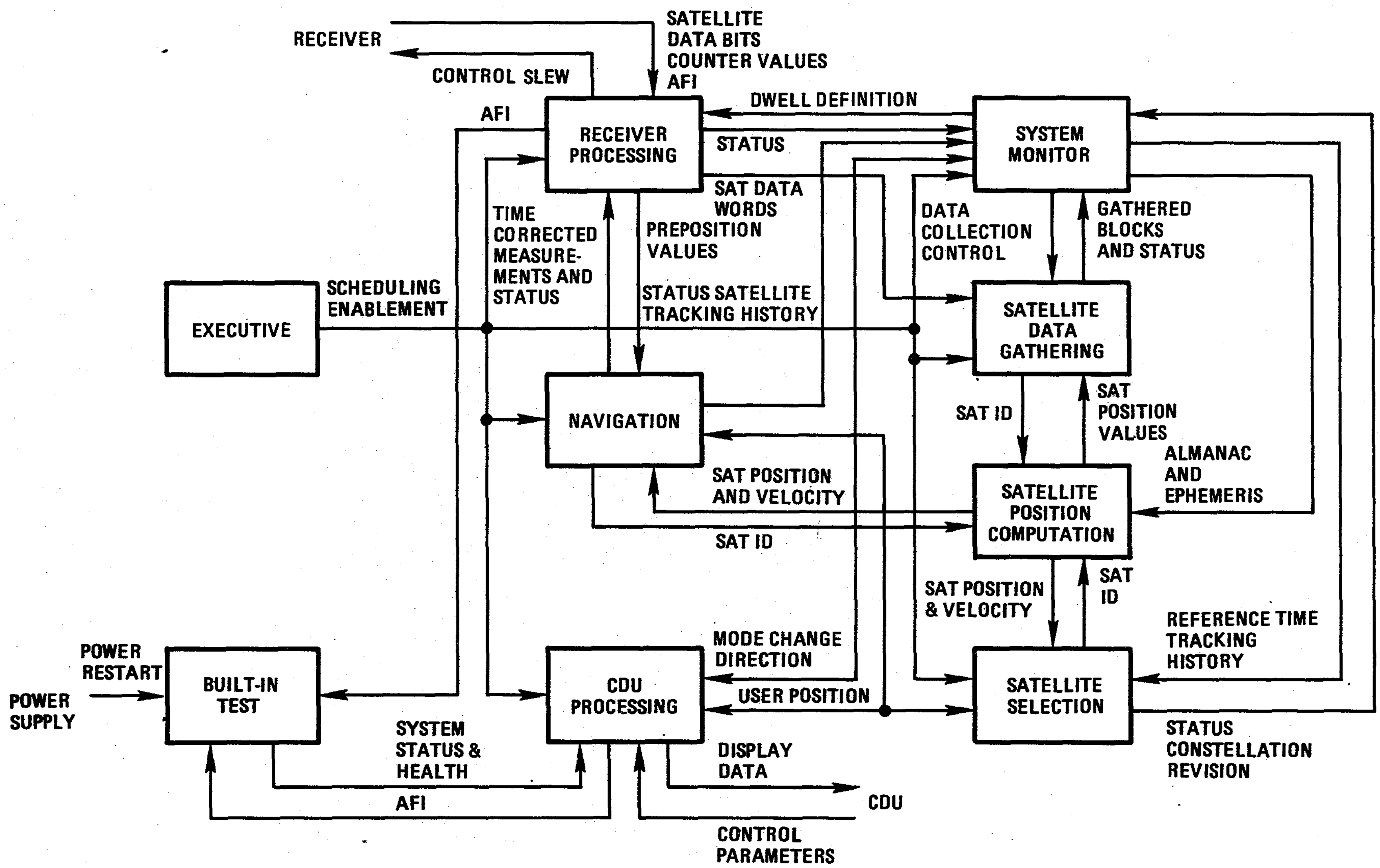


Figure 6-3. Low Cost GPS Set Module Diagram

The set software will consist of an 11-state Kalman filter for navigation. The states are three components each of position, velocity, and acceleration plus one component each of clock phase and frequency (position and velocity). The software will be designed to provide automatic operation in nearly all situations and to cue the operator in those situations where automatic operation is not possible (typically only after repairs or after months of inoperation). Additional software functions will be provided to support the navigation. The information flow of these functions is shown in Figure 6-4.

The satellite selection function periodically determines the visible satellite constellation and the sub-constellation of four satellites which has best weighted GDOP, the weighting being done to account for low elevation, going out of view, and previous recent tracking failures. Satellite position computation provides satellite position for each receiver measurement, for satellite selection computation of visible satellites and for pre-positioning the receiver to acquire the next scheduled signal. The satellite data gathering function maintains current



979-6487

Figure 6-4. Information Flow Diagram

ephemerides for all visible satellites and maintains a recent almanac for each satellite deployed. The system monitor provides the moding for the sequencing receiver. It also controls the scheduling of other functions such as data gathering and satellite selection. The executive function is the computer controller which handles interrupts and priorities of other tasks. The built-in-test function monitors receiver automatic fault indicators and displays some warning to the operator. It also provides checksum and memory tests for the software data and data processor.

Another important feature of the set is the real-time-clock. This is a continuously running low power oscillator which is powered from a rechargeable battery. By providing the set with time across power downs it allows automatic startup at power on. It also aids in maintaining set continuity across power glitches. Finally, by giving the set time beyond the one week rollover of GPS time, it enables the set to determine age of almanac and to use this information accordingly.

6.4 NAVIGATION PROCESSING

The navigation processing of the set employs an eleven state Kalman filter to process pseudorange and delta-pseudorange measurements. The filter may also process operator input altitude and/or speed-heading measurements even though no external measurement devices are expected to be coupled to the low-cost set.

The outputs from the filter will be three components of position and three components of velocity useable for display, three components of acceleration and one component each of clock phase and clock frequency used internally for state propagation. Also available will be the Kalman covariance which provides a figure-of-merit for the navigation solution.

The eleven state configuration was chosen after simulations showed much improvement in the solution by using the acceleration states. The Kalman filter itself was used (at significant computational expense) to provide flexibility as to the type and number of measurements, number of satellites and satellite geometry without having a different computational configuration for every possibility. The filter provides the capability of graceful degradation during periods of underdetermined measurements.

This is especially important in a single channel set where, strictly speaking, the measurements at every time point are undetermined. Beyond this however, the filter automatically takes advantage of previous tracking results and the stability of the user clock to provide an optimal solution and concurrently provides covariance information to show the quality of the solution.

The other key element in navigation processing is the concept of satellite switching. Whenever the receiver fails to find a measurement from a satellite, the set selects a temporary replacement with the available satellite furthest in angle from the missing satellite. To make this possible the set initially tracks and collects ephemerides from all visible satellites and then maintains current ephemerides from every visible satellite. Since the replacement satellite is chosen without respect to constellation GDOP, the set will periodically switch back to determine when the optimal satellite is available. Given the Phase III constellation, switching satellites is the technique designed to continue navigation during shading from dynamics without resorting to multiple antennas, multiple channels or external aiding devices.

Another navigation processing job in the sequencing set is to pre-position the receiver for its next measurement. This involves providing the receiver with an estimate of pseudorange and pseudorange rate at the beginning time of the next search. By projecting the Kalman covariance upon the satellite line-of-sight a search window is also established.

6.5 SIMULATION SETUP AND RESULTS

In order to test the various navigation processing schemes considered, a dynamic simulation is employed. By modelling the dynamics of the satellites, the user, including antenna shading, and by providing realistically corrupted measurements to the filter, the simulation provides a realistic example of filter performance. A receiver acquisition model is an especially important element in simulating a sequencing set. By providing degraded or lost measurements as a function of poor pre-positioning from the filter, this model simulates the elements most likely to cause navigation failures in the sequencing set. Figure 6-5 provides a block diagram of the dynamic simulation.

Figure 6-6 and Table 6-1 define the receiver acquisition model used. The regions defined are position/velocity error boxes and Table 6-1 provides the probabilities that given measurement errors will occur. For a satellite that was tracked on the previous sequence, any pre-position error outside the CREEP box will

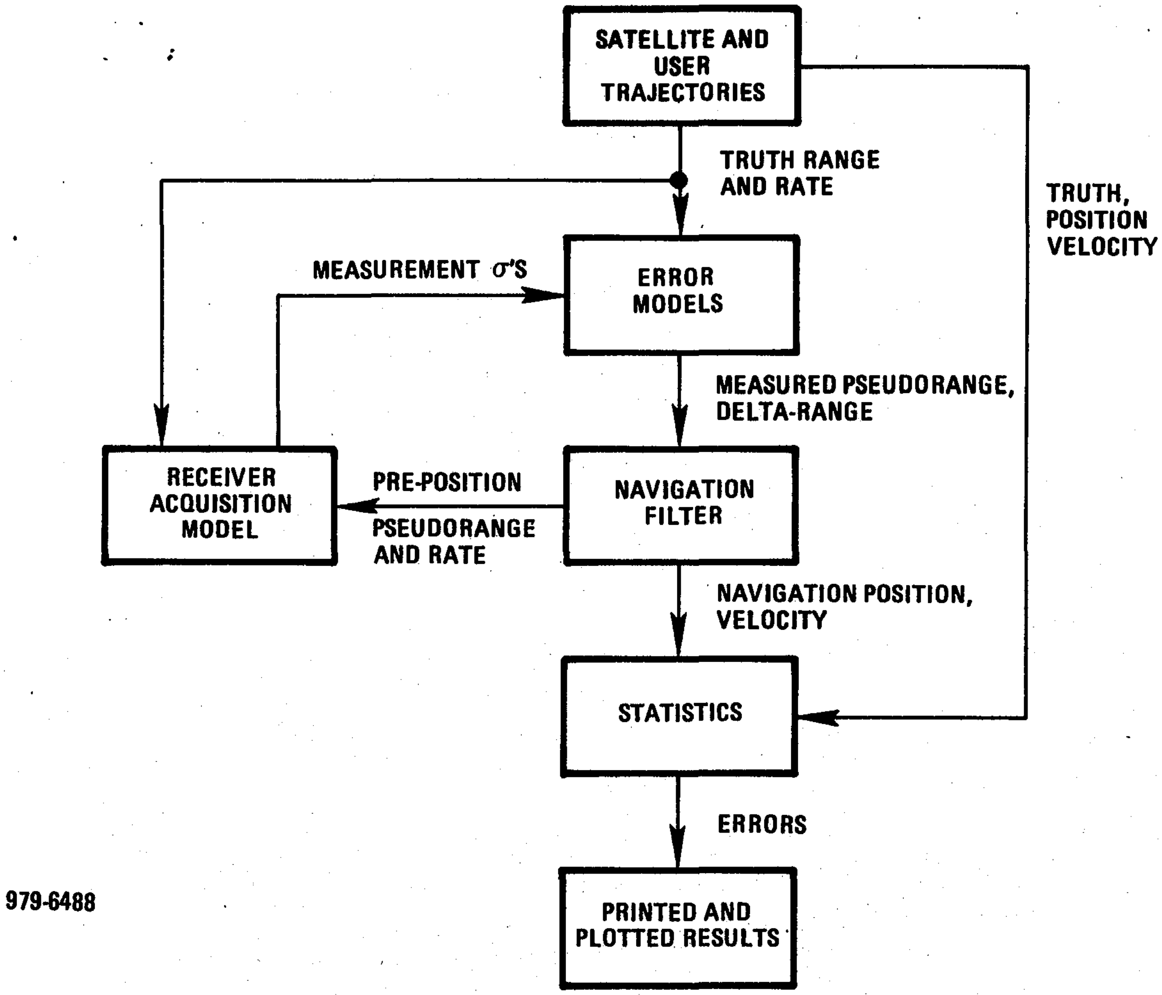


Figure 6-5. Dynamic Simulation Block Diagram

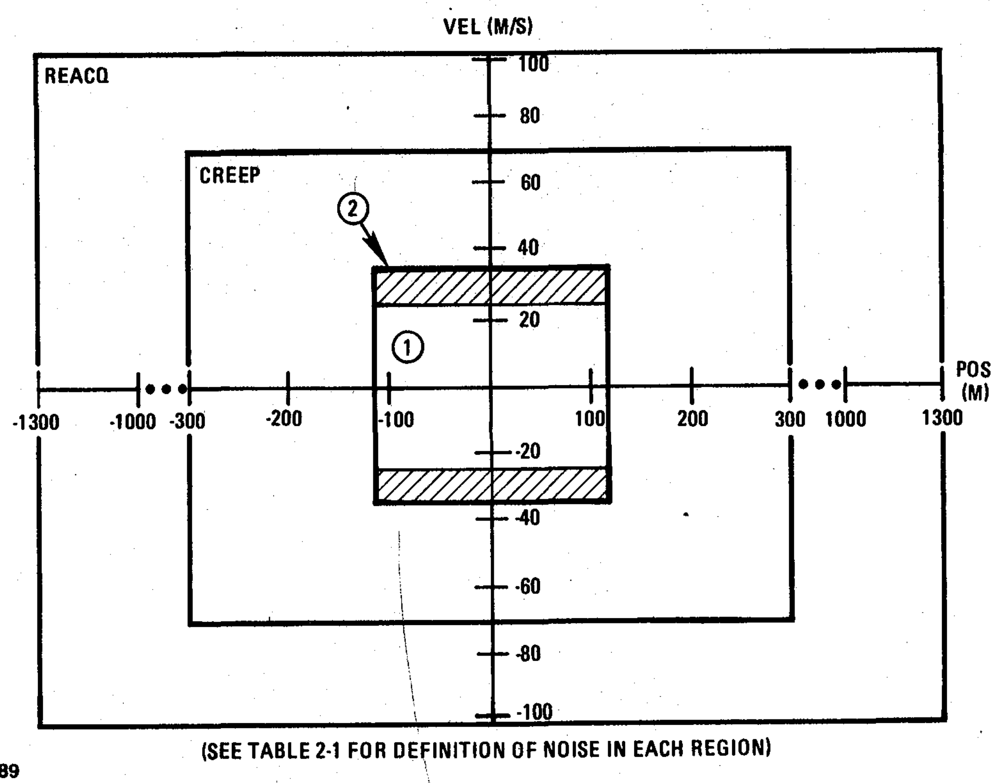


Figure 6-6. Receiver Acquisition Model

Table 6-1. Definition of Noise Parameters for Noise Model for C/A Receiver Model

Graph Section	Definition of Noise Parameters	
Sequential Track		
1	Prob of .98 that	σ_{PRNGE} = 15m σFRERR = .02 m/s
	Prob of .02 that	σ_{PRNGE} = 75m σ_{FRERR} = 1.0 m/s
2	Prob of .70 that	σ_{PRNGE} = 15m σ_{FRERR} = .02 ms
	Prob of .30 that CREEP Noise Case is used	
CREEP	Prob of .90 that	σ_{PRNGE} = 15m σ_{FRERR} = .02 m/s
	Prob of .05 that	σ_{PRNGE} = 75m σ_{FRERR} = 1.0 m/s
	Prob of .05 that no measurement is received	
REACQ	Same as CREEP	

result in no measurement. For a new satellite or a satellite being reacquired after a missed measurement, any pre-position error outside the REACQ box will result in no measurement.

The rest of the error model used is presented in Table 6-2. The clock error model used is for the high-performance oscillator in the current military sets. Section 6.7 identifies a cost/performance trade study to determine the needs of the civil aviation user. However, as the simulation results show, those needs are more than met with this oscillator.

The errors corresponding to Table 6-2 are all picked randomly except for ionospheric delay. Here a fixed ten meter overhead group delay was taken to represent typical noontime (or maximum) delay expected. This is a bias (or slowly changing) error that will not especially affect the dynamic results being considered here. For times of greater ionospheric delay an increased bias offset can be expected in the solution.

Table 6-2. Simulation Error Model

Term	Bias (1-σ)	Random (1-σ)
Pseudorange	4m	15m (75m)$^{(1)}$
Delta-Range	--	0.02m (1m)$^{(1)}$
Clock Phase		1°rms/sec Random Walk
Clock Frequency	--	$\frac{\Delta F}{F}$ = 1E-10 (Exponentially Correlated 2 hr Time Constant)
Ionosphere$^{(4)}$	$10^{(2)}$-$32^{(3)}$m	---
Troposphere	$0.06^{(2)}$-$0.35^{(3)}$m	---

(1) Measurement noise during RCVR degraded reacquisition
(2) Error for an overhead satellite
(3) Error for a 10° elevation satellite
(4) Not a 1-σ error. Fixed overhead group delay of 10m used.

The simulation was run several times with different initial condition and error selections on both the mid-plane and in-plane constellations in order to provide a limited Monte Carlo simulation. The aim was to run enough simulations to avoid the possibility of having results where all the errors combine in some especially good or bad fashion but not go to the expense of so many simulations to provide confidence that the output statistics actually correspond. Table 6-3 presents the maximum errors attained on the one-half g simulations. Since the position errors represent about ten percent of the receiver reacquisition box and the velocity errors about twenty percent, a substantial margin is seen before these errors would fall outside that box and all measurements would be lost. Moreover, a similar study using a P-code receiver in a two-g turn showed better than 90 percent success using a P-code reacquisition box with position limits only one tenth those for C/A code. While not strictly comparable these results do indicate that sequencing sets can survive by satellite switching even while shading occurs above 70 degrees elevation.

Table 6-3. Maximum Magnitude Errors

	Mid-Plane Constellation Worst Case	In-Plane Constellation Worst Case
Horizontal Magnitude Error	64.8m	120.3m
Vertical Magnitude Error	118.6m	65.3m
Position Magnitude Error	121.9m	124.6m
Velocity Magnitude Error	23.9 m/s	32.2 m/s

Figures 6-7 through 6-10 show the navigation errors occurring on one of the simulations. Throughout the turn, position spikes can be seen as various satellites are shaded and then replaced. Near the beginning and end of the plot, velocity and acceleration error spikes are seen as a result of the unmodelled jerk.

Figures 6-11 and 6-12 display the error in the pre-position information provided by the navigation for the receiver. This is error which drives the receiver acquisition model in Figure 6-6.

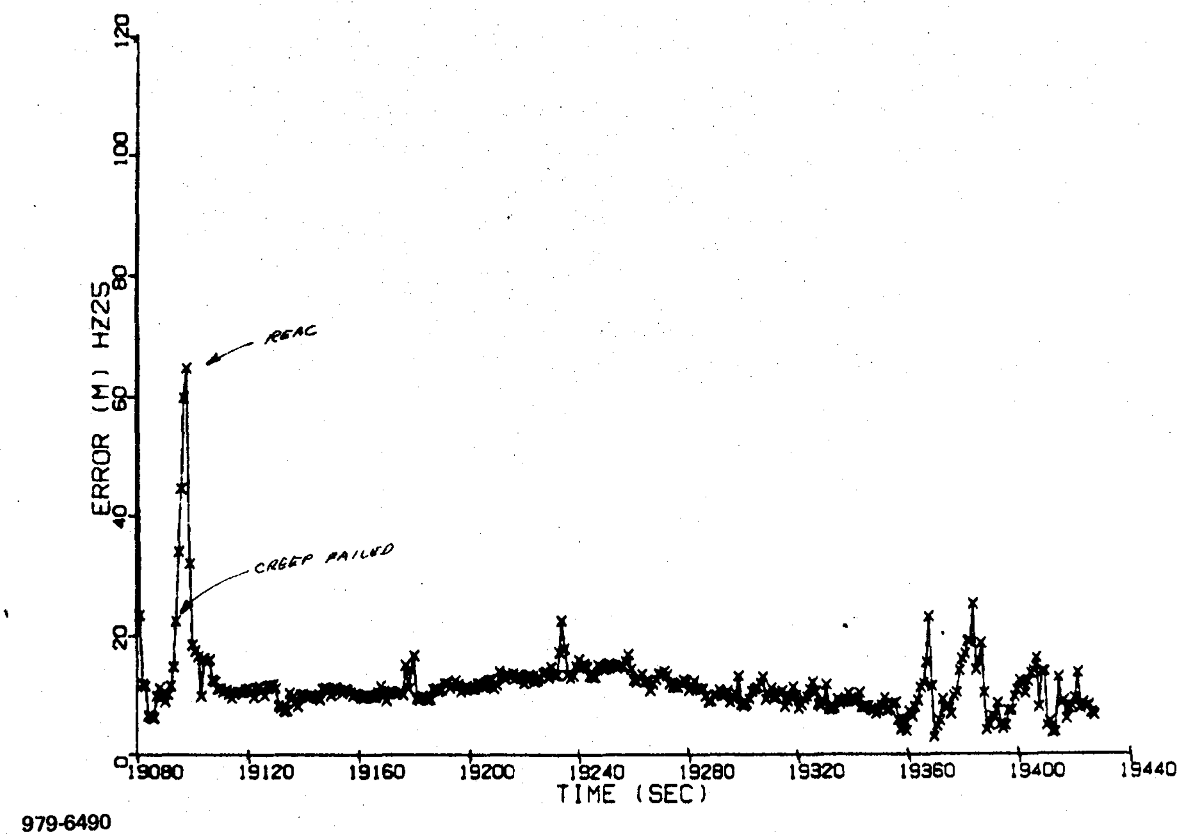


Figure 6-7. Horizontal Position Error Magnitude

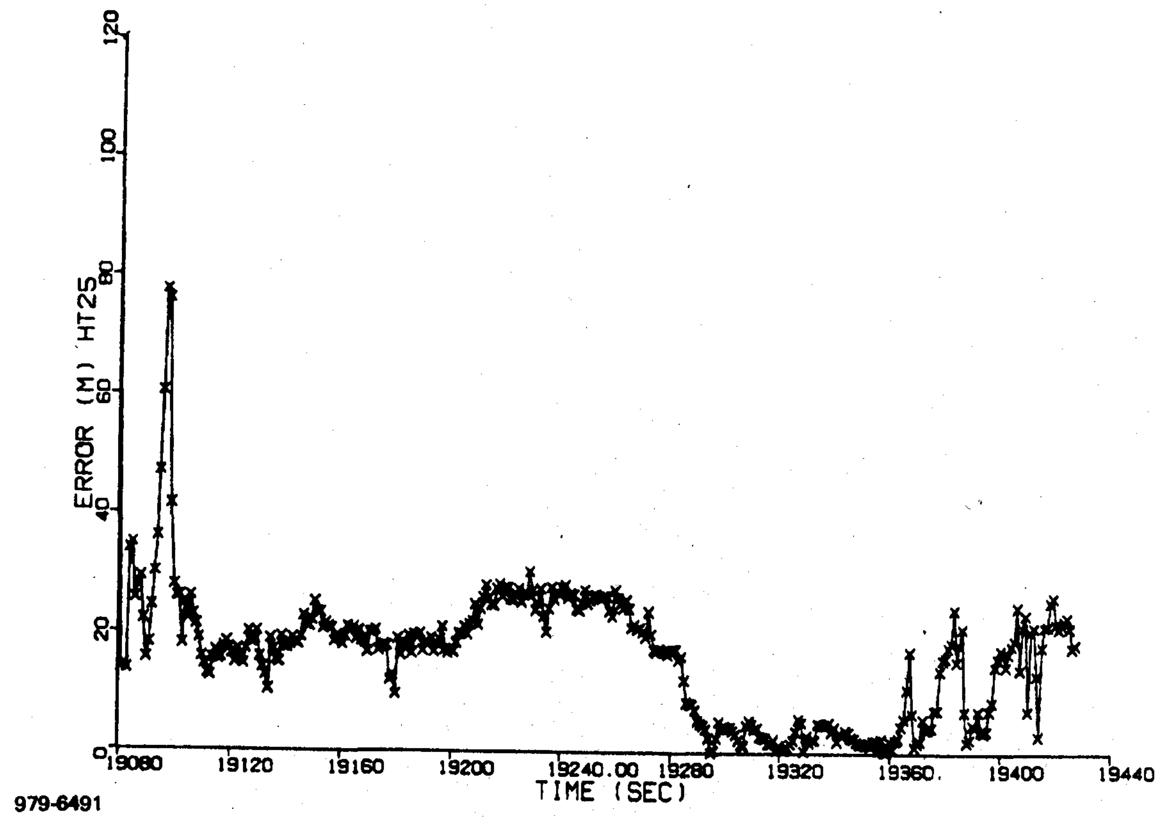


Figure 6-8. Vertical Position Error Magnitude

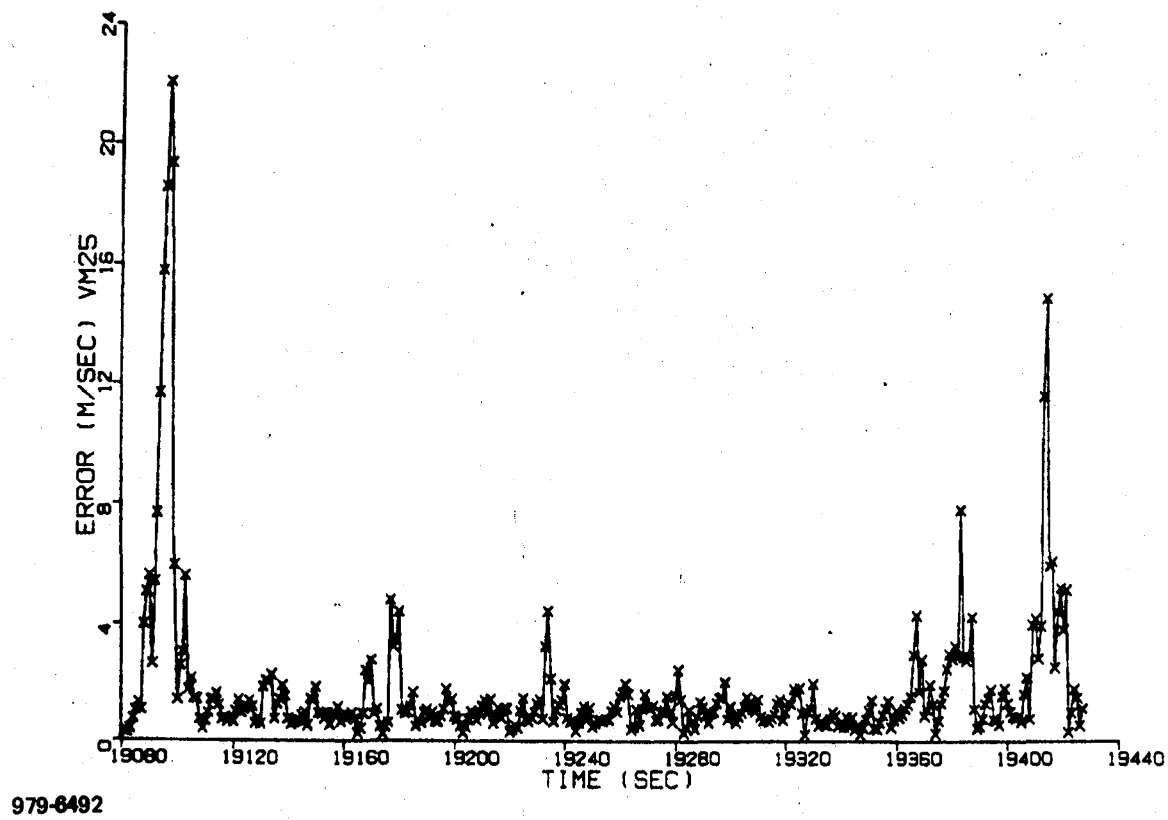
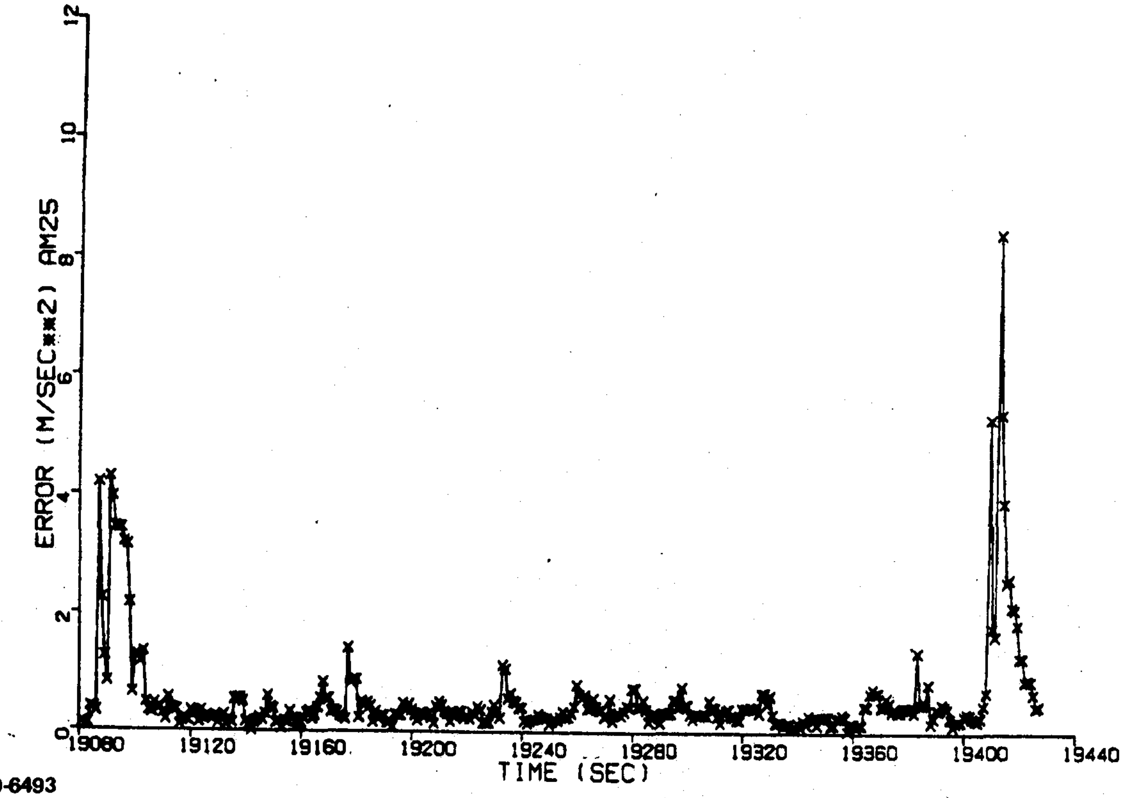
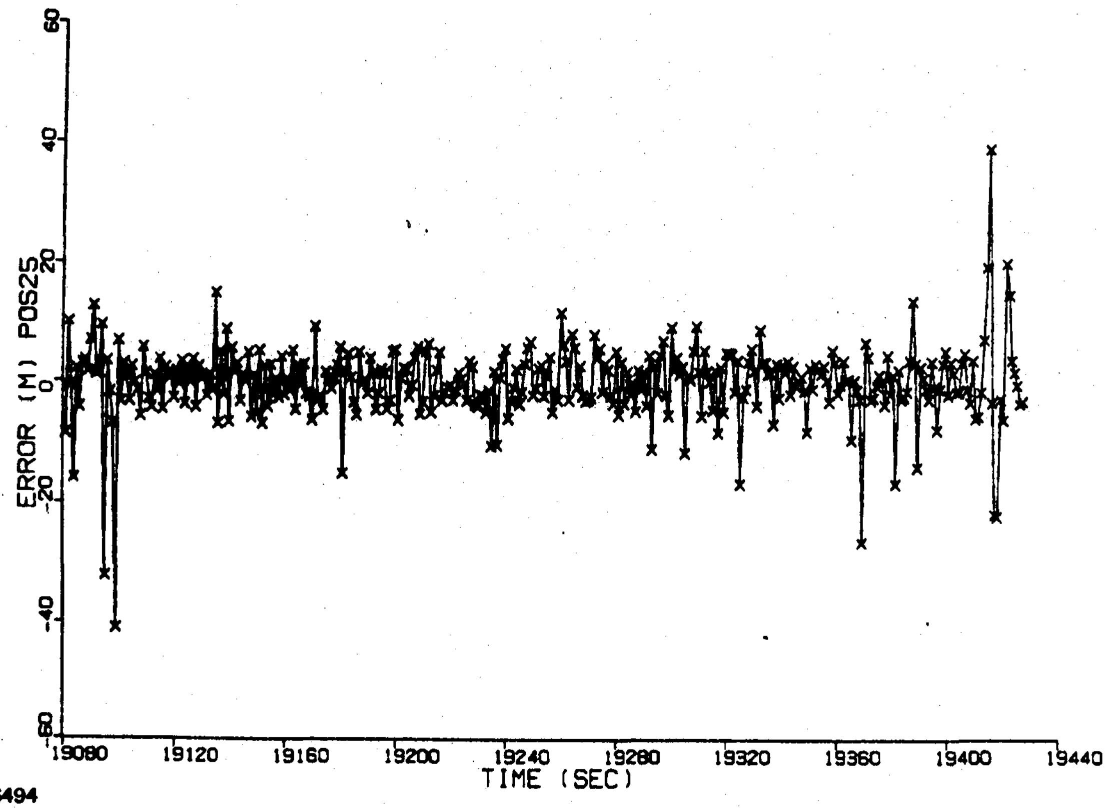


Figure 6-9. NAV Velocity Error Magnitude



979-6493

Figure 6-10. NAV Acceleration Error Magnitude



979-6494

Figure 6-11. Receiver Pre-Position Range Error

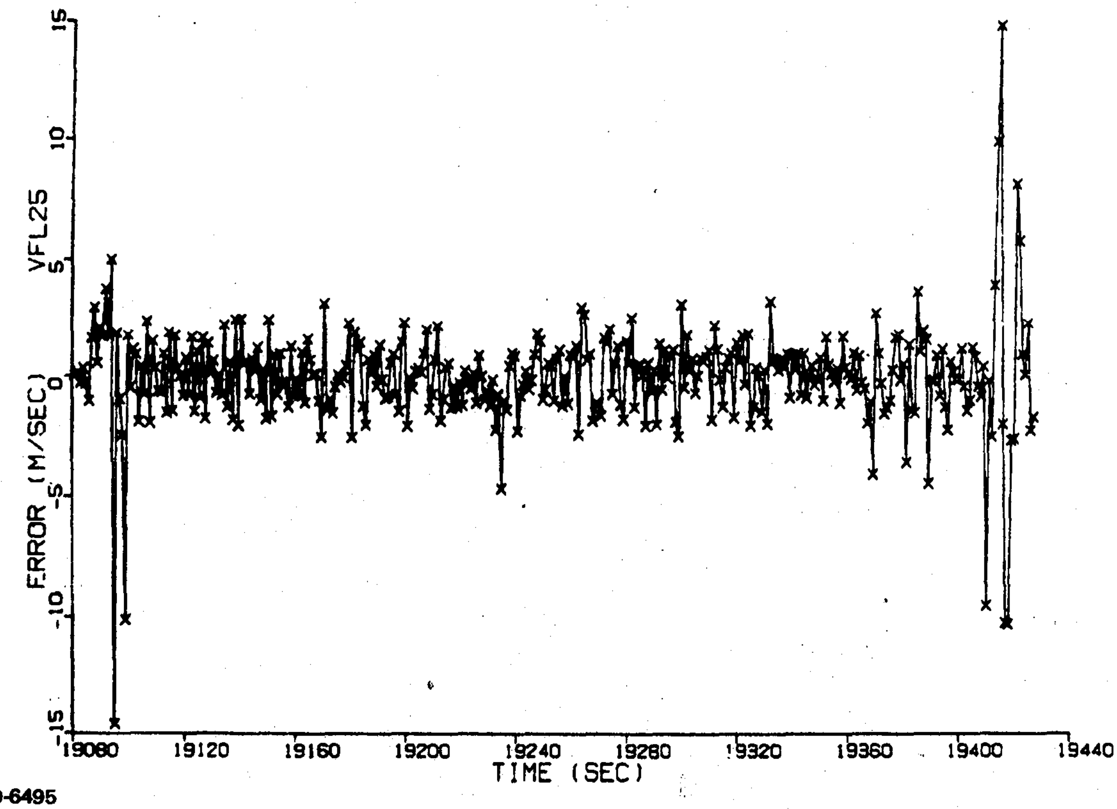


Figure 6-12. Receiver Pre-Position Rate Error

6.6 AIDING SENSORS

Based on the navigation performance demonstrated by simulation, the use of aiding sensors is not required for civil aviation applications. Certainly, aiding is undesirable from the standpoints of cost, weight, power, interfacing requirements and the like. Use of the low cost turn rate sensor provides minimum benefit because of the uncertainties acquired by assuming coordinated turns. Another problem with automatic aiding devices is that the computer program must assess their reliability and accuracy. As an alternative, it is proposed that the operator could provide such aiding as altitude or direction/speed through the CDU. This alternative should not be an operator burden because of its infrequency of use; moreover, it does take advantage of those higher order human faculties that would be so difficult to program in determining whether the potential aiding information is valid.

6.7 CONCLUSIONS

The design of the low cost moderate accuracy GPS receiver for civil aviation consists of minimal hardware recurring costs (other than data processor) combined with a sophisticated software system. The one channel, one frequency receiver attached to a single antenna/pre-amplifier with no aiding devices will meet the civil aviation requirements. This design also meets the aircraft objectives of minimal weight.

The software implements an eleven-state Kalman filter with a satellite switching algorithm and stored ephemerides to provide one hundred meter dynamic performance. The software also provides control of all other set functions to the extent that an operator need only turn the set on.

6.8 ISSUES REQUIRING ADDITIONAL TRADE STUDY

Although this study shows the complete feasibility of an unaided low cost civil aviation set, other issues have become visible which should be resolved before such a set is built. The purpose here is to identify these issues for future reference.

6.8.1 SWITCHING VS. SEQUENCING ON MORE SV'S

The proposed navigation scheme involves adopting an optimal constellation of four satellites and switching from it only in case of shading. An attractive alternative would be to sequence on all visible satellites. This scheme is relatively simple to implement and might give better performance during dynamic situations. If implemented, the satellite selection algorithm would not compute GDOP's and no logic for switching and switching back would be necessary.

6.8.2 OSCILLATOR COST VS. PERFORMANCE

The simulations are based upon an oscillator of the same quality as in the Z-Set and Manpack systems developed during GPS-Phase I. However, there are advantages in terms of cost and volume producability for using a less stable oscillator. Thus studies are needed to determine what levels of oscillator long and short term stability are necessary to maintain navigation performance. Of most concern are oscillator stability over a delta-range interval (nominally 0.3 seconds) and stability over the interval of poor GDOP due to shading (5-60 seconds). Longer term stability is of little concern given the Phase III constellation and the aircraft usage.

SECTION VII

ANTENNA/PREAMPLIFIER

7.1 REQUIREMENTS

7.1.1 ANTENNA

The antenna is required to be a low cost single frequency antenna that will receive the GPS satellites. The desired coverage is for all angles 10° above the horizon. Table 7-1 lists the basic requirements. Many of the specifications are tradeable with other receiver parameters to achieve a low system cost. It is also desired for the antenna to reject interfering signals below the airplane, but not to loose GPS signals in turns.

The preamp and antenna should be packaged together as an integrated package for cost and performance reasons. The antenna must be mounted in an area that allows horizon to horizon visibility for the antenna. A flat ground plane area is required for any antennas requiring a ground plane, or a nonmetallic mounting area for nonground plane type antennas. The antenna and preamp should be mounted near the receiver to keep cable losses down and installation costs of long cables down. Typical mounting locations for two types of antennas are shown in Figure 7-1.

7.1.2 PREAMPLIFIER

The preamplifier is required to establish the receiver noise figure and provide L-Band signal gain. The preamp must have sufficient dynamic range to handle the weak satellite signals simultaneously with strong adjacent unwanted

Table 7-1. Antenna Baseline Requirements

Antenna	Requirements
Freq:	1575.42 MHz
BW:	>10 MHz
Gain:	>-2 DBIC
Coverage:	10° to 90° Elevation, Omnidirectional
Polarize:	RHC
VSWR:	<1.5:1 Fo ± 10m
Type:	Conformal, Blade, Turnstile, Helix, etc.
Size:	<10 x 10 x 1/2"; 3 x 3 x 1/2"

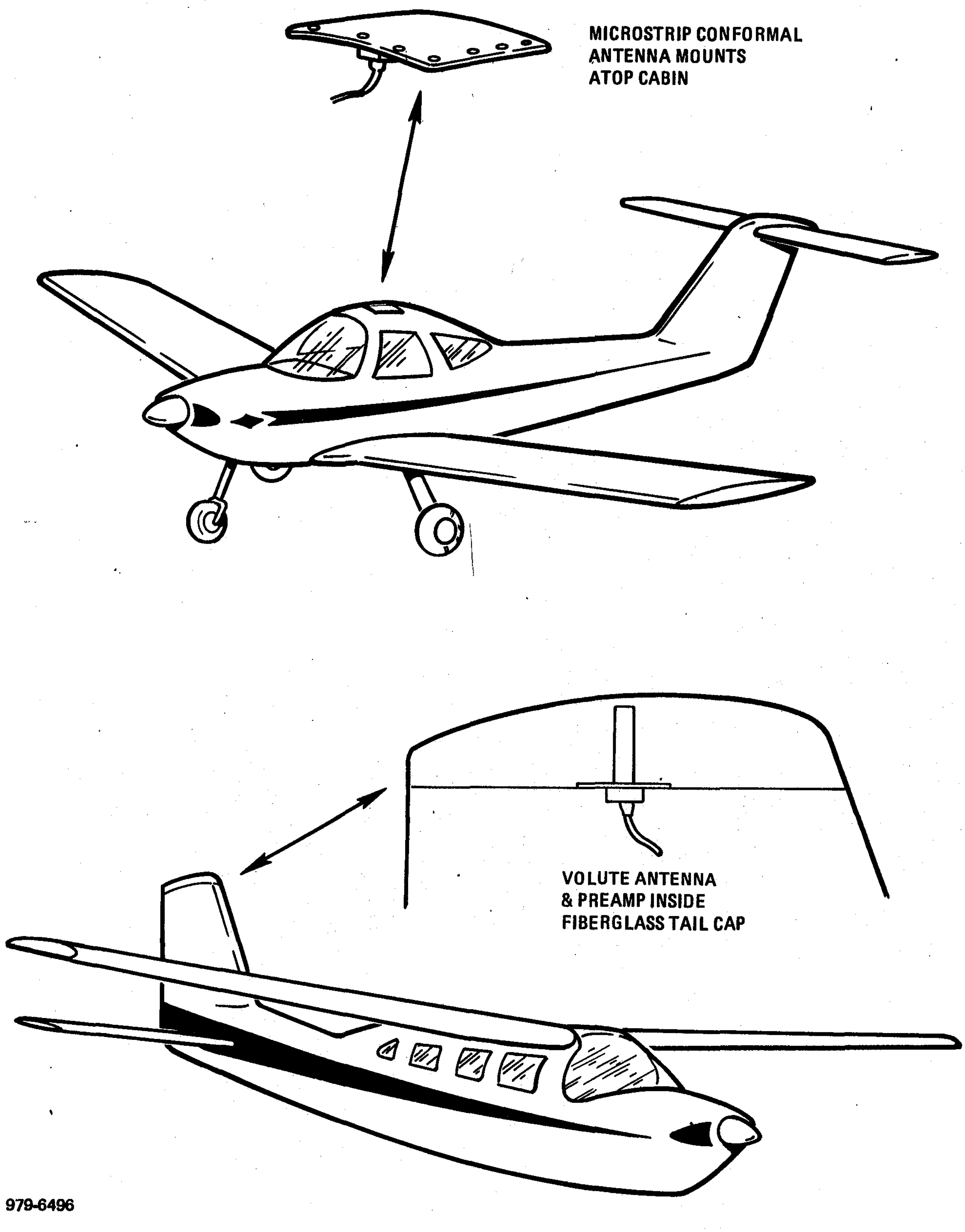


Figure 7-1. Typical Antenna Locations

signals. Any out of band intermodulation can cause receiver desensitization due to intermodulation spurious signals. The basic requirements of the preamp are shown in Table 7-2. The parameters are tradeable with the antenna, bandpass filter and receiver performance parameters to lower costs.

The preamp must be physically near the antenna in order to reduce the input cable loss which adds directly to the system noise figure. The preamp output (to receiver) cable can be long if needed. The preamp block diagram showing the bandpass filters and amplifier is shown in Figure 7-2.

7.1.3 BANDPASS FILTER

The preamplifier requires low cost input and output bandpass filters at 1575 MHz. The input filter is required to reject strong out of band signals that can cause intermodulation distortion or overload the preamp. The input filter before the preamp must be also low loss to preserve the noise figure. The output filter must also provide additional out of band selectivity to reject signals as well as to provide image noise rejection at twice the 1st IF frequency removed from the input 1575 MHz signal. The basic filter requirements are shown in Table 7-3. The passband curves of the filters are shown in Figure 7-3.

Table 7-2. Preamplifier Requirements

Parameter	Requirement
Freq	1575 MHz
BW3	AMP >100 MHz
BW3	BPF >20 MHz
BW50	BPF <300 MHz
NF	<5 dB*
Gain	>40 dB
VSWR In	<1.5:1
VSWR Out	<2.0:1
PO -1 dB	>+3 dBm Compression
PWR	.2 W
	+6-12V
	15-30 ma
Size	3" x 3" x 1"
Input SIG Range	-140 dBm to -125 dBm

*Dependent on antenna gain

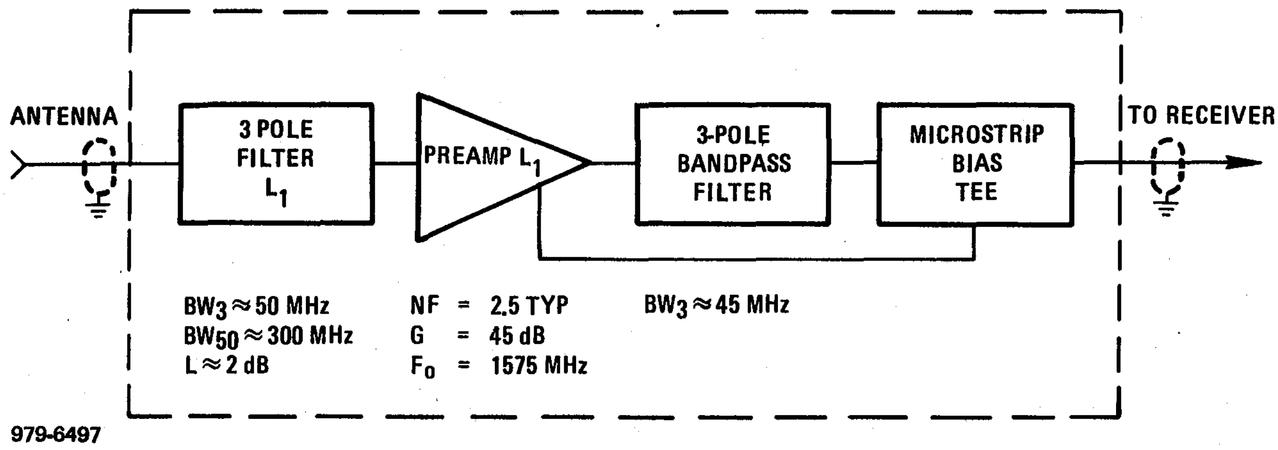


Figure 7-2. Baseline Preamp Assembly

Table 7-3. Bandpass Filter Requirements

Parameter	Input	Output
BW3	35-60 MHz	30-50 MHz
BW15		300 MHz max
BW50	300 MHz max	250 MHz
Loss	1-2 dB	1-4 dB
VSWR	1.3:1 max	1.3:1 max

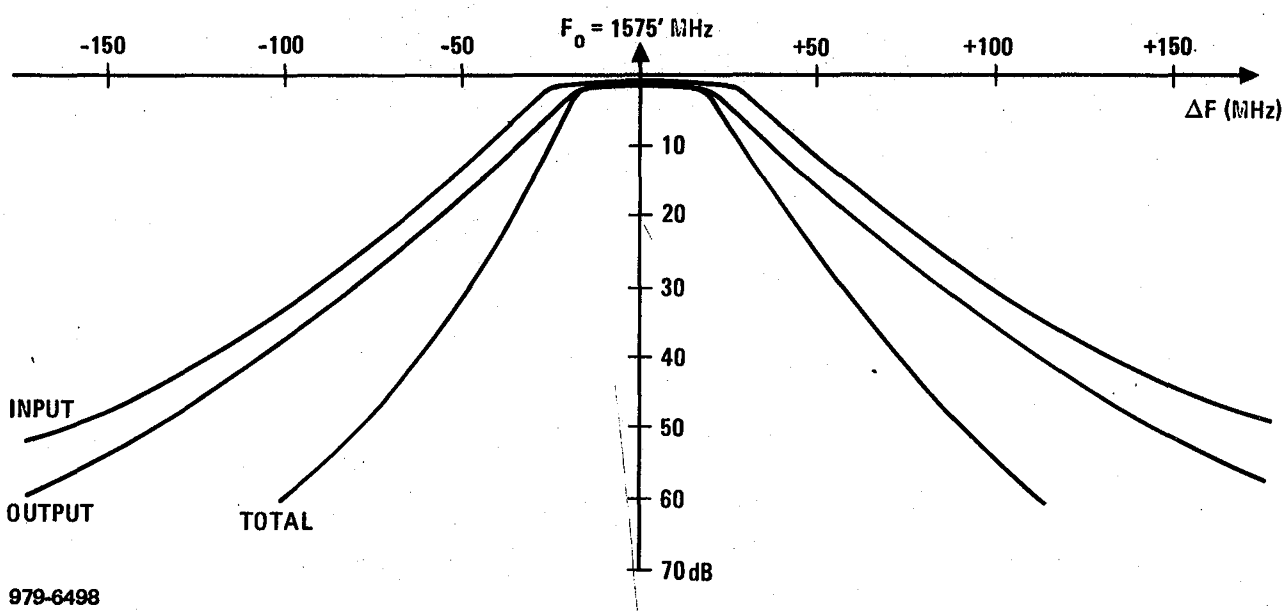


Figure 7-3. Bandpass Filter Selectivity

7.2 COST TRADEOFFS FOR PERFORMANCE

7.2.1 ANTENNA

The antenna gain, size, location and installation can be traded off for reduced costs. Figure 7-4 shows the relation between antenna gain (at low elevation angles) and cost. A larger antenna will generally have more gain but the installation cost would be higher and the required ground plane would be larger. An antenna located in the tail will cost more due to installation costs and cable costs, but will yield better performance for low angle coverage.

7.2.2 PREAMP

The preamp performance can be directly traded for antenna gain. Figure 7-5 shows the relation between total antenna + preamp cost to maintain a certain performance and antenna gain. Figure 7-6 shows the direct performance tradeoff between the antenna gain and preamp noise figure.

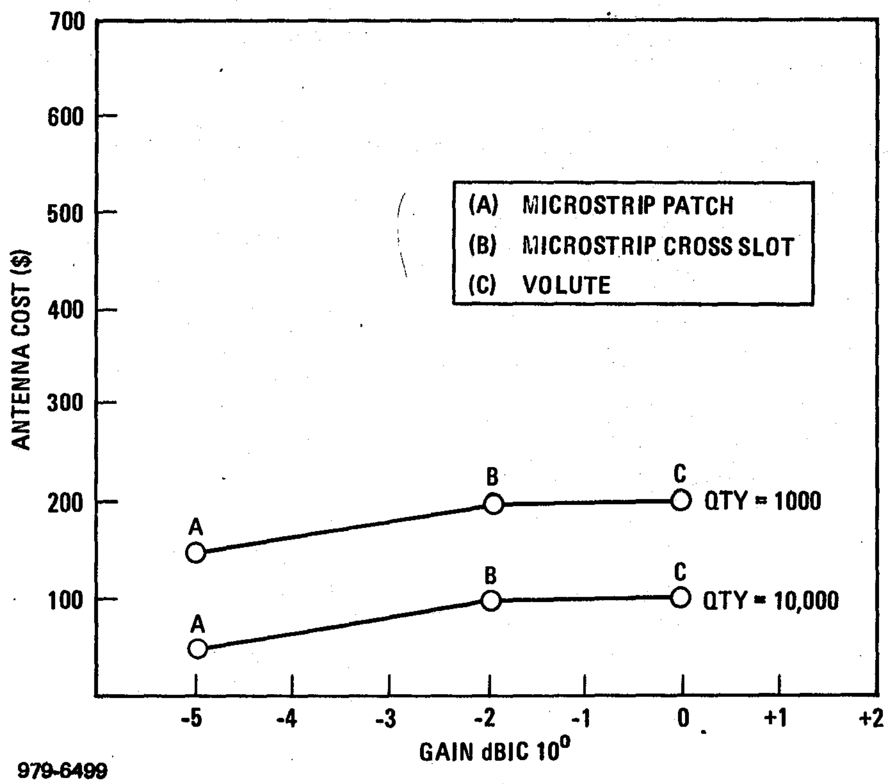


Figure 7-4. Antenna Gain vs Cost

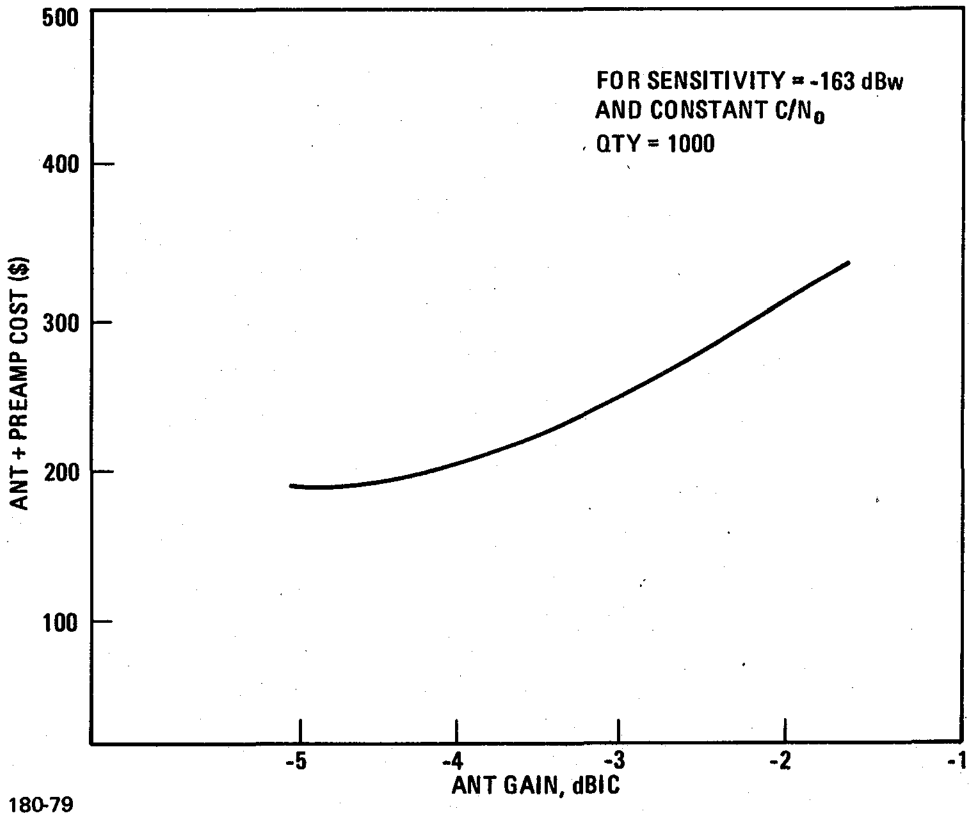


Figure 7-5. Preamp Cost Sensitivity-to-Ant Gain

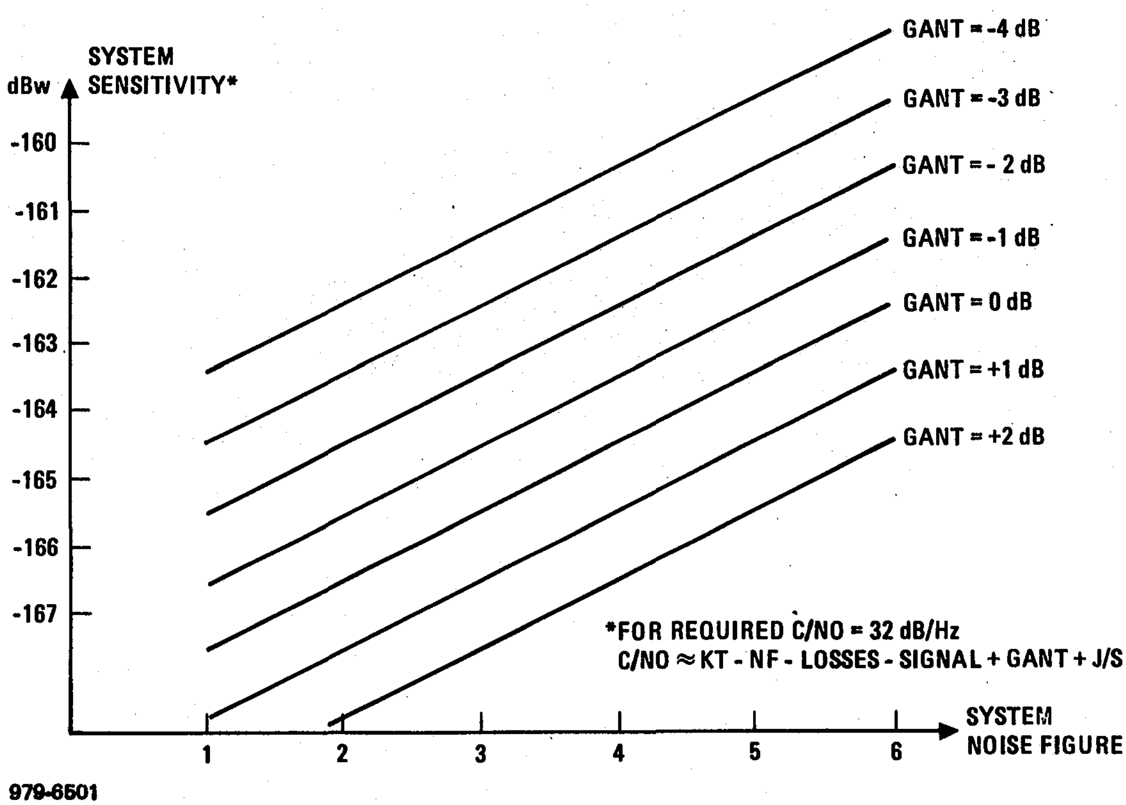


Figure 7-6. System Antenna Gain vs Noise Figure Tradeoff

Currently the minimum cost for the preamp transistors is reached around 3 dB. This results in an amplifier cost vs noise figure as shown in Figure 7-7.

The cost of the preamp is also affected by gain, size and construction technology. Discrete and hybrid technologies are available in bipolar or GaAs FET form.

7.2.3 BANDPASS FILTERS

The filters can be traded for loss, rejection bandwidth, 3 dB bandwidth, size and packaging construction technology. Figure 7-8 shows the cost vs loss for various filters. The basic filter technologies are cavity, microstrip, stripline and helical. Each has its own advantages and disadvantages as shown in Table 7-4.

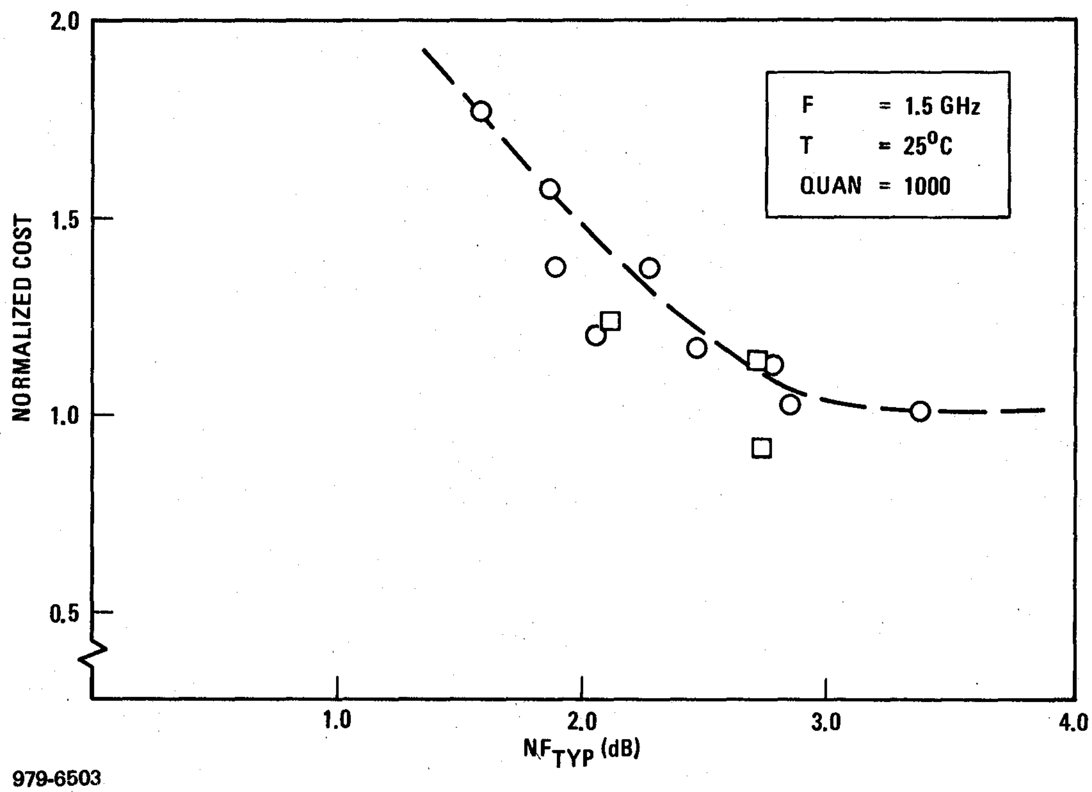


Figure 7-7. Preamp Amplifier NF vs Cost

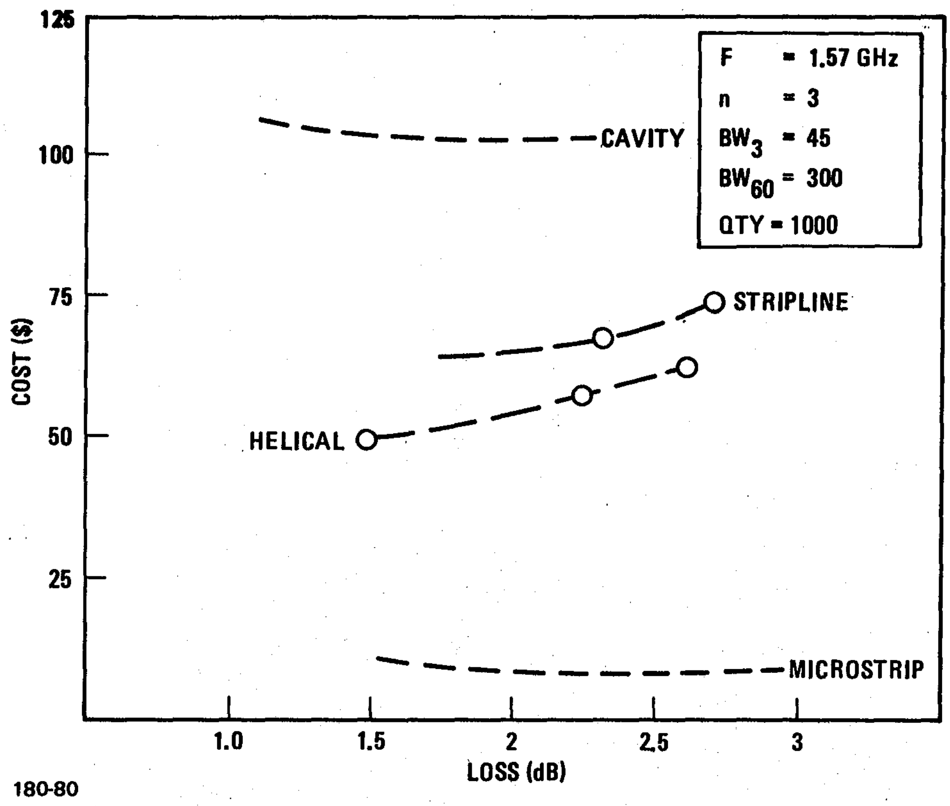


Figure 7-8. BP Filter Loss vs Cost vs Selectivity

Table 7-4. Filter Types - Advantages/Disadvantages

Type	Loss	Size	Cost
Cavity	Low	Large	Hi
Microstrip	Hi	Med	Lo
Stripline	Med	Med	Med
Helical	Med	Med	Med
Saw	Hi	Small	Hi

7.2.4 PREAMP ASSEMBLY

When the bandpass filter and amplifier are combined together, the resulting preamp assembly cost vs noise figures is shown in Figure 7-9. Some reduction in cost would occur if the preamp was integrated into the front of the receiver and a short low loss cable run to the antenna. However, for the case where the antenna is in the tail section, the performance loss due to not remoting the preamp with the antenna would be too great.

The preamp receives dc power via the conductor of the RF output coax cable from the receiver. This saves installation costs of separate dc wires. The preamp amplifier input match is achieved with special circuit techniques. This eliminates an expensive isolator or dual coupler approach. All interconnects are made with microstrip, avoiding the high cost and size of coaxial cables and connectors.

7.3 ALTERNATIVES

7.3.1 ANTENNA TYPES

Characteristics of various antennas available to meet the antenna requirements, were shown in Table 7-5. Figures 7-10 through 7-12 show patterns of these antennas.

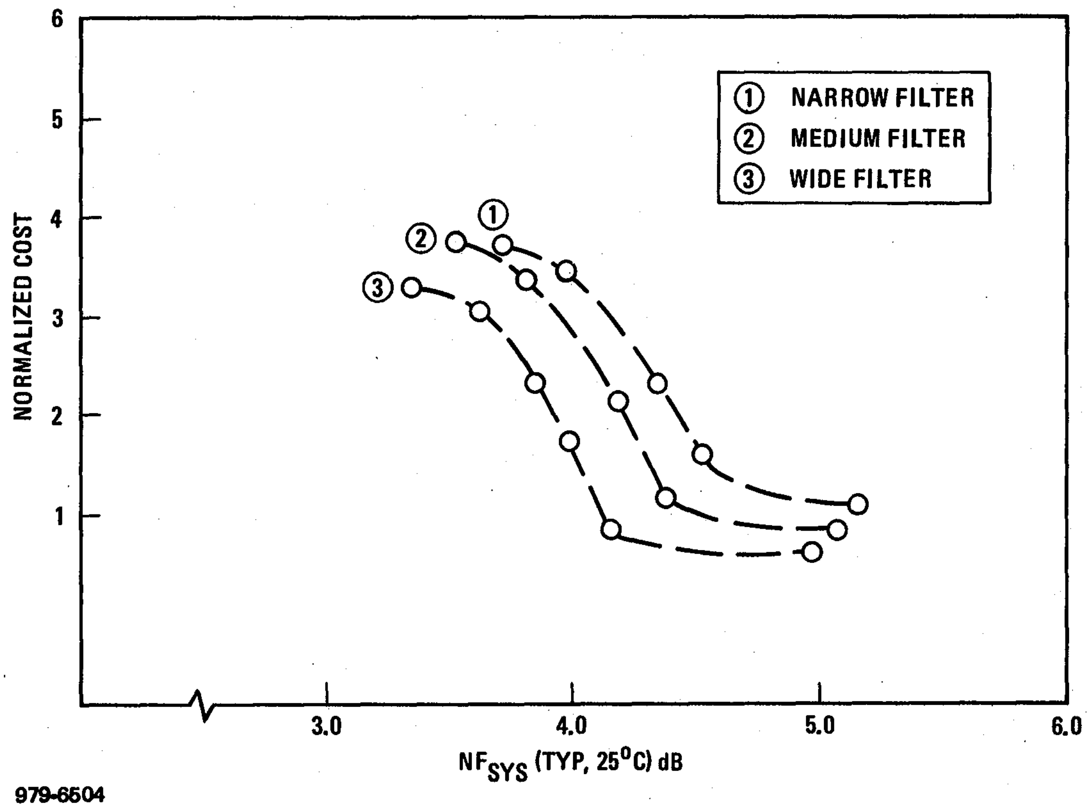


Figure 7-9. Preamp Assembly NF vs Cost

Table 7-5. Antenna Characteristics

	RHC	Gain Lo Angle	Gain Hi Angle	Conformal	Omni Pattern	Cost
Microstrip Patch	yes	fair	good	yes	good	med
Cross Slot	yes	good	good	yes	good	med
Vertical	no	fair	poor	no	poor	lo
Volute	yes	good	good	no	good	hi

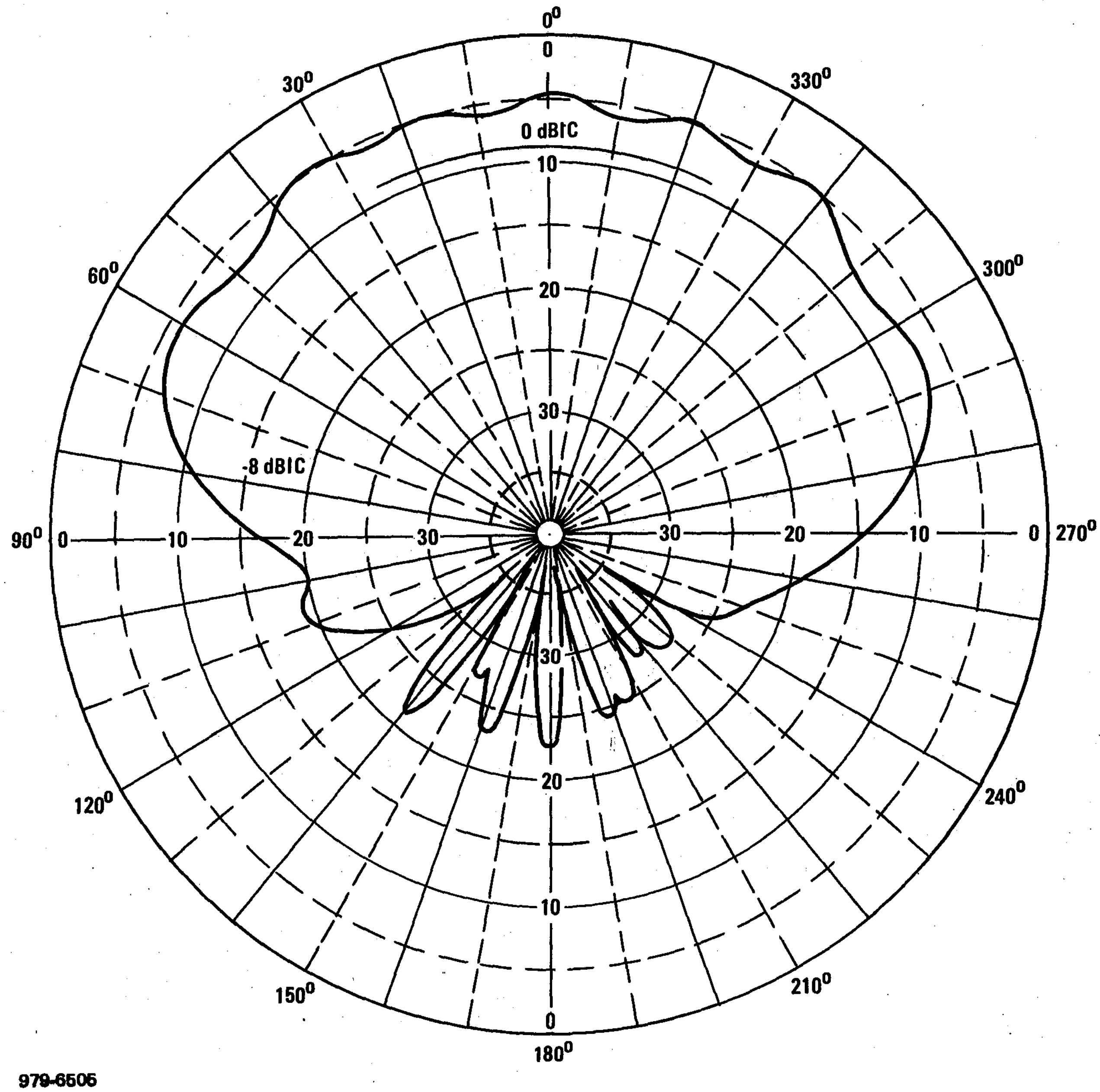
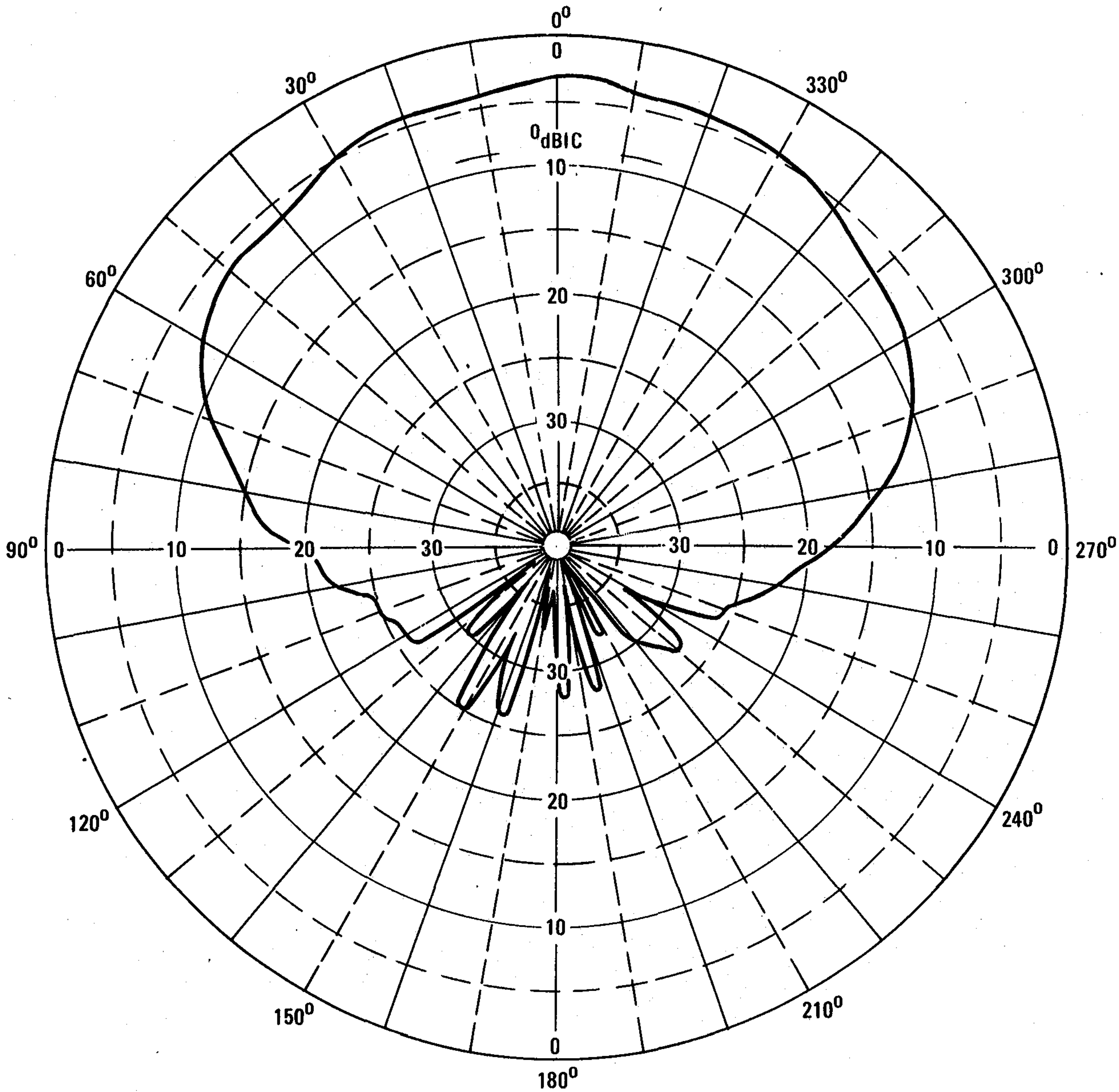


Figure 7-10. Elevation Plot of a Cross Slot Antenna



979-6506

Figure 7-11. Elevation Plot of a Microstrip Patch Antenna

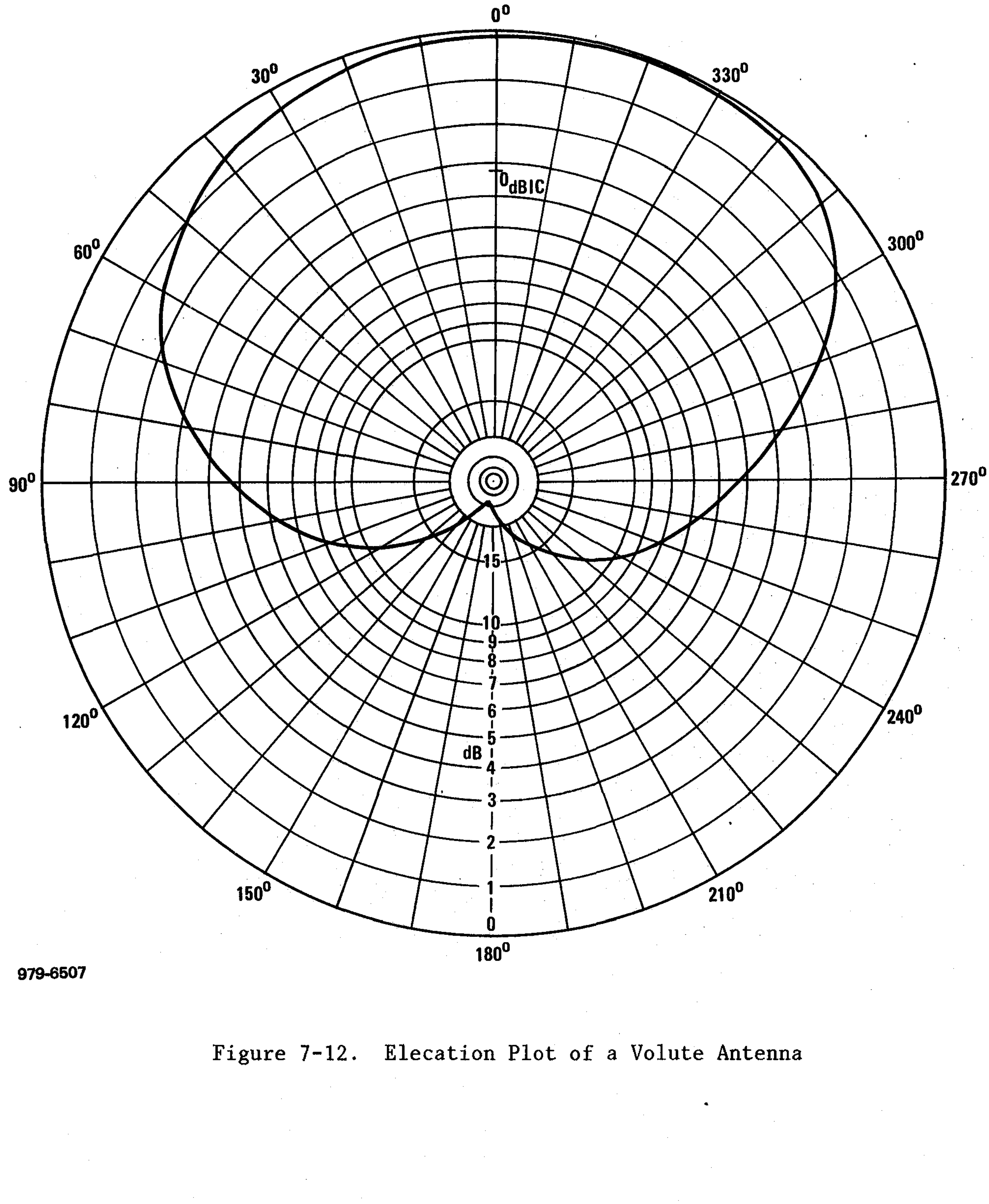


Figure 7-12. Elecation Plot of a Volute Antenna

7.3.2 ANTENNA LOCATIONS

The antenna can be mounted as shown in Figure 7-1 in front or in the tail. To be considered are drag, gain, size and coverage. Signals cannot be received below the horizon or during a bank without two antennas or a switched phased array antenna. The cost of these antennas would be high. The volute antenna can also be mounted on the top canopy if packaged as a blade as shown in Figure 7-13.

7.3.3 PREAMP TYPES

The preamp amplifier can be constructed in discrete, hybrid, or LSI RF form. The hybrid and LSI RF forms are the trend in the future. The discrete is presently the lowest cost. The preamp performs best when it is located near the antenna which minimizes input losses. The use of a low cost short length of output coax cable will minimize the cable and installation costs.

The microstrip filter has the lowest cost performance of filters today, however, the SAW filter may become competitive in five years.

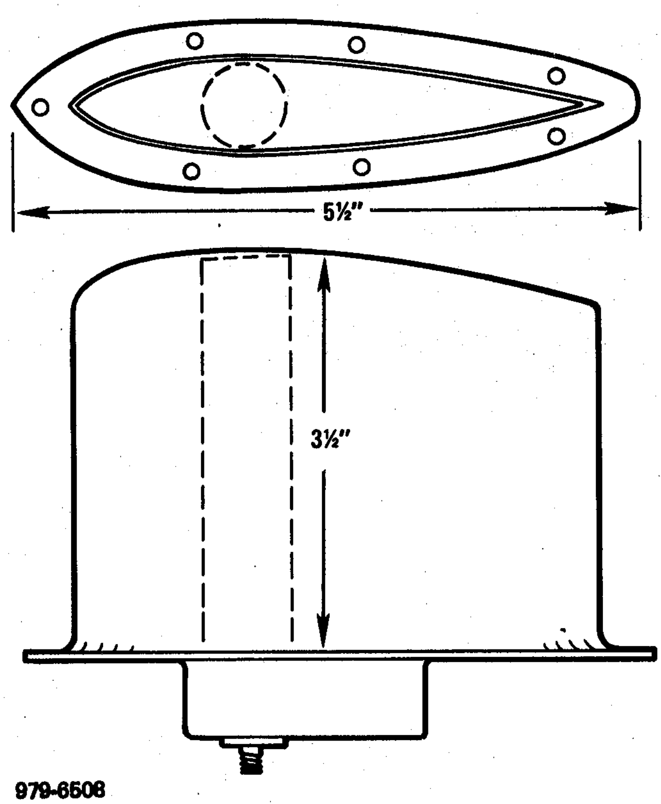


Figure 7-13. Volute Antenna with Aerodynamic Radome

7.4 PROJECTED 1985 LOW COST ANTENNA/PREAMP DESIGN

A majority of the technology is available today to build a low cost GPS Antenna and preamp unit for civil applications. Future expansions of today's technologies will yield better performances at about the present cost, or equal performance for less cost. The recommended antenna/preamp design is shown in Figure 7-14.

7.4.1 ANTENNA

The recommended antenna should be a conformal microstrip cross slot or volute depending on the application. These achieve good pattern coverage with reasonable gain and low cost. By connecting the antenna directly to the preamp, performance is improved and costs are lowered. The microstrip antenna is mounted over the front canopy. For those applications where a tail mounted antenna is desirable, a volute antenna can be used.

7.4.2 PREAMP

The recommended preamp would consist of discrete bipolar transistors and components on standard Teflon glass PCB. The input and output bandpass filters would be etched onto the same PCB. This results in very low cost filters. Any performance loss is made up by using slightly improved lower noise input transistors. The preamp unit is a fixed tuned assembly approximately 2 x 4 inches in size. No adjustment is required after initial alignment for drift or aging. The preamp unit is designed to connect and mount on the back side of a conformal type antenna or at the base of a volute type antenna.

7.5 TECHNOLOGY DEVELOPMENT

7.5.1 ANTENNAS

Our best judgment is that 0 dB gain at 10° above horizon may not be possible with a conformal antenna and possibly not with any antenna when installed. Continued development is required in antennas to achieve a low cost unit that has good gain at 10° and greater above the horizon. The microstrip patch and cross slots are useful as conformal antennas. The volute is a good approach for a tail mounted antenna. Improvements in low cost high volume manufacturing technology are needed in the antenna areas.

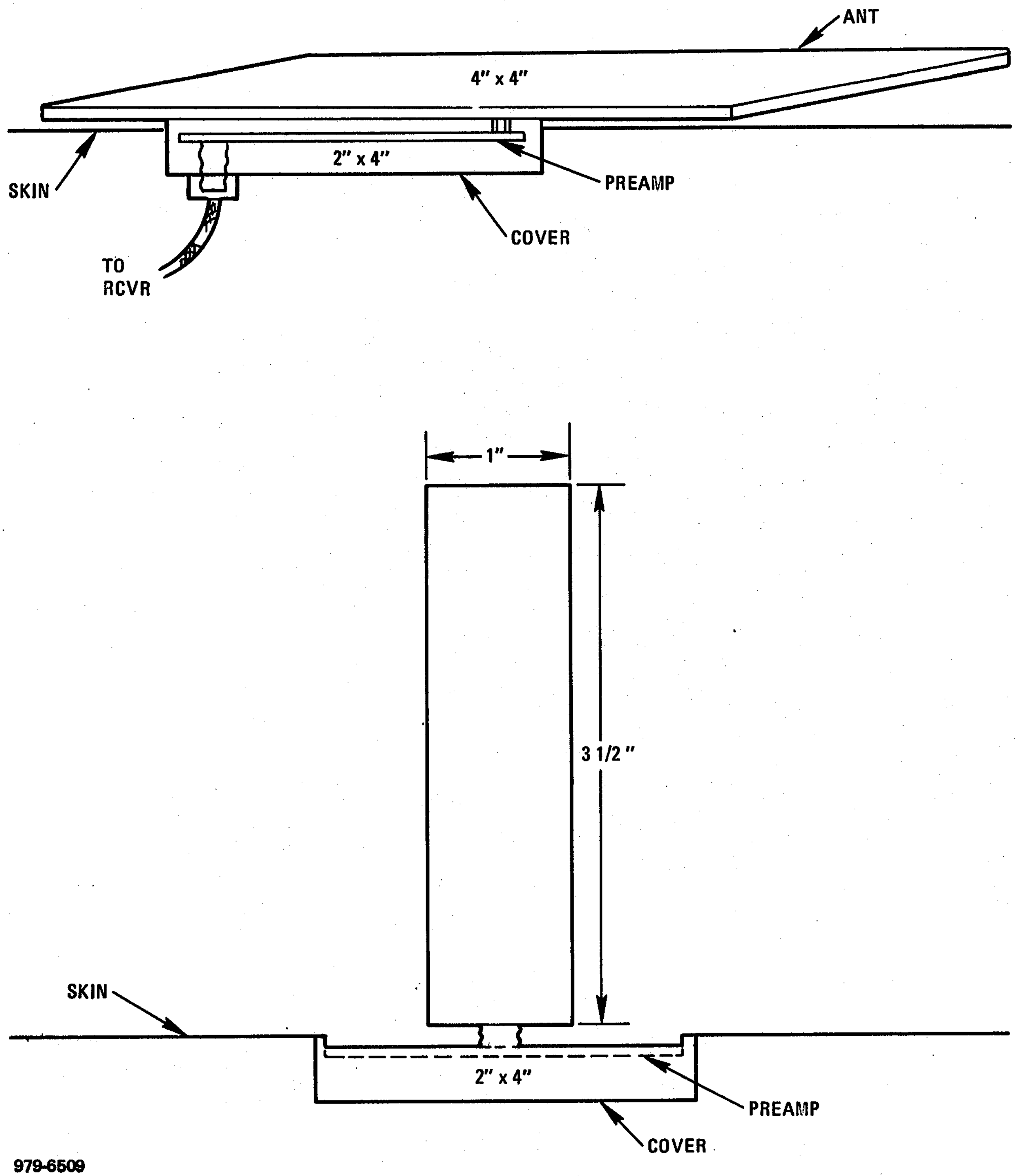


Figure 7-14. Volute Antenna/Preamp

7.5.2 PREAMPS

Transistor development sets the pace for the amplifier costs and performance. Lower noise figure higher performance devices are continuously becoming available with lower costs. Lower noise preamps allow the antenna gain to be lowered, thus lowering costs. New reductions in costs are possible with the development and availability of low cost hybrid and MIC RF circuits, especially using the latest GaAs FET's and bipolar devices.

7.5.3 FILTERS

Most of the present filter technologies are mature in the cost and performance area. Integration of the filters directly onto the amplifier board will lower system costs. Manufacturing methods to lower costs for high volume need to be improved. SAW filters promise a potential reduction in size and cost when they can be developed at L-band and high volume produced.

SECTION VIII

RECEIVER

8.1 REQUIREMENTS

The basic requirements for a low cost GPS receiver are to acquire the coarse/acquisition (C/A) code from four satellites on the L1 frequency, demodulate data and measure time of arrival of the GPS signals relative to a local user time clock (UTC). The fundamental design parameters for civil aviation users are given in Table 8-1.

Table 8-1. Basic GPS Receiver Requirements

Input Frequency	1575.42 MHz (L1)
Signal Type	1.023 MBps C/A code
Sensitivity	
Acquisition	-130 dBm (0 dBic Antenna)
Tracking	-140 dBm (0 dBic Antenna)
Dynamics	
Velocity	400 m/sec max.
Acceleration	5 m/sec^2 max.
Interference Rejection	50 dB, f_o ± 10 MHz
Range Measurement Accuracy	50 meters
Delta Range Measurement Accuracy	0.1 meters
Code Search Rate	50 chips/sec.

The input frequency and the code clock rate constrain the frequency plan and determine the local oscillator frequency synthesizer complexity. The use of the L1 carrier frequency and the C/A code only minimize the frequency synthesizer complexity. The C/A code does not afford the jamming protection of the P-code; however, intentional jamming of civil users is not likely to be a problem. The C/A code allows measurement accuracies of a tens of meters which is quite adequate for general aviation.

Without the use of the L2 signal at 1227.6 MHz in conjunction with L1 signal direct measurement of ionospheric propagation delay errors is not possible. Under extreme conditions of sun spot activity errors on the order of a 100 meters can be introduced. For critical situations the propagation error corrections can be broadcast to users along with weather and other pertinent flight information. The barometric altimeter can also be used for altitude correction of the GPS measurement.

The input sensitivity along with code search rates dictate receiver noise figure and detection bandwidths. To achieve a code search rate of 50 chips per second (i.e., 100 half-chips per second, since the reference code is precessed in discrete half-chip steps) a predetection bandwidth of 1 kHz is required for an average dismiss rate of 10 ms. As shown by simulation results in Figure 8-1, an effective C/N_0 of 32 dB is required to provide a probability of acquisition of 90%.

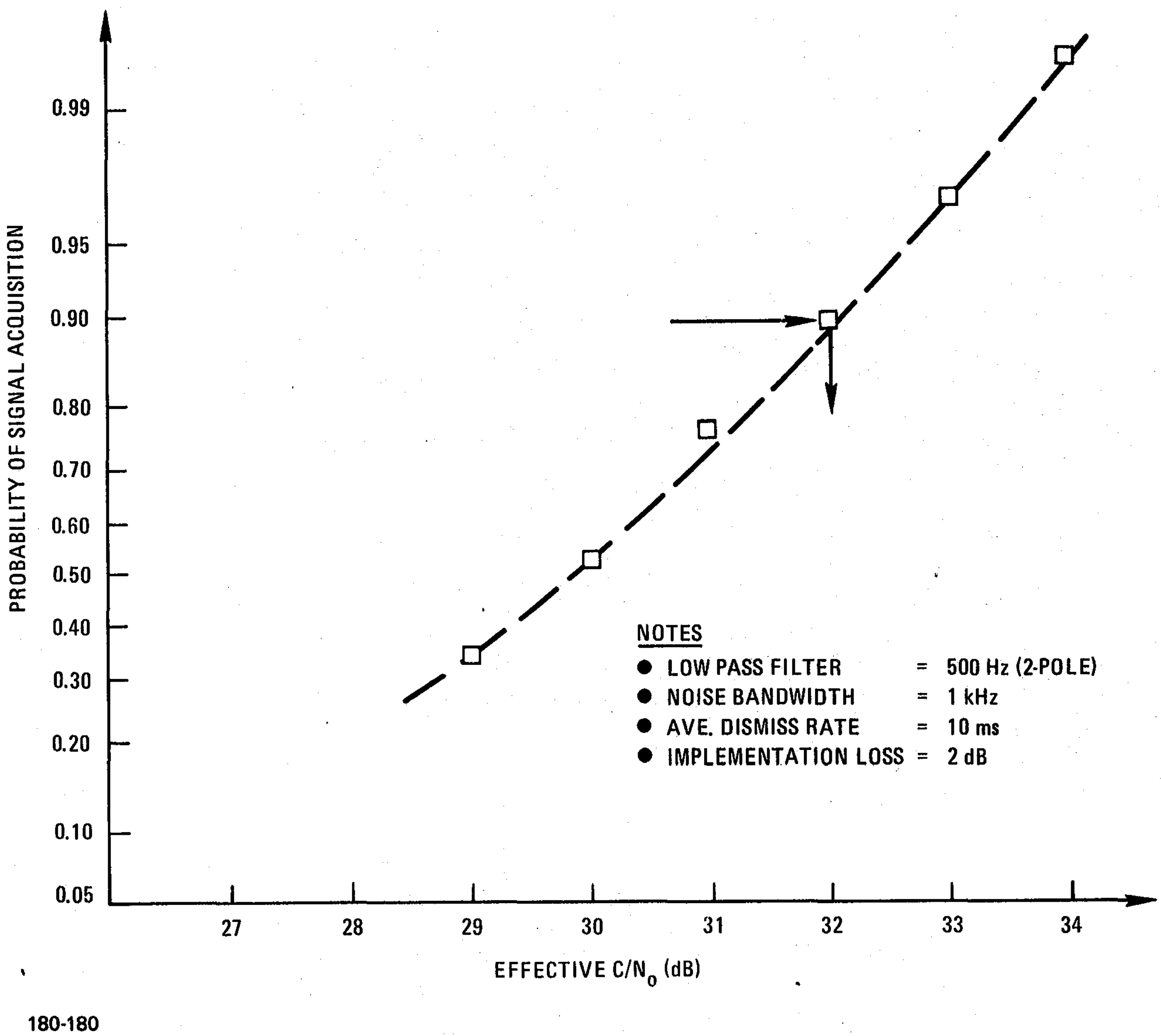


Figure 8-1. Sequential Detector Performance

For signal acquisition using a -2 dBic gain antenna, a -133 dBm signal and an assumed receiver implementation loss of 2 dB, the receiver noise figure can be calculated as follows:

$$\begin{aligned} NF &= (S - C/N_o - I.L. - kt + G)\ dB \\ &= -133 - 30 - 2 - (-174) + (-2) \\ &= 7\ dB \end{aligned}$$

where:
- NF = Noise Figure (dB)
- S = Signal strength (dBm)
- C/N_o = Carrier to Noise ratio (dB-Hz)
- I.L. = Implementation Loss (dB)
- kt = Boltzman's Constant (dBm)
- G = Antenna Gain (dBi)

To accommodate a $5 m/sec^2$ (1/2 g) acceleration with a -140 dBm (C/N_o = 25 dB-Hz) received signal level, a 20 Hz costas loop bandwidth is required. Likewise, a 10 meter RSS measurement accuracy at -133 dBm (C/N_o = 32 dB-Hz) and a 30 meter RSS measurement accuracy at -140 dBm requires a 1 Hz τ-dither code tracking loop with a predetection bandwidth of 250 Hz. These parameters are related by the following equation:

$$BL = \frac{C/N_o \left(\frac{\text{RMS error}}{300}\right)^2}{1 + \frac{2\ B_{IF}}{C/N_o}}$$

where:
- B_L = Loop Bandwidth (Hz)
- C/N_o = Carrier to Noise Ratio (numeric)
- B_{IF} = Predetection Bandwidth (Hz)
- RMS error = Error in Meters

The 400 m/sec. aircraft velocity requirement combined with a satellite velocity as large as 960m/sec. results in a ±7.1 kHz doppler uncertainty which in turn dictates an IF bandwidth ahead of the AFC or costas loop of 19 KHz.

A summary of the design parameters as they apply to a sequential GPS receiver are given in Table 8-2.

Table 8-2. Sequential GPS Receiver Design Parameters

Minimum Signal Level	-140 dBm
Maximum Noise Figure	7 dB
Maximum Doppler	±7.1 KHz
Pre-correlation Bandwidth	$\leq$20 MHz
Range Measurement Resolution	$\leq$0.1 meters
Code Search Rate	50 chips/sec.
Acquisition Predetection Bandwidth	1 KHz
AFC Bandwidth	2 Hz
Code Loop Bandwidth	1 Hz
Costas Loop Bandwidth	20 Hz
Oscillator Stability	
Long Term and Temperature	$\pm 1 \times 10^{-6}$
10 Second Average	$\pm 1 \times 10^{-9}$
1 Second Average	$\pm 1 \times 10^{-10}$

The AFC bandwidth is driven by the desire to acquire frequency lock within a fraction of a second after detection of code synchronization with a frequency uncertainty as large as 500 Hz, yet not interact with the code tracking loop.

Oscillator long term and temperature stability is driven by the limits on the number of frequency bins which can be searched upon turn-on and obtain a first position fix within five minutes. The ten second frequency stability is constrained by the allowable time uncertainty permitted over the averaging time of the Kalman navigation filter. The one second stability is driven by the delta range accuracy requirements which relates directly to the ability of the set to sequentially reacquire satellites during acceleration.

8.2 RECEIVER ARCHITECTURE

To obtain a navigation fix the GPS receiver must acquire and track the navigation signals, measure time of arrival, and demodulate satellite position data from a selected constellation of four satellites. Acquisition involves a search through all possible phases of the C/A code until synchronization is detected followed by pull-in and lock to the code and carrier phase of each of the satellite signals. Once code phase is acquired the time of arrival of the signal can be measured to better than a microsecond. However, to measure delta range and therefore velocity with the necessary accuracy requires Costas phase lock to the GPS carrier signal. The demodulation of satellite data also requires Costas carrier phase lock.

All of the above functions have to be accomplished for each of the four satellites in a time period which is short relative to the rate of change of position and velocity of the receiver. For a stationary or constant velocity user, the measurement functions could take place over a relatively long period of time. For a low acceleration user such as a subsonic aircraft a satellite by satellite measurement update of one second or a complete update of four satellite measurements every four seconds is adequate.

These measurement update rates can be met in a variety of ways. Four independent receivers each with a separate code and carrier loops tracking four satellites simultaneously can be used. Alternatively, a single receiver can be time shared between satellites. Furthermore, because of the coherency between the GPS code clock and carrier signals, code and carrier tracking need not be performed simultaneously; rather a single receiver channel can be time shared between code and carrier acquisition and tracking.

In the extreme case a separate code and carrier channel can be dedicated to each of the four satellite signals. Reference Figure 8-2. This would be referred to us as a maximum architecture receiver. However, because of the coherency relation between the code clock and carrier signal, nearly equivalent performance can be achieved with four carrier tracking channels and a single code channel which is time shared between the four satellite signals, i.e. a five channel receiver.

Time sharing of a single receiver channel can be performed in either a high speed sampled data manner tracking all four satellites simultaneously or in a slow speed sequential, satellite by satellite manner. The simplest lowest cost approach is the single channel sequential receiver architecture shown in Figure 8-3. The single channel sequential receiver architecture was very successfully demonstrated in the transport aircraft and land vehicle environment under the DoD GPS Phase I program. The airborne sets tested utilized one second update rates and provided accuracies better than 15 meters.

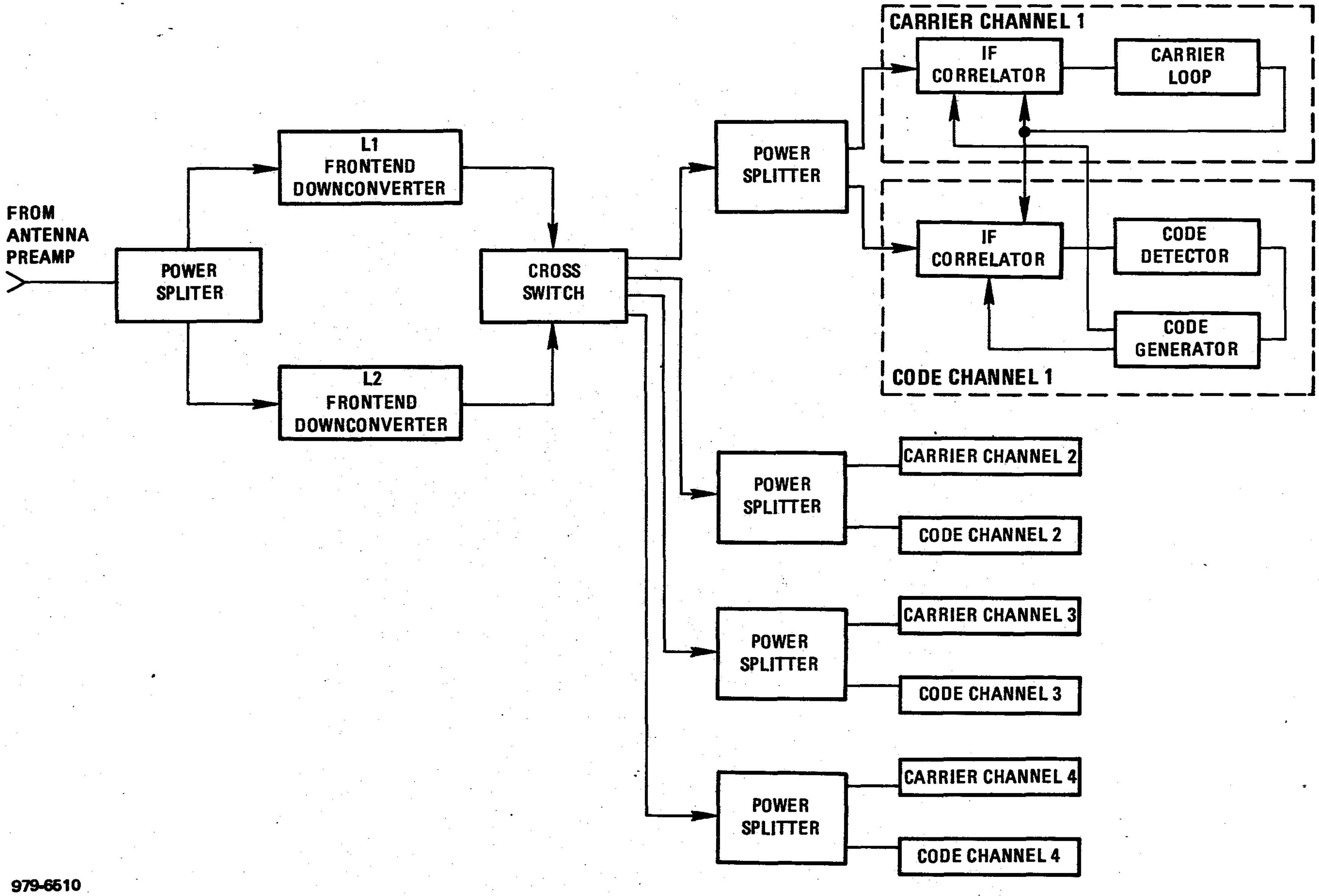


Figure 8-2. Maximum Architecture GPS Receiver with 4
Continuously Tracking Code and Carrier Channels

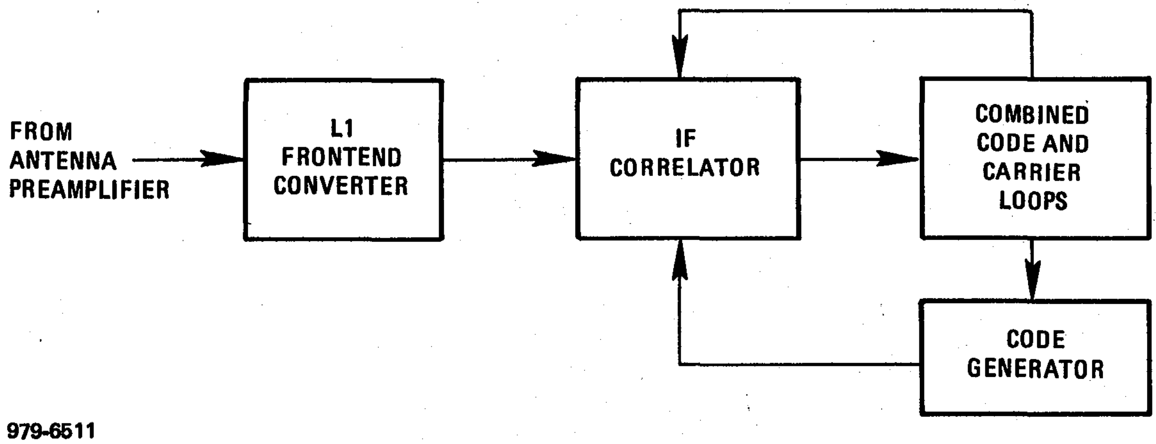


Figure 8-3 Minimum Architecture GPS Receiver with One Timeshared Channel Sequenced Between Satellites

Based upon the navigation performance analysis a single channel receiver used in a set having an eleven state Kalman filter with the ability to rapidly revise the constellation upon loss of satellites will provide more than adequate performance for civil aviation users. A set utilizing a sequenced single channel receiver will have the simplest hardware configuration and the lowest cost.

8.3 RECEIVER DESIGN ALTERNATIVES

Once the basic receiver architecture in terms of numbers of channels is defined by the user's application and requirements several alternatives exist in the implementation, i.e. frequency plan alternatives, direct versus indirect LO frequency synthesis, hardware versus software signal processing, and analog versus digital signal processing.

The fundamental frequency plan for a GPS set utilizing the L1 signal and C/A code only, is shown in Figure 8-4. This fundamental frequency plan would be impractical to implement literally for two reasons: First, the 140 dB amplification of the weak satellite signal would have to be split between L-band and video without any IF stages. Second, the L-band LO would have to be phase locked to the satellite signal and could not be used as a local time reference and the high speed ÷ 1540 would have to have provision to shift the clock phase independently of the local oscillator.

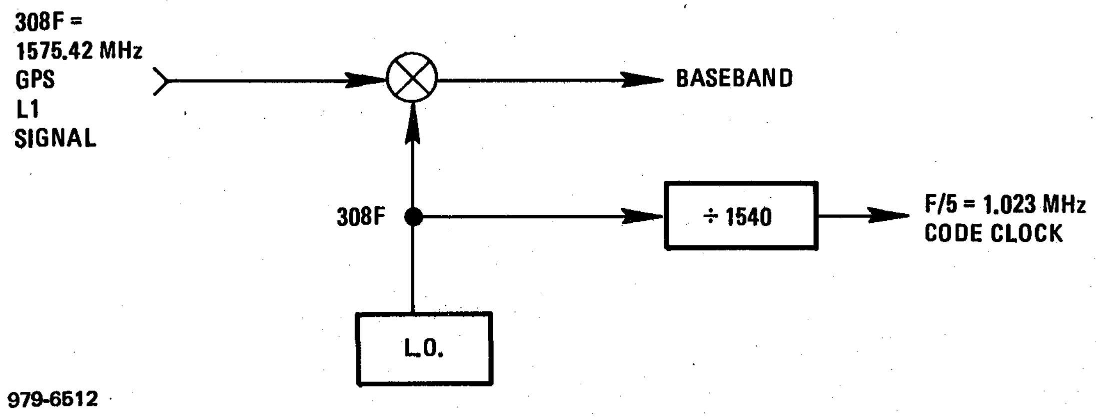


Figure 8-4. GPS Frequency Plan

The solution to the above problems is to do the downconversion to baseband in steps using one or more intermediate frequency (IF) stages and to do the code clock division at a lower IF and translate it back to 1.023 MHz using fixed frequency LOs.

One of the simplest frequency plans and the one proposed as the baseline for the low cost GPS receiver is shown in Figure 8-5. The feature of this frequency plan are a first mixer image frequency nearly 10% removed, a second IF in a band relatively free of interference, a low final IF for signal processing, no LO signals harmonically related to signal path frequencies and synthesized frequencies which required simple multiplication and division ratios.

The baseline frequency plan can be implemented with either direct multiply and mix or indirect phase locked synthesis methods. Direct frequency synthesis requires more circuitry and more tuned circuits requiring factory adjustment. Indirect synthesis lends itself to the greater use of integrated circuits and ultimately to a larger scale of integration. The indirect synthesizer requires only a single, non-critical tuning adjustment for the phase locked VCO.

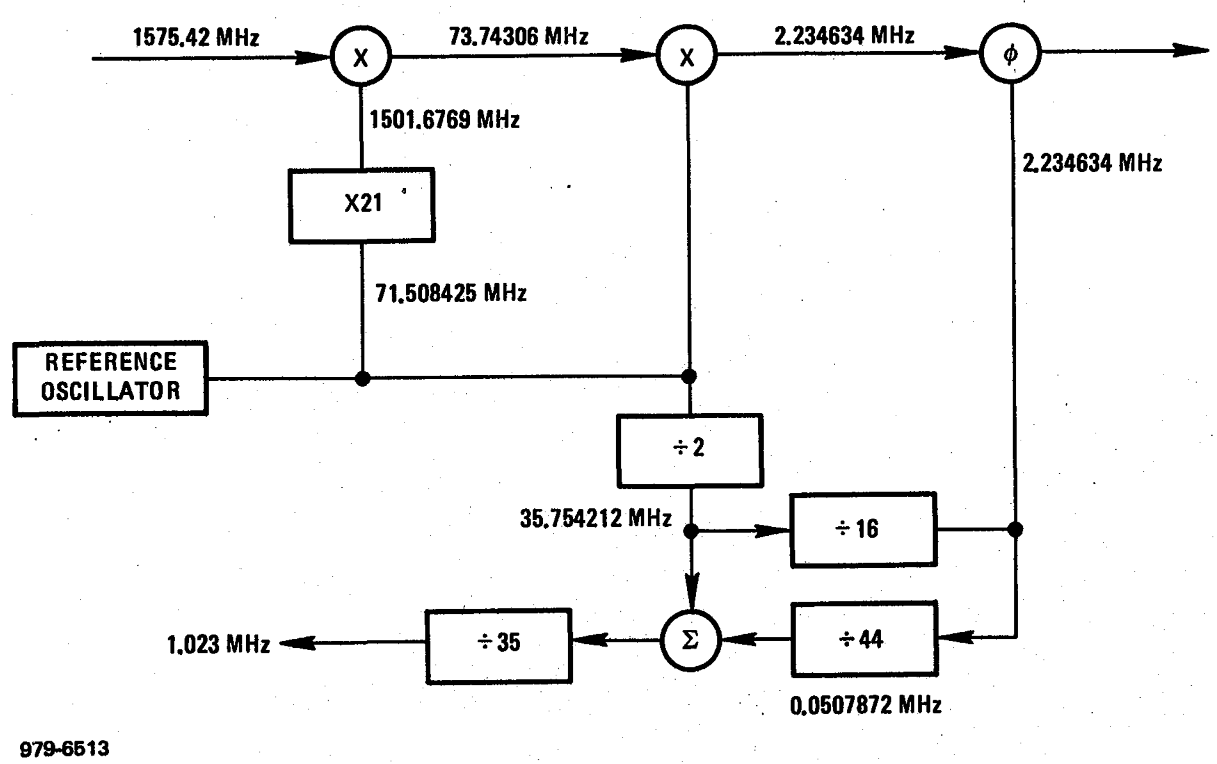


Figure 8-5. Low Cost GPS Receiver Frequency Plan

The functional block diagram of a sequential receiver showing the signal processing requirements is given in Figure 8-6. Other than the synthesis and downconversion which have already been addressed the main functions of the receiver are correlation, narrowband predetection filtering and quadrature multiplication followed by five parallel detectors and feedback tracking loops.

Several alternative implementations exist for processing the GPS signal at the output of the downconverter. The signal processor must have provisions for stepping the local C/A code through all 1023 code states while simultaneously examining the output of the correlator for synchronization using the sequential detector. Upon sensing synchronization the signal processor must utilize a τ-dither code tracking loop (time shared delay lock loop) to pull-in and reduce the code phase error to a value consistent with the signal to noise ratio. Simultaneously with code lock an automatic frequency control (AFC) loop must reduce the carrier frequency error to the point where the Costas loop can acquire phase lock to the carrier signal. Data demodulation and delta range measurements can be made once Costas lock is achieved.

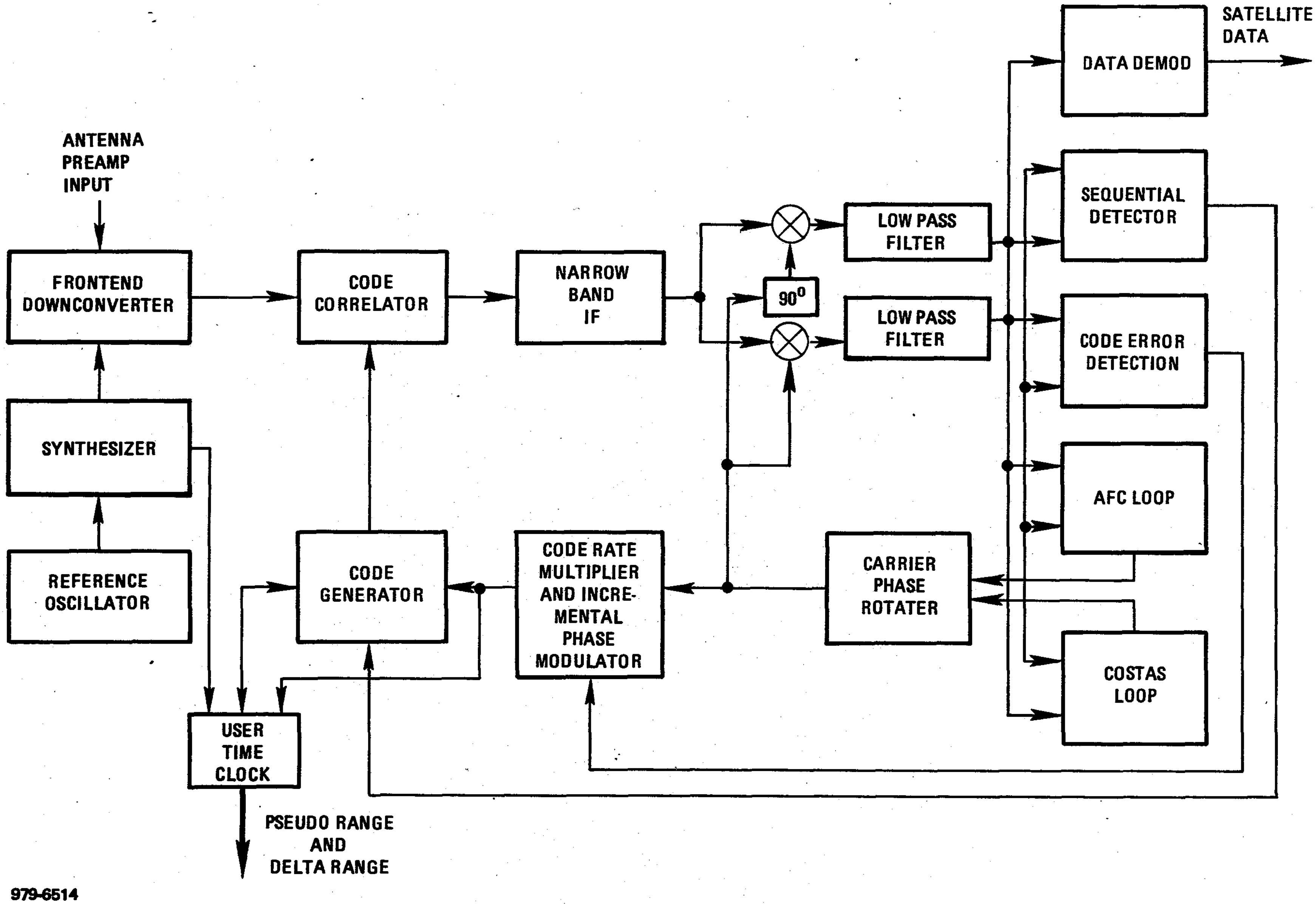


Figure 8-6. Sequential GPS Receiver Functional Block Diagram

Several alternatives exist for implementing the above signal processing functions. Other than the code generator and control logic the receiver can be implemented with conventional analog signal processing circuitry. An alternative is to digitize the signal either at IF or at the output of the quadrature detectors and process the signals with a combination of digital hardware and software using a digital computer.

In the extreme case the signal could be digitized ahead of the correlator at the first IF and all of the signal processing could be performed using a high speed digital computer. This approach would not be cost effective at anytime during the foreseeable future due to the high speed requirements to handle the 73 MHz IF and the 1.023 MBps code. Generally it is desirable to perform preprocessing ahead of a signal processing computer to reduce the real time speed requirements to only the uncertainties of the signal to be processed. In the case of GPS the uncertainties are limited by the total residual doppler frequency uncertainties plus any oscillator frequency uncertainty. These uncertainties are limited to less than 10 KHz if the highly predictable satellite doppler shift is accounted for. Due to these relatively low residual uncertainties the cost and complexity of high speed sampling and preprocessing at the 1st IF is unwarranted.

The remaining alternatives other than analog processing are to sample at the low final IF or to sample the baseband at the output of the quadrature multipliers. Sampling at the last IF allows the demodulation and carrier tracking to take place totally in software or in a combination of a hardware phase comparator circuit and software. Sampling at baseband requires a hardware voltage controlled oscillator (VCO) or a combination of a rate multiplier and incremental phase modulator (RM/IPM); both of which are more complex than a phase comparator network.

In all practical implementations the code clock must use a VCO or a RM/IPM to drive the code generator.

The above discussion leads to two remaining alternatives for the low cost GPS receiver baseband: Analog processing or digital processing with sampling at the last IF. The analog processing is linear and therefore provides the lowest threshold under ideal conditions. Digital processing gives equivalent processing if four or more bits of amplitude quantization are used. In the worst case with hard limiting of the IF signal in a 20 KHz predetection bandwidth a digital phase sampler will have a little over 1 dB higher threshold than a linear system. However, in a jam free environment, which is the case for civil users, the GPS signals will have 4 or 5 dB signal to noise ratio margin and the signal loss due to hard limiting will have a negligible impact on initial acquisition and range measurement accuracy. The use of hard limiting and phase sampling at IF requires significantly less hardware than IF or baseband digital sampling using multilevel quantization.

The final tradeoff is therefore between analog processing and digital processing using hard limiting and phase sampling at IF. Analog processing requires many discrete components for bandwidth and time constant selection, analog switches, a precision VCO as well as MSI or LSI analog multipliers, OP amps and threshold detectors. The analog design requires careful control of DC offsets during manufacturing.

The digital baseband can be implemented with a digital phase sampler and comparator combined with a single chip microcomputer. The phase sampler and comparator can be built with 15 or 20 MSI chips or can be incorporated into an LSI chip which contains the C/A coder, code control logic, code clock rate multiplier and incremental phase modulator, code clock synthesizer and the user time clock (UTC).

In production quantities of 10,000 sets or more the custom LSI chip containing the coder, digital baseband and UTC combined with a single chip 8 bit microprocessor for baseband signal processing will have significantly lower cost than an analog or digital signal processor using SSI or MSI circuits.

8.4 TECHNOLOGY

It is feasible to design a low cost GPS receiver using current technology. However, due to the high input frequencies envolved the frontend circuit and the first LO are most economically implemented with a combination of discrete, SSI and MSI devices. The digital coder, baseband and UTC can be implemented with SSI and MSI devices or a CMOS/SOS LSI chip and a commercial microprocessor depending upon the production quantities. A block diagram of low cost receiver using current technology without custom LSI circuits is shown in Figure 8-7. The printed circuit board area and power estimates for the 1979 vintage receiver is shown in Table 8-3. The technology and development risk for this design is low.

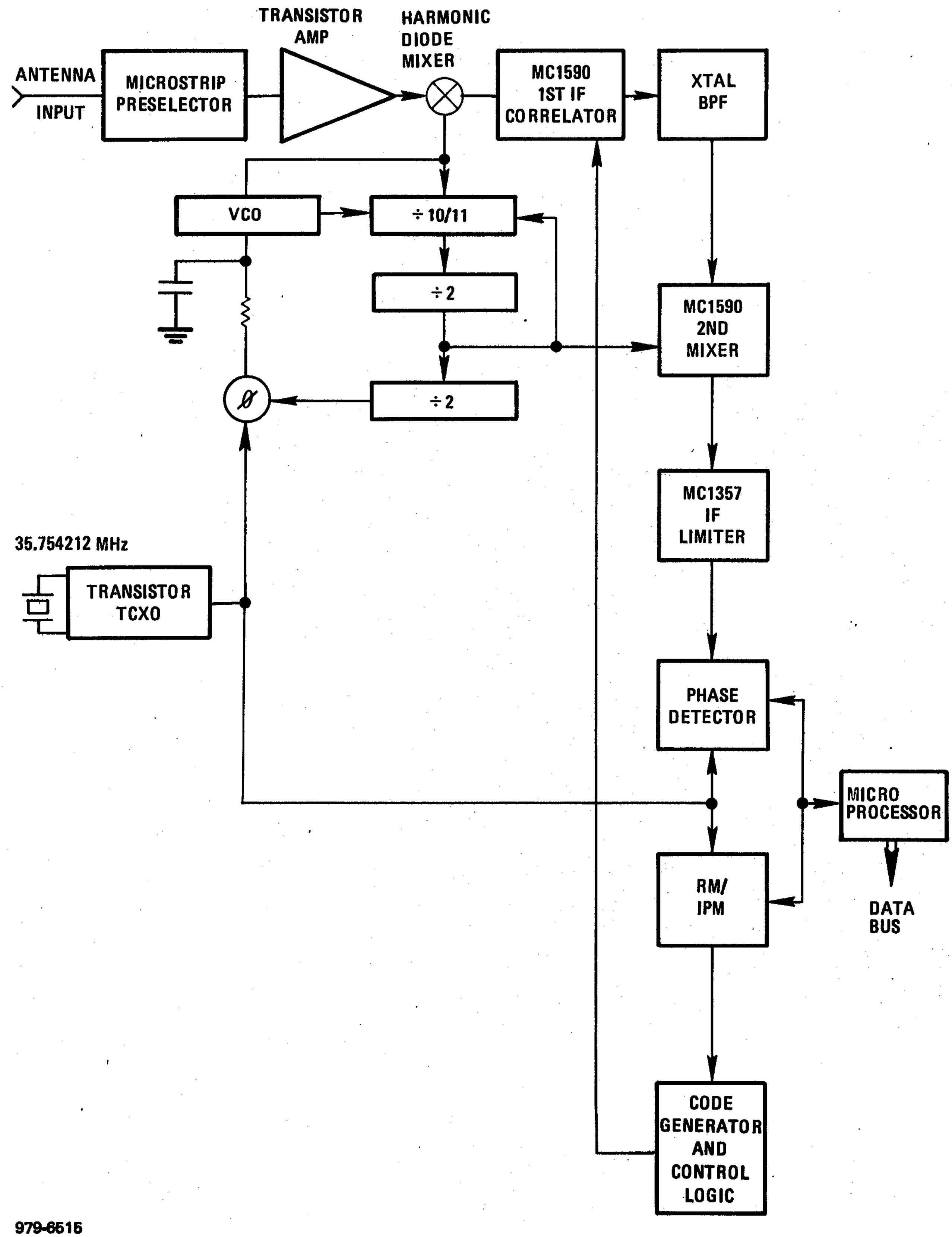


Figure 8-7. 1979 Low Cost GPS Receiver Without Custom LSI

Table 8-3. 1979 Low Cost Receiver Size and Power Estimates

Function	Size (in^2)	Power (milliwatts)
Preselector	2	0
RF Amp	3	10
Diode Mixer	2	0
1st IF Correlator	1.5	100
XTAL Filter	1	0
2nd Mixer Amp	1.5	100
IF Limiter	1.5	100
TCXO	4.0	25
Phase Lock Multiplier	6.0	1000
Phase Detector	4.0	500
Rate Multiplier/IPM	12.0	300
Code Generator	30	2000
Microprocessor	16	1500
Totals	84	5635

The first step in departing from the SSI and MSI implementation is to incorporate the digital phase detector, code rate multiplier/incremental phase modulator, and code generator into a single custom LSI chip. An analysis of the requirements to implement the functions using CMOS/SOS yields the transistor count given in Table 8-4. This technology was chosen since CMOS/SOS is one of the few LSI technologies which can currently operate at 35.75 MHz. It is anticipated that as IC lithography and processing techniques improve the smaller geometries will allow the functions to be implemented on a smaller chip and allow lower cost technologies to operate at 35.75 MHz. The size projections for the custom CMOS/SOS GPS signal processing chip (includes code, baseband and UTC functions) now and in 1985 are given in Table 8-5. The projected chip sizes for other technologies during the 1985 time period are shown in Table 8-6.

Table 8-4. 1979 Low Cost Receiver Transistor Count

	# Transistors
Command Buffer	310
Tri-State I/O	384
Coder and Slew Counter	614
C/A Coder and CMDE	1030
Course Range Buffers	744
Fine Range Buffers	360
Front End UTC	876
Back End UTC	320
8 Bit Adders	800
Sine and Cosine	640
8 Bit Register with Clear	640
8 Bit Register	640
Synchronous ÷ 16 Counter	175
Synchronous ÷ 10/11/12 Counter	175
Synchronous ÷ 4 Counter	200
÷ 35 Counter	150
Timing	580
	8638 Transistors Total

Table 8-5. CMOS/SOS Coder/Baseband/UTC Chip Size

51828 Mil^2	$(228\ Mils)^2$	6 sq Mils/Transistors	1979
25914 Mil^2	$(161\ Mils)^2$	3 sq Mils/Transistors	1985
# Gates = 2160			

Table 8-6. Projected GPS Coder Baseband UTC Chip Sizes for Various Technologies in 1985

	Die Size ($mils^2$)	Power
CMOS/SOS	161	50 mW @ 5V
NMOS (HMOS)	120	500 mW @ 5V
LST^2L	192	1.3 W @ 5V
I^2L (ISL)	120	80 mW @ 1V
CMOS/SI-Gate Bulk	192	30 mW @ 5V

The next logical area to apply custom LSI technology to the low cost receiver is in the LO frequency synthesizer. The GPS frequency plan is sufficiently unique that the synthesizer will not benefit directly from the normal evolution of commercial integrated circuits. Furthermore, because of the high output frequency of the first LO, advances in the IC state-of-the-art will be required. Currently 1500 MHz is about the upper limit for operation of silicon bipolar digital synthesizer logic. Gallium arsenide holds the potential for meeting the GPS synthesizer speed requirements; however, production quantity ICs are not expected to be available for a few years. Gallium arsenide IC technology may very well become mature at the time the full GPS constellation is operational.

The receiver frontend and downconverter are also candidates for a custom IC. These functions may be combined with the synthesizer if a higher level of RF integration is feasible during the 1985 time period. The frontend downconverter is more likely to benefit the normal evolution of commercial RF integrated circuits.

The lower frequency RF and IF circuitry can most cost effectively take advantage of commercial bipolar ICs. Both the general purpose and the more specialized FM radio and TV signal processing circuits may be adapted for the lower frequency portions of the GPS receivers.

Depending upon advances in the levels of RF integration it may be feasible and cost effective to combine all of the GPS receiver RF, IF and synthesizer functions into two or more custom RF integrated circuits.

Another technology area which should be addressed deals with the post correlation 20 KHz filter at the 73.75 MHz first IF. Presently both crystal and SAW resonator filters can satisfy the requirements; however, neither technology currently yield a low cost filter in this frequency range. It is anticipated that the SAW technology will provide the lowest cost solution by 1985.

Another important area where technology improvement are required to minimize the cost of civil GPS receivers is in the reference oscillator design. The minimum stability requirements currently are pushing the state-of-the-art for non-ovenized crystal oscillators. Since ovens add to the oscillator cost and require a warm up period, improvements in the state-of-the-art of temperature compensated crystal oscillators or SAW resonator oscillators could reduce the cost and improve performance of low cost GPS receivers.

8.5 PROJECTED 1985 LOW COST RECEIVER IMPLEMENTATION

Using the technology projection from the preceding section it is possible to estimate the size and power of a low cost GPS receiver in the 1985 time frame. Figure 8-8 shows the partitioning of a L1, C/A code sequential receiver into integrated circuits and filter elements. The projections are based upon the use of a custom integrated circuit for the synthesizer and a custom chip for the baseband coder UTC. The first downconverter may use a commercial IC if such a device becomes available by 1985. The remaining function can use standard commercial ICs. Figure 8-9 is a board outline showing the physical partitioning of the receiver. The projected receiver can be fully implemented with component technology which is starting to emerge today and expected to be mature by 1985.

8.6 RECOMMENDATIONS FOR TECHNOLOGY DEVELOPMENT

To assure the availability of components to manufacture a truly low cost GPS receiver during the mid to late 1980s technology advances must be made in the areas of high frequency, high speed RF integrated circuits, low cost, high performance crystal oscillators, and SAW filters and resonators.

Advances in RF ICs primarily using GaAs are required to reduce the cost and increase the level of integration of the synthesizer and frontend active circuitry. Advances in oscillators and resonators are required to yield a low cost oscillator which has little or no warm-up period yet meets the short term stability requirements for the GPS receivers. The advances in SAW technology are required to realize a low cost post correlation filter. Improved SAW technology may also yield a lower cost reference oscillator operating at a higher frequency which may also result in a simpler lower cost synthesizer.

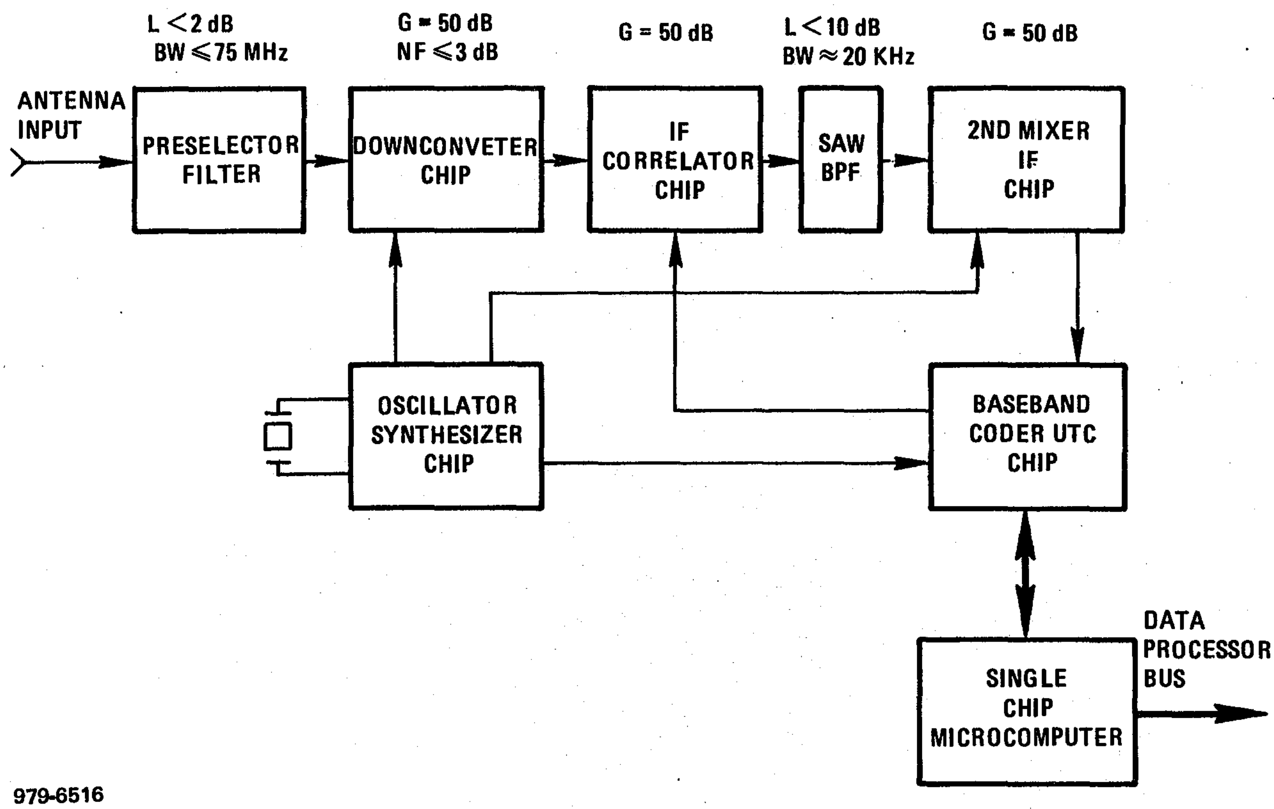


Figure 8-8. 1985 Low Cost GPS Receiver

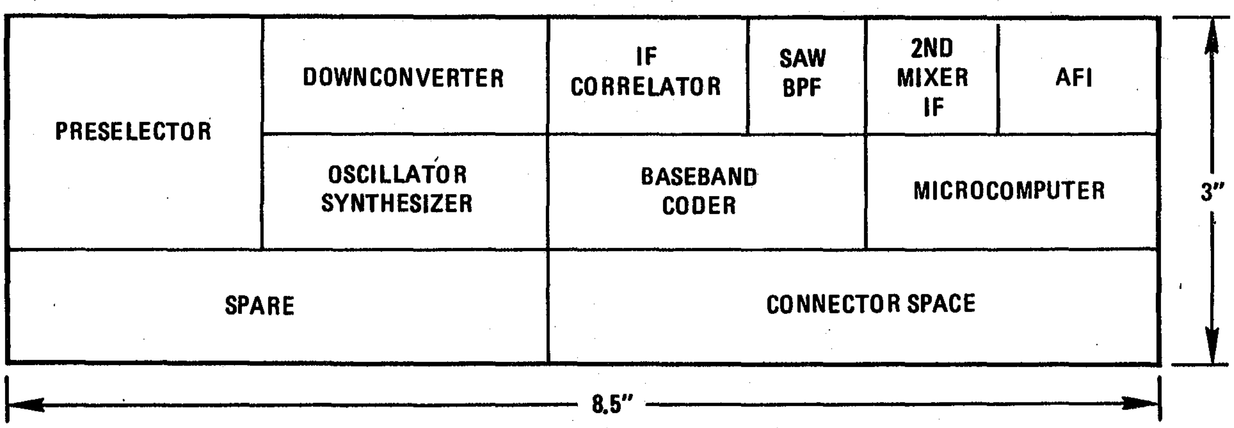


Figure 8-9. Low Cost Receiver Board Partitioning

SECTION IX
COMPUTER PROCESSOR

9.1 PROCESSOR REQUIREMENTS

The processor requirements for a low cost civil aviation GPS set are very close to those for GPS Set Z. The Z-Set was developed during GPS Phase I for SAMSO and has capabilities similar to the requirements identified in this report for Civil Aviation users. The processor characteristics are outlined in Table 9-1.

Several performance criteria important to the evaluation of candidate processors are:

1. Throughput (the number of instructions executed per second)
2. Arithmetic capability (floating point capability)
3. Addressing range
4. Memory size
5. Interrupt system
6. Availability of support hardware and software
7. Size, power and cost goals.

9.1.1 THROUGHPUT

The instruction execution times for the Set Z processor are listed in Table 9-2. These execution times are representative of one solution to the throughput problem. If some instructions are faster than those listed in Table 9-2 then others can be slower. For purposes of discussion, instructions are grouped into three major classes. These are:

1. Single precision floating point
2. Extended precision floating point
3. Basic instructions such as MOV, ADD which includes all instructions other than floating point.

Table 9-1. Processor Characteristics

Description	Characteristics
Main memory ROM	30,720 words x 16 bits
Main memory RAM	6,144 words x 16 bits
Main memory cycle	800 ns (ROM) 800 ns (RAM)
I/O program control	56 parallel I/O ports 1 serial I/O port
Interrupts	8 external vectored-interrupts, one internal vectored-interrupt and one flag for power Fail/Auto Restart
Central processing unit	16-bit arithmetic logic unit, 2's complement arithmetic general purpose computer with hardware floating point

Table 9-2. Average Instruction Execution Times for Z-Set Processor

Average Times for LSI-11[1]	μsec
Basic instructions (Mode 3)	7.7
Single precision flt. pnt.	
Add/subtract	48
Multiply	85
Divide	175
Extended precision flt. pnt.	
Add/subtract	63
Multiply	200
Divide	450

[1]LSI-11 is a registered trade mark of Digital Equipment Corp.

In Set Z about 40% of the time is spent executing basic instructions, about 35% on single precision and 25% on extended precision floating point instructions. If an additional 20% throughput is available, it can be used to do the CDU formatting and eliminate the need for a microprocessor in the CDU.

9.1.2 ARITHMETIC CAPABILITY

The arithmetic capability required is estimated to include extended precision 40 bit mantissa, 8 bit exponent floating point arithmetic for ADD, SUBTRACT, MULTIPLY and DIVIDE as a minimum supplement to the basic instruction set.

9.1.3 ADDRESSING RANGE

The present addressing range in Set-Z is 64K bytes which includes 128 bytes for I/O. A bank select bit addresses an additional 8K bytes of program memory. Increasing the addressing range from 72K bytes to 96K bytes is recommended to provide some design margin and for future growth.

9.1.4 MEMORY SIZE

The memory size requirements are estimated to be:

Program Memory	30K words x 16 bits
Data Memory	5K words x 16 bits
Almanac Memory	1K words x 16 bits

9.1.5 PROGRAM MEMORY

The program memory, at a minimum, requires a non-volatile, random access, read only memory. The non-volatility requirement eliminates the need for a memory loader. Read-only is a lesser requirement than read/ write and allows the use of low cost semiconductor ROM for program memory.

9.1.6 DATA MEMORY

The data memory may be volatile since it is used for the temporary storage of computed results. The data memory is required to be a read/write random access memory.

9.1.7 ALMANAC MEMORY

The almanac is required to be a non-volatile, read/write, low power, random access memory. Battery backup is required if CMOS RAM is used to make it non-volatile for a minimum of 25 weeks.

9.1.8 INTERRUPT SYSTEM

It is recommended that the interrupt vector address generation and device priority arbitration be performed in hardware. Single NMOS chips are available now to perform this task.

9.1.9 SUPPORT HARDWARE AND SOFTWARE

The availability of adequate hardware facilities and support software needed to develop application programs can have a significant cost and schedule impact on a development program. The hardware facilities should include a high speed host computer which supports several CRT terminals, one or more printers, a 20 megabyte hard disk for programs currently in use and a magnetic tape unit for software library control. The support software should include: a relocatable assembler, an acceptable higher order language compiler, loader-linker, math package and a proven operating system.

9.1.10 SIZE, POWER AND COST GOALS

It is desirable to have a low cost GPS receiver which meets the needs of the majority of the civil aviation community. Good navigation performance at low cost is key to wide acceptance; but so is packaging. In addition, the set should be easy to install in most civilian aircraft.

To do this, the set must be small; which suggests the use of LSI integrated circuits to achieve not only small size but also low power and low cost in the processor design.

9.2 TECHNOLOGY DEVELOPMENTS

Considerable effort is being expended by the semiconductor industry toward increasing function density, improving speed and at the same time lowering power dissipation in newly developed integrated circuits. Impressive gains have been achieved in NMOS. For example, NMOS memory chips have increased function density by at least a factor of 4 in the past few years with improved performance. Table 9-3 projects memory chip density growth from 1979 through 1985. The estimates are based on information received from semiconductor marketing personnel. About a year to a year and a half was added to the time estimates received. Past experience with "announced parts" versus "delivered parts" indicates that there is often a rather long waiting period and often a redesign cycle before the parts are really available.

Table 9-3. Memory Chip Technology Projection During Next Six Years

Chip Type	Year 79	80	81	82	83	84	85
EPROM	32K	64K				128K	
ROM NCH	64K	128K		256K			
ROM CMOS	16K	64K	128K				256K
ROM CSOS	1K	4K	16K				
PROM LS	16K		32K	64K			
PROM CMOS	1K		4K	16K			32K
RAM NCH Static	16K						
RAM CMOS Static	64K	HYB		16K	256K	HYB	
RAM CSOS Static	4K		16K				
RAM I^2L Dynamic	16K						
RAM NCH Dynamic	64K						

Microprocessors have gone from 8 bit to 16 bit data processing devices with addressing capability increased from 64K bytes to 1 million bytes or more. Table 9-4 lists 16-bit microprocessors which are available today or have been "announced" and are expected to be available within the next year. Note the 32-bit arithmetic-logic unit in the Motorola 68000. This is a feature associated with high performance medium sized computers. The wider accumulator speeds up address calculations in a memory system greater than 64K bytes and speeds up 32-bit arithmetic operations resulting in a significant improvement in throughput. Any of the microprocessors listed in Table 9-4 have adequate throughput as far as basic instruction execution times are concerned but none of them have the computing capability to perform the GPS navigation problem except the Digital Equipment Corporation LSI-11/23 which has support from a relatively high performance floating point unit. Table 9-5 indicates the status of several floating point arithmetic chips announced or available today. A trend is developing to support the higher performance 16-bit microprocessors with improved floating point arithmetic capability. In the next few years, supporting chips for high speed floating point arithmetic, timing and I/O control operations will give the microprocessor chip sets of 1984-85 the computing power of today's medium sized computers.

Table 9-4. 16-Bit Microprocessor Features

Feature	Intel 8086	Zilog 8000	Motorola 68000	Fairchild 9445	DEC LSI-11/23
Technology	NMOS	NMOS	NMOS	I^2L	NMOS
Avg Basic Instr ms	3.4	2.5	2.5	1.4	3.5
No. Reg/Reg. Bits (Avail. to Programmer)	16/16	16/16	16/32	4/16	8/16
ALU Bit Size	16	16	32	16	16
Addressing Range (Bytes)	1 MEG	8 MEG	16 MEG	128K	256K
Number of Pins Dip Package	40	48	64	40	40 (2 DIPS)
Power Requirements	5V, .27A	5V, .3A	5V, .3A	1.05V, .5A 5V, .15A	+12V, .12A + 5V, .2A

Table 9-5. Floating Point Chip Status

	Single Precision μSec Avg.	Double Precision μSec Avg.	Comments
AMD 9511	130	No DPFP	Available in Quantity
AMD 9512	170	937	Samples Available
INTEL 8087	?	?	Information Release Planned 4Q79
FCH 9443	?	?	Design Data not Available at This Time
DEC KEF11-AA	77	166	Available 1Q80

9.3 PROCESSOR CANDIDATES

The LSI-11/23 (Table 9-4) is an acceptable processor for the low cost civil aviation GPS set if the three DIP packages required are supported by several LSI gate arrays to minimize SSI, MSI support chips. The other microprocessors in Table 9-6 require fewer support chips and would be likely candidates when suitable floating point capability is available.

The N-channel technology will most likely offer the lowest cost memory and microprocessor system. NMOS is a satisfactory choice for the civil application since neither nuclear hardening nor ultra-low power are required.

9.4 RECOMMENDED PROCESSOR DESIGN

The recommended processor (Figure 9-1) has a central processing unit (CPU), a memory system, a real time clock and input/output interfaces.

9.4.1 CENTRAL PROCESSING UNIT

The CPU is made from a single chip NMOS microprocessor packaged in a 64 pin DIP. The microprocessor is supported with a 40 pin DIP floating point unit, three LSI gate arrays and an LSI timer such as the AMD 9513.

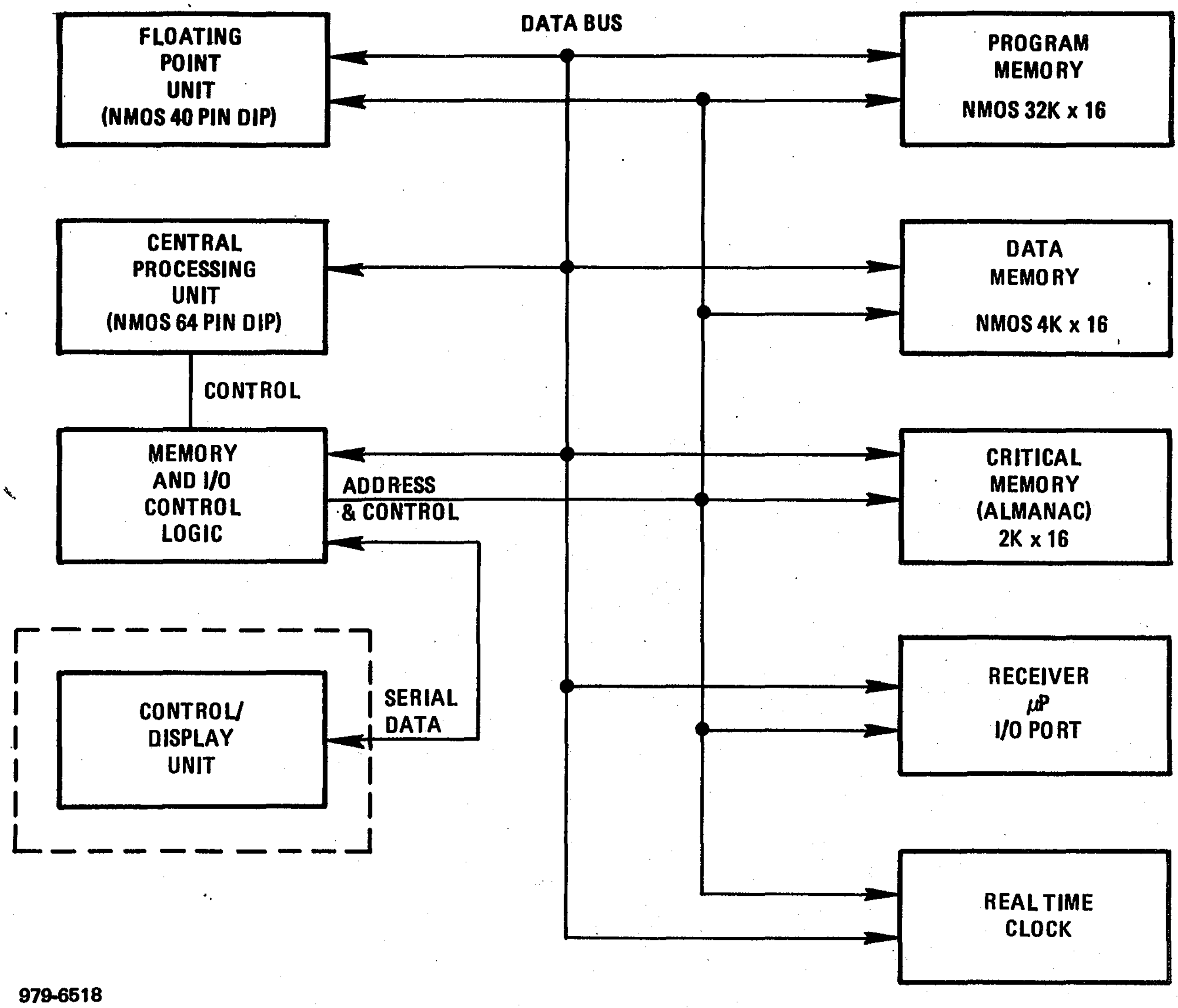


Figure 9-1. Processor Block Diagram

9.4.2 MEMORY SYSTEM

By 1985 it is expected that the 32K word program memory would require two 256K bit (32Kx8) NMOS ROM chips or four 128K bit (16Kx8) NMOS EPROM chips. The data memory would consist of two 32K bit (4Kx8) NMOS RAM's. The almanac memory would require two 16K (2Kx8) EAROM's. EAROM's of the future will require fewer voltages and have faster write times and will probably be the best choice for almanac memory. However, an alternative would be two 16K (2Kx8) CMOS RAM's and the backup battery used for the real time clock.

9.4.3 REAL TIME CLOCK

The real time clock is a lower power (CMOS) Counter supported by a small rechargeable 4-volt battery to provide keep-alive power.

The real time clock allows automatic initialization. The set does not require operator entries to start navigating on power turn on after power has been off for as long as 25 weeks.

9.4.4 RECEIVER INTERFACE

The receiver I/O port is an interface to an 8-bit microprocessor in the receiver. It is primarily a tri-state gate interface which allows 8 bit data to be gated onto the main processor data bus.

9.4.5 CONTROL/DISPLAY UNIT INTERFACE

The interface between the processor and the Control/Display Unit is serial to reduce the number of pins required for the CDU input data register as shown in the CDU Block Diagram, Figure 9-2.

The interface signals are defined as serial data, clock, enable read and load signals in Table 9-6.

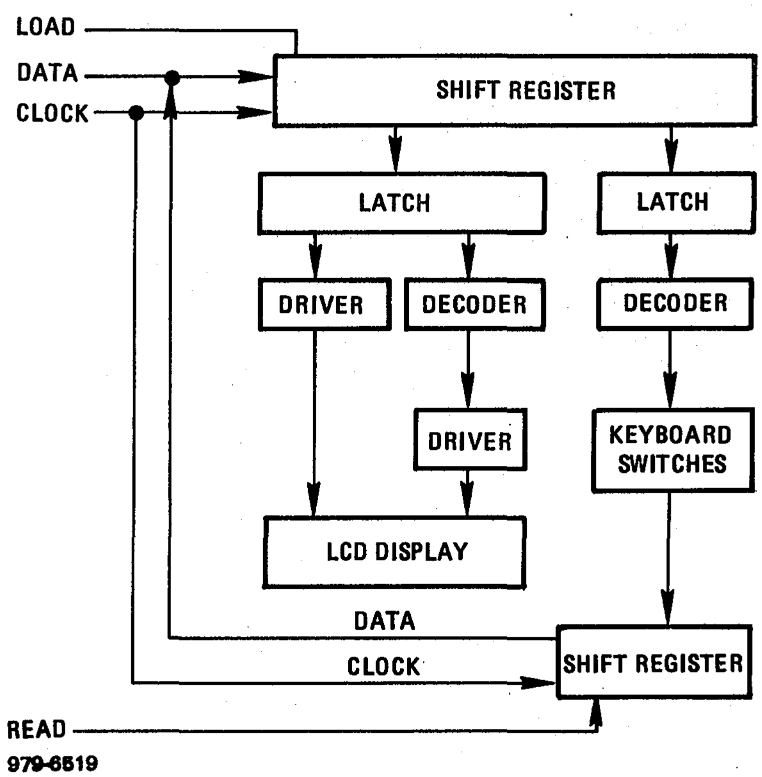


Figure 9-2. CDU Block Diagram

Table 9-6. RPU/CDU Interface Definition

Signal Name	Type	I/O	From	To
1. Clock	500 KHZ Gated Clock, TTL	O	RPU	CDU
2. Data	Serial Bidirectional, TTL	I/O	RPU	CDU
3. Enable Read	Data Direction Control, TTL	O	RPU	CDU
4. Load	Data Load Strobe, TTL	O	RPU	CDU
5. Standby	Standby Position of Mode Switch (switch closure to ground)	I	CDU	RPU
6. ON	ON Position of Mode Switch (switch closure to ground)	I	CDU	RPU
7. Power	+9 VDC	O	RPU	CDU
8. Ground	System Ground	O	RPU	CDU

9.5 SET INTERFACES

9.5.1 ANALOG INTERFACE OPTION

An analog interface to a Course Deviation Indicator is provided as an option for the General Aviation GPS Set as shown in Figure 9-3.

A more detailed picture of the analog interface (Figure 9-4) shows the desired course resolver interface consists of a 26 volt, 400 HZ reference a synchro to digital converter and a parallel data buffer interface to the main processor. The horizontal RIGHT/LEFT course indicator interfaces to a digital to analog converter. The D/A input from the main processor is held in a register as are the two bits which drive the TO/FROM indicator on the CDI.

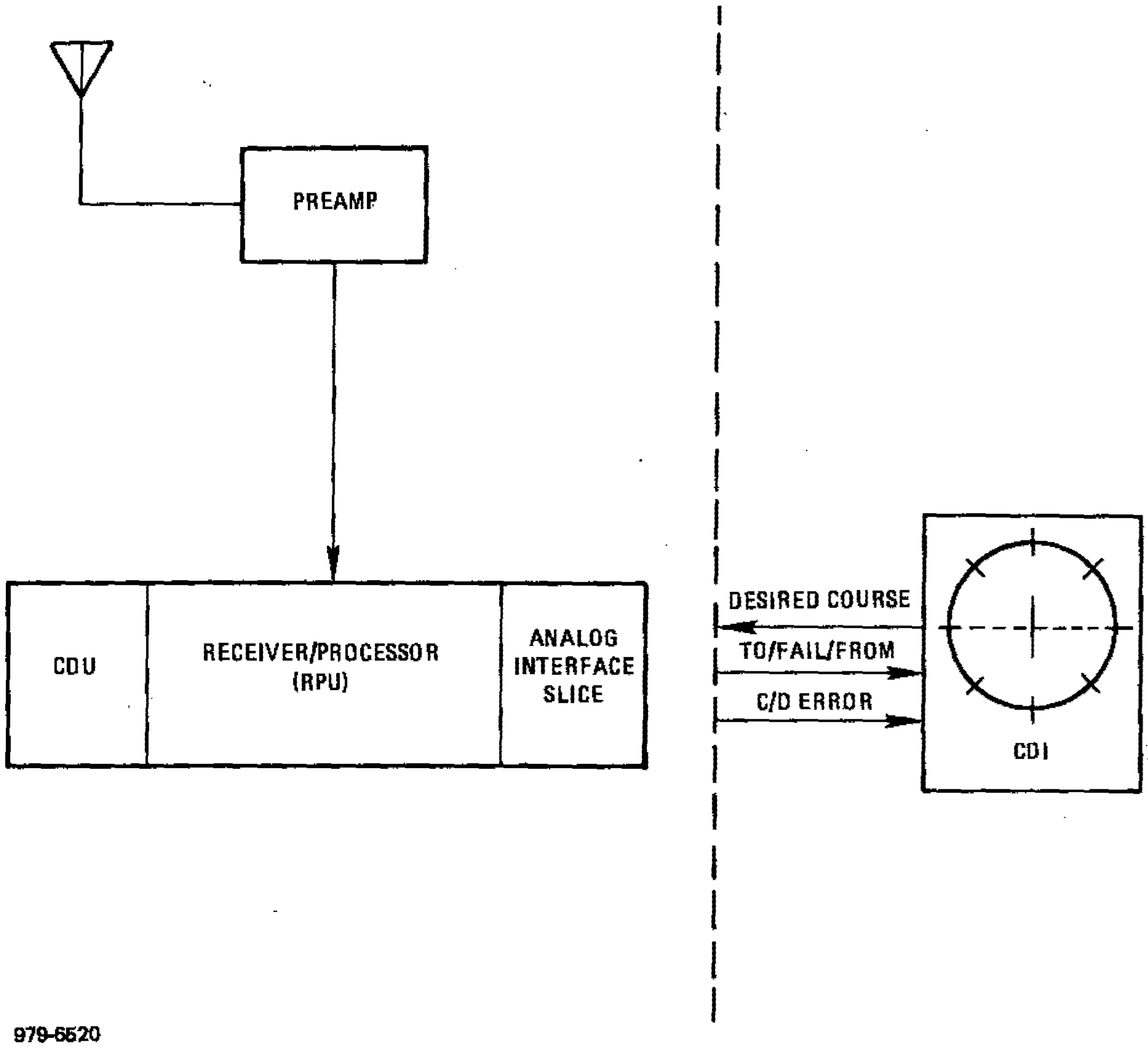


Figure 9-3. General Aviation GPS User Set

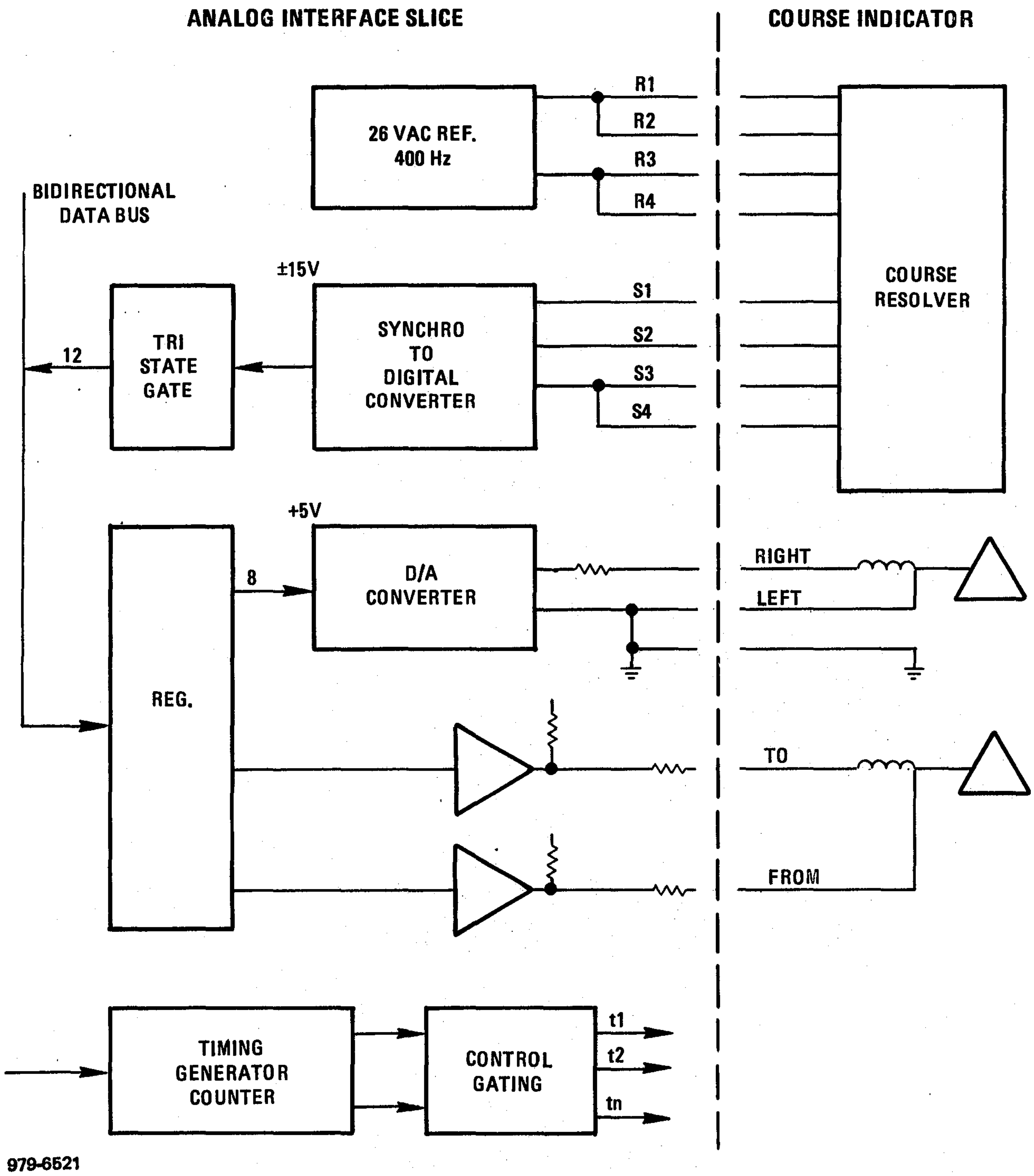


Figure 9-4. Analog Interface Block Diagram

The remaining logic on the analog interface slice provides timing and control to initiate and terminate data transfers. The CDI interface is summarized in Table 9-7.

Table 9-7. Interface Definition, General Aviation GPS Users

Signal Name	Type	I/O	From	To
1. Cross Track Deviation	Analog ± 200 μA	O	RPU	CDI
2. TO/OFF/FROM	Discrete +/0/- 200 μA	O	RPU	CDI
3. Omni Bearing Selector	Analog 4-Wire Resolver	I	CDI	RPU

9.5.2 DIGITAL INTERFACE OPTION

Commercial airline applications should take advantage of the Area Navigation Computer and navigation display hardware already on the aircraft to reduce their GPS Set cost. Figure 9-5 shows a GPS Set which is minus a CDU but has a simple digital interface to a commercial airline Area Navigation Computer.

The digital interface block diagram (Figure 9-6) is just a bidirectional serial to 16-bit parallel interface. The serial interface Table 9-8 follows the ARINC 429 timing and driver/receiver circuit recommendations.

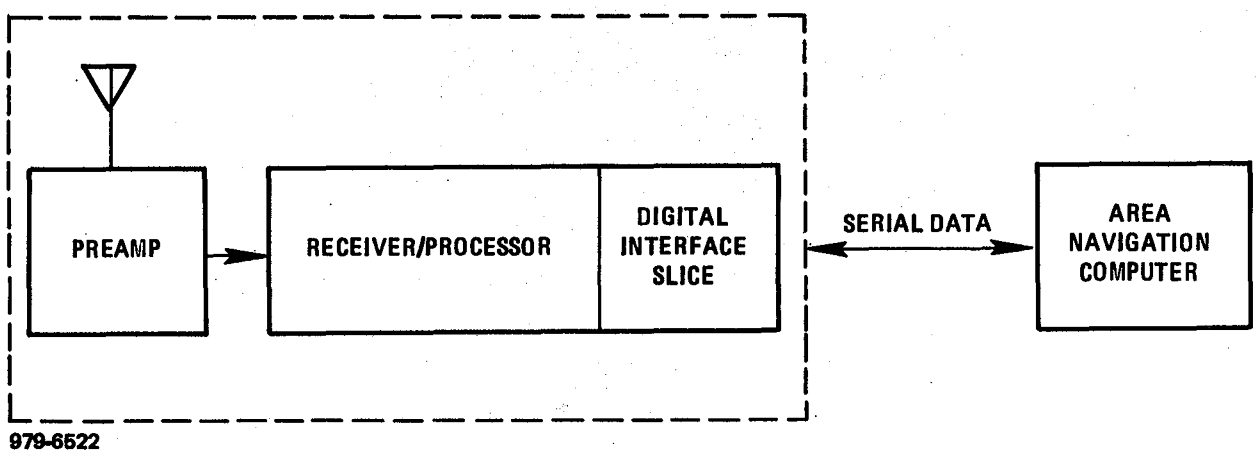


Figure 9-5. Commercial Airlines GPS User Set

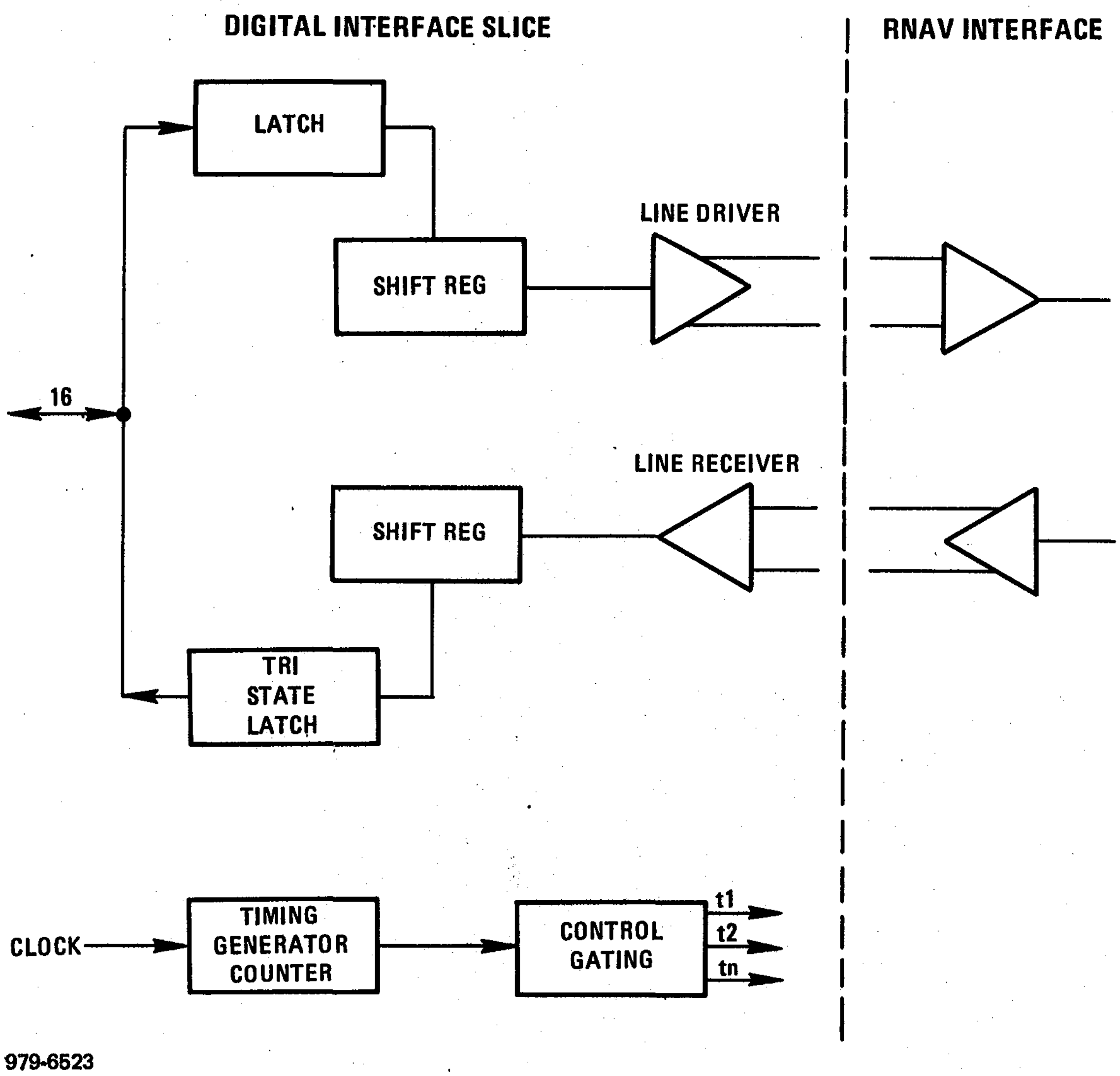


Figure 9-6. Digital Interface Block Diagram

Table 9-8. Interface Definition, Commercial Aviation GPS User

Signal Name	Type	I/O	From	To
1. Serial Data Out	Digital ARINC 429	O	RPU	RNAV
2. Serial Data In	Digital ARINC 429	I	RNAV	RPU

SECTION X
POWER SUPPLY

10.1 GENERAL

The objective of this study is to identify power supply design techniques which meet the general aviation requirements in the most cost effective manner. In pursuing this objective, the designer must be aware of system performance requirements and their impact on known power-conditioning techniques. The number of variables to be designed in a converter generally exceeds that of the constraints linking variables to various performance requirements. The basics of design optimization, therefore, is to design a minimum set of variables required for adequate performance. A minimum set of variables will reduce the number of parts, improve reliability, reduce size and cost. The basic power supply requirements are given in Table 10-1.

10.2 TRADE-OFF'S

10.2.1 ON-LINE BOOST REGULATOR

The on-line boost regulator illustrated in Figure 10-1 is the most extensively used converter. The on-line chopper is a buck-regulator followed by a boost converter. The attraction for this approach is the ability to maintain regulated multiple outputs under substantial load current variations (down to zero loads). However, since the system under study is characterized by relatively steady loads, a more suitable approach would be to remove the chopper and line filter and drive the converter directly from the pulse-width modulator. This approach reduces the number of active power stages from two to one; thus, reducing complexity and improving efficiency by approximately 7%. The estimated parts count for the on-line chopper approach is 60, and for the pulse-width modulated converter is 54 parts.

Table 10-1. General Power Supply Specifications

Input Line Voltage ⟶ 9.6VDC to 13VDC

		REG	RIPPLE	LOAD (max)	USE
Outputs:	9VDC	±5%	50 MV P-P	390 ma	Receiver + LCD's
	5VDC	±3%	50 MV P-P	1000 ma	Processor

Input Power: h ≈ 75%, 11.4 W (max.)

Size: 3" x 2" x 1/2"

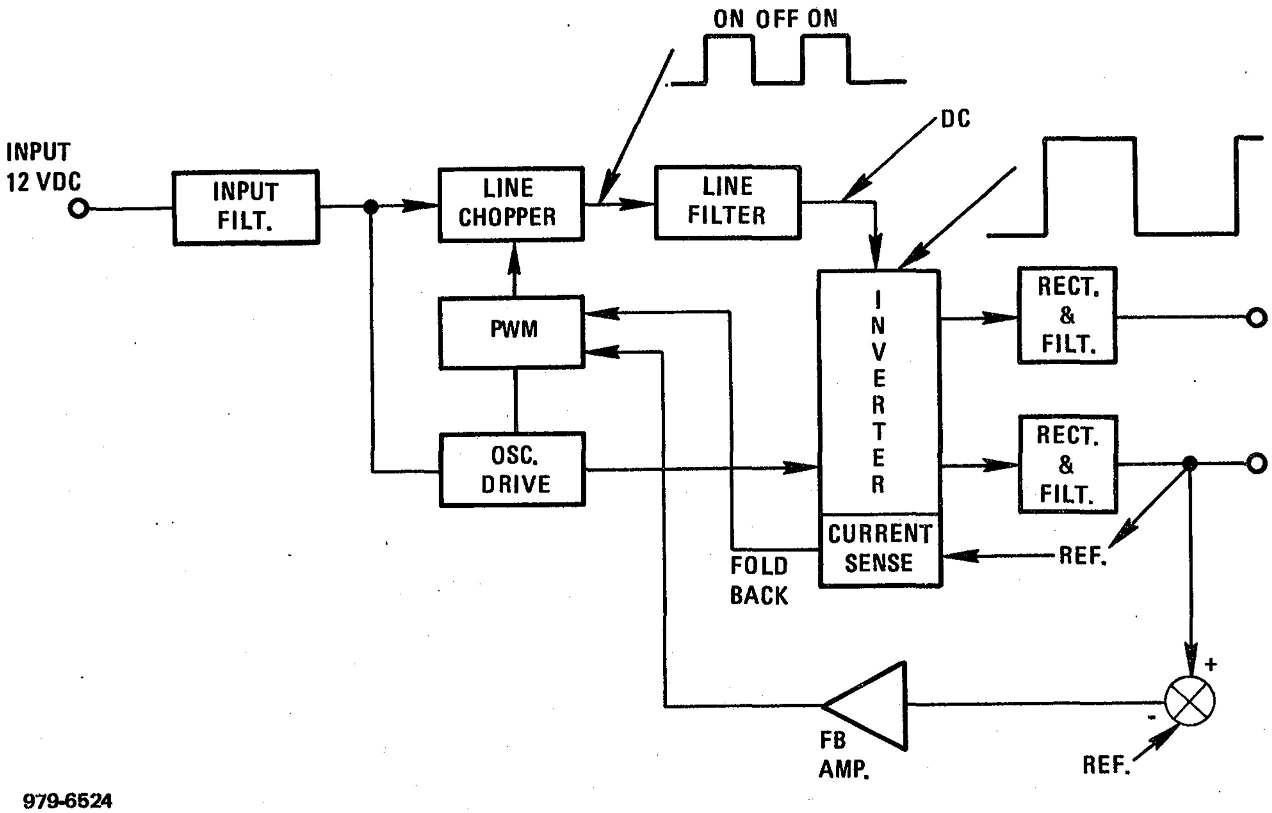


Figure 10-1. Chopper Regulator

10.2.2 OFF-LINE BOOST REGULATOR

A more suitable design approach than the two previously discussed is illustrated in Figure 10-2. Like the directly driven pulse-width modulated converter. This approach is classified as an off-line boost regulator. However, only two transistors are used and the parts count is reduced to approximately 28.

10.2.3 DESIGN SIMPLICITY

The design approach of Figure 1-B uses an input L-C filter followed by a free-running multivibrator inverter stage. The inverter stage drives a series magnetic amplifier from the inverter transformer secondary winding. The magnetic amplifier will use two gate windings and two control windings. One control winding will be directly coupled to the output by means of a simple low voltage avalanch zener. The other control winding will be coupled by the current transformer (converted to a voltage gradient) and connected (through the control winding) to the 5 volt output which is used as a reference. With the exception of the inverter stage, all other functions may be regarded as passive circuits. Together the functions include output voltage regulation and overcurrent (fold-back) control.

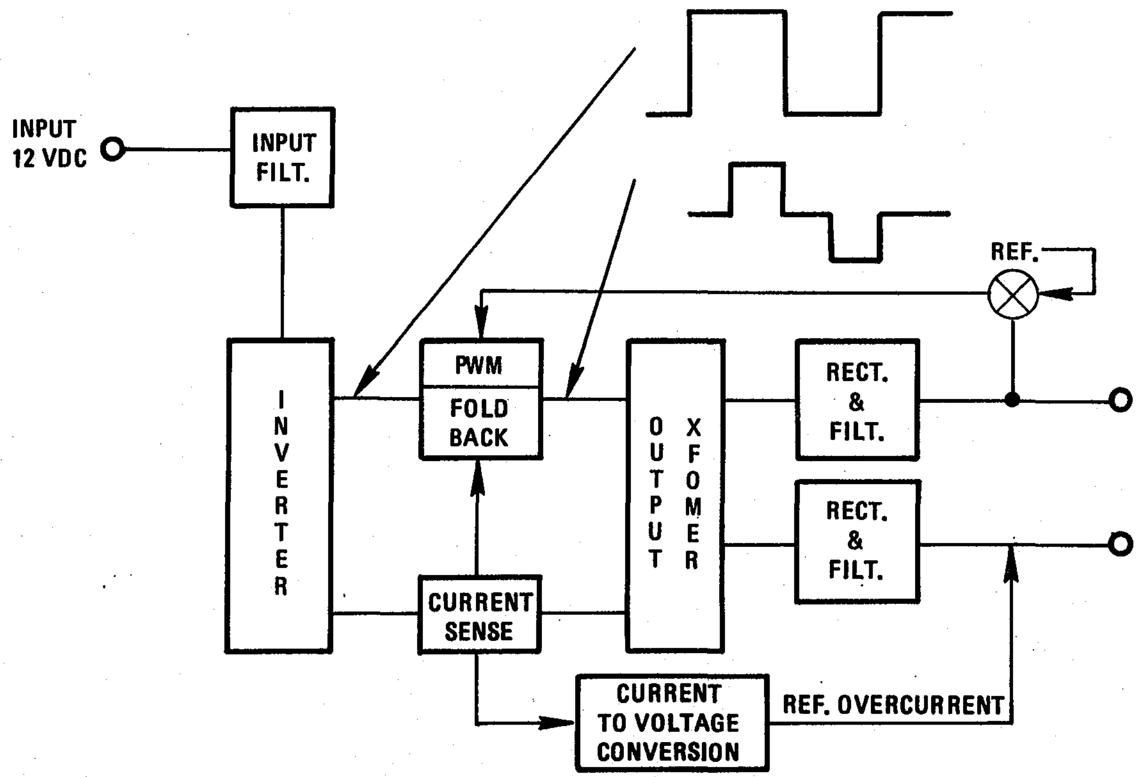


Figure 10-2. Off-Line Regulator

With the exception of the mag-amp and current transformer, ferrite pot cores (varnished-unpotted) will be used for power transformers and chokes. The proposed frequency of operation will be 100 KHz.

10.3 COST EFFECTIVENESS

The power supply may be completely assembled on one printed board (6 square inch area) and interconnected by a plug-in connector; thus eliminating all wiring in assembly. Semiconductors, resistors, capacitors and magnetics will be commercial quality parts.

10.4 POWER SOURCE (LEAD ACID BATTERY)

Most widely used battery to fit 4 to 6 cylinder aircraft are 6 cell 35 AH. Battery characteristics range from 13 volts (fully charged open-circuit voltage) down to 9.6 volts (fully discharged).

SECTION XI
PACKAGING

11.1 PACKAGING ASSUMPTIONS

Basic packaging groundrules for a civil aviation set are summarized as follows:

- Low Cost
- Light Weight
- Compatibility with civil panel cut-outs
- Civil environmental conditions

To meet the low cost objective, the basic design will consist of a flex print harness containing the required PWB's held in place on spindles. Connectors will be molded in the harness and removal of the dust cover will allow complete access for testing. The light weight objectives will be met by minimizing the total number of parts and employing light-weight construction techniques.

To provide a set which will be compatible with panel cut-outs and/or space allocations in existing general aircraft, a standard ATI package configuration was specified. An alternate approach for multi-function sets is a package configuration which is a direct swap-out for present day VOR and/or Transceiver sets.

Environmental requirements are based on ARINC Report No. 403, "Guidance for Designers of Aircraft Installations". These environmental requirements are summarized in Table 11-1.

Table 11-1. Civil Aviation Environmental Requirements

Parameter	Requirement
Temperature Ambient	+19°C to +55°C, 70°C for 30 minutes
Humidity	95%
Storage Temperature	-65°C (-85°F)
Vibration	10~ to 55~ .060 double amplitude in any axis
Shock	15 g's - 10 milliseconds, 3 shocks in each plane

11.2 SIZE REQUIREMENTS

Package requirements are driven by the size requirements of the following major functional areas:

- Control/Display
- Receiver
- Computer/Processor
- Power Supply
- Interface

The height and width of a civil aviation set are essentially dictated by the control-display panel requirements. As shown in Sections 4 and 5 of this report, a conservative CDU size is 4 x 4 inches and a minimum size CDU is 3.375 x 3.375 inches.

The size requirements for the receiver are developed in Section 8. Technology projections for 1985 indicate that the receiver will require approximately 25 square inches. Figure 11-1 is a board outline showing the physical partitioning of the receiver.

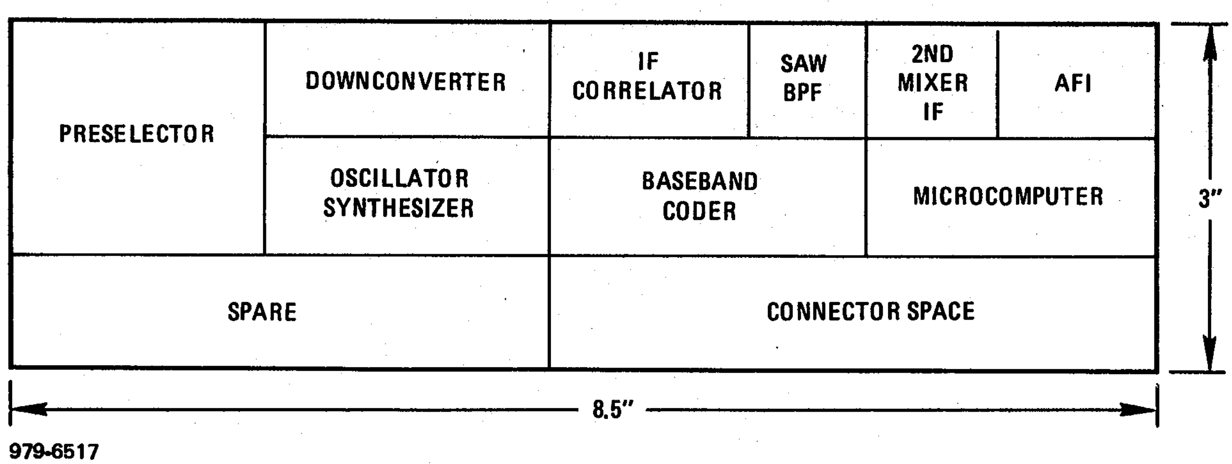


Figure 11-1. Receiver Board Configuration

The CPU defined in Section 9 will be implemented with a 64 pin DIP CPU supported with a 40 pin DIP floating point unit and several LSI gated arrays. The memory will consist of 4 DIP packages. The RTC and I/O will be implemented with 16 pin DIP packages. Figure 11-2 is a board outline showing the physical partitioning of the Computer Processor.

11.3 EQUIPMENT CONFIGURATIONS

Three separate packaging configurations have evolved from this study as a result of considering the groundrules for a civil aviation set and its size requirements:

- NAVSTAR Set - 1980 Technology
- NAVSTAR Set - 1985 Technology
- NAVSTAR/COMM Set

Figure 11-3 shows a conservative approach to the NAVSTAR set. The set is packaged in an ATI-4 case (4" x 4" x 8"). A total of six boards are used. The receiver uses two boards, the computer requires two boards, the power supply has one board, and one board is allowed for optional features. Table 11-2 shows the size, weight and power projections.

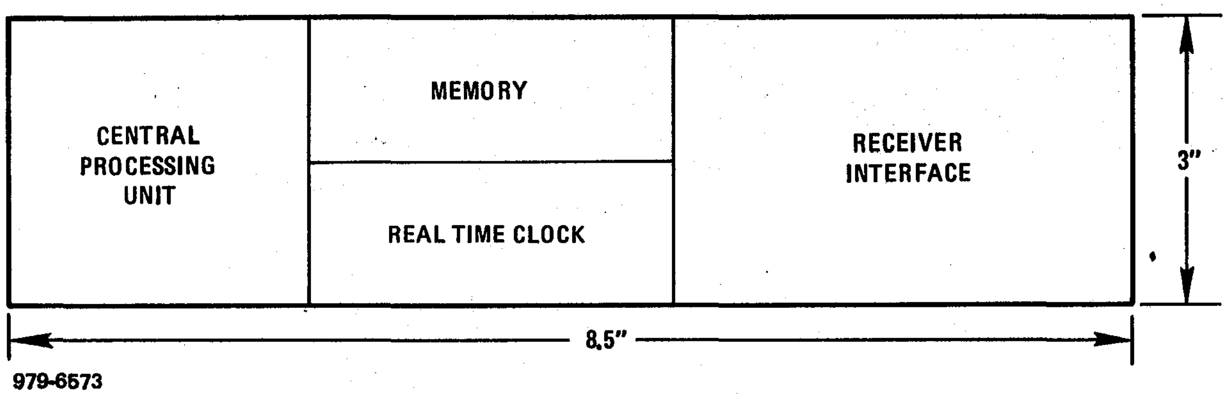


Figure 11-2. Computer/Processor Board Configuration

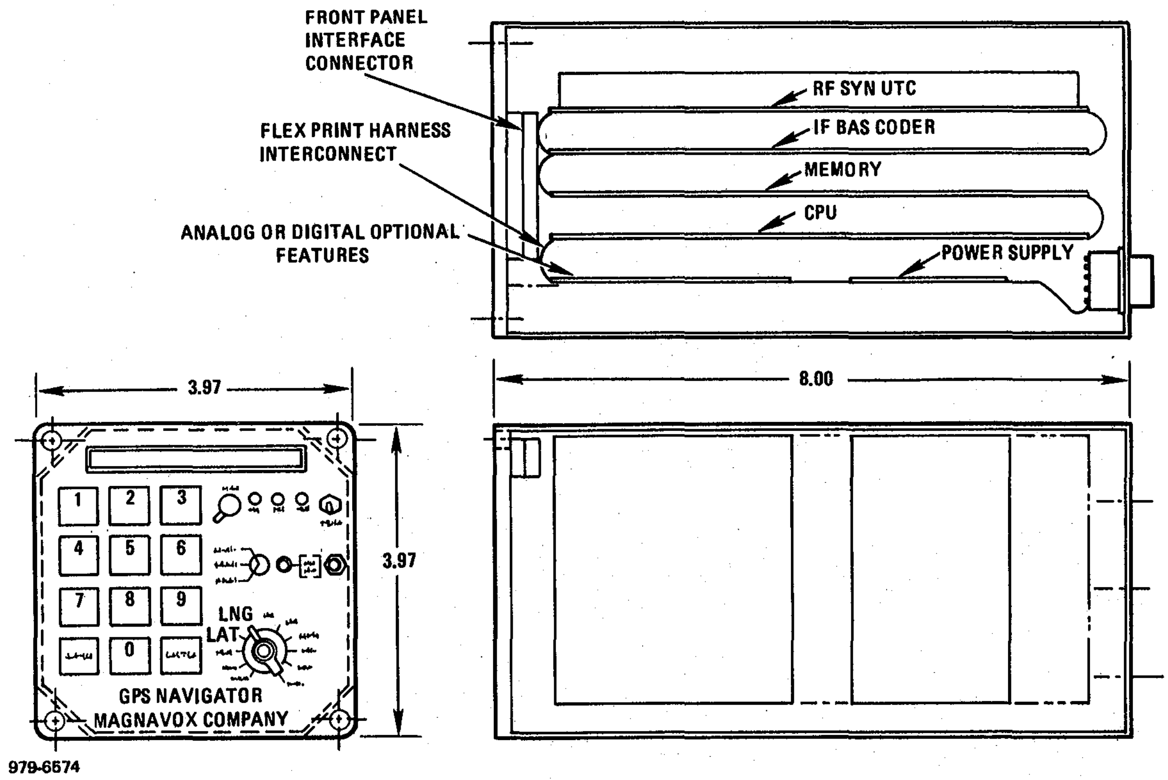


Figure 11-3. NAVSTAR Package - 1980 Technology

Table 11-2. NAVSTAR Packaging Parameters - 1980 Technology

Parameter	Projected - Value
Volume	126 in^3
Weight	4.5 lbs
Power	8 watts
Thermal Dissipation	0.25 $watt/in^2$ (top surface)

Figure 11-4 shows an optimistic approach to the NAVSTAR set. The set is packaged in an ATI-3 case (3.175" x 3.175" x 9"). One board each is allocated for the receiver and computer. The power supply and optional features are contained on two half size boards. Table 11-3 shows the size, weight and power projections.

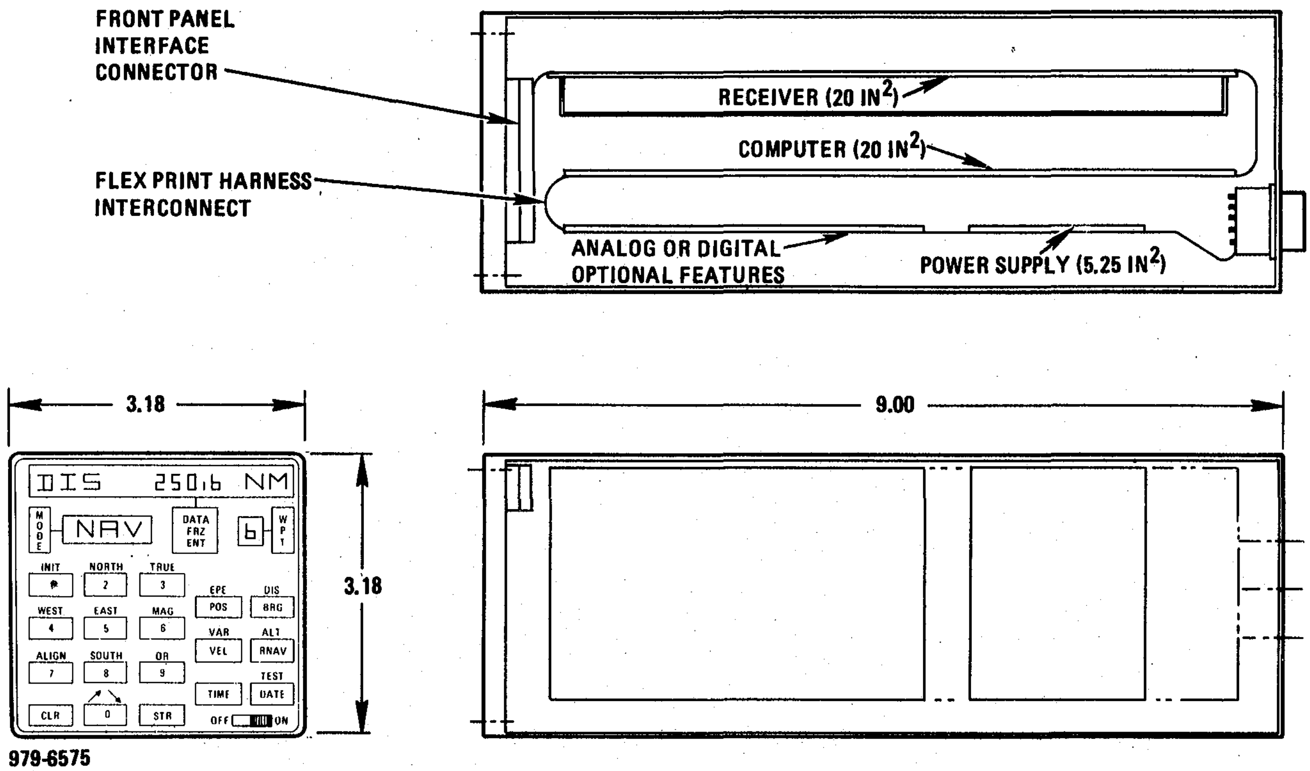


Figure 11-4. NAVSTAR Package - 1985 Technology

Table 11-3. NAVSTAR Packaging Parameters - 1985 Technology

Parameter	Estimated Value
Volume	91 in^3
Weight	3 lbs
Power	5 watts
Thermal Dissipation	0.2 $watts/in^2$ (top surface)

Figure 11-5 shows a NAVSTAR set with the addition of a CDI and transceiver unit. One additional board is attached to the front panel containing the LCD control/display and a transceiver module is located behind the CDI. Table 11-4 shows projected values for size, weight and power.

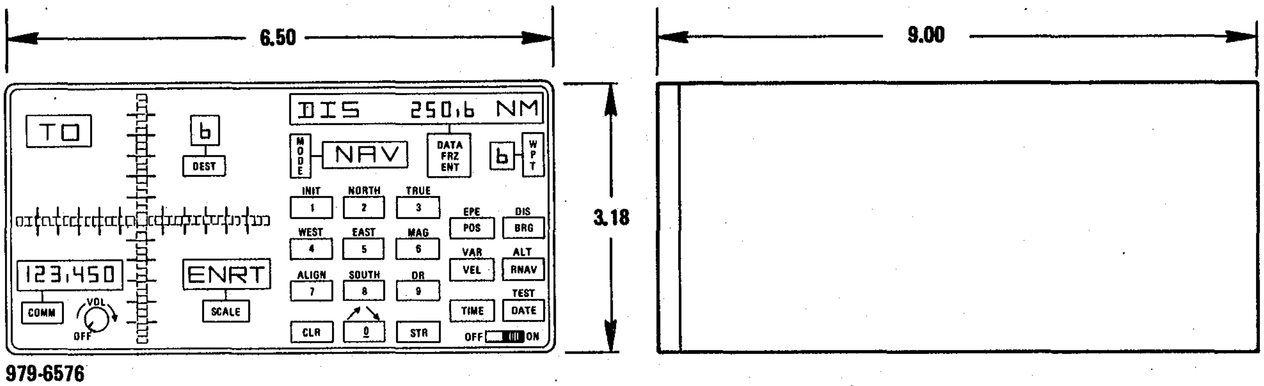


Figure 11-5. NAVSTAR/COMM Package

Table 11-4. NAVSTAR/COMM Packaging Parameters

Package Parameter	Estimated Value
Volume	186 in^3
Weight	5 lbs
Power	10 watts
Thermal Dissipation	0.2 $watts/in^2$ (top surface)

REFERENCES

1. Denery, D. G. et al.: Integrated Avionics for Future General Aviation Aircraft, AIAA Paper 78-1482. American Institute of Aeronautics and Astronautics, New York, 1978.
2. Gilbert, Glen A.: IFR Helicopter Operations in the National Airspace System. FAA Aviation Review Conference, May 1975.
3. Godfrey, G. W.: Crew Station Illumination. Aerospace Lighting Institute, Columbus, 1974.
4. Hemesath, N. B. et al.: Three and Four Dimensional Area Navigation Study, Report No. FAA-RD-74-150. Department of Transportation, Washington, 1974.
5. Krippner, R. A. and Fenwick, C. A.: A Digital Flight Management System Concept for Advanced Tactical Fighter Aircraft. NAECON '75 Record, Dayton, 1975.
6. Litchford, G.: Aeronautics and Traffic Control in the Year 2000, AIAA Paper 78-1513. American Institute of Aeronautics and Astronautics, New York, 1978.
7. McIver, D. and Hatfield, J. J.: Coming Cockpit Avionics. Aeronautics and Astronautics, March 1978.
8. Morgan, C. T. et al.: Human Engineering Guide to Equipment Design. McGraw-Hill, New York, 1963.
9. Moses, F. T.: Electronics Afloat. Yachting, pp. 62, July 1974.
10. Ropelewski, R. R.: L-1011 Cockpit Automation Cuts Crew Workload. Aviation Week, 18 June 1979.
11. Warner, R. T.: The Needs of General Aviation in the Future Air Traffic Control System, AIAA Paper 78-1538. American Institute of Aeronautics and Astronautics, New York, 1978.
12. Airman's Information Manual, Part 1, Basic Flight Information and ATC Procedures. Department of Transportation, Washington, issued quarterly.
13. Air Transport Inertial Navigation System (INS), ARINC Characteristic 561. Aeronautical Radio, Inc., Annapolis, 1971.

14. Calculator-Timer Makes Life Easier for Light-Aircraft Pilots. Electronic Design, November 8, 1976.

15. Code of Federal Regulations, Title 14, Chapter 1, Subchapter C, Part 23, Airworthiness Standards for Normal, Utility and Acrobatic Category Airplanes. Superintendent of Documents, U. S. Government Printing Office, Washington, issued annually.

16. Digital Nav Head. General Aviation News, pp. 33, July 30, 1979.

17. Factors Involved in the Use of Course Line Computers, 3-57/DO-76/SC54. Radio Technical Commission for Aeronautics, Washington, 1957.

18. FLYER Aviation Buying Guide. Aircraft Components, Inc. Benton Harbor, July/August 1979.

19. Human Engineering Design Criteria for Military Systems, Equipment and Facilities, MIL-STD-1472B. Department of Defense, Washington, 1974.

20. Initial Report on Civil Aviation Frequency Spectrum Requirements 1980-2000, DO-165/SC-129. Radio Technical Commission for Aeronautics, Washington, 1976.

21. Long Range Planning for the Air Traffic System, DO-135/SC-104. Radio Technical Commission for Aeronautics, Washington, 1967.

22. Mark 2 Air Transport Area Navigation System, ARINC Characteristic 582-5. Aeronautical Radio Inc., Annapolis, 1974.

23. Mark 33 Digital Information Transfer System (DITS) ARINC Specification 429-2. Aeronautical Radio Inc., Annapolis, 1979.

24. Minimum Operational Characteristics - Vertical Guidance Equipment used in Airborne Volumetric Navigation Systems, DO-152/SC-116E. Radio Technical Commission for Aeronautics, Washington, 1972.

25. Minimum Operational Performance Standards for Airborne Area Navigation Systems (First Draft), RTCA Paper No. 145-79/SC137-24. Radio Technical Commission for Aeronautics, Washington, 1979.

26. One Chip Takes All Avionics Data-Comm Protocols. Electronic Design, pp. 22, August 2, 1979.

27. Operational and Airworthiness Approval of Airborne Omega Radio Navigation Systems as a Sole Means of Overwater Long Range Navigation, AC 120-37. Department of Transportation, Washington, 1978.

28. Operator's Manual for Manpack/Vehicle Navigation Set, Magnavox Report R-5900A. USAF Space and Missile Systems Organization, Los Angeles, 1978.

29. User's Manual (Computer Program) for User Equipment Set Z of the NAVSTAR Global Positioning System, Magnavox Report No. 80017. General Dynamics Electronics Division, San Diego, 1979.

30. VHF Radio Frequency Assignment Plan for Aeronautical Operations, AC 90-50B. Department of Transportation, Washington, 1977.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-159176		

4. Title and Subtitle	5. Report Date
DESIGN STUDY OF A LOW-COST CIVIL AVIATION GPS RECEIVER SYSTEM – FINAL REPORT	December 15, 1979
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
R. Cnossen - Magnavox; G. Gilbert - GAC Assoc.	R-6132
9. Performing Organization Name and Address	10. Work Unit No.
Magnavox Gov't & Ind. Elec. Co. Advanced Products Division 2829 Maricopa Street Torrance, CA 90503	11. Contract or Grant No. NAS-1-15343
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics & Space Admin. Washington, D.C. 20546	Contractor Report TYPE III
	14. Sponsoring Agency Code
15. Supplementary Notes	
Langley Technical Monitor: William E. Howell	

16. Abstract

The purpose of this report was to define a low-cost Navstar receiver system for Civil Aviation applications. User objectives and constraints were established. Alternative navigation processing design trades were evaluated. Receiver hardware was syntehsized by comparing technology projections with various candidate system designs. A control display unit design was recommended as the result of field test experience with Phase I GPS sets and a review of special human factors for General Aviation users. Finally, areas requiring technology development to ensure a low cost Navstar Set in the 1985 timeframe were identified.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Trade off Study Design Information Civil Aviation GPS Navstar	UNCLASSIFIED-UNLIMITED

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclasssified	Unclassified	135	

*For sale by the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

2634

Nat'l Tech Information Service Springs 22161
703-487-4650