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NAVSTAR GPS Simulation and Analysis Program

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Cambridge MA 02142

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Interim Report

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study assesses the capability of the planned NAVSTAR Global Positioning System) to meet civil navigation requirements. When it becomes operational in about , NAVSTAR GPS will provide accurate two-dimensional and three-dimensional service wide spectrum of users. The quality of the service will depend on the avail- ty of the satellite signals, the satellite geometrics, the timing accuracy of the ls, and the user receiver design. In this study ten specific issues are identi- which have not yet been resolved. These issues provide the focus for the effort.

, air, marine and land requirements are cited. Next, the approach is described, by a combination of analysis and receiver simulation is used to address the s. Receiver design alternatives are then discussed, focusing on the resulting distributions. Outages caused by poor satellite geometries are described, and preliminary estimates given for the ability of receivers to "coast" through them. ffects of Selective Availability (reduced accuracy) are then analyzed. Differ- l operation is treated in some detail. The effects of ionospheric and tropo- ic delays are estimated. It is shown that differential operation can provide lent reduction in bias errors over a considerable region. Finally, costs are ated for single- and dual-channel user receivers for the next 20 years.

Words
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PREFACE

The work described in this report was performed in support of the Navigation and Communication Division of the Research and Special Programs Administration (RSPA). The Federal Aviation Administration, U.S. Coast Guard and RSPA have the major responsibility in developing the Department of Transportation's portion on the civil radionavigation for air, marine and land navigation system. This effort supports that responsibility.

The work was performed by the Transportation System Center's Navigation Systems Division, part of the Center for Navigation. This report is an interim report on the results to date. The results will be incorporated into a more formal Final Report during FY 83.

The report was the result of a team effort. John Kraemer contributed Section 2 on operational requirements and Appendices A-C on the simulation models. Norman Knable wrote Section 5 on satellite outages, Appendix D on oscillators, and contributed to Section 7 on Selective Availability. Differential operation, Section 8, was written by Janis Vilcans. The remaining material was written by Rudy Kalafus, Project Engineer.

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TABLE OF CONTENTS

Section		Page
	Preface	iii
1.0	INTRODUCTION	1.1
	1.1 Purpose	1.1
	1.2 Scope	1.1
	1.3 Background	1.1
	1.4 Issues	1.3
2.0	OPERATIONAL REQUIREMENTS	2.0
	2.1 General	2.0
	2.2 Air Requirements	2.0
	2.3 Marine Requirements	2.4
	2.4 Land Requirements	2.10
3.0	METHOD OF APPROACH	3.0
	3.1 General	3.0
	3.2 Analysis and Simulation Tools	3.2
	3.3 Characterization of Civil Air Users and Equipment	3.5
	3.4 Characterization of Civil Marine Users and Equipment	3.10
	3.5 Characterization of Land Users and Equipment	3.13
4.0	RECEIVER/PROCESSOR DESIGN ALTERNATIVES	4.0
	4.1 General	4.0
	4.2 Receiver Implementation	4.0
	4.3 Satellite Selection	4.2
	4.4 Tracking Techniques	4.3
	4.5 Future Receiver Designs	4.7
5.0	SATELLITE OUTAGES	5.0
	5.1 General	5.0
	5.2 Sparing Strategy	5.0
	5.3 Conditions for Insufficient Numbers of Satellites	5.4
	5.4 Parameters Needed for a Navigation Fix	5.9
	5.5 Effect of User Clock on Normal 3D GPS Operation - Coasting with 3 Satellites and a Clock	5.9
	5.6 Aiding with Vertical Information	5.11
6.0	SATELLITE FAILURES	6.0
	6.1 General	6.0
7.0	SELECTIVE AVAILABILITY	7.0
	7.1 General	7.0
	7.2 Approach	7.1
	7.3 Navigation Accuracy Under Selective Availability	7.3

LIST OF ILLUSTRATIONS

Figure		Page
3-1	TYPICAL HDOP's OVER CONUS - FULL 18 + 3 SATELLITE CONSTELLATION, 3 DIMENSIONAL SOLUTION, 10° MASK ANGLE	3.3
4-1	HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION BEST-SET STRATEGY	4.4
4-2	HDOP DISTRIBUTION, 3-DIMENSIONAL SOLUTION, BEST-SET STRATEGY	4.5
4-3	HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION 10-DEGREE MASK ANGLE	4.6
5-1	PLANNED SATELLITE CONSTELLATION WITH NEW SPARING STRATEGY	5.1
5-2	PDOP VARIATION - 18 SATELLITE CONSTELLATION, 3-DIMENSIONAL SOLUTION, 5° MASK ANGLE (95°W/35°N)	5.2
5-3	PDOP VARIATION - FULL 18 + 3 SATELLITE CONSTELLATION, 3-DIMENSIONAL SOLUTION, 5° MASK ANGLE (95°W/35°N)	5.3
5-4	CONUS HDOP DISTRIBUTION - FULL 18 + 3 SATELLITE CONSTELLATION, 3-DIMENSIONAL SOLUTION, BEST-SET STRATEGY	5.5
5-5	HDOP VARIATION DURING OUTAGE - FULL 18 + 3 SATELLITE CONSTELLATION, 3-DIMENSIONAL SOLUTION, 10° MASK ANGLE	5.6
5-6	CLEARANCE NEEDED FOR NON-RECISION APPROACH WITH GPS	5.8
7-1	SELECTIVE AVAILABILITY PROBABILITY DISTRIBUTION	7.4
7-2	HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION, ALL-IN-VIEW STRATEGY	7.7
7-3	HDOP DISTRIBUTION, 3-DIMENSIONAL SOLUTION, ALL-IN-VIEW STRATEGY	7.8
7-4A	ESTIMATED AND ACTUAL TRAJECTORY, NO SELECTIVE AVAILABILITY	7.10
7-4B	ERRORS, NO SELECTIVE AVAILABILITY	7.11
7-5A	ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABIILTY SAMPLE NO. 1	7.12

LIST OF ILLUSTRATIONS

Figure		Page
8-13	TROPOSPHERIC DELAYS AND BIAS ERROR AT DIFFERENT ALTITUDES	8.47
9-1	COSTING MODEL BLOCK DIAGRAM FOR SINGLE CHANNEL RECEIVER	9.1
9-2	GPS RECEIVER COST ESTIMATE, TWO MODELS	9.2
9-3	SENSITIVITY OF RECEIVER COSTS TO PREDICTION ERRORS IN TRENDS - 1990	9.6
9-4	SENSITIVITY OF RECEIVER COSTS TO PREDICTION ERRORS IN TRENDS - 2000	9.7
9-5	COSTING MODEL BLOCK DIAGRAM FOR DUAL CHANNEL RECEIVER	9.8
9-6	GPS RECEIVER COST ESTIMATE, DUAL CHANNEL RECEIVER	9.9
E-1	RECEIVER COST ESTIMATE - ARINC MODELS, LIST PRICE, 1978 DOLLARS	E.2
E-2	RECEIVER COST ESTIMATE - ARINC AND SCI MODELS LIST PRICE, 1980 DOLLARS	E.5

LIST OF TABLES (Continued)

Table		Page
8-2	FRP REQUIREMENTS MET UNDER SPS WITHOUT SELECTIVE AVAILABILITY	8.3
8-3	FRP REQUIREMENTS MET WITH DIFFERENTIAL GPS USING SPS ACCURACIES WITH SELECTIVE AVAILABILITY	8.4
8-4	DIFFERENTIAL CORRECTION MESSAGE	8.22
8-5	DIFFERENTIAL NAVSTAR GPS RECEIVER CHARACTERISTICS	8.25
8-6	PSEUDORANGE ERROR BREAKDOWN - MARINE/LAND RECEIVER	8.27
8-7	PSEUDORANGE ERROR BREAKDOWN - AIRBORNE RECEIVER	8.28
8-9	DIFFERENTIAL STATION RECEIVER CHARACTERISTICS	8.48

1.0 INTRODUCTION

1.1 Purpose

The purpose of this project is to examine the technical issues associated with widespread civil usage of the NAVSTAR Global Positioning System (GPS), assess the system's capabilities, determine any system limitations, and estimate the effectiveness of new developments in techniques to improve system performance.

Since a considerable body of experience already exists on the performance and potential of NAVSTAR GPS, the project is focused on issues that have not yet been definitely resolved.

The results of this project will serve to support the Secretary of Transportation in establishing jointly with the Department of Defense a preliminary recommendation on Radionavigation System Utilization.

1.2 Scope

This report describes the unresolved issues that need to be addressed before NAVSTAR GPS can be accepted as a reliable navigation system for civil use. The methods used to address these issues are discussed, and the analysis and simulation tools are described. Results and conclusions are provided in considerable detail. Finally, recommendations for the remaining work effort are included.

1.3 Background

When the NAVSTAR Global Positioning Satellite (GPS) becomes operational, the community will have access to worldwide navigation service with a precision currently available only in limited areas for limited periods of time. Since it is a military system, deployed with military objectives in mind, the Department of Defense (DOD) has no responsibility to promote civil use of the system; however, the coarse acquisition (C/A) signal is currently not encrypted and is available to civil users. Current plans are to have an 18-satellite configuration operational by 1987, with 3 additional active spares available by 1989 (1).

is already known about the performance of GPS, it is apparent that it may have the potential to replace some of the major civil navigation systems. Whether this potential can be realized depends on whether GPS performance meets the following conditions:

- o Coverage matches or exceeds that of existing systems.
- o Accuracy is adequate to meet operational requirements of navigation service users.
- o System availabilty and reliability are adequate to meet operational requirements of navigation service users.
- o Costs of user equipment do not cause a significant economic burden on the users.
- o Any additional costs borne by the government are justified by the accrued benefits.
- o Sufficient time is allowed for decommissioning of existing navigation aids to enable users to phase into GPS without an undue economic burden.

The first four of these are technical in nature and they comprise the focus of the present work effort.

1.4 Issues

After reviewing the considerable literature on NAVSTAR GPS ten issues were identified which need to be addressed in order to evaluate the capabilities of the system. These ten issues, as perceived at the beginning of FY 83 are listed below:

ISSUE 1: Satellite Outages

In the 18-satellite, 6-plane configuration currently being planned by the Department of Defense, there are three geographic regions in the United States that will experience satellite constellations with unfavorable geometries for periods up to twenty minutes twice a day. Does this render the system inadequate to the National Airspace System and to other civil users, or can receiver/processors be designed to accomodate these outages?

NOTE - Since then, the NAVSTAR GPS Joint Program Office has announced the intention of providing three active spaces, and locating them in such a way as to remove these outages over the conterminous U. S. (CONUS) (1). (See Section 4).

effects by the broadcast of correction data. What accuracies could be practically achieved by differential operation under Selective Availability?

ISSUE 7: Receiver Costs vs. Level of Service Provided.

The level of service provided by a GPS receiver/processor depends on the accuracy required, the degree of reliability required, the amount of operator involvement, and user preference. Since each affects the purchase price of user equipment, what are the tradeoffs?

ISSUE 8: "ALL-IN-VIEW" Position Computation

Would a low-cost GPS receiver provide better capability to deal with temporary loss of a satellite signal if all satellite pseudoranges are employed in the position computation, rather than the four "best" ones? If so, is the technique cost effective?

ISSUE 9: Kalman Filter vs. Alpha-Beta Tracker

Processors frequently incorporate Kalman filters that optimally employ knowledge of the vehicle dynamics and error sources to smooth data and provide accurate position and velocity estimates, with a penalty in complexity and cost. Alpha-Beta trackers are simpler, but less accurate. Which is cost-effective for civil users?

ISSUE 10: Aiding

Do low-cost GPS receivers require external aiding to meet the requirements of the Federal Radionavigation Plan? If so, for which applications and under what conditions?

As the project has progressed, new wrinkles have emerged, and the relative importance of the issues has shifted somewhat. Also, in order to address several of the issues, the receiver/processor design alternatives need to be described first. Therefore, after Section 2 on Operational Requirements and Section 3 describing

2.0 OPERATIONAL REQUIREMENTS

2.1 General

The requirements of civil users for radionavigation services are based upon the technical and operational performance needed for transportation safety and economic efficiency. The requirements are defined in terms of discrete "phases of navigation". These "phases" are categorized primarily by the characteristics of the navigational problem as the craft passes through different regions of its voyage. For example, the marine navigational problem becomes progressively more complex and risky as a ship passes from the high seas into the coastal area and finally through the harbor approach to the dock. Thus, it is convenient to view each segment separately for purposes of analysis. The navigation requirements which follow are taken from the Federal Radionavigation Plan, Vol. II, March 1982 (2).

2.2 Air Requirements

The two basic phases of air navigation are approach/landing and enroute/terminal. The current requirements for each of these phases of navigation are summarized below.

2.2.1 Approach/Landing Phase

The approach/landing phase is that portion of the flight conducted immediately prior to touchdown. It is generally conducted within 10 nautical miles (nm) of the runway. Two sub-phases may be classified: as (1) non-precision approach and (2) precision approach and landing. Since it is not currently anticipated that GPS will be used for precision approach and landing, only the non-precision approach phase is considered here.

While the achieved capabililty for non-precision approaches varies widely, depending on the location of the navigational facility in relation to the fix location and type of navigational system, approximately 30% of the non-precision

TABLE 2-1. CONTROLLED AIRSPACE NAVIGATION ACCURACY NEEDED TO MEET CURRENT REQUIREMENTS

Phase	Sub-Phase	Altitude (Flight Level)	Traffic Density	Route Width (NM)	Accuracy 2 drms (meters)
EnRoute/ Terminal	Oceanic	FL 275 to 400	Normal	60	
	Domestic	FL 180 to 600	Low	16	2000
			Normal	8	1000
		500 - 18,000 ft.	High	8	1000
	Terminal	500 - 18,000 ft.	High	4	500
	Remote	500 - 60,000 ft.	Low	8 to 20	1000 to 4000
	Helicopter Operations	500 - 5000 ft.	Low (Off-Shore)	Not Determined	1000 to 2000
		500 - 3000 ft.	High (Land)	4	500
Approach and Landing	Non-Precision	250 to 3000 ft. above Surface	Normal	2	100

Area Navigation (RNAV) routes have the same protected airspace as regular airways.

C. TERMINAL

Terminal routes are transitions from the en route phase to the approach phase. The accuracy capability of navigation systems using the VOR/DME in terms of bearing and distance to the facility is defined in the same manner as described for en route navigation. However, the usually closer proximity to facilities provides greater effective system use accuracy, since both VOR and Flight Technical Error are angular in nature and are related to the distance to the facility. The DME distance error is also reduced, since it is proportional to distance from the facility, down to the 0.5 nm minimum error capability. The minimum terminal route width is $\pm$ 2 nm within 25 nm of the facility.

D. REMOTE AREAS

Remote areas are defined as regions which either do not meet the requirements for installation of VOR/DME service or where it is impractical to install this system. These include offshore areas, mountainous areas and a large portion of the State of Alaska. Thus the minimum route width varies and can be greater than $\pm$10 nm.

E. HELICOPTER OPERATIONS

Helicopter operations occur in offshore areas and on low-altitude domestic routes. The current navigational accuracy requirements are listed in the Table 2-1.

2.3 Marine Requirements

Marine navigation in the United States consists of five distinct phases identified as Ocean, Coastal, Harbor Approach, Harbor, and Inland Waterway navigation. Standards or requirements for safety of navigation and reasonable economic efficiency can be developed around these five phases. Specialized requirements, which may be generated by the specific activity of a ship, must be addressed separately.

For safe general navigation under normal circumstances, the requirements for accuracy and frequency of position fixing on the high seas are not very strict. As a minimum, these requirements include a predictable accuracy of 2 to 4 nm coupled with a maximum fix interval of 2 hours or less. While these minimum requirements would permit all vessels to navigate with relative safety on the high seas, more desirable requirements would be predictable accuracy for 1 to 2 nm and a fix interval of 15 minutes or less.

Economic efficiency in trans-oceanic transportation, special maritime activities and safety in emergency situations require or benefit from navigational accuracy higher than that needed for safety in routine, point-to-point ocean voyages. Predictable accuracy requirements may be as stringent as 10 meters for special maritime activities, and may range to 0.25 nm for large, economically efficient vessels, including search operations. Search operations must also have a repeatable accuracy of at least 0.25 nm. The required fix interval may range from as low as once per five minutes to as high as once per minute. These requirements are based on current estimates and are to be used for the purposes of system planning.

B. COASTAL NAVIGATION

Coastal navigation is considered that phase in which a ship is within 50 nm from shore or the limit of the Continental Shelf (200-meter depth), whichever is greater, and where a safe path of water at least one mile wide (if a one-way path), or two miles wide, (if a two-way path), is available. In this phase, a ship is in waters contiguous to major land masses or island groups where transoceanic traffic patterns tend to converge in approaching destination areas; where interport traffic exists in patterns that are essentially parallel to coastlines; and within which ships of lesser range usually confine their operations. Traffic-routine systems and scientific or industrial activity on the Continental Shelf are encountered frequently in this phase of navigation. Ships on the open waters of the Great Lakes also are considered to be in the coastal phase of navigation.

There is need for continuous, all-weather radionavigation service in the coastal area providing, at the least, the position fixing accuracy required

Government studies established that a navigation system providing a capability to fix position to an accuracy of 0.25 nm will satisfy the minimum safety requirements if a fix can be obtained at least every 15 minutes. As a secondary economic factor, it is required that relatively higher repeatable accuracy be recognized as a major advantage in the consideration of alternative candidate radionavigation systems for the coastal area. In such activities as marine scientific research, hydrographic surveying, commercial fishing, and petroleum or mineral exploration, there is a need to establish position in the coastal area with much higher accuracy than that needed for safety of general navigation.

C. HARBOR ENTRANCE

Harbor/Harbor Entrance navigation (HHE) is conducted, in general terms, in waters inland from those of the Coastal Phase. For a ship entering from the sea or open waters of the Great Lakes, the Harbor Approach phase begins generally with a transition zone between the relatively unrestricted waters where the navigational requirements of Coastal navigation apply, and narrowly restricted waters near and/or within the entrance to a bay, river, or harbor phase requires navigation of a well defined channel which, at the seaward end, is typically from 180 to 600 meters in width if it is used by large ships, but may narrow to as little as 120 meters farther inland. Channels used by smaller craft may be as narrow as 30 meters.

The pilot of a vessel in restricted waters must direct its movement with great accuracy and precision to avoid grounding in shallow water, and avoid collisions with other craft in congested waterways. Unable to turn around, and severely limited in the ability to stop to resolve a navigational problem, the pilot of the large vessel (or a tow boat and barge combination) may find it necessary to hold the total error in navigation within limits measured in tens of feet, while negotiating the straight channel segments and turns dictated by the configuration of the channel.

D. INLAND WATERWAYS

Inland Waterway navigation is conducted in restricted areas similar to those for harbors or harbor approaches. However, in the inland waterway case, the focus is on non-seagoing ships and their requirements on long voyages in restricted waterways, typified by tows and barges in the U.S. Western Rivers system and the U. S. Intracoastal Waterway.

Requirements from the consideration of practically achievable performance and expected benefits have not been defined. However, research in Harbor/Harbor Entrance navigation is expected to produce results which will have some application to Inland Waterway navigation.

2.4 Land Requirements

Government studies have identified a number of areas in both the automatic vehicle monitoring (AVM) and site registration phases where productivity and operational improvements have been predicted. Since land application of radio-location adopted systems has not been widely adopted by the civil community, no official requirements or systems have been recognized by the Government.

A. AUTOMATIC VEHICLE MONITORING

There is no definitive statement of requirements for AVM service since it is still under investigation. It appears that there are requirements in safety, transportation management and economic areas. Study efforts and field measurements to date have led to some preliminary estimates of accuracies and costs required to make radiolocation service beneficial to various user groups. These data are shown in Table 2-5. No other characteristics have been determined.

B. SITE REGISTRATION

There are no definitive statements of requirements for this service since it is still under investigation. It appears that there are requirements in both the safety and economic areas. Study efforts and field measurements to date have led to some preliminary estimates of accuracies required to make radiolocation service beneficial to various user groups. These data are also shown in Table 3-5. No other characteristics have been determined.

3.0 METHOD OF APPROACH

3.1 General

The basic methodology used on this project is straightforward:

1. Identify the issues which are not yet resolved.

2. For each issue, formulate a set of questions that span the issue and are capable of resolution.

3. Determine whether the analysis and simulation tools are adequate, and determine what data exists.

4. Modify current tools and/or develop new areas to meet the need.

5. Characterize the users and their appropriate equipment.

6. Apply the tools, using the scenarios and receiver design options.

The computer simulation models AIRGPS and MARINEGPS contained numerous errors as received from the contractor, who denied that such errors existed. It was decided the in-house staff should deloug the models and make modifications to the simulations as necessary. At this writing, the MARINEGPS simulation appears to be running properly; the AIRGPS simulation is close, but needs some further work. These simulations can demonstrate how a marine or airborne receiver/processor would behave under a variety of conditions: with or without Selective Availability, with different mask angles (minimum satellite elevation angle), and using 3 or 4 satellites in the navigation solutions. Receiver and processor parameters, trajectories, and satellite geometries are operator-selectable.

The error-bound model (TSCERR) was developed by Bradley University(3) and Input-Output Computer Services (IOCS)(4) and is currently operated at TSC by Bradley University. It provides a performance measure of an optimally designed receiver, i.e., one which takes full advantage of all the information

3.2 Analysis and Simulation Tools

The analysis and simulation tools used in the study are computer programs which are written in FORTRAN-10 on the DEC-10 mainframe computer at TSC. Their chief features are described below. The simulation models are described in more detail in Appendices C-E.

3.2.1 Dilution-of-Precision Programs

GDOP subroutine - calculates XDOP, YDOP, HDOP, VDOP, and PDOP measures for specified ranges of latitude, longitude and time, for specified satellite selection criteria: choice of mask angle, best-set or all-in-view algorithms, three- or four-satellite algorithms.

GDOP distribution program - calculates distributions of DOP measures; generates plots.

GDOP map generator - generates values of DOP measures and number of satellites in view over the CONUS at a specified time. Figure 3-1 shows an example of this.

Satellite Faulting Program - Modifies satellite selection to allow selective removal of satellite signals, and calculates the resulting DOP measures.

3.2.2 Selective Availability (SA) Programs

SA delay Statistics - calculates probability densities and cumulative probabilities of SA delays from data.

SA rate statistics - calculates probability densities and cumulative probabilities of SA rates of change.

SA rate change statistics - calculates probability densities and cumulative probabilities of SA second derivatives.

SA MARINEGPS interface program - an interpolation routine that sends typical SA pseudorange delays to MARINEGPS. AIRGPS can be likewise accommodated.

3.2.3 TSCERR Error Bound Model

The error bound model has the following features:

a. It can be used to analyze sudden satellite outage or faults.

b. It accommodates different clock stabilities to enable stability requirements assessment during outage.

c. It accommodates external aiding.

3.2.4 MARINEGPS and AIRGPS

Each simulation model has the following features:

a. Each can handle a full nonlinear receiver model as well as a simplified receiver model.

b. Each operates with 18-satellite constellation, with spares.

c. The nonlinear model provides detailed behavior of AFC loop, phase-lock loop, and code-tracking loop.

d. Each has Kalman Filter navigation processor; the AIRGPS model includes a turn rate state.

e. Each has a user-selectable clock quality, vehicle trajectory, receiver/processor parameters, system time, and rate-aiding of code loop.

f. Each can be modified to handle sequential receiver operation.

TABLE 3-1. CIVIL AIR USER CLASSIFICATION SCHEME

Class A

- o IFR capability in all controlled (mixed, positive control, and high density) airspace regions of the National Airspace System under instrument meteorological conditions (only VFR flights may be conducted in uncontrolled airspace).
- o Equipped with dual, high quality avionics characteristic of air carrier and military aircraft.

Class B

- o IFR capability in all mixed and positive controlled airspace regions (requiring 3D-RNAV), except where Strategic Control procedures (requiring 4D-RNAV equipment) are in effect.
- o Equipped with dual, high quality avionics characteristics of expensive general aviation aircraft.

Class C

- o Typically operates IFR in mixed airspace regions.
- o Has nonredundant, medium quality avionics of limited navigation (2D-RNAV) and data link communications capability.

Class D

- o Generally operates VFR in all low density terminals and mixed enroute airspace.
- o Has low cost avionics without area navigation equipment.

Class E

- o Typically operates VFR in mixed airspace only if within line-of-sight of a radar site, otherwise operates in uncontrolled airspace.
- o Has low cost avionics with VOR Navigation equipment.

Class F

- o Operates in uncontrolled airspace with ground-based voice communications and minimum VOR navigation capabilities.

TABLE 3-2. GENERAL CHARACTERISTICS OF A CIVIL AIR USER OF LOW-COST GPS NAVIGATION EQUIPMENT

Class C User	-	Typically operates IFR in mixed airspace regions.
	-	Has nonredundant, medium quality avionics of limited (2D-RNAV) and data link communications capability.
Typical Aircraft	-	Twin Otter, Beech Baron, Piper Navajo
Maneuvers	-	Straight and level at accelerations up to 0.2 g's.
	-	Climbs and descends up to 2000 fpm.
	-	Standard 2-minute turns.
	-	Nonprecision approaches
Bank Angle	-	30°.
Maximum Speed	-	210 knots over a fix or in terminal area.
Receiver/Processor	-	C/A Code only, 1575.42 MHz.
	-	Two channels: Navigation, Data [1]
	-	One antenna [2]
	-	Aiding: None, initially
	-	Satellite Tracking Algorithm: Best Set of Four, initially.
	-	Position Algorithm: 3 dimensional solution.

Notes:

1. Receiver architecture is patterned after the Experimental Dual Channel Receiver (EDCR) developed by the FAA.(6)

2. Consistent with low-cost user application.

3.4 Characterization of Civil Marine Users and Equipment

Civil marine navigation may be characterized by four specific phases: the ocean, coastal, harbor and harbor approach, and inland waterway phases. GPS will clearly satisfy the requirements for oceanic navigation and almost certainly those of the coastal phase. The harbor approach and harbor phase requirements are significantly more demanding and it is not clear that they can be met with a low cost GPS set. Requirements have not yet been defined for inland waterway navigation.

Navigation requirements apply to all craft and we have selected a vessel of 50 meters length as representative of the class of users of low-cost GPS sets. For a given speed, the roll amplitude and roll frequency tend to increase with decreasing ship length. Consequently, for a given sea condition the increased dynamics of smaller craft can be expected to place a greater burden on the GPS set. Both moderate and calm sea conditions can be accommodated by the MARINEGPS simulation. It is anticipated that harbor approaches with narrow channels will not be attempted in severe conditions.

Although we have limited our consideration to the navigation requirements which apply to safety of navigation, there are additional benefits to be derived from more precise navigation. Specific user applications, including commercial fishing, hydrography, resource exploitation, search operations, law enforcement and recreational sports fishing, can benefit from increased navigation precision. The minimum performance necessary to achieve these benefits generally falls between the requirements for coastal navigation and those for harbor approach and harbor navigation. Consequently, if GPS can satisfy the more stringent harbor approach and navigation requirements, it will most likely yield the additional benefits described above.

Table 3-4 shows the characteristics of the users and navigation scenarios which will be used to address the main issues. Table 3-5 lists the receiver/processor parameters which characterize the receiver to be evaluated for the civil marine user. The parameter values listed in Table 3-5

TABLE 3-5. RECEIVER PARAMETERS - MARINE

PARAMETER	VALUE NAV. CH	DATA CH.
CLOCK		
Clock Stability	1 X 10^{-8}(1-3 Sec)	1 X 10^{-8}
CODE LOOP		
Type	Tau-Dither	
Order	2nd	
Bandwidth	0.30 Hz	
Damping Factor	0.707	
Delay Prepositioning	Yes	
Doppler Prepositioning	No	
Satellite Dwell Time	0.68 sec.	
Dither Timestep	0.01 sec.	
Dither Code Shift	$\pm$ 0.5 CHIP	
IF Noise Filter Bandwidth	300 Hz	
CARRIER LOOP		
Type	AFC	AFC/Costas
Order	1st	1st/2nd
Bandwidth	10 Hz	10 Hz/10
Hz Damping Factor	N.A.	N.A.
Doppler Preposition	Yes	Yes/Yes
Satellite Dwell Time	0.68 sec	0.68 sec.
IF Noise Filter Bandwidth	300 Hz	300 Hz/300 Hz
NAVIGATION FILTER		
Type	Kalman	
States	6	
Observables	Pseudorange	
SATELLITES TRACKED		
Satellites Tracked	3	
Satellite Mask Angle	10°	

Table 3-6 shows the characteristics of the users and scenarios which will be used in this program to address the main issues. The receiver is patterned after the FAA's Experimental Dual Channel Receiver with parameters selected to be consistent with the intended land application. The receiver parameters given in Table 3-7 will be used in MARINEGPS and will also serve to define the inputs to the error bound software TSCERR.

TABLE 3-7. RECEIVER PARAMETERS - LAND

PARAMETER	VALUE NAV. CH	VALUE DATA CH.
CLOCK		
Clock Stability	1×10^{-8}	1×10^{-8}
CODE LOOP		
Type	Tau Dither	
Order	2nd	
Bandwidth	1.0 Hz	
Damping Factor	0.707	
Delay Prepositioning	Yes	
Doppler Prepositioning	No	
Satellite Dwell Time	0.5 Sec.	
Dither Timestep	0.01 Sec.	
Dither Code Shift	$\pm$ 0.5 Chip	
IF Noise Filter Bandwidth	300 Hz	
CARRIER LOOP		
Type	AFC	AFC/Costas
Order	1st	1st/2nd
Bandwidth	10 Hz	10 Hz/17 Hz
Doppler Preposition	Yes	Yes/Yes
Satellite Dwell Time	0.5 Sec.	N.A.
IF Noise Filter Bandwidth	300 Hz	300 Hz/300 Hz
NAVIGATION FILTER		
Type	Kalman	
States	6	
Observables	Pseudorange	
SATELLITES TRACKED		
Satellites Tracked	4	
Satellite Mask Angle	10°	

4.0 RECEIVER/PROCESSOR DESIGN ALTERNATIVES

4.1 General

This section describes some of the features of NAVSTAR GPS receivers, how they may differ to achieve low-cost status or be tailored to particular applications, and how they may change in the future.

4.2 Receiver Implementation

The NAVSTAR GPS Interface Document(7) leaves a number of design factors unspecified:

a. Mask angle - the elevation angle below which satellites are ignored. This is generally chosen to be 5° or 10°.

b. Satellite Selection Algorithm - the selection criterion to determine which satellites are chosen to derive the navigation solution.

c. Navigation solution - Four satellites are generally used to provide three dimensions of position plus time. However, if altitude can be determined by an independent method, only three satellites are needed.

d. Number of receiver channels - In principle, the number of channels could be one to eight. The reasons for preferring different numbers of channels is discussed below.

e. Receiver implementation technique - the choice of functions that could be accomplished digitally is broad and is expected to broaden even further in the future as faster circuitry comes down in price.

f. Tracker Implementation - The navigation tracker can range from no tracker at all to highly adaptive Kalman filters. Alpha-Beta trackers and fixed-gain Kalman filters form the intermediate choices.

The Experimental Dual-Channel Receiver (EDCR) was buit by Standard Telecommunications Inc., it was then integrated with a navigation processor and a data acquisition system by Lincoln Laboratory and tested for the FAA Office of System Engineering [10]. It uses one channel for tracking all satellites in view, and uses the other for data decoding. As a result, startup time is five minutes or less, and satellite fades do not result in erratic position estimation.

4.3 Satellite Selection

Most designs to date have employed a best-set-of-four satellite selection algorithm to choose the four satellites which give the lowest PDOP (PDOP $=\sqrt{HDOP^2 + VDOP^2}$). Actually the algorithm usually used computes the volume of the tetrahedron formed by each combination of satellites taking four at a time, and selects the constellation having the largest volume. This is believed to select the constellation having the lowest PDOP as well.

To avoid blockage by terrain or obstacles, low signal-to-noise ratios resulting from antenna pattern fold at the horizon and tropospheric noise, and multipath, a mask angle is chosen, usually 5^o or 10^o, below which satellites are not included in the navigation solution. The DOD sets use 5^o, but the FAA prefers 10^o. This choice is less significant when the all-in-view strategy is used, because noisy signals can in principle be down-weighted in their effects on the position estimate.

When altitude is known, as few as three satellites are needed for a solution. (2D Solution). In effect, knowledge of the altitude is tantamount to having an extra satellite at the center of the earth. The navigation processor still performs computations with four "satellite" pseudorange. For an ocean-going vessel, the distance of the antenna from the center of the earth can be approximated by the height above an average waterline plus the earth radius for that latitude as given by the WGS-72 model [11]. Errors resulting from tides, ship heave, and ship roll and pitch are small. Inland marine or land receivers could use the three-satellite solution if altitude could be entered manually. For aircraft, altimeter aiding could provide this information (See Section 5).

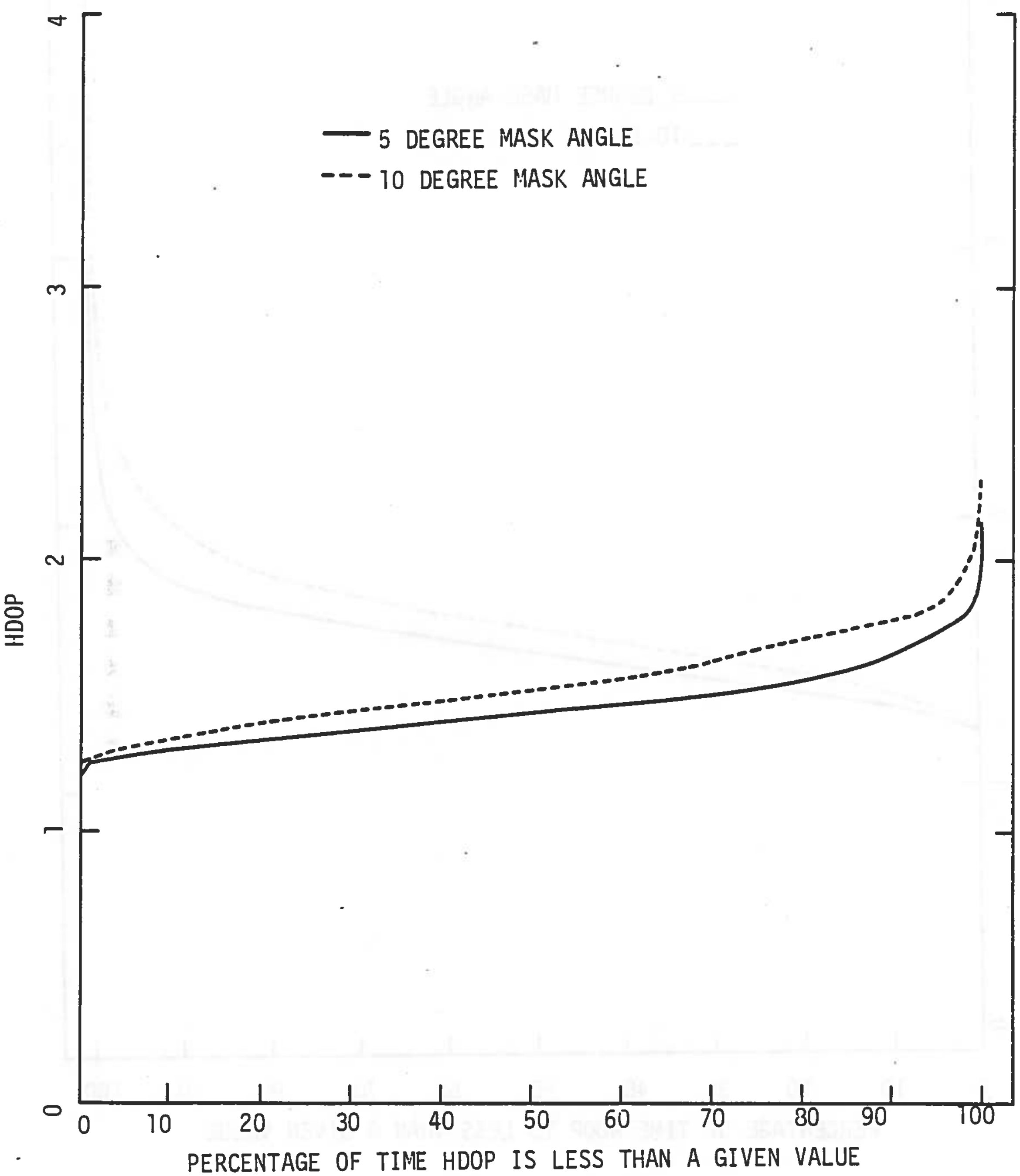


FIGURE 4-1. HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION, BEST-SET STRATEGY

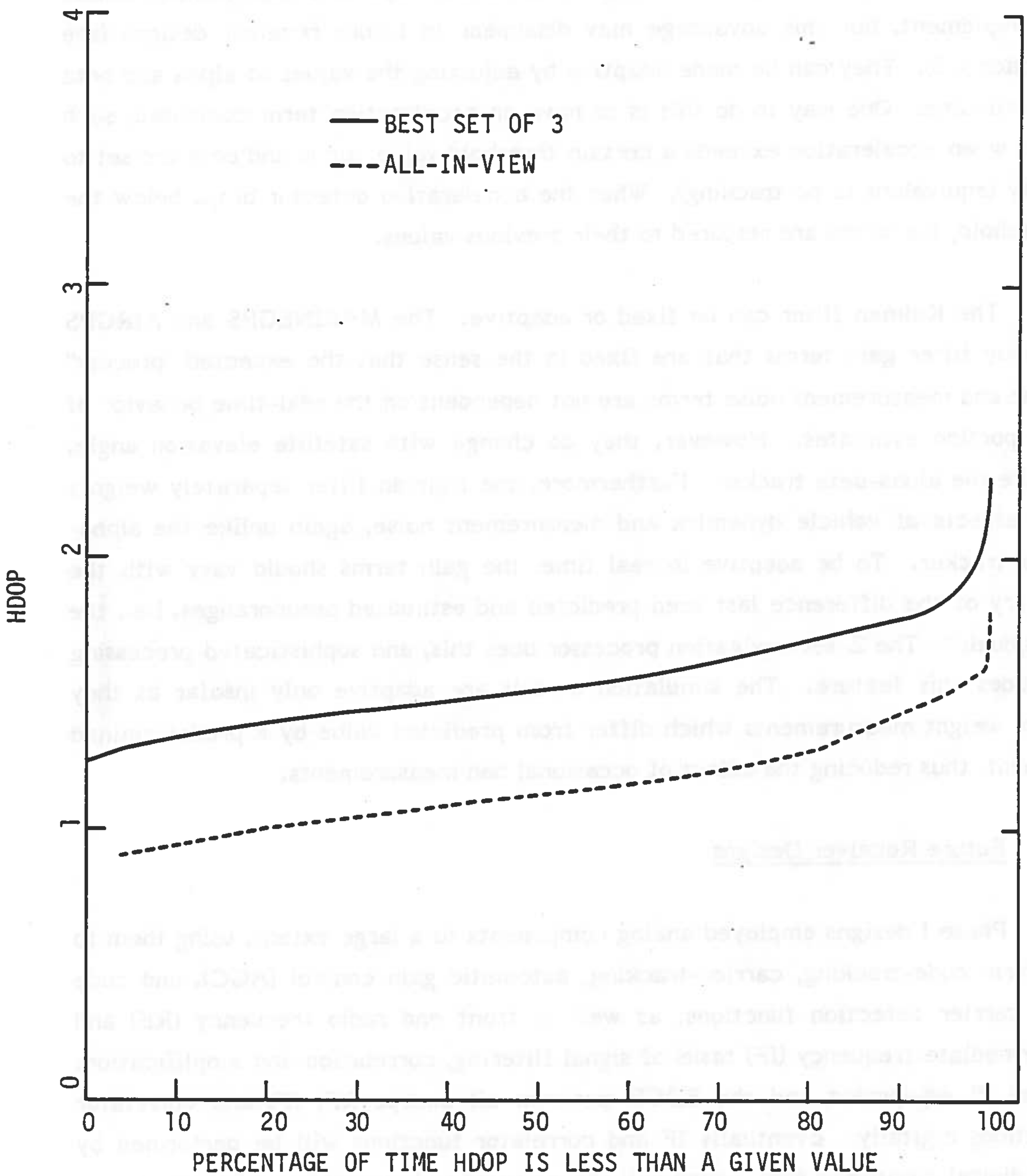


FIGURE 4-3. HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION, 10 DEGREE MASK ANGLE

Microprocessors are progressing rapidly in speed and capability due to the mass market for microcomputers and other consumer applications. As a result, it can be anticipated that much more capability will be possible in receivers at a given cost.

Bradley University recently completed a study for this project on microprocessor loading [12]. The following results are excerpted from that study. The GPS processing work load was divided into functions performed at several different rates:

a. Very Frequent (1 kHz): analog-to-digital conversion, tracking function.

b. Frequent (50 Hz): data decoding, statistics, keyboard, amplitude estimates.

c. Occasional (1 Hz): Satellite state update, navigation updates, pseudorange prediction, position estimates.

d. Infrequent (.01Hz): ephemeris computations, complete navigation solution.

Each function was analyzed to determine the precision required and the number and type of arithmetic operations involved. Several efficient microprocessors were considered: their register size, data bus size, and maximum speed. All this information was analyzed in a computer model for both Kalman filtering and alpha-beta tracking.

Table 4-1 shows the capabilities of a number of current and planned microprocessors. The "processor class" refers to the register and data bus widths: 16/8 means the registers use 16 bits and the data bus uses eight. Tables 4-2 and 4-3 show the amount of time per second required for each task for each microprocessor. When the total time per second exceeds one second, the "duty precent" exceeds 100%, and more than one microprocessor is required.

TABLE 4-2. MICROPROCESSOR LOADING, LAND/MARINE APPLICATION

PROCESSOR	TASK GROUP TIME SECONDS				DUTY PERCENT
	1 KHZ	50 HZ	1HZ	.01 HZ	
6502	.4	1.9	.39 .17 *	.0033	270 247 *
8085A-2	.52	1.9	.45 .23 *	.0008	287 265 *
68b09	.5	.53	.13 .065 *	.0007	116 109 *
68000	.15	.16	.019 .0075 *	.00015	33 32 *
68000/32	.15	.13	.014 .0048 *	.00013	29 28 *

1. Nav update once per/sec
2. 4 satellites track
3. 6 filter states
4. * indicates Alpha-Beta Tracker

Table 4-2 addresses a land or marine application, where altitude is not tracked. It can be seen that several 8-bit processors are needed, operating in parallel. However, with the new 68000 microprocessor, all functions can be performed with a single microprocessor. The 68000 can be programmed to perform the high-precision navigation solution computations without the need of a floating point co-processor, and the numbers in the table include these computations. Since co-processors are expensive compared to microprocessors (e.g., $200 vs $20), this is a significant cost savings. Table 4-3 shows the corresponding numbers for an airborne receiver. Note that a single 68000 still performs all the functions, whereas up to six microprocessors would be required for 8-bit designs.

The tables also demonstrate that while alpha-beta trackers have a measurable cost advantage for the less capable microprocessors this advantage all but disappears with the advanced processors. Therefore the added costs of incorporating high sophistication in a receiver will be limited primarily to up-front program costs, which will be negligible when amortized over a production run.

5.0 SATELLITE OUTAGES

5.1 General

Ideally the GPS constellation would provide a minimum of four visible satellites with low PDOP to all potential users of the system. The restriction on the size of the constellation to 18 satellites (plus 3 spares) has given rise to concern that coverage may not be adequate under several conditions: outside of the CONUS, satellite failure, signal blockage, or coplanar distribution of satellites. The result could be a severe deterioration of accuracy. The extent to which aiding by altimeter input or coasting by clock can ameliorate this deterioration needs to be explored.

In this section an investigation will be made the frequency of interruption of service, the effects on user classes, and the effect of clock or altimeter aiding on navigation accuracy following an interruption.

5.2 Sparing Strategy

The recent JPO decision to use three active spare satellites with the 6-plane, 18 satellite constellation will provide uninterrupted service within the CONUS for users who utilize all satellites with elevation angles greater than 5°. The configuration of 18 satellites with three active spares is detailed in Figure 5-1. Figure 5-2 shows the time variation of PDOP for the 18 satellite constellation with the observer in a singular position. Note the singularity of PDOP at approximately 2 and 15 hours for times lasting approximately one half hour. The singularities arise when the visible constellation consists of 4 coplanar satellites. Figure 5-3 shows the time variation of PDOP for the 18 satellite constellation of Figure 5-1 with 3 active spares. In this case PDOP is less than 6 for the whole of the CONUS. The deployment transfers the singularities to other parts of the world which will then contain singular areas with time variations of PDOP similar to those in Figure 5-2.

Figures 5-2 and 5-3 apply to a receiver utilizing a best-set-of-four satellite selection strategy, a 3-dimensional navigation solution, and a mask angle of 5; this represents a typical design for an airborne receiver. If the mask angle is 10°, a figure preferred by the FAA, the sparing strategy is not totally effective. Figure

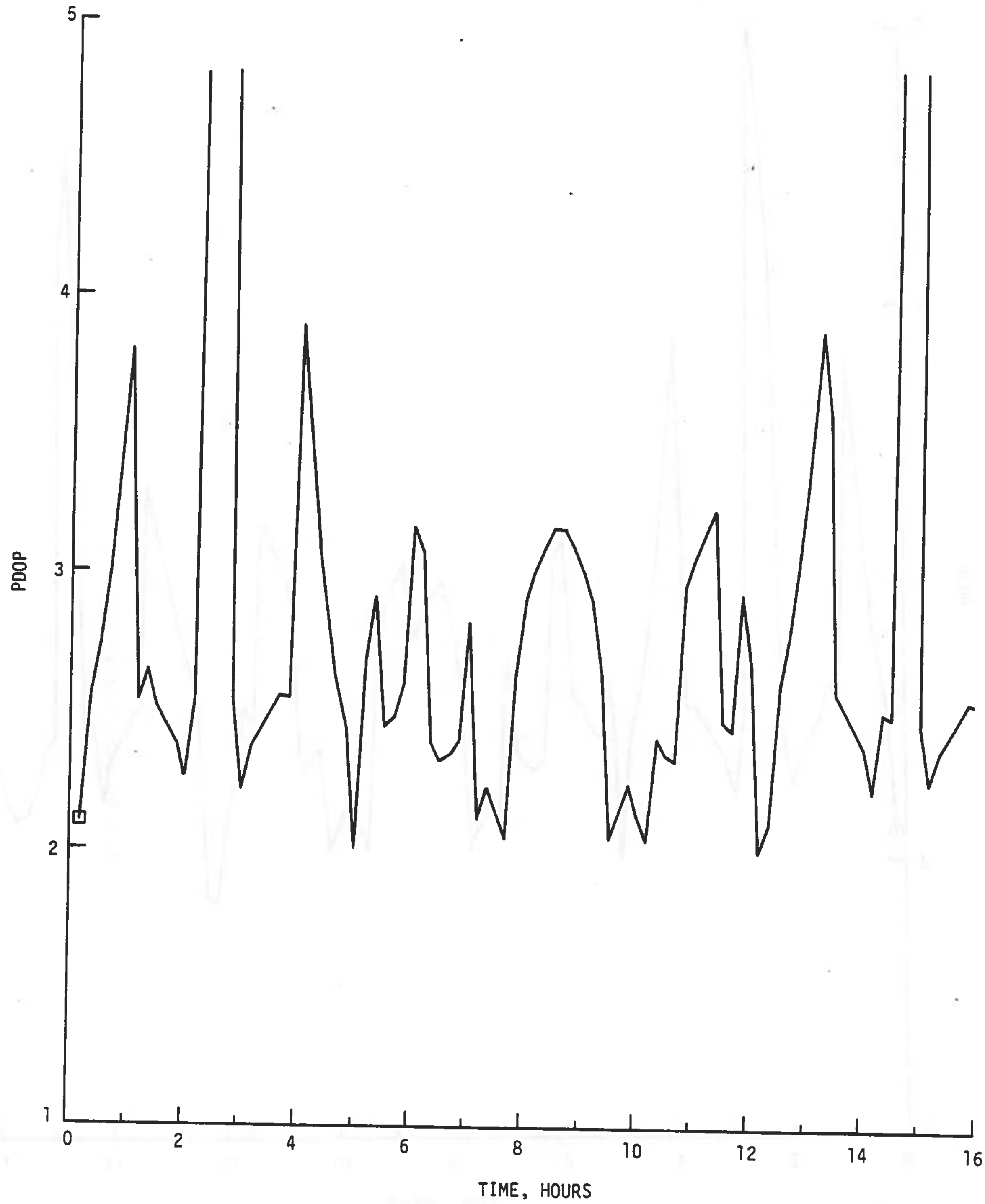


FIGURE 5-2. PDOP VARIATION - 18 SATELLITE CONSTELLATION, 3-DIMENSIONAL SOLUTION, 5° MASK ANGLE (95°W/35°N)

5-4 shows the distributions for the two mask angles. It can be seen that there still remain outage periods for the 10° mask angle receivers. A closer examination reveals there are five locations that experience outages varying in time from 1 to 15 minutes. One of these is shown in Figure 5-5 for 50° North Latitude and 85° West Longitude at about 9:45 hours GPS time. Whether the receiver can "coast" through such brief outages is discussed in Section 5.5.

The outages discussed above do not apply to receivers that have independent altitude determination, i.e., either by altimeter input or by employing the two-dimensional navigation solution for ocean-going vessels. This is shown in Figure 4-1 where all HDOP's are below 2.5 for mask angles of 5° or 10°.

In the case of failure of a satellite or signal blockage due to buildings or terrain or vehicle attitude, there may be periods in which less than 4 non-coplanar satellites are visible to the user. These periods will vary from 60 seconds in the case of turning aircraft to 20 minutes, for satellite failures where a spare has been properly positioned, to periods in excess of an hour in the case of failures where the spare has not yet been moved or where failure occurs in a plane in which there are no spares.

5.3 Conditions for Insufficient Number of Satellites

It has been stated that there are several conditions which decrease the usable number of satellites visible to the observer:

1. Satellite failure.

2. Signal blockage due to terrain and buildings.

3. Signals are unusable because of large tropospheric paths which cause the signal to be delayed by amounts not amenable to prediction. The tropospheric delay can be approximated down to elevation angles of 5 degrees by the following expression:

   Delay = 7930 N csc(E) meters,

   where E is the satellite elevation angle and N is the average tropospheric refractivity.

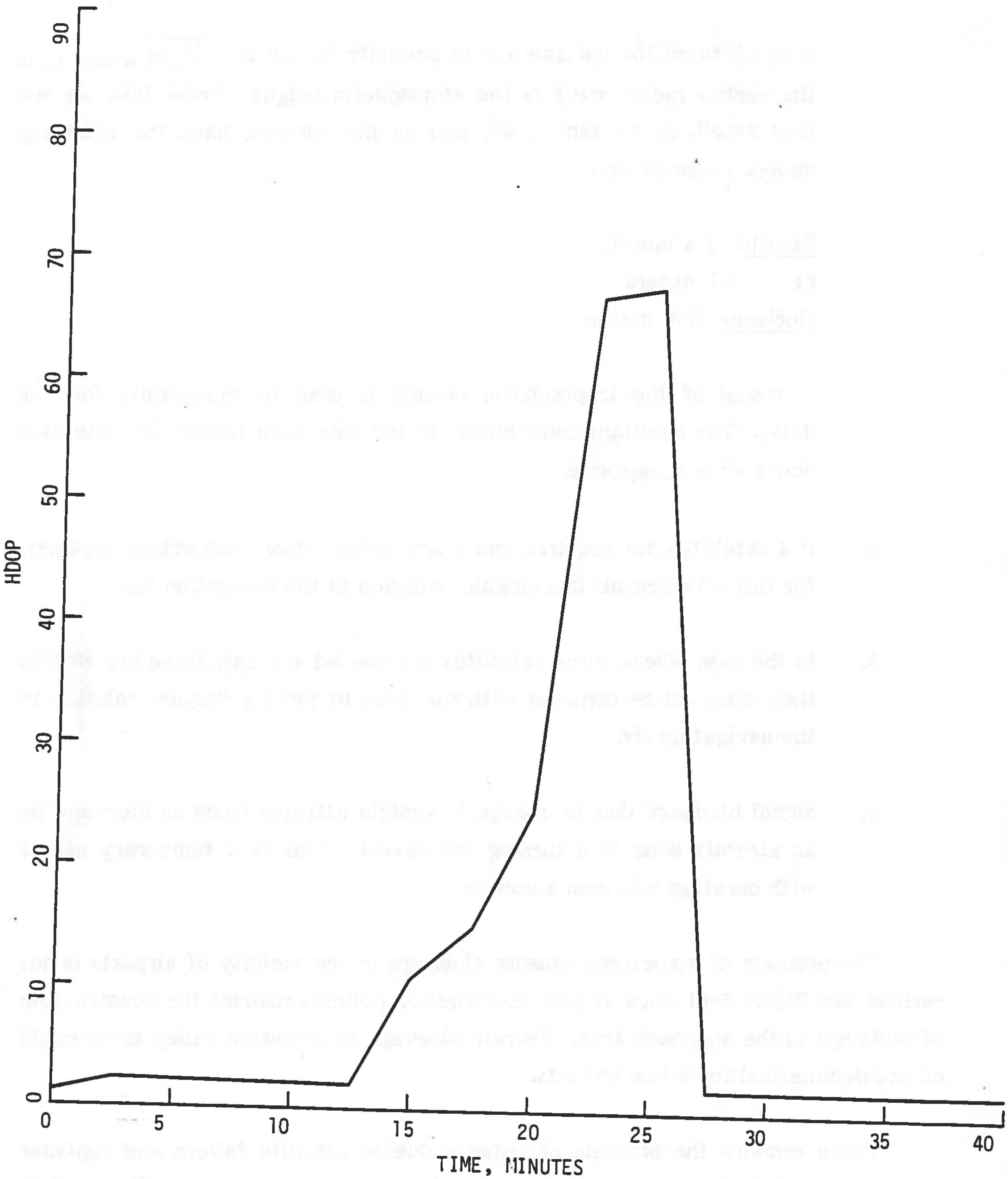


FIGURE 5-5. HDOP VARIATION DURING OUTAGE - FULL 18 + 3 SATELLITE CONSTELLATION 3-DIMENSIONAL SOLUTION, 10° MASK ANGLE

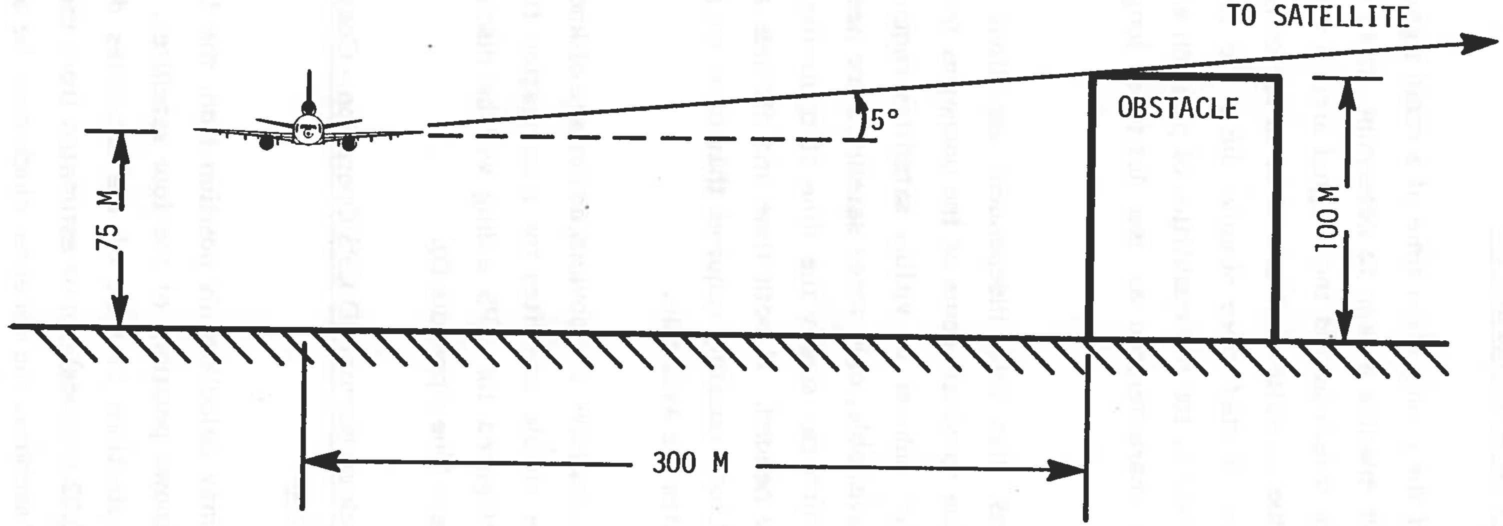


FIGURE 5-6. CLEARANCE NEEDED FOR NON-PRECISION APPROACH WITH GPS

If the receiver is sequential, the measurement of signal arrival time for each satellite may require one second, so that a three-second spread occurs between measurements. The clock must have good frequency precision (not accuracy) for three seconds in order that there be nanosecond estimated delay errors. The constant velocity approximation for the satellites is adequate to represent satellite motion during this period.

If the observer is on a moving vehicle, the use of a Kalman filter permits the user to add user velocity states to predict position. The addition of a clock state to model the expected inaccuracies of the user clock decreases the effect of those clock errors which fit the clock model.

While four or more satellites are available to the user, the clock must be stable to nanosecond accuracies over periods of three seconds. The errors due to longer term variations in the clock can be modelled by the Kalman filter and greatly reduced. The phase fluctuation of the clock caused by mechanical vibrations is the principal contributor to navigation errors in this mode of operation.

When only three satellites are available and the clock is used to provide accurate system time, the clock must have nanosecond accuracies during the period that only three satellites are available. The period may be 30 seconds in the case where a satellite is lost from view in a maneuver. It may be of the order of 20 minutes in the case of a coplanar constellation configuration or longer in the case of a failed satellite. Here, it is the variation of frequency of the clock that provides the largest contribution to navigation error.

For the periods of interest in computing navigation errors due to clock errors; (3 seconds, 30 seconds, and 1000 seconds), we may attribute the clock errors to environmental effects only. In the case of crystal clocks, acceleration forces result in a hysteresis effect for a net frequency shift even when the mean force is zero. Thermal changes also cause a frequency drift. Atomic clocks are usually well isolated from temperature effects but are subject to frequency pulling by changing magnetic fields produced by adjacent equipment.

The Radio Altimeter

The radio altimeter measures the propagation time of a signal transmitted from the aircraft, then reflected from the ground to the plane. The altitude is proportional to this time interval. The nature of the terrain and the altitude itself determine the accuracy of the measurement. Pulsed transmitters can differentiate areas immediately under the aircraft from other areas by time discrimination while FM systems average over a larger area of terrain.

Radio altimeters are used primarily below 500 ft above local ground. The errors present in the system are terrain dependent but average errors of 2% of the altitude may be expected. For altitudes of 1000 ft to 5000 ft, average errors run from 20 ft to 100 ft.

Strategy

The barometric altimeter has an accuracy at high altitudes which is far less than that necessary to produce a 4-satellite navigation fix of normal accuracy. In spite of this limitation, the requirements for lateral separation of aircraft specified in the Federal Radionavigation Plan (FRP) [(2)] are such that the 3-satellite-fix with barometric altimeter aiding, has sufficient accuracy to be acceptable. Table 5-1 compares the expected accuracy of GPS with FRP requirements.

Cost

Present costs of an encoding altimeter are about $2,000 for a barometric instrument and $3,500 for a radio altimeter.

TABLE 5-2. GPS USER COVERAGE REQUIREMENTS

<u>LAND USE</u>	
Normally needs only 3 visible satellites.	Terrain and building blockage may require more visible satellites or a good clock.
<u>MARINE USE</u>	
Normally needs only 3 visible satellites.	High sea state or harbor operation may cause blockage and more visible satellites or a good clock are required.
<u>AIRCRAFT ENROUTE</u>	
Normally needs 4 visible satellites.	In case of satellite failure, an encoding altimeter will provide accuracy necessary for FRP requirements. A good clock will provide normal GPS accuracy.
<u>AIRCRAFT APPROACH LESS THAN 1000 FT. ALTITUDE</u>	
Normally needs 4 satellites.	Encoding altimeter or a good clock will provide normal GPS accuracy in case of satellite failure or blocking by terrain or buildings.

6.0 SATELLITE FAILURES

6.1 General

With the recent decision to place the three spare satellites in positions which reduce the geometric outage periods across the CONUS noted in Section 5, the amount of time less than five satellites are in view has also been reduced. It would thus appear that the NAVSTAR GPS satellite constellation should be fairly forgiving of a satellite failure. That is, if a satellite becomes non-operational through exhaustion of fuel, clock failure, power supply failure, or some other fatal cause, the periods of time when less than four satellites are visible, or when the geometry results in high HDOP's, should be minimal.

However, there are outages for some satellite failures that are problematical. Shively [15] points out that the failure of certain satellites results in outages even for marine receivers or airborne receivers with altimeter aiding. These results were obtained using spare positions that had been planned prior to the recent change.

The computer analysis programs at TSC have been modified to output the DOP measures and number of satellites visible for several receiver options, using the new spare positions. However, it has not been exercised to date beyond validating the program. This work will be performed during the next period.

Shively also points out in another study [16] that the probability of continuous navigation service from all 21 satellites is not as high as might be expected. Using an MTBF for long-term failures of 10 years, which is consistent with NAVSTAR design goals, the probability of having at least four satellites in view over a given location for a year is only 95%, and for 10 years is only 70%. This is not likely to be a problem for marine and land users, nor is it out of line with other navigation systems. However, the system does not appear to be adequate as a primary system for air navigation as a consequence of the possibility of failures. Unlike the VOR system, there is no backup within the system. In VOR navigation, the loss of a station is not serious.

The issue of satellite failures and reliability will be addressed in more detail during the next period.

7.0 SELECTIVE AVAILABILITY

7.1 General

While many aspects of the Selective Availability program are classified, it is known that there are two types of errors to be used: (1) errors which would cause position measurements to wander; (2) errors which would confound velocity measurements.

The current plan promulgated by the NAVSTAR GPS Joint Program Office calls for a horizontal position accuracy of 18 meters (2drms) with the Precise Positioning Service (PPS) and 500 meters with the Standard Positioning Service (SPS) when the system becomes operational in 1987. This policy is stated in the Federal Radionavigation Plan[17]. PPS will be available to civil users only by special permission. Most users will only have access to the SPS. Higher levels of Selective Availability, i.e., less accuracy, could be employed if security considerations required them. The more likely series of events is that the Selective Availability level will be reduced, eventually enabling SPS having accuracies approaching 20 meters (2drms). Beser and Parkinson of Intermetrics, Inc.[18] for example, postulated a possible enemy potential navigation capability scenario that would allow reductions in the Selective Availability level starting about 1990. Thus it is reasonable to anticipate marked improvement in available NAVSTAR GPS accuracy during the 1990's. The decision to introduce SPS at the 500 meter level is not irrevocable, so it is important to identify the beneficiaries and the impact on their operation of higher accuracy Selective Availability levels. There are a discrete but large number of levels that can be activated by the NAVSTAR GPS Control Segment between 500 meters and 20 meters.

Examination of the requirements set forth in the Federal Radionavigation Plan[2] shows that the 500 meter accuracy level of the SPS is adequate for Marine Oceanic and Coastal Navigation safety requirements. Applications not met with Selective Availability, but which would be met if it were removed, include the following:

- o Marine commercial fishing.
- o Search & rescue operations

impact of the imposition of Selective Availability. These segments were analyzed to determine the distributions of the pseudorange errors, their rates of change, and their second derivatives. From these properties the effects of Selective Availability on the navigation solution, on receiver performance, and on the design of differential stations were inferred.

The pseudorange errors translate into navigation errors via the dilution-of-precision measures. Specifically, if the rms value of the satellite pseudorange errors at a specific time and place were 100 meters, and the HDOP were 2, the standard deviation of horizontal position error would be 200 meters, and the 2 drms error would be 400 meters. The two-dimensional navigation error distribution depends on the HDOP distribution over time and location. The HDOP distribution in turn depends on receiver/processor mask angle, satellite selection algorithm, and position computation algorithm. To estimate the navigation errors introduced by SA, HDOP distributions were computed for several of these design choices. In addition, a marine receiver computer simulation was exercised using the Selective Availability data segments. The resulting tracks provide a comparison of the navigation position estimates obtained from a marine receiver/processor with the true trajectory. The signal delay and frequency changes resulting from Selective Availability were compared with the code and carrier loop bandwidths and the capture windows.

The first and second derivative distributions of the SA determine the data update rate required by a differential system to provide a given level of accuracy. In particular, even if a differential transmission provided an exact correction at one instant, the variations in the Selective Availability signals would render that correction useless in a minute or so. Therefore the corrections must be updated often enough to maintain the desired accuracy. The update requirements are treated here using pseudorange corrections.

Design considerations of a differential station for local area marine use are discussed, and some of the problems associated with a network of differential stations are cited in Section 8.

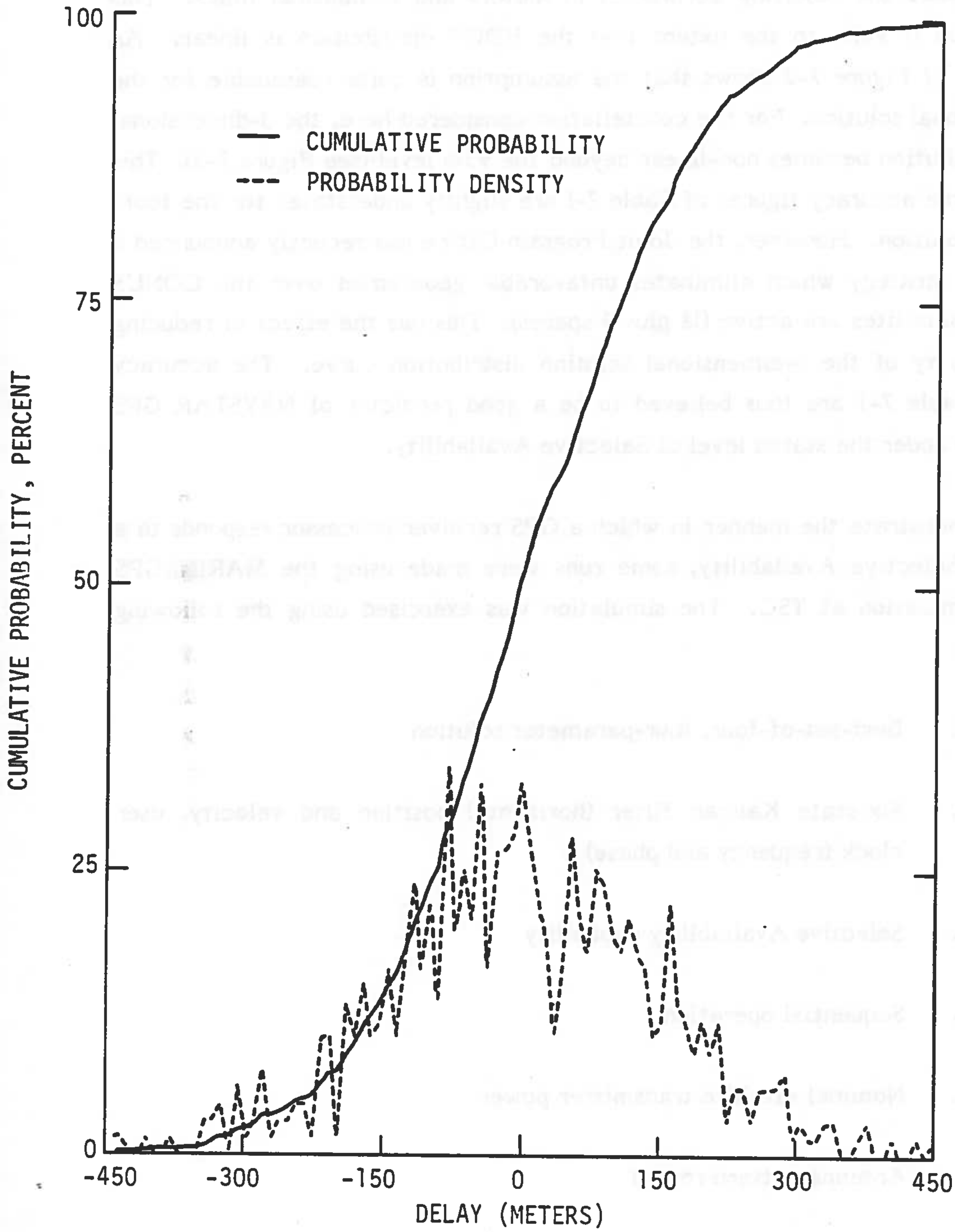


FIGURE 7-1. SELECTIVE AVAILABILITY PROBABILITY DISTRIBUTION

TABLE 7-1. ACHIEVABLE ACCURACIES UNDER SELECTIVE AVAILABILITY (2DRMS)

Navigation Solution Algorithm	Satellite Selection Algorithm	Mask Angle	Median HDOP	Accuracy	
				Meters	n.m.
2-D (Marine, aided air)	Best-set-of-three	5°	1.43	415	0.22
		10°	1.52	442	0.24
	All-in-view	5°	1.08	314	0.17
		10°	1.20	349	0.19
3-D (Airborne)	Best-set-of-four	5°	1.50	436	0.23
		10°	1.60	465	0.25
	All-in-view	5°	1.13	328	0.18
		10°	1.32	384	0.21

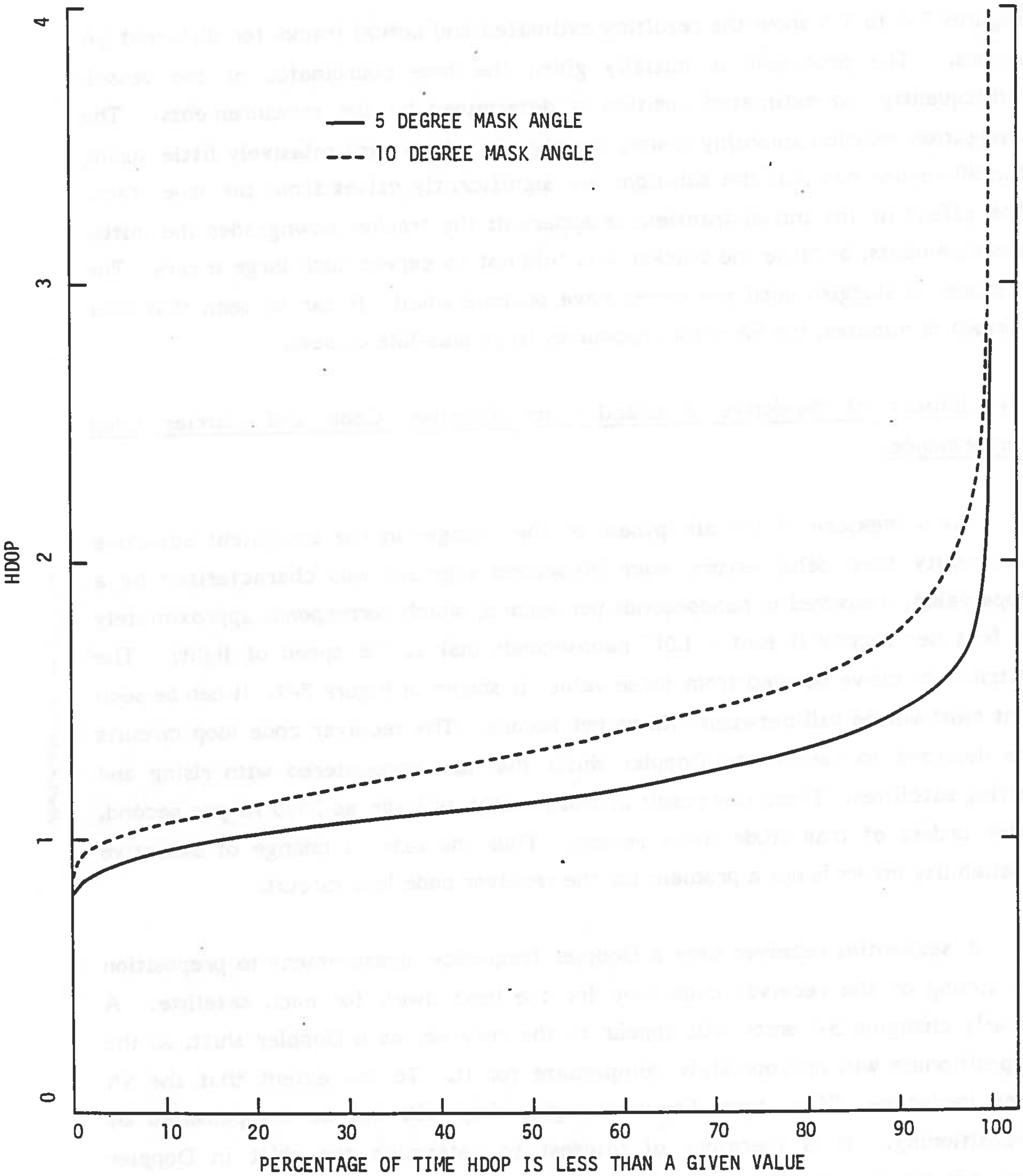


FIGURE 7-3. HDOP DISTRIBUTION, 3-DIMENSIONAL SOLUTION, ALL-IN-VIEW STRATEGY

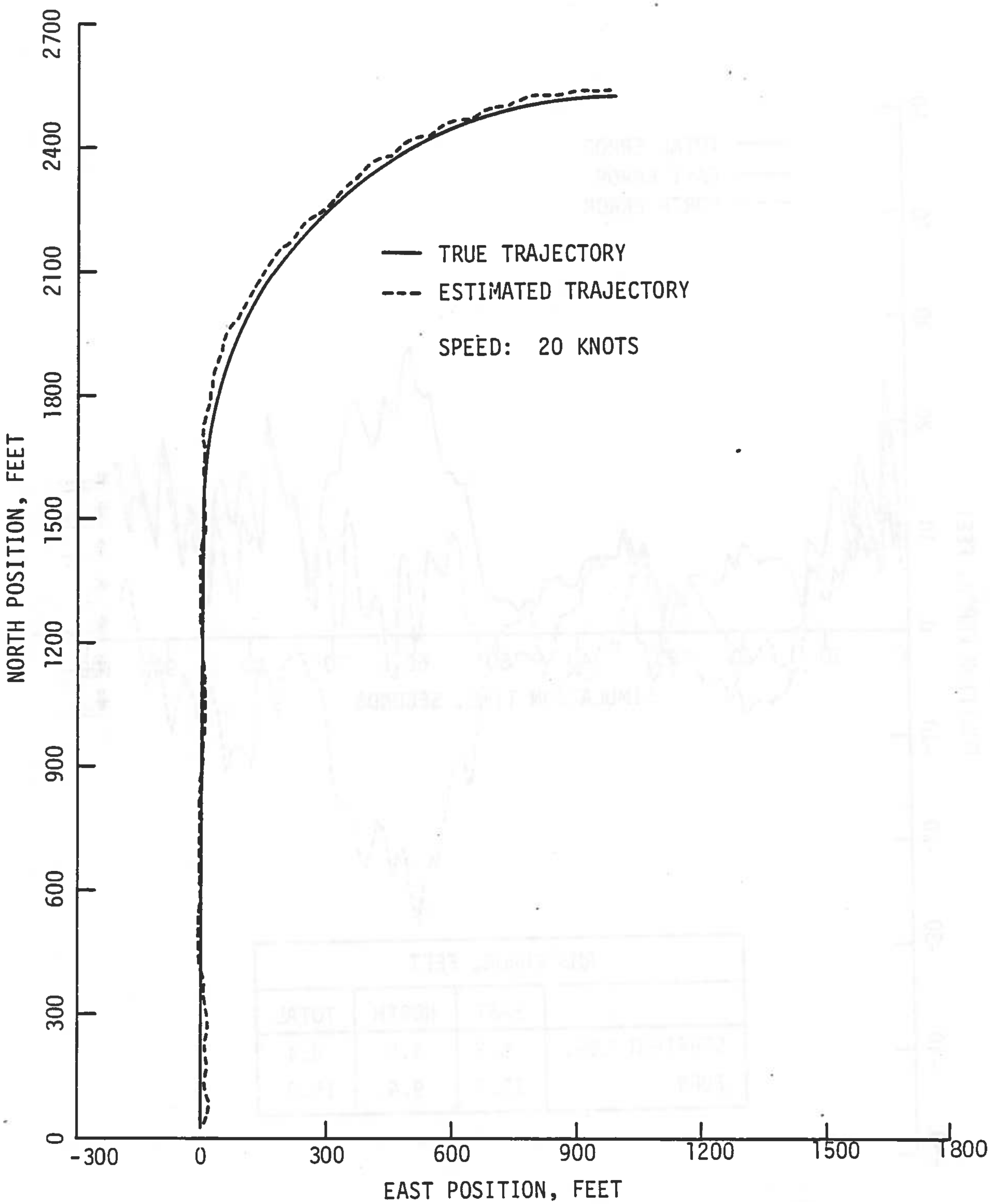


FIGURE 7-4A. ESTIMATED AND ACTUAL TRAJECTORY, NO SELECTIVE AVAILABILITY

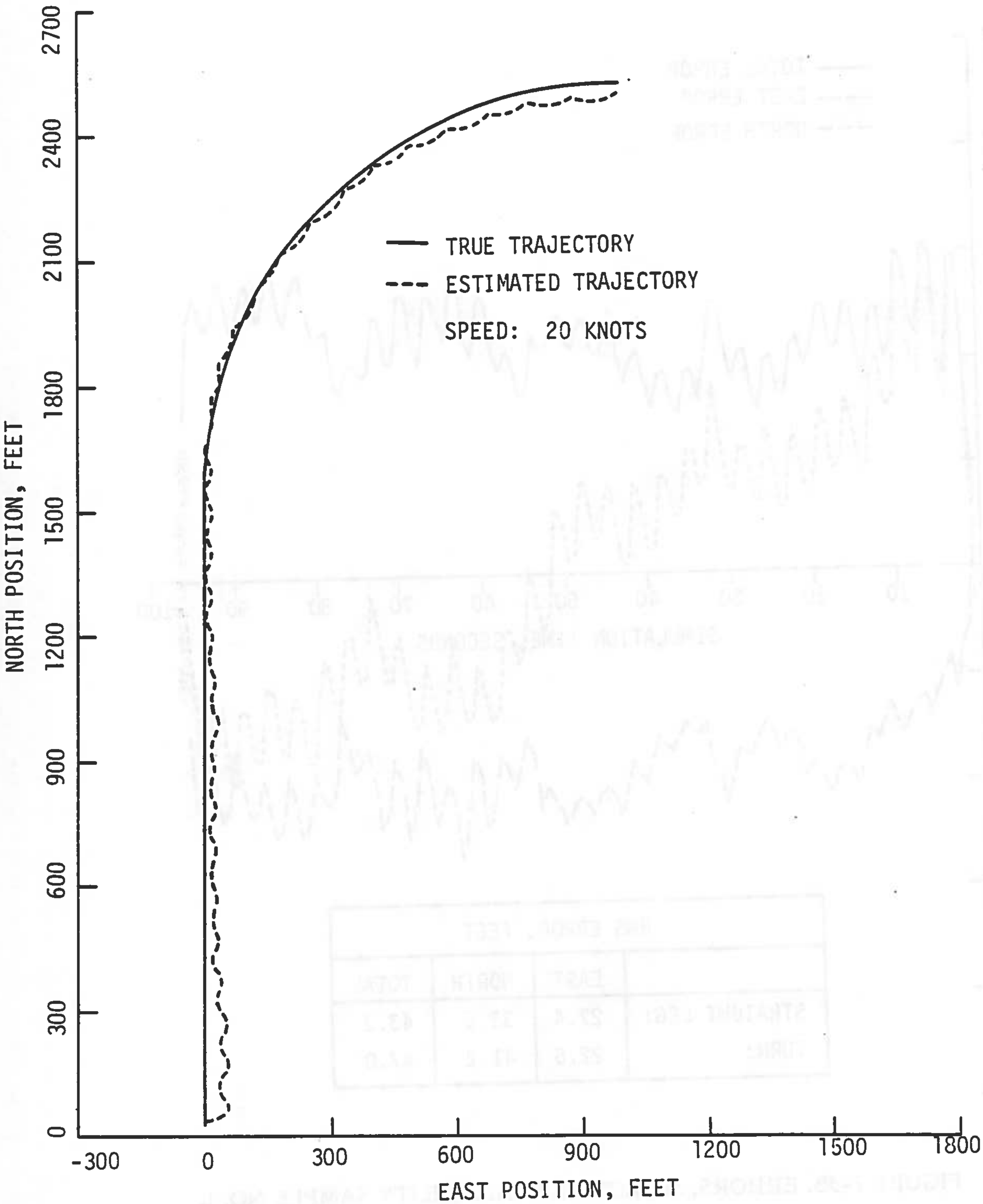


FIGURE 7-5A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 1

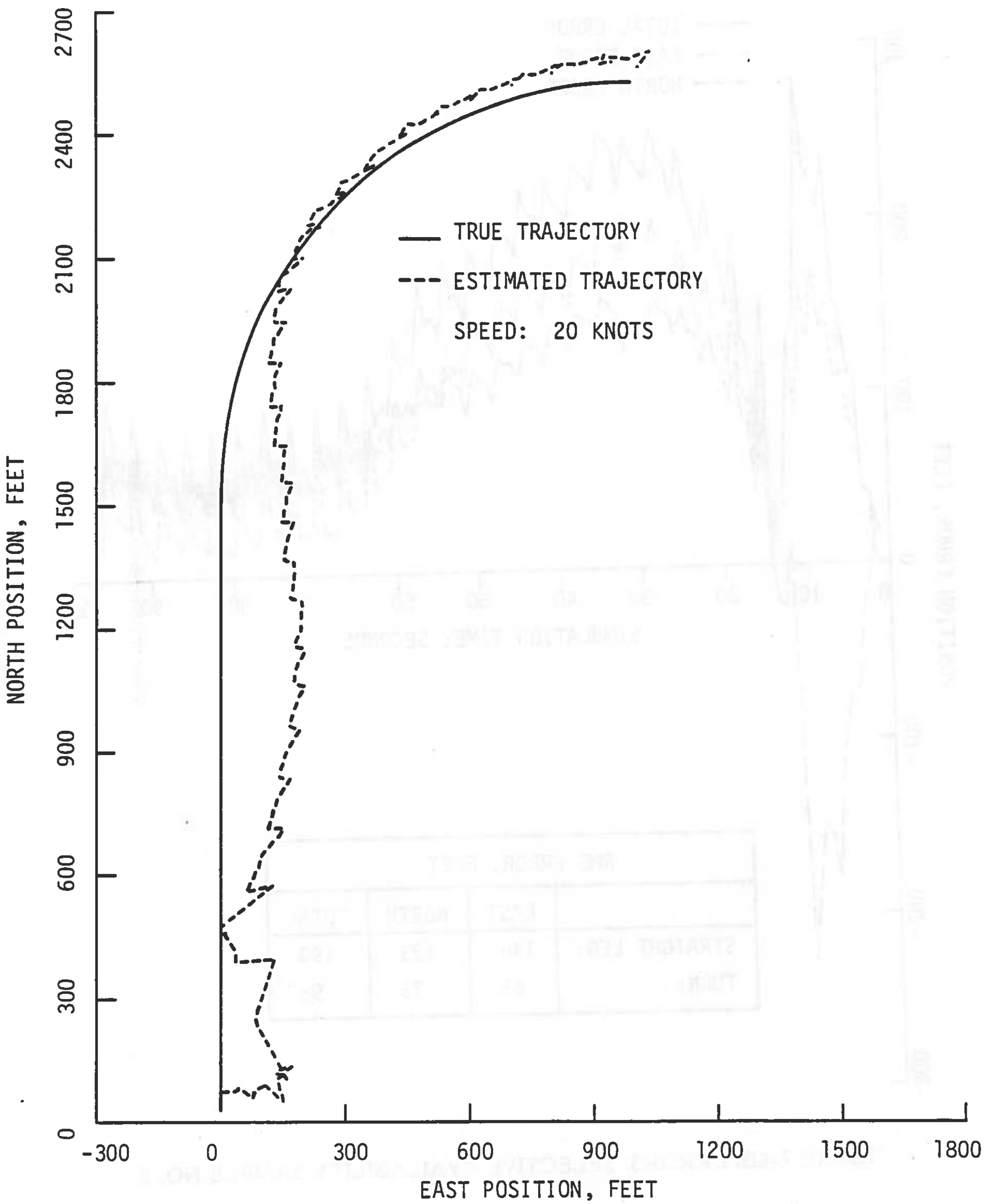


FIGURE 7-6A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 2.

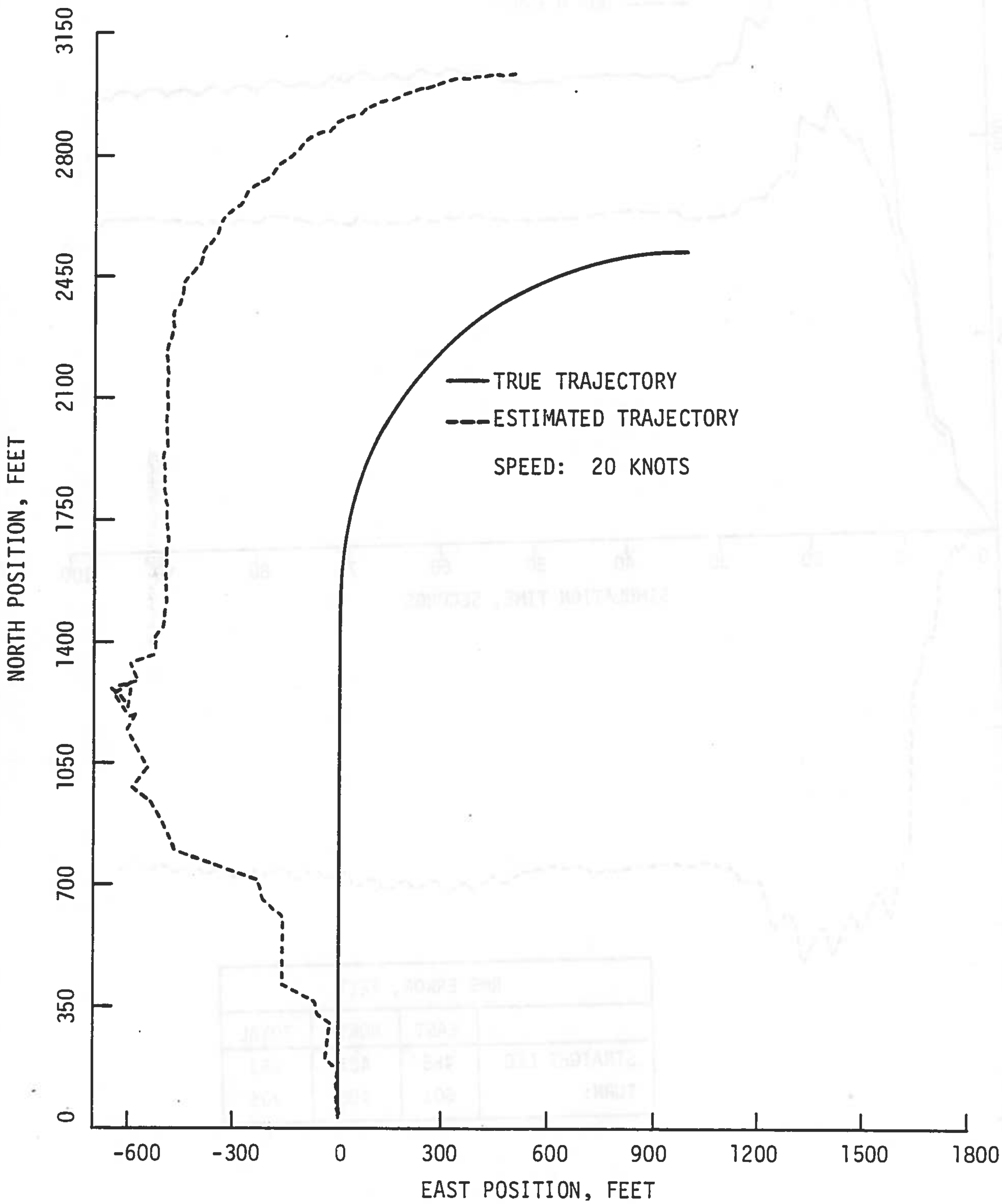


FIGURE 7-7A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 3.

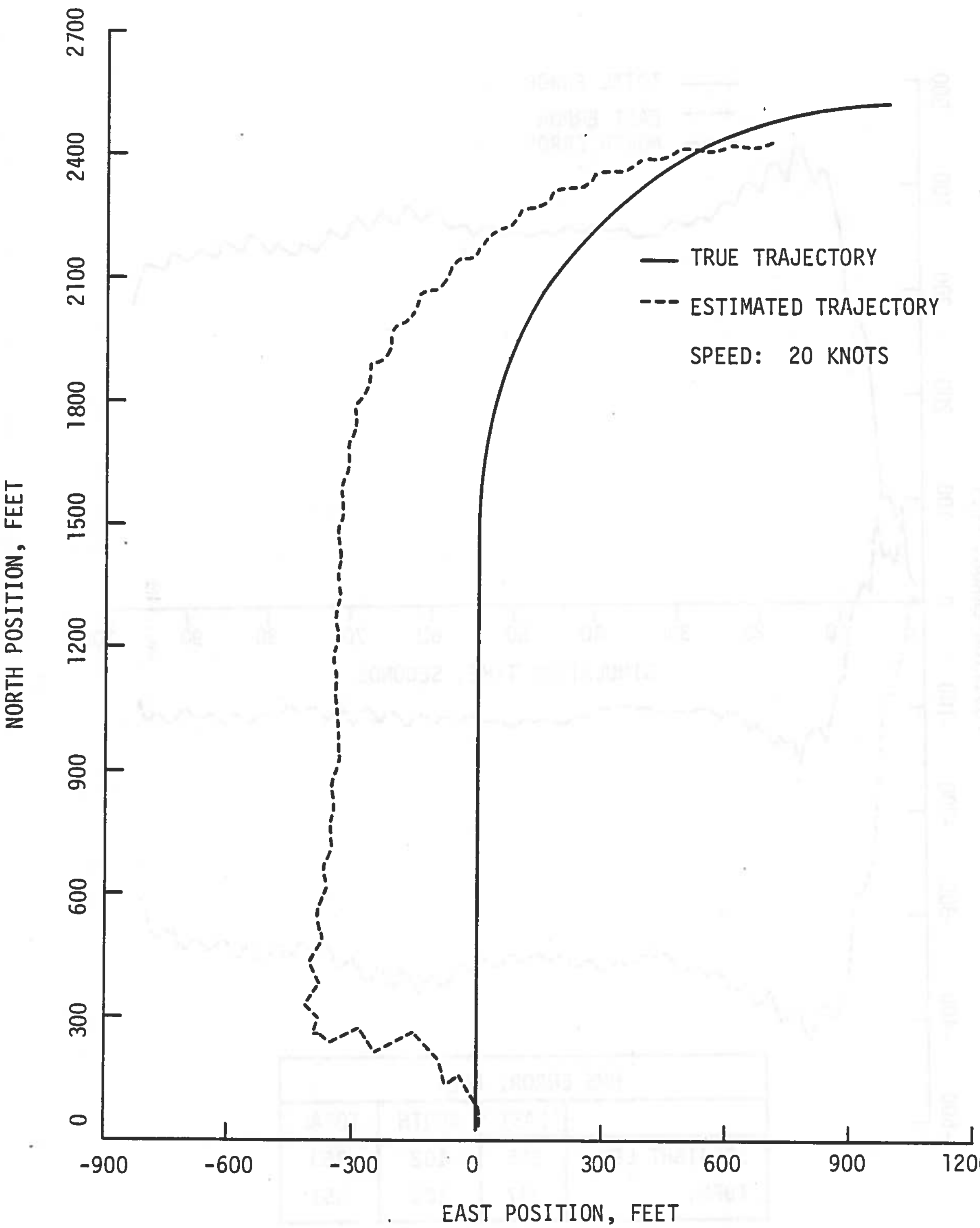


FIGURE 7-8A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 4.

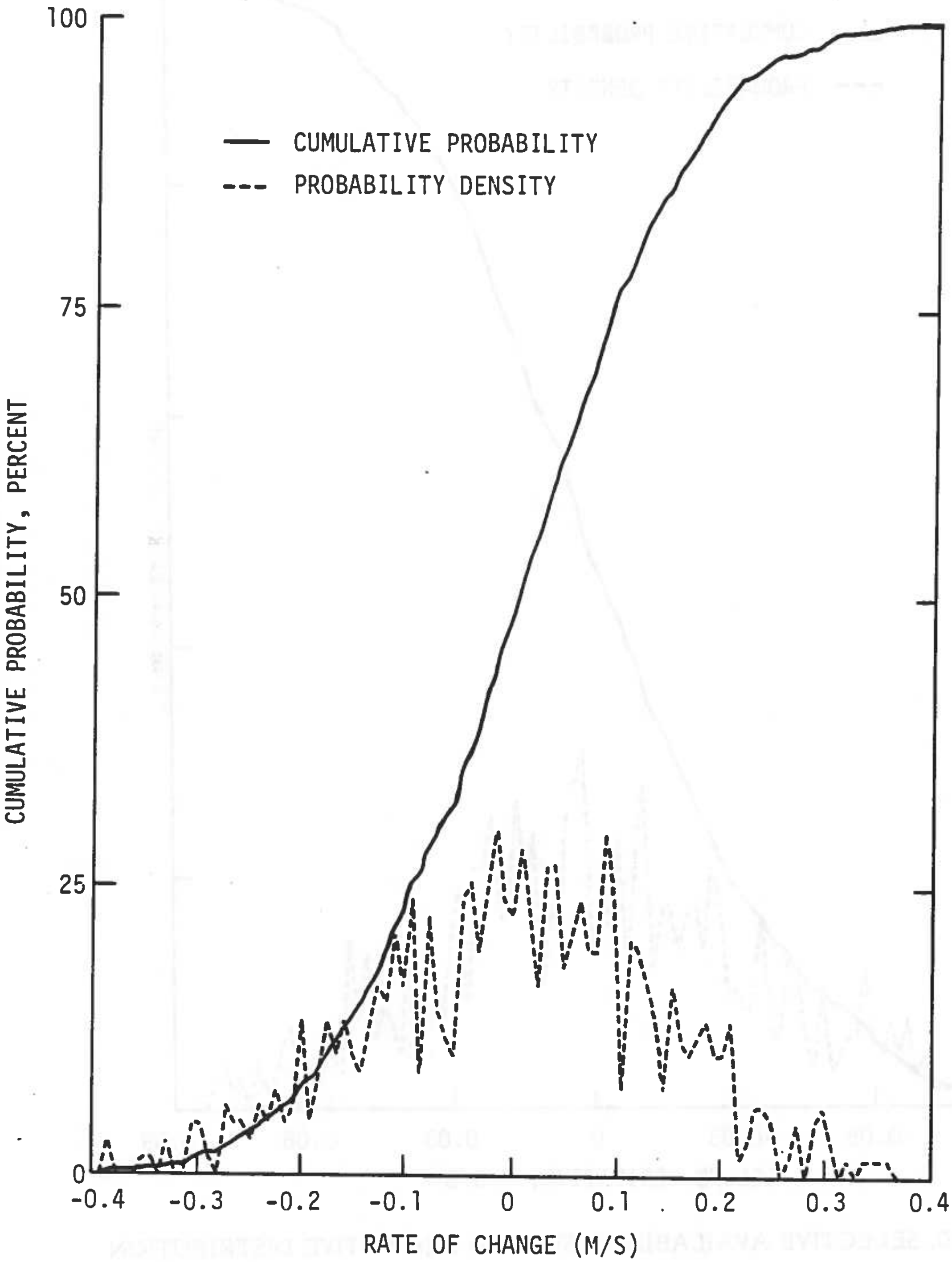


FIGURE 7-9. SELECTIVE AVAILABILITY RATE DISTRIBUTION.

the frequency shift corresponding to 0.012 ns/s/s is 0.2 Hz. Most receivers have carrier loop bandwidths of 0.75 Hz or more, and have pull-in ranges of 20 Hz or more. Therefore, the SA error changes can be expected to cause no receiver carrier loop problems, either.

8. DIFFERENTIAL OPERATION OF NAVSTAR GPS

8.1 General

Differential operation employs a fixed surveyed-in reference station which determines the pseudorange offset to each satellite caused by atmospheric delays, uncompensated satellite data errors, ephemeris errors, and Selective Availability; it then broadcasts these offsets to nearby users. By applying these corrections a user can significantly reduce his bias errors. It appears possible to reduce potential bias errors to well below 10 meters, which means that the total accuracy achievable would be limited primarily by the receiver quality and short-term noise sources.

In this section the usefulness of differential operation is described, the error sources are analyzed, system design alternatives are explored, and a system implementation concept is introduced.

8.2 The Need for Differential Operation

Under Selective Availability the Standard Position Service (SPS) accuracy provided for civil users will not meet the navigation requirements of several desirable user operations. Selective Availability is a program for controlling the accuracy of user/satellite range measurements. The user is in essence given a false time delay for each satellite so that the resulting pseudorange measurement is in error by a controlled amount. The accuracy available to civil users under the SPS will be maintained at a level consistent with U.S. national security interests. It is presently projected that the predictable and repeatable accuracies of 500 meters (2drms) horizontally and 820 meters (2 sigma) vertically will be made available during the first year of full NAVSTAR GPS operation with possible accuracy improvements as time passes.

Errors in pseodorange to each satellite translate into navigation errors via the Geometric Dilution of Precision (GDOP). The navigation error

TABLE 8-1. FRP REQUIREMENTS MET UNDER SPS WITH SELECTIVE AVAILABILITY

SPS Nominal Accuracy:

LATERAL: 500 m (2 drms)
VERTICAL: 820 m (2 sigma)

Phase	Accuracy in meters (2drms)
AIR	
EnRoute and Terminal	
- Oceanic	(Route Width 6 nm)
- Domestic	1000
- Terminal	500
- Remote	1000-4000
- Helicopter (Off-shore)	1000
(Land)	500
MARINE	
Ocean Phase	
- Safety of Navigation	3700-7400 min 1800-3700 desired
Coastal Phase*	
- Safety of Navigation	460-3700
LAND	
Transportation	
- Truck (Hazardous Cargo)	3333.3

*Meets Requirements above 500 m (2 drms)

TABLE 8.3 FRP REQUIREMENTS MET WITH DIFFERENTIAL GPS USING SPS ACCURACIES WITH SELECTIVE AVAILABILITY

USER RECEIVER CHARACTERISTICS:

AIR: 25.4 m (2 drms)
at 50 km Range
MARINE: 15.0 m (2 drms)

Phase	Accuracy Meters (2 drms)
AIR	
Meets all Requirements in Controlled Airspace Including Non-Precision Approach and Landing	
Will Not Meet: Precision Approach Landings	
MARINE	
All Requirements in Table 8.1 Met	
Ocean Phase - Hydrography Science o Resource Exploitation	10-100 m*
Coastal Phase - Hydrography Science o Resource Exploitation	1.0-100 m*
Harbor Approach and Harbor Phase - o Safety of Navigation Large Ships	8-20 m*
LAND	
All Requirements	

*Meets requirements above 15 m (2drms).

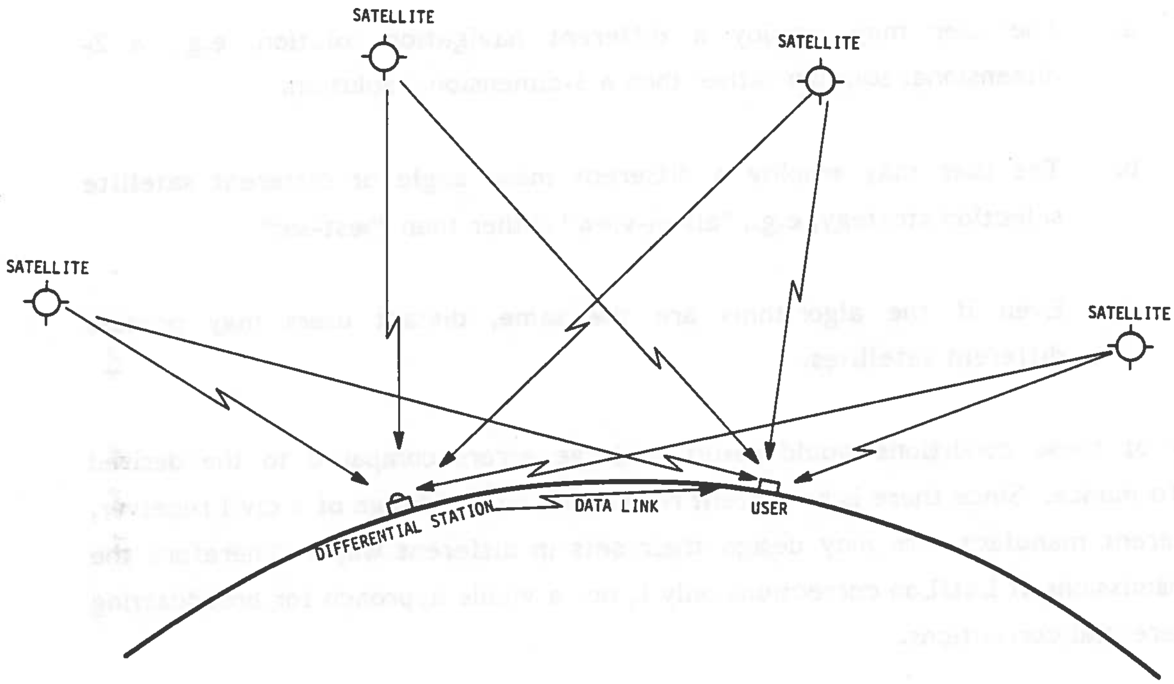


FIGURE 8-1. DIFFERENTIAL GPS GEOMETRY

8.3.3 Sources of Errors

The key element in differential operation of GPS is a high-quality reference receiver at a surveyed fixed location. The reference receiver computes a true range estimate from each satellite in view by using decoded ephemeris and satellite clock correction data and the surveyed coordinates of the reference site position. Corrections derived from the differences between the estimated range and the true range can then be used by nearby GPS receivers to remove most of the bias errors. The three major bias error contributing sources are: ionospheric and tropospheric delays, user clock error, and (most significant of all) the intentional delay generated by Selective Availability.

A significant design consideration for the differential station is that an accurate estimate of true range is achieved in a single measurement at the reference site. The user, on the other hand, must make three or more pseudorange measurements, one to each satellite, in order to obtain a position determination.

The reasons why the reference site can improve GPS position estimate are the following: (1) the bias errors determined at the reference site are common to all nearby GPS users and are relatively insensitive to the user's separation distance from the reference site, (2) bias errors vary slowly, and (3) the accuracy achieved in the true range measurement assures a high accuracy in the bias corrections.

A GPS receiver always deals with two types of errors: "bias", slowly varying noise error, which can be cancelled out by subtraction of differential corrections and "noise", rapidly varying random noise error, which can be reduced only by filtering. Figure 8-2 shows a diagram of measurements and their relation to true range between the receiver and each satellite.

A number of sources contribute biase and noise errors to make up the system error budget, but their contribution level depends on the characteristics of the operating system's processing requirement and the application (airborne, marine, land). To illustrate these differences, errors common to GPS and to differential operation, and the errors only unique to the differential operation, and the errors only unique to the differential mode, are identified and discussed in the following paragraphs.

The common GPS user error sources are following:

- o Ephemeris Update - degradation of the best fit of the corrected ellipse to the true orbit with an elapsed time of update.
- o Space Vehicle Clock Error - drift from GPS system time.
- o Unmodelled Ionospheric Bias/Noise - delay error variations.
- o Selective Availability - intentional delay errors.
- o User Clock Drift - deviation from strict time during measurements.
- o Receiver Bias - acceleration of the vehicle.

Noise contributions from the data link implementation, distance and time related error variations will enter the receiver channels unreduced. Estimated values of these errors are given later in the report when the performance of the differential mode operation is assessed.

Differential system performance varies with operational conditions and environment. These factors and others are well recognized when service coverage area and service range is specified.

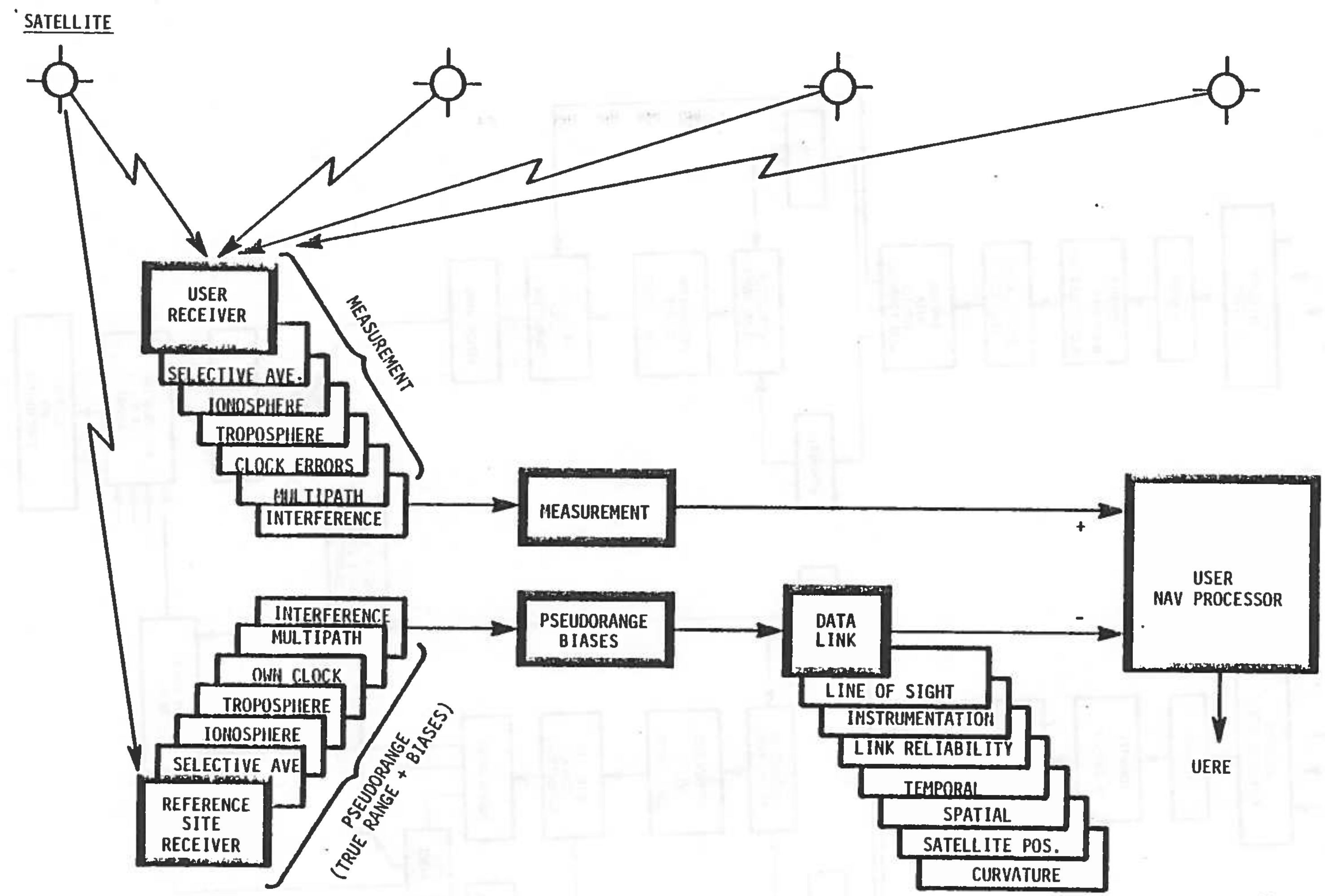
Not all bias errors are cancelled by use of a differential mode. Two unique classes of bias error enter into consideration, not present in normal operation, when the differential system error budget for the user is estimated: first, errors sensitive to the distance between the reference site and a user, often referred to as "spatial decorrelation errors"; second, errors related to the elapsed time during the establishment of a measurement correction value at a reference site and the delivery of the correction to the user, often referred to as "temporary decorrelation errors". Both classes of errors are identified by their components as follows.

2. Time-Sensitive Errors

- o Age of Ephemeris Update: error added during update.
- o Age of Space Vehicle Clock Update: clock error, (changes with update time from the ground control site).
- o Ionosphere: Irregularities (ionospheric drifts)
  - Diurnal - (TEC changes with solar changes)
  - Flare (TEC changes with time)
- o Time delay in measurement correction: error caused by elapsed time between measurement and application of correction data.
- o Selective Availability: rate of change and delay.

Distance and time sensitive errors will directly add to the user's receiver error budget. In general, the user's range measurements are less accurate than the reference site's for the following reasons: (1) the user's clock is of lesser stability, (2) reference site data smoothing is more effective in reducing noise further since the site is fixed, and (3) the reference site pseudorange error can be determined directly from the satellite ephemeris and fixed coordinate data on a single satellite without resorting to a full navigation solution. The range errors, spatial and temporal errors, data link, geometry, and receiver noise are the major contributors to the user's error budget. Interference also adds a noise-like error. Typical interference sources are multipath and multiple-access noise of satellite signals.

User receivers generally operate under much more severe operating environment than the receivers at fixed reference sites. Aircraft maneuvers and wind buffeting require bandwidths large enough to accommodate the deviations in position from unaccelerated straight-line motion. In addition, the tracking filter parameters must be chosen to accomodate these deviations. As a result, the signal-to-noise ratios are smaller, and less smoothing is possible for users.



Position Estimate (2 drms) = $2 \cdot GDOP \cdot$ [RMS ERROR] = $2 \cdot GDOP \sqrt{bias^2 + (\frac{noise}{3})^2}$

AFTER FILTERING

FIGURE 8-3. DIFFERENTIAL GPS ERROR PROPAGATION DIAGRAM

8.4.2 Differential Station

A GPS receiver with a suitable data link complement is located at a carefully surveyed site. The site is optimized for minimum multipath interference and line-of-site blockage. A GPS antenna is elevated at a proper altitude with antenna patterns adjusted to allow to monitor satellites at lower mask angles than the presently planned 5 degrees. This allows early acquisition of rising satellites. The second antenna, to be used for transmission of range corrections, may operate in a preferred or in a restricted sector of the operational coverage area. This might require customization of the antenna pattern. The height of both antennas are chosen to assure the required coverage range.

Satellite signals are received with an antenna with hemispherical coverage. Only a single frequency band at 1575.42 MHz is used, carrying C/A coded navigation messages at a rate of 50 Hz. A single channel receiver processes all satellites in view sequentially at a rapid rate, e.g., employing a dwell time of 0.2 seconds per each satellite. Five subframes of satellite data, each carrying repeated clock and ephemeris data every 6 seconds form a data frame which repeats continuously, once every 30 seconds. However, the almanac information and the ionospheric data are repeated on a 12.5 minute update interval. The GPS antenna receives satellite signals at a nominal -160 dbW/Hz level specified at 5^{o} elevation. Typical antenna patterns exhibit a rolloff of about 0.5 db per degree below 5^{o}.

Another feature of a differential receiver installed at the site is the better clock stability. It would be worthwhile to install a rubidium clock of $1:10^{-11}$ stability (.44 Hz drift in 28 seconds). A typical system layout is shown in Figure 8-5. Ground site installation will provide service coverage up to a few hundred kilometers.

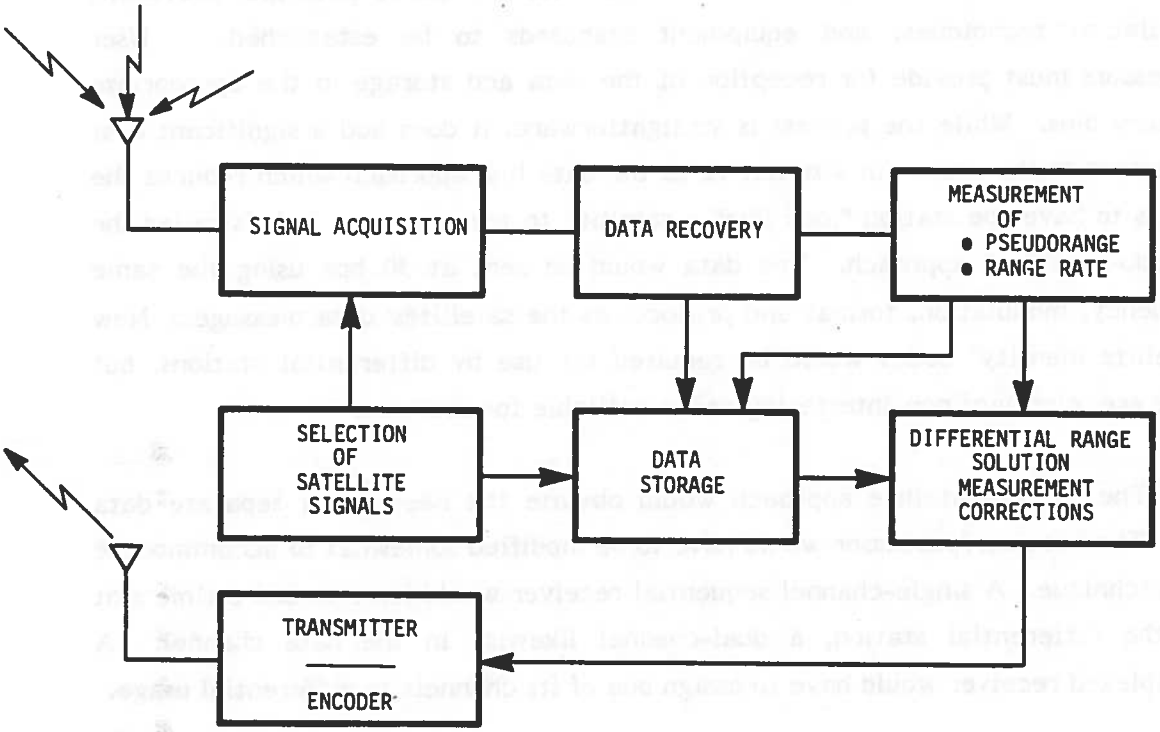


FIGURE 8-5. DIFFERENTIAL REFERENCE STATION BLOCK DIAGRAM

The discussion so far has been confined to one station and one user. Coverage of a large region would require a number of differential stations with overlapping areas of influence. In such an environment a user would frequently be closer to one station than another, but a useful satellite visible to the user could be hidden from the nearer station while being visible to the one further away. Enabling the user to get this information requires that differential stations communicate with each other; or, if differential stations and communication sites are separated, the communications sites would have to talk to more than one differential station. In either case, the differential system designer faces the problem of integrating the multiple differential station inputs.

Data update rate is a key parameter of a differential system. If a differential station issued pseudorange corrections periodically, users in the area could achieve momentarily high-accuracy positioning by incorporating these corrections. After a period of time, however, the Selective Availability errors would change, and the users' navigation solutions would deteriorate back to the normal SPS accuracy. To determine this period of time, and thus to determine the required differential correction update time, it is necessary to examine the rate of change of the Selective Availability pseudorange errors, and the system design accuracy that is desired.

Referring to Section 7, most rates of change fall beween ±.85 ns per second, the standard deviation being 0.43 ns per second. This translates to a 2drms value of positional change of about 0.4 meters per second, which suggests that in 30 seconds positional error would typically grow to 12 meters. To this 12 meters must be added (in root-sum-square fashion) the differential receiver error and user receiver noise error contributions to obtain the total system error after a period of time.

It would be desirable to meet the Harbor/Harbor Entrance requirements of 8-20 meters (2drms), which would require pseudorange measurement accuracies of 3-7. meters (1 sigma), assuming an HDOP of 1.5. However, even at the instant corrections are applied, the best achievable pseudorange accuracy is about 3.4 meters (1 sigma) when receiver errors are accounted for (assuming sequential receivers).

TABLE 8-4 DIFFERENTIAL CORRECTION MESSAGE

Message Element	Bits
Bookkeeping: Start, stop, parity	25
Station I.D.	12 } 40 bits
Number of Satellites	3
Each Satellite (up to 8)	
Satellite I.D.	6 } 18 bits
Pseudorange correction	12 } each satellite

Total: 40 + 18 x 18 = 184 bits, pseudorange corrections

For a pseudosatellite differential system the data rate would be constrained to 50 bps, which at first glance appears to be adequate. However, single channel sequential receivers can only devote a fraction of the time to the differential data, i.e., 20-25 percent. Furthermore, the asynchronous nature of the differential transmissions requires that two successive message sets be allowed for to ensure that the entire message is received during the dwell time. In order to reach users having single-channel sequential receivers, the data rate of a pseudosatellite differential station would have to be 66 bps, which is greater than the 50 bps rate of the system. Dual-channel receivers can devote a higher proportion of time to the differential transmissions, but the pseudosatellite station would still have to transmit the message at least four times during the update period to insure that a dual-channel receiver devoting 50 percent of the data channel time to differential data reception would receive it. The data rate requirement is 26 bps for a dual channel receiver.

Consequently, a pseudosatellite differential station could provide single channel sequential receivers with 16 meter service, and could provide dual-channel sequential receivers with 12-14 meter service. Parallel-channel receivers having one channel devoted to differential data would have no problem, but modifying a

8.5 Performance Estimates

8.5.1 Receiver Performance Summary

The performance of a receiver operating in the differential mode depends on four factors:

1. Receiver design characteristics.

2. Operational environment and geometry.

3. Signal characteristics and update rate.

4. Service requirements.

The complexity of the receiver design is determined by the manner in which functions are shared between the fixed receiver located at the differential station site and the moving receiver installed on the users vehicle, vessel or aircraft. Selection of receiver functions in an optimal manner would be governed by system cost-performance effectiveness and is beyond the scope of this study. The performance analysis presented here is based primarily on published GPS technical information, augmented by in-house analysis and simulation.

The performance of three classes of receivers was analyzed based on their unique service requirements. The three classifications are:

1. Differential station receiver.

2. Marine/Land receiver.

3. Airborne receiver.

The results are summarized in Table 8-5. More detailed discussion on the error components is provided in Section 8.5.2.3.

One characteristic common to all three receivers is a significant receiver performance degradation for the signals of satellites at low elevation angles. Results characterizing low angle operation, 10 degrees and below, are presented in Figure 8-6 for the marine/land receiver and in Figure 8-7 for the airborne receiver. It is evident that mask angles below 3 degrees result in larger errors and should be avoided in the differential mode. Quantitative data of this study are given in Table 8-6 for the marine/land receiver and Table 8-7 for the airborne receiver respectively. Computed errors are biased intentionally towards the worst error condition. In these figures "ΔE - Iono Bias" refers to the residual error in ionosphere delay resulting from the difference in elevation angles associated with the user -reference separation; the worst-case orientation was chosen, namely the case where satellite, user, reference, and earth's center and coplanar. "Iono Bias" refers to the residual ionospheric delay errors caused by inhomogeneities in the ionosphere. The worst case orientation was chosen, namely the case where user-reference line and user satellite lines are perpendicular. These situations do not occur simultaneously, but using the worst-case situation for both is a conservative approach.

From these data the following conclusion can be drawn. A typical uncertainty in the pseudorange correction information sent to users by the differential site is 2.3 meters (1 sigma). Using pseudorange corrections with noise errors given in Tables 8-6 and 8-7 for 5° elevation angle, the user's RSS error in a single measurement for marine and airborne applications are 5.6 meters and 8.5 meters respectively. After reasonable filtering by the navigation tracker these errors reduce to 3.4 meters and 4.1 meters respectively; a noise reduction factor of 3 was assumed. These errors are referred to as user-equivalent range errors (UERE).

The 2drms measure is used to connote two-dimensional position errors, and corresponds roughly to a 95%-98% probability level. It depends on the pseudorange error and the horizontal dilution of precision (HDOP). The formula used here, and a typical set of values are as follows (ignoring temporal errors):

$$2\,drms_{5^{\circ}ELEV} = HDOP \times 2 \times \left[BIAS^2 + \left(\frac{NOISE}{3}\right)^2\right]^{\frac{1}{2}}$$

$$= 1.5 \times 2 \times \left[2.9^2 + \left[\frac{5.6}{3}\right]^2\right]^{\frac{1}{2}}$$

TABLE 8-7. PSEUDORANGE ERROR BREAKDOWN - AIRBORNE RECEIVER

DELAY LOOP BANDWIDTH, B_L = 1 Hz

FILTERED UERE = $[(\text{TOTAL BIAS} + \text{DIFF. STA. UNCERTAINTY} + \text{ALT. BIAS})^2 + (\frac{\text{USER RECEIVER NOISE}^2}{3})]^{1/2}$

USER	BIAS IN METERS						NOISE IN METERS	$[BIAS^2 + NOISE^2]^{1/2}$	FILT. UERE = $[BIAS^2 + (\frac{NOISE^2}{3})]^{1/2}$
ELEVATION ANGLE E	EPHEMERIS ERROR (480 Meters)	ΔE IONO (50 KM)	IONO BIAS (50 KM)	TROPO BIAS (50 KM) (10,000 Ft. ALT)	DIFFERENTIAL STATION UNCERTAINTY	TOTAL BIAS	USER RECEIVER NOISE	UNSMOOTHED UERE (RSS)	SMOOTHED UERE
1	1.20	0.16	0.42	20.20	2.20	20.36	8.00	20.88	20.53
2	1.20	0.21	0.41	5.20	2.20	5.79	8.00	9.88	6.38
3	1.20	0.38	0.40	2.30	2.20	3.45	8.00	8.71	4.36
4	1.20	0.50	0.39	1.90	2.20	3.21	8.00	8.62	4.17
5	1.20	0.54	0.39	1.40	2.20	2.95	8.00	8.53	3.97
6	1.20	0.58	0.39	1.10	2.20	2.82	8.00	8.48	3.88
7	1.20	0.62	0.38	0.90	2.20	2.76	8.00	8.46	3.84
8	1.20	0.65	0.38	0.80	2.20	2.74	8.00	8.45	3.82
9	1.20	0.68	0.38	0.70	2.20	2.72	8.00	8.45	3.81
10	1.20	0.70	0.38	0.60	2.20	2.70	8.00	8.44	3.79

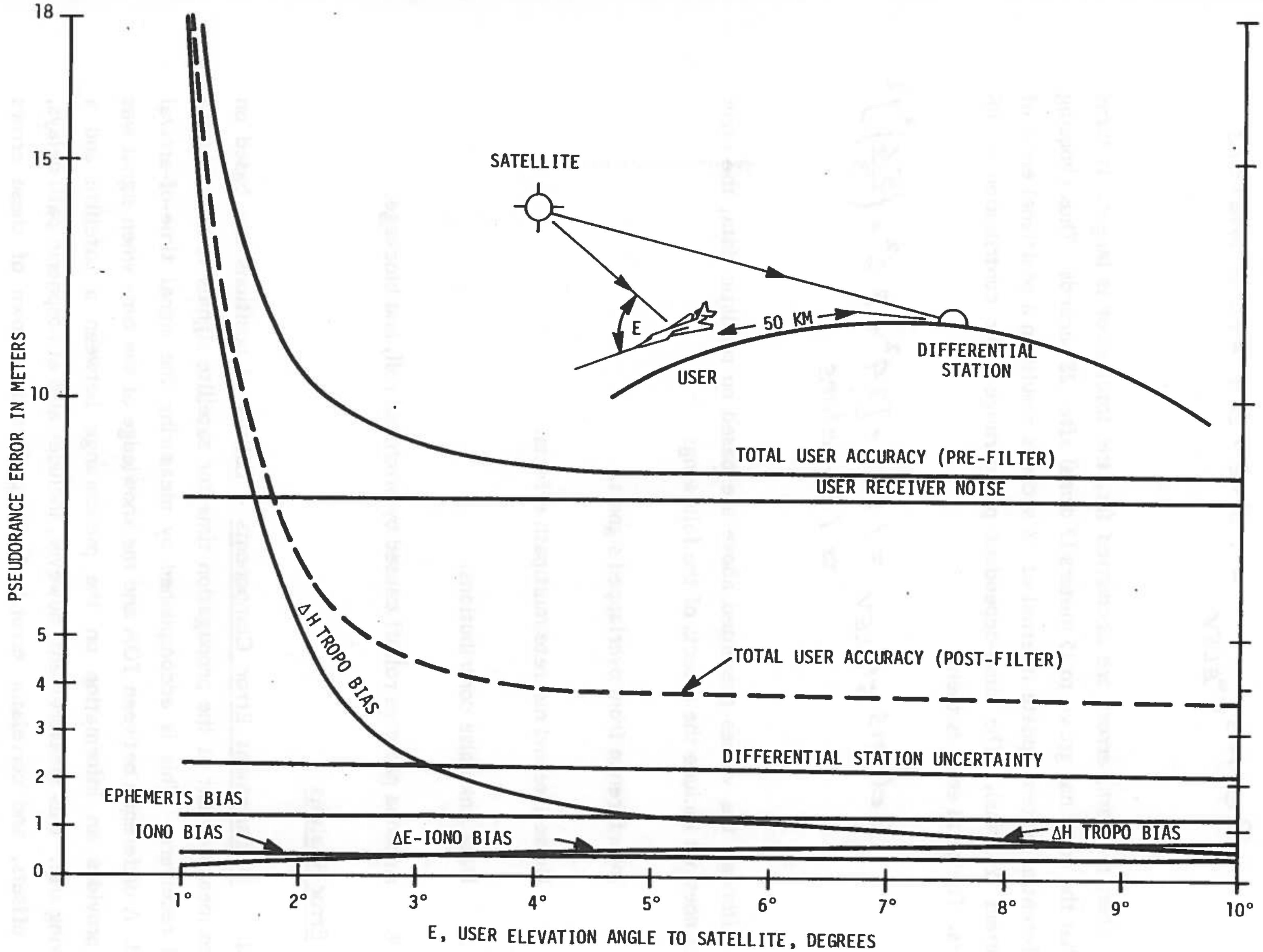


FIGURE 8-7. PSEUDORANGE ERROR CONTRIBUTION - AIRBORNE RECEIVER
50 KM USER/STATION SEPARATION

$$\Delta R = \delta_E + \delta_R + \delta_{IONO+TROPO} + \delta_{SV_C} + \delta_{SA}$$

where the terms have the following definitions:

ΔR - measured pseudorange error.

δ_E - ephemeris error

$\delta_{IONO+TROPO}$ - Atmospheric delay

δ_{SV_C} - error in space vehicle clock correction send with navigation message

δ_R - receiver noise error.

δ_{SA} - Selective Availability

The following error subdivision was used in Tables 8-6 and 8-7 to produce graphs in Figures 8-6 and 8-7.

1. BIAS ERRORS
   - Ionospheric - TEC changes with distance.
   - Ionospheric -ΔE + TEC changes with angle.
   - Ephemeris - Error in satellite position.
   - Differential Station Uncertainty - error in measurement.
   - ΔH - TROPO - Uncorrected component in the altitude difference delays.

2. NOISE ERRORS
   - Receiver Noise - error in pseudorange measurements.
   - Tropospheric Noise - fluctuation in the atmosphere.

A discussion of these errors will be addressed in Section 8.5.2.4.

Receiver design is based on the capability of acquiring all satellites in view. More constraints are imposed on the differential station receiver than to other users to have full data collection continuously. Users, on the other hand, can make their optimum selection at will. From analysis it was determined that for marine receivers the time is divided as follows for each satellite:

T_L - loop time: 1.52 seconds/satellite
T_G - Ground time: 0.04 seconds/satellite
T_D - dwell time 1.52 + 0.04 = 1.56 sec/s
T_u - update time = (1.56) x 3 + .72 = 5.4 seconds

Residual error introduced to settling time to 95% original value in acceleration condition is

$$E_a = .05 \times 1/2g\, T_u^2$$

Typical values for 1/2g acceleration are shown in Figure 8-8.

8.5.2.3 Receiver Range and Range Rate Error Calculations -Receiver noise errors and the interference affect the range measurement and the range tracking performance. To compute these errors and to establish their dependence on the receiver characteristics a step-by-step analysis is performed. The receiver range errors are the sum of the receiver noise, quantification and instrumentation errors and are classified as being random and uncorrelated errors between measurements, and the bias errors are caused by acceleration. The uncorrelated range errors are as follows:

$$\sigma_R = (\sigma^2_{NOISE} + \sigma^2_{QUANTIZATION} + \sigma^2_{INSTRUMENTATION})^{1/2}$$

For the non-coherent dither type receiver, the noise error has two error sources: phase jitter generated in the carrier loop, and the phase jitter in the delay loop.

Mathematical expressions for various noise sources are as follows:

1. Total Noise Component Due to Phase Jitter

$$\sigma_N = \frac{\Delta}{2\pi}\left[\sigma_D^2 + \left(\frac{\sigma_C}{N}\right)^2\right]^{\frac{1}{2}}$$

where

Δ = chip length, 293.2 meters

N = carrier-to-data-rate ratio, 1540

Delay Loop Phase Jitter:

$$\sigma_D^2 = (2\pi)^2\left[\frac{B_D}{\left(\frac{C}{N_o}\right)_D}\left(1 + \frac{2B_{IF}}{\left(\frac{C}{N_o}\right)_D}\right)\right]$$

$$= (2\pi)^2\left[\frac{.5}{2041.7}\left(1 + \frac{2\times 1000}{2041.7}\right)\right]$$

$$= (2\pi)^2 \times 484.786 \times 10^{-6} \text{ radians}$$

3. Instrumentation Error

$$\sigma_I = \frac{\Delta}{N} = \frac{293.2}{1540} = .19 \text{ meters}$$

A. Total Range Error

$$\sigma_R = [\sigma_N^2 + \sigma_Q^2 + \sigma_I^2]$$

$$= (6.45^2 + .055^2 + .19^2) \quad , \quad Q = 1540 \text{ was used}$$

$$= 6.45 \text{ meters}$$

Range bias error due to receiver acceleration causes additional jitter in the receiver carrier loop:

$$\Delta\phi = \frac{.615}{B_c^2} \cdot \frac{a}{\lambda_c}$$

$$\Delta R = \frac{\lambda_c}{2\pi} \frac{\Delta\phi}{N} = \frac{1.845}{B_c^2} \cdot \frac{a}{\frac{\lambda_c}{N}} \cdot \frac{\lambda_c}{2\pi N} = \frac{1.845 a}{2\pi B_c}$$

$$\Delta R = \frac{1.845 \times 4.9}{6.28 \times 100} = .01 \text{ meter}$$

where

$$a = 4.9 \text{ meters } (1/2_g)$$

B. Total Range Rate Error

$$\sigma_{\dot{R}}^2 = \sigma_{N(\dot{R})}^2 + \sigma_{Q(\dot{R})}^2$$

where

$$\sigma_{N(\dot{R})} = \frac{\lambda}{2\pi T}\left[\frac{2B_c}{\left(\frac{C}{N_o}\right)_c}\left(1 + \frac{B_{LP}}{2\left(\frac{C}{N_o}\right)}\right)\right]^{\frac{1}{2}}$$

Range rate error is a phase noise in the carrier tracking loop. The receiver range rate counter averages carrier frequency for T seconds (averaging time for doppler count). In particular:

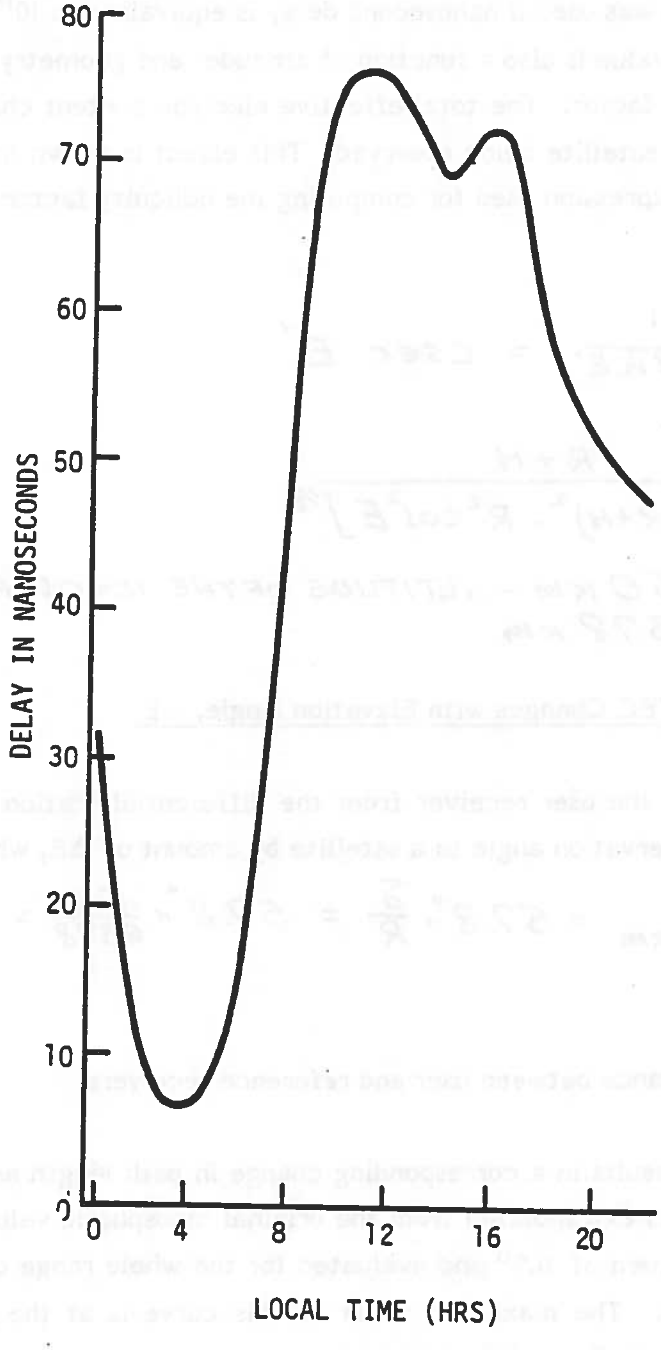


FIGURE 8-9. IONOSPHERIC VARIATIONS WITH TIME

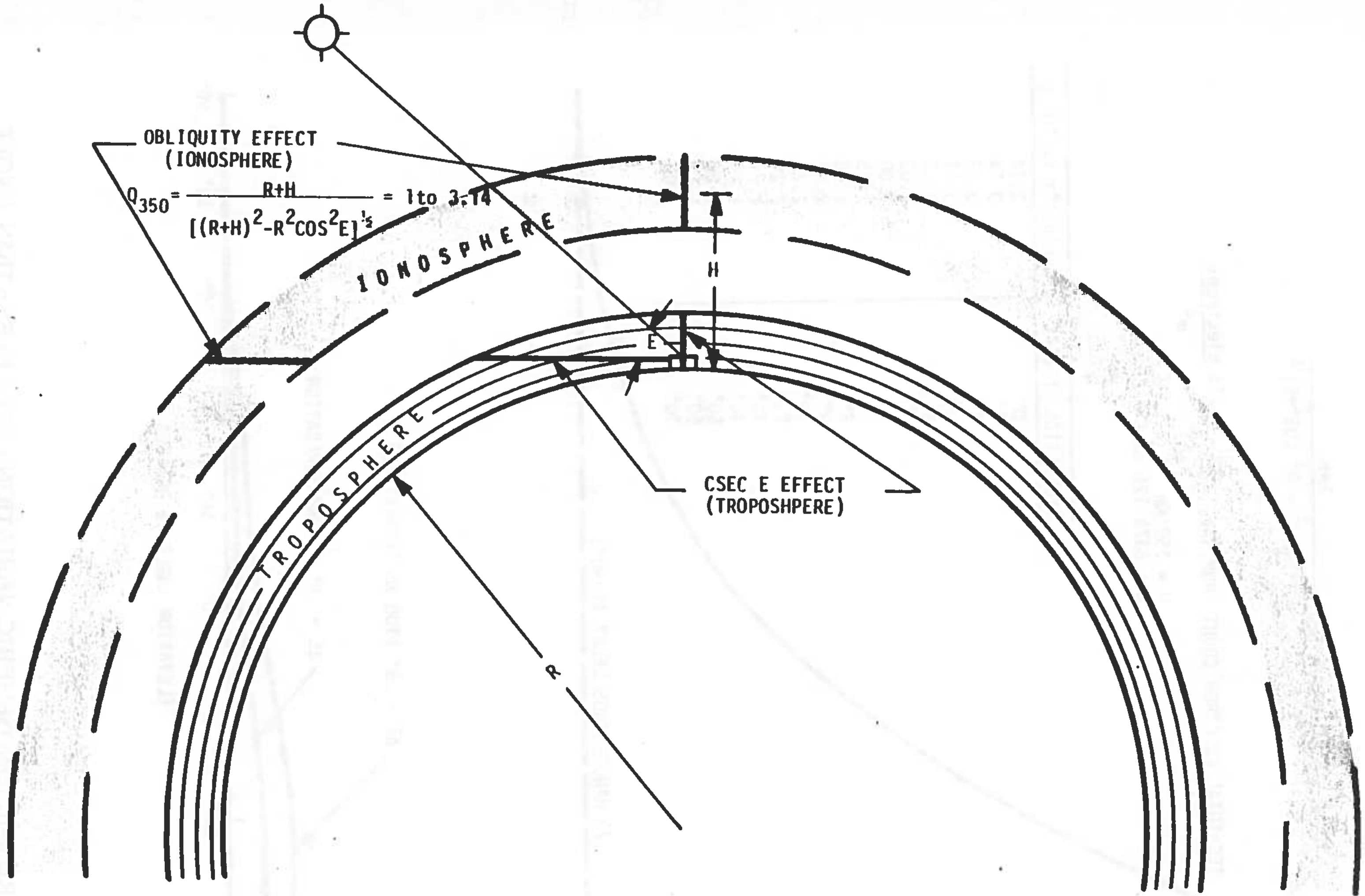


FIGURE 8-10. ATMOSPHERIC DELAY GEOMETRY

C. Ionosphere: TEC Changes with Time

Ionospheric irregularities of various sizes exist, which means that the satellite-receiver path delays can be somewhat different for user and reference site. These irregularities travel horizontally so that the vertical electron content changes with time. The rate of change of TEC is the product of the horizontal gradient and the velocity. Measured values have been observed up to 1200 m/sec but average around 100 to 150 m/sec. Using a 800 m/sec velocity and a 10 mm/km spatial gradient the maximum change of delay will be 8 mm/sec or .024 nanoseconds per second. The difference in signal delays experienced by the user and the GPS reference site can be expressed as a distance error in the measurement as a function of time. Typical values derived for the maximum variability rate of the ionosphere are shown in Table 8-8.

TABLE 8-8. TYPICAL IONOSPHERIC DELAY TEMPORAL VARIATIONS

Irregularity	4.85 mm/sec
Diurnal	1.82 mm/sec
Flare	2.42 mm/sec
Total(RSS):	5.72 mm/sec or .0192 nsec/nsec

For the GPS operation without Selective Availability, the ionospheric temporal errors will become the dominating factor in the determination of the update rates for the transmission pseudorange corrections. A typical error in pseudorange measurement for a 3 minute update interval is one meter.

D. Ephemeris Error

An error in the satellite position may be intentionally introduced. Ephemeris error is the position error between the true and assumed satellite position. The effect of ephemeris error affects pseudorange measurements is shown in Figure 8-12. Assuming that small angle approximations are valid, which is true for the relatively small distances on the earth surface, a 1.2 meter bias error results from a 480 meter ephemeris error for an extreme case observing a satellite along the 50 km baseline.

E. Differential Station Uncertainty in the Measurement

In addition to bias error components in the pseudorange correction values sent to users there is a noise error component associated with the correction component which cannot be removed by subtraction. A user has to absorb this error as a bias in his measurement. The magnitude of this error is shown in Table 8-9. The noise error is assumed to be time invariant during the short interval of the measurement cycle.

F. Tropospheric Errors

The atmosphere has a small, but significant refractive index which causes propagation delays that can reach 30 meters at low elevation angles. The refractive index is stable with frequency, but is affected by temperature, pressure and humidity variations. The total delay as a function of elevation angle is quite predictable, so that a simple cosecant model can remove all but a meter or so of the pseudorange error for a user near sea level. An aircraft receiver at altitude will experience significantly different delays, but again the effects are quite amenable to modelling. However, there is less correlation with the delays of a ground based reference station. The delays and residual errors as a function of elevation angle are shown in Figure 8-13.

G. Receiver Noise in Pseudorange Measurement

A computation of the receiver noise component is derived in Section 8.5.2.2. The resultant value is a function of the satellite evaluation angle. Factors related to the receiver noise characteristics are input signal-to-noise ration, tracking filter bandwidth and receiving antenna pattern effects.

TABLE 8-9. DIFFERENTIAL STATION RECEIVER CHARACTERISTICS

Receiver noise	6.0 meters
Multipath noise	1.0 meters
Noise error after smoothing	2.0 meters
Clock error, bias	.8 meters
Total error	2.2 meters

9.0 RECEIVER COSTS

9.1 General

This section draws on existing cost models to project costs of NAVSTAR GPS receivers, primarily at the lower-cost end of the spectrum. Two existing cost models were exercised and found to give similar results, in spite of the difference in the approaches used. One model can be used to project trends and thus provide predictions on future costs of receivers, subject to the condition that the receiver architecture doesn't change. Of course, in practice receiver architectures will change to take advantage of rapidly improving digital technology. These changes are addressed qualitatively.

Both single and dual channel receiver designs are considered here. A sensitivity analysis is performed on the single channel receiver cost trends that show that fairly large trend projection errors do not greatly change the predicted receiver costs.

9.2 Cost Estimates for Single-Channel Receivers

The cost models described in Appendix E are based on the use of analog components for many receiver functions that in today's designs would be performed with digital circuitry [22, 23]. Both models give similar results, and show general agreement on the functional breakdown. Figure 9-1 shows the block diagram on which the model is based. Figure 9-2 shows the comparative costs obtained by the two models, where 1982 dollars are used. The shaded region in the right-hand bar graph is the expected decrease in cost of the digital circuits during the time that elapsed between the studies. The most noticeable dissimilarity is in the costs of the enclosure/chassis. Of course, the SCI model was aimed at a marine user, while the ARINC model was geared to avionics so some differences would be expected, but we have no explanation for their difference. All in all, the similarities are more impressive than the differences.

These costs can be trended to provide predictions of future costs using the SCI model, which groups subcomponents into trendable units, i.e., subcomponents which are similar enough that they could be expected to follow similar cost

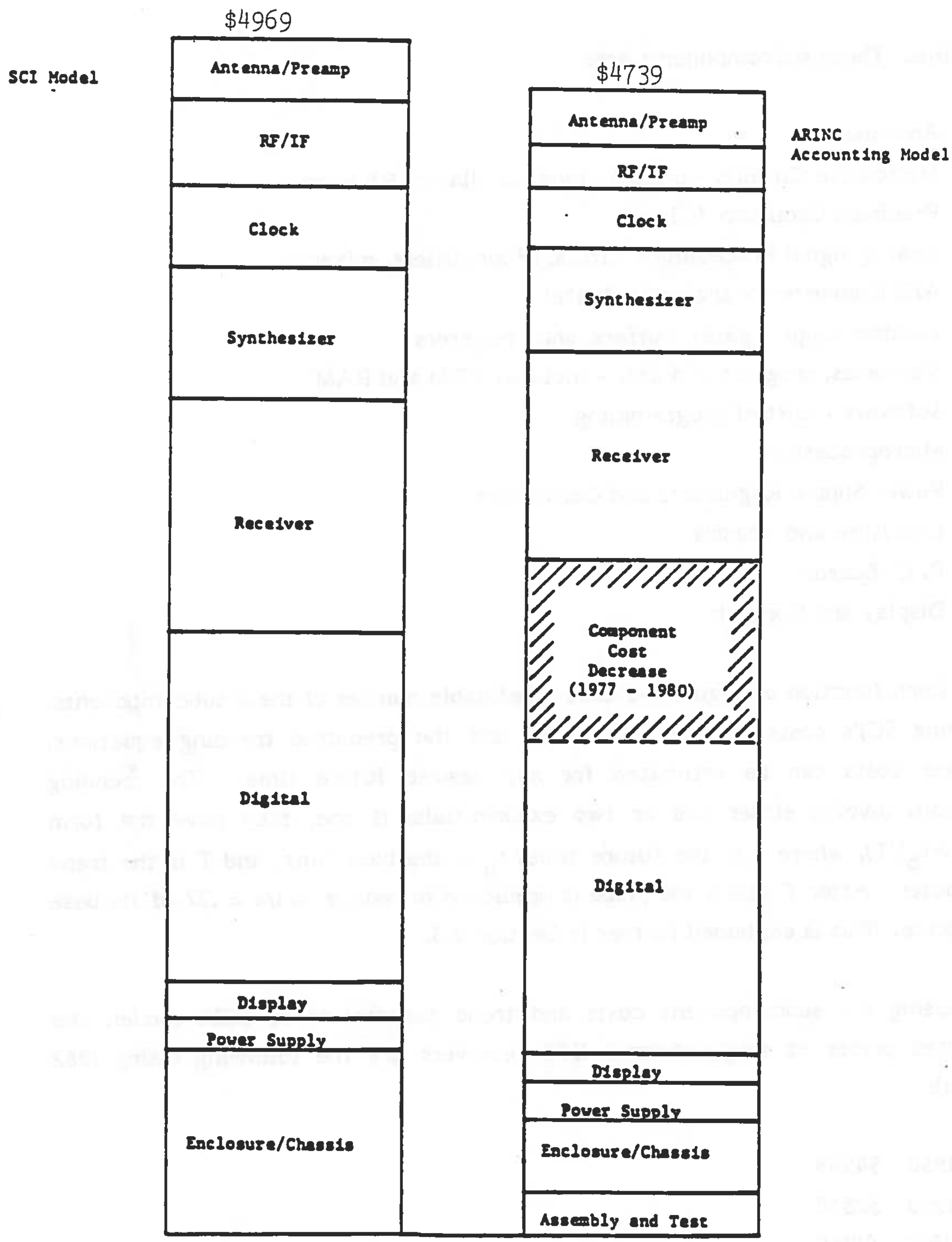


FIGURE 9-2. GPS RECEIVER COST ESTIMATE, TWO MODELS

Producer Price Index (PPI) variations, which has not risen as rapidly as the Consumer Price Index (CPI). The reason is that the CPI is affected strongly by housing and food prices, which have risen sharply. For example, between 1980 and mid-1982, the CPI rose by 17.4% while, the PPI rose by only 11.4%. The $4969 receiver price of 1980 is comprised of $2276 that is material-related, and $2693 labor-related.The 1990 and 2000 prices used the same labor-materials split.

The 1990 and 2000 projections are open to question for several reasons:

a. The receiver architectures will use more digital and less analog components, which will tend to reduce the prices.

b. Labor costs will rise faster than material costs, a factor not completely accounted for in the prices. This will tend to raise the price figures (see reference 24).

c. The higher labor costs will probably raise the manufacturing burden and the distribution percentages. As a result, the ratio of list price to manufacturing cost will probably increase.

With these caveats, the numbers give a rough idea of future receiver prices. The factors mentioned are offsetting to some extent, and difficult to predict, in any case.

9.3 Sensitivity Analysis

The trending equations used to derive the receiver cost figures for 1990 and 2000 are exponential in nature. Most subcomponent trends are single exponential equations, mentioned above in Section 9.2. Some are expressed as the sum of two exponentials, one sharply dropping with time, the other slowly decreasing. To a first approximation, each trend can be characterized by a period of time whereby the subcomponent price is cut in half, called the "cost-halving" time.

The sensitivity analysis performed here considered the effect of doubling this cost-halving time for each subcomponent, and observing the effect on the total

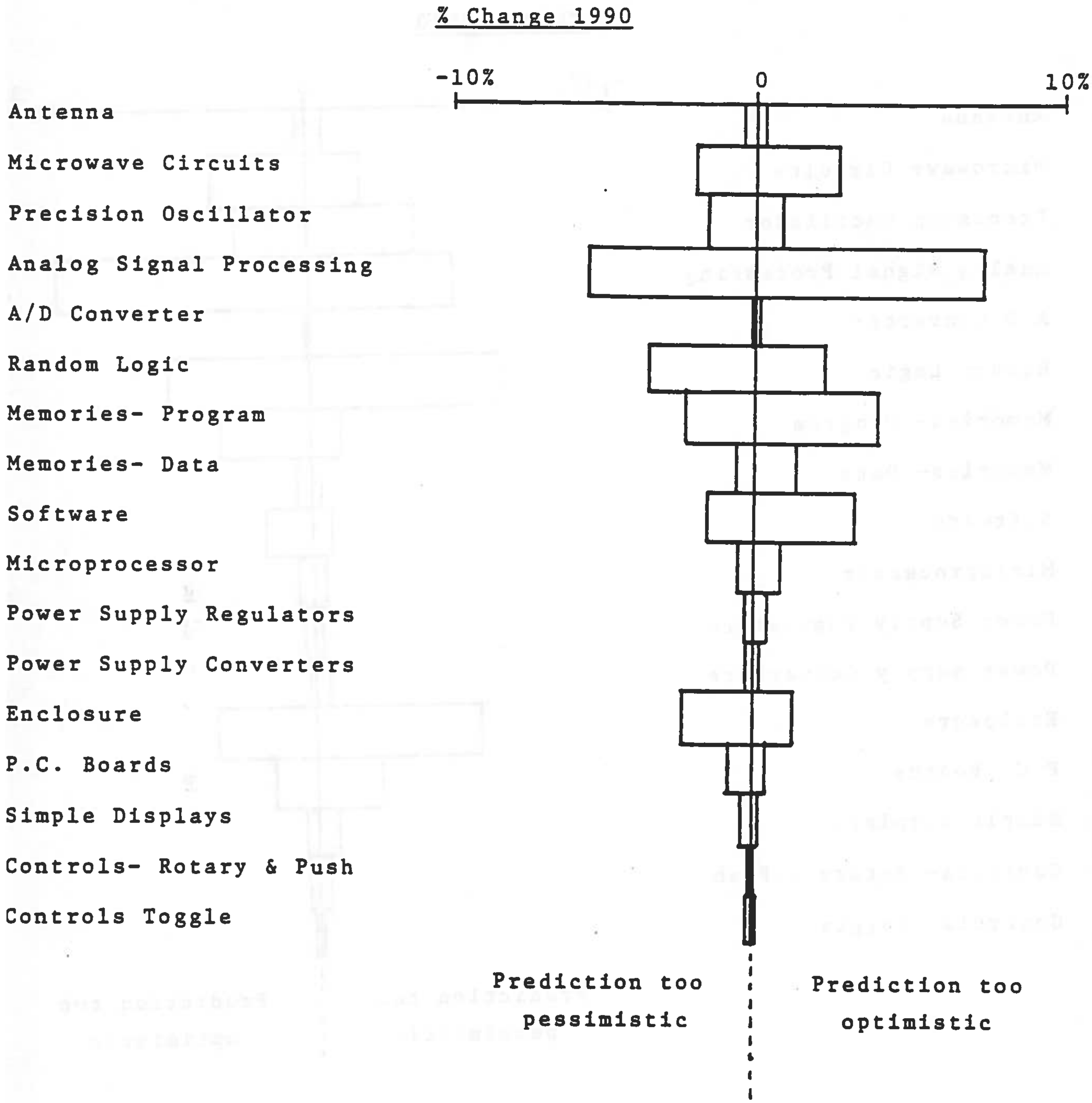


FIGURE 9-3. SENSITIVITY OF RECEIVER COSTS TO PREDICTION ERRORS IN TRENDS - 1990

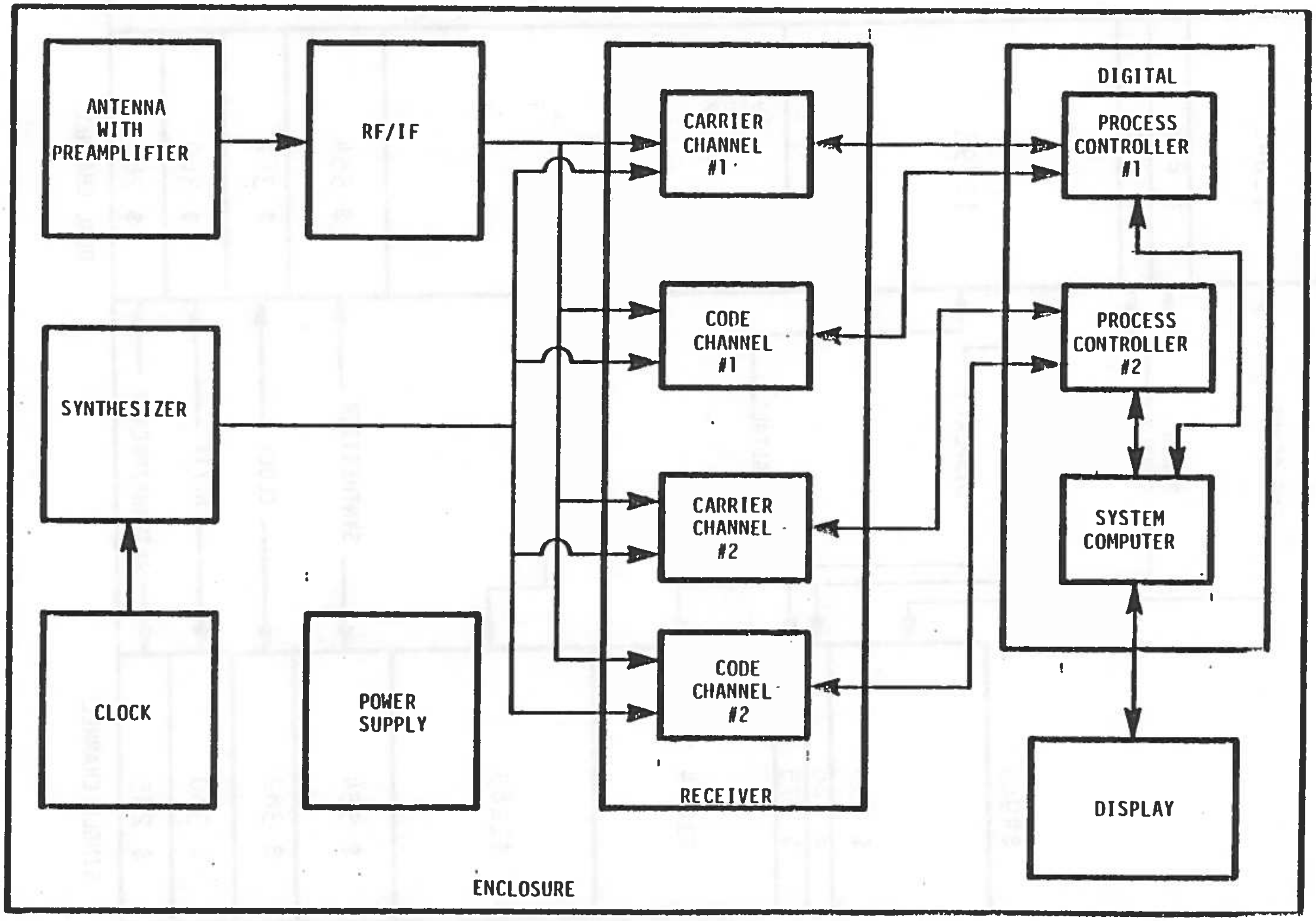


FIGURE 9-5. COSTING MODEL BLOCK DIAGRAM FOR DUAL CHANNEL RECEIVER

part of this increase is in analog components, which will be replaced by digital circuits in future designs. The effect of digital circuits will be not only to reduce the costs for both single and dual channel designs, but reduce the cost ratio. As a rough estimate dual channel receivers wil probably cost about 25%-30% more than single-channel receivers.

9.5 Impact of Possible Changes

Differential Operation - Since one satellite clock drives both the precise P-code and the coarse acquisition C/A-code signals, and since both traverse the same inonspheric/tropospheric path, the inherent precision of the C/A signal is the same as the P-code, namely in the 5-10 meter range. If bias errors could be removed, the C/A code could provide accuracies adequate for Harbor/Harbor Entrance marine requirements, non-precision aircraft approach requirements, and even lateral/longitudinal requirements for precision approaches. Differential operation can remove most of the bias errors by having a fixed, known station broadcast correction terms.

In order to receive correction terms, the navigation processor must interface with some kind of communications channel. One candidate is a VHF data link which might be a separate VHF radio receiver, a link to an existing radio, or a link to an existing data link. The channel could also be to another data link such as Mode S, which is planned for that time period by the Federal Aviation Administration. A third candidate is a "pseudo-satellite", a ground station transmitting a GPS-like code, which would provide correction terms in its data message (it could also serve as an additional satellite).

The hardware implications fall into three categories:

1. Data link receiver, plus interface.

2. Interface to existing data link.

3. Software modifications to accommodate a pseudo-satellite message.

some impact for the low-cost user. Some vendors could offer a cheaper version of the system that would be geared towards the 500 meter accuracy figure. Specific cost-reducing design techniques could include:

1. Cheaper clocks could be used, having 10^{-7} sec/sec stability behavior, rather than the 10^{-8} sec/sec required to achieve higher accuracies.

2. Receiver loop bandwidths could be broadened to minimize reacquisition time at the expense of noisy tracking performance.

3. Little or no smoothing of the data by the navigation processor would be involved.

4. An 8-bit microprocessor might be able to perform all receiver, navigation, and channel management functions.

For higher performance aircraft and ships, and for receivers compatible with differential operation, such designs would not be adequate. Therefore the imposition of Selective Availability can be expected to have no effect on their receiver costs.

Cost Recovery Policy - Currently under consideration is a policy to assess user charges to pay for the maintenance and operation of the NAVSTAR GPS system. The probable implementation of such a policy would involve the encryption of the satellite C/A codes, whereby only users with licensed "keys" could unscramble the satellite codes and use the signal. The encryption codes would change annually, and new keys would be distributed to paying users.

This would add some cost to the CPS receiver unit, since the keys would probably take the form of ROM cartridges, which would plug into the units. A ROM connection and seal would be added to the unit, and software would be required to combine the keyed and nominal codes to drive the receiver encoders.

approach. Such a scheme obviates the need for sequential operation and the associated channel management bookkeeping function. Each satellite in view can be continuously tracked on a separate virtual channel. Their theoretical analysis indicates that a one-bit correlator may be adequate. Interstate Electronics [25], has built a similar "all-digital" receiver using two-bit correlation for use with the P-code as well as the C/A code, but the faster P-code requirements necessitate the multiplexing of the satellites. Thus for C/A-code-only operation, the all digital approach is now technically feasible, but probably not yet cost-effective. High speed sampling will eventually allow single stage downconversion of the L-band signal.

4. Charge-Coupled Devices - Charge-coupled devices offer a means of achieving high speed correlation of the C/A signal with several satellites simultaneously. They have the advantage of providing high resolution analog correlation at high speeds. It is not clear whether they will compete with digital correlation techniques in cost in the next few years.

10. CONCLUSIONS

10.1 Ability of NAVSTAR GPS to Meet Air Application Requirements

The chief considerations in determining whether NAVSTAR GPS is a useful system for air navigation are (a) coverage, (b) accuracy, (c) short-term availability, and (d) reliability. The stringency of each consideration depends on whether the system is primary (used to determine ATC procedures) or secondary (supplementary; used to enhance ATC operations and aircraft safety). The effects of selective availability must be considered as well.

a. Coverage - NAVSTAR GPS shines in this category. Coverage is world-wide, almost continuous, and is maintained down to the earth's surface. By contrast the current navigation system, VOR/DME, provides service limited to most of the CONUS, and drops out at low altitudes. There are numerous holes in the coverage within the U.S. and contiguous countries, and no off-shore coverage or oceanic coverage. The ATC radars also have coverage gaps, and lose targets at low altitudes.

b. Accuracy - With Selective Availability imposed on the Standard Positioning Service (SPS), NAVSTAR GPS will provide nominally 500 meters (2drms) accuracy, approximately 1/4 nm. This makes the system attractive for oceanic enroute and terminal navigation. Helicopter operations will be greatly enhanced by GPS because of the remote-area, offshore, and low altitude coverage. Non-precision approach requirements would not be met near the airports. The current VOR/DME system provides 100 meter accuracy at the missed-approach-point. (The closest point to the airport that accurate guidance is required). With differential operation, non-precision approach guidance accuracy appears to be feasible.

If and when SPS is restored to the full accuracy possible, 20-50 meters, non-precision approach accuracy requirements could also be met. With differential operation, the accuracies approach the precision approach requirements.

10.2 Ability of NAVSTAR GPS to Meet Marine Applications Requirements

The chief considerations for the acceptability of NAVSTAR GPS as a civil marine navigation system are the same as for the air system. However, there are different requirements in each category. Selective Availability is more of a problem for marine applications than for air applications.

a. Coverage - Coverage of NAVSTAR GPS is global, which makes it highly attractive for marine use.

b. Accuracy - The accuracy of NAVSTAR GPS is more than adequate to meet the safety requirements for the Ocean and Coastal Phases of Navigation. Commercial fisherman, however will find that under Selective Availability, the system is inferior to LORAN-C, because the repeatable accuracy is not as good. The repeatable accuracy of LORAN-C is better than 30 meters in popular coastal fishing waters, which enables fishermen to return to favorable fishing spots. The SPS provides nominally 500 meters (repeatable and predictable accuracies are not very different). If and when SA is removed, the SPS will provide 30 meter repeatable accuracies. The considerations are similar for search-and-rescue operations.

For Harbor/Harbor Entrance (HHE) and Inland Phases of navigation, until Selective Availability degradation is turned off, these requirements can only be met with differential operation. A figure of 8-10 meters (2drms) is cited as a requirement for HHE [2], and even with SA turned off, the expected accuracy of GPS is 20-40 meters, which would be adequate for navigation in less stringent harbor areas. With differential operation, 15 meters appears to be achievable. Since this is the middle of the 8-20 meter estimated requirement, it appears that the usefullness of differential GPS will have to be established by field tests.

The Federal Radionavigation Plan [17] attributes a relative accuracy of 10 meters to NAVSTAR GPS. That is, two receivers at the same point and the same time should differ by less than 10 meters. However, this is premised on the unstated assumption that the mask angle, satellite selection algorithm, and navigation solution algorithm are the same. If they are not, the solutions could differ by up to 500 meters under Selective Availability.

a. Coverage - Coverage is universal for land users, except where blockage limits satellite visibility.

b. Accuracy - The accuracy figures of Section 2.4 are educated guesses, and range from 30 meters to 300 meters. These can't be met at the planned level of Selective Availability degradation, but could be met when it is removed. For surveying applications, differential techniques could ameliorate the effects of Selective Availability, because reference receivers could be placed at nearby surveyed points, and the readings compared with time, using similar receiver algorithms. Vehicles could not identify which street and block they were on with 500 meter service, but could do this quite nicely at 30 meter service. For rural police and medical service applications, the 500 meter service might be adequate to guide vehicles within sight of accidents or other targets.

c. Availability - There is a considerable uncertainty in this area, because of the unassessed impact of blockage on land receivers. Certainly navigation guidance would be lost during transit through a tunnel, but of course there is then little uncertainty on the user's part as to his location. Unlike aircraft and ships, land applications are frequently in valleys, near buildings, and other areas where low-lying satellites may be blocked by natural and man-made objects.

A moving vehicle could easily lose two or more satellites temporarily for a period of time, during which errors could build up. There is also the real possibility that a satellite could be blocked from view, but its signal could be received via a reflection from a nearby building. Such a signal would appear to the receiver as a valid satellite signal. Large errors could result if this situation remained for several minutes. This is an area that needs both analysis and field tests.

d. Reliability - Not enough is known about applications to determine whether GPS reliability will be adequate. It certainly meets the availability figures of Section 2.4.

APPENDIX E. RECEIVER COST MODELS

This appendix compares two applicable cost models and describes a method for treating cost-trends.

Comparison of Existing Cost Models of Low-Cost Receivers

ARINC Study: "Avionics Cost Development for Civil Application of Global Positioning system" (23)

This study treats two classes of GPS avionics receivers: (1) a high-performance set, suitable for air-carrier and corporate users, and (2) a low-performance set, suitable for general aviation users. The Magnavox Z-set was used as a point of reference, but MIL-spec components were replaced by commercial quality components, and control/display and packaging were chosen appropriate to aircraft installation. The author used two methods in his approach: (1) an Accounting Method, which counts parts down to the IC's and printed circuit boards, and (2) a Block Diagram Method, using the RCA Price Model. Some uncertainties in the Block Diagram method were removed by cross-correlation with the Accounting Method. The Accounting Method can only be used when the design is known and frozen, while the Block Diagram method is useful for estimating the cost of equipment whose detailed design is not known down to its parts. This work is a carefully executed study, and much care went into the justification of the numbers used. Figure E-1 shows the functional breakout of costs for each method for the low-performance receiver.

Trends in component prices and labor costs were not addressed. Therefore the results represent a well-founded checkpoint in time, but provide no information on future costs of GPS receivers.

Some relevant features of the study are the following:

1. The receiver is comprised of components quite similar to those in Figure E-1.

2. Labor and parts for each component are derived separately.

3. A production base of 3000 units is assumed.

4. A 135% labor overhead ("burden") is assumed.

5. The cost-to-manufacture (labor + materials) is adjusted by G&A of 20% and a profit of 15% to get the factory selling price.

6. Distribution is set at 100%; thus, the list price is double the factory selling price. The ratio of list-price to cost-to-manufacture is 276%.

7. The list-price to materials-cost ratio, a rule-of-thumb measure often invoked by avionics vendors, is about 4.5:1.

8. The study is based on 1977 prices.

SCI* Study: "Economic Analysis of Civil Navigation Alternatives", Systems Control Inc. (22)

This study attempts to cover a lot more ground than the ARINC study in three respects: (1) cost trends are estimated through 2020; (2) several other navigation receivers besides those for NAVSTAR GPS are considered, and (3) several equipment options are considered. For the GPS navigation system, three classes of marine receiver performance are used: High, low, and medium. In order to perform trending analysis each receiver design is disaggregated by subcomponents, where the subcomponents chosen represent a middle ground between parts and functional components. An example is "Printed Circuit Boards": they are used in several functional components, and can be expected to trend differently from "Digital Memory", for example, since the technology improvement potential and the labor involved in manufacturing them are quite different. More subject to question are subcomponents such as "analog Signal Processing" units where filters, mixers, and amplifiers are grouped together. Whether they can be

*Now called Systems Control Technology, Inc. (SCT)

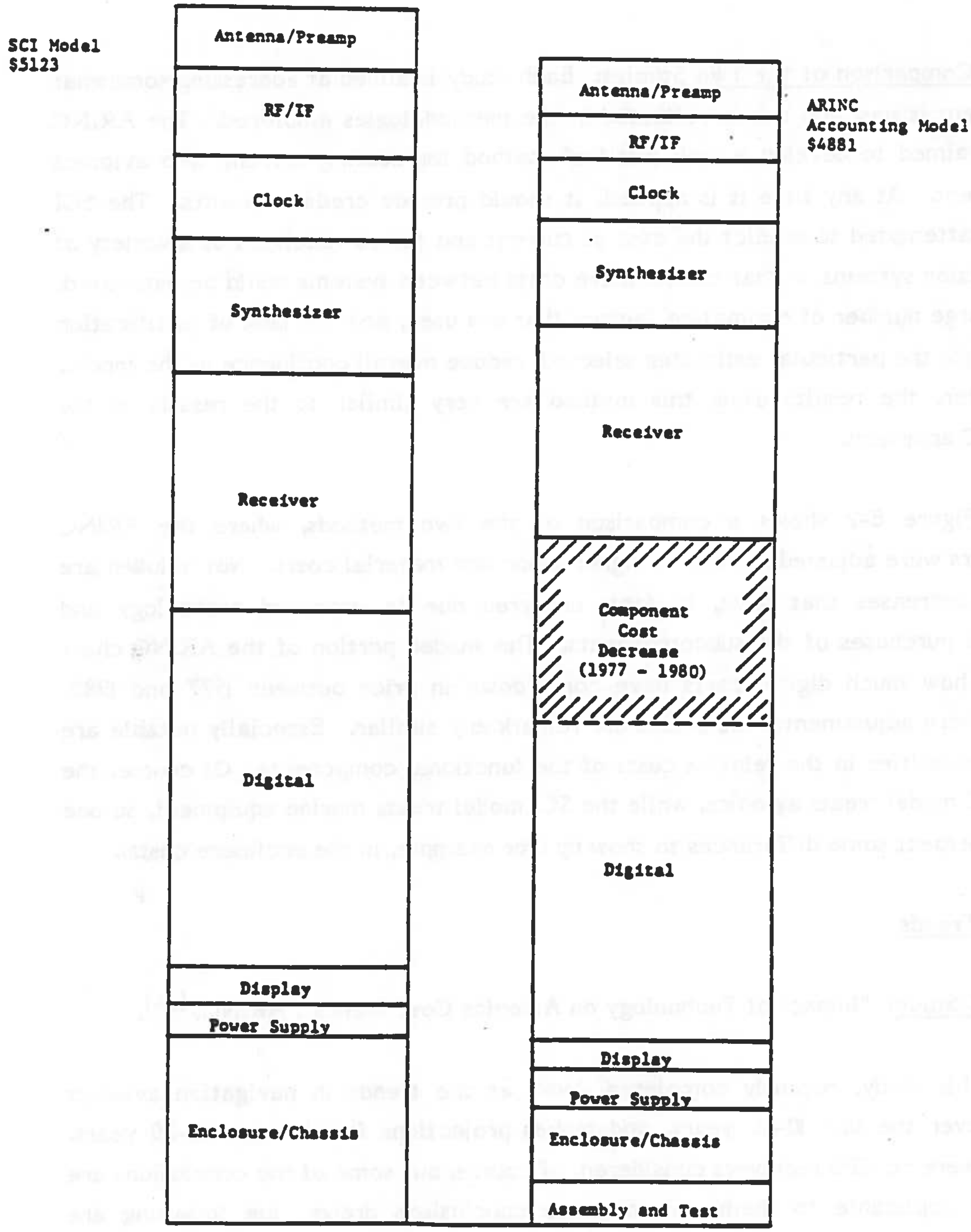


FIGURE E-2. RECEIVER COST ESTIMATE - ARINC AND SCI MODELS
LIST PRICE, 1980 DOLLARS

primarily to the sensitivity of the CPI to costs of housing and food, factors that don't influence the PPI.

3. Labor costs will continue to increase slightly faster than the CPI, due (hopefully) to productivity gains.

4. Components will continue to be produced by more capital-intensive manufacturing methods. This will reduce the labor-hours, but increase the manufacturing burden.

5. Receivers will continue to decrease in weight, volume, and power usage.

6. Receiver prices have held more-or-less constant relative to the PPI. The new technological improvements have been reflected in higher performance rather than reduced costs.

7. Mechanical parts can be expected to increase in costs, while electronic parts will decrease dramatically, especially digital circuits.

8. Mechanical displays are expected to be replaced eventually by cheaper electronic displays.

Discussion: The ARINC trend study does provide some projected material cost trends (e.g., TTL/MOS integrated circuits, resistors, radio hardware) but not enough to compare with each of the trends projected in the SCI study. As one example of comparable trends, the ARINC study predicts a cost-halving period of 5 years (relative to the PPI) for TTL/MOS integrated circuits, while the SCI study uses a cost-halving period of about 3.5 years for program memory and microprocessors. While these are different, they are similar enough for our purposes.

It would be desirable to use the cost models to estimate the effects of radical design changes on receiver costs. For example:

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