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NAVSTAR GPS Simulation and Analysis Program

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Final Report

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16. Abstract

This study assesses the capability of the planned NAVSTAR Global Positioning System (GPS) to meet civil navigation requirements. When it becomes operational in about 1983, NAVSTAR GPS will provide accurate two-dimensional and three-dimensional service to a wide spectrum of users. The quality of the service will depend on the availability of the satellite signals, the satellite geometries, the timing accuracy of the signals, and the user receiver design. In this study ten specific issues are identified which need resolution. These issues provide the focus for the effort.

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

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PREFACE

The work described in this report was performed in support of the Office of Management and Programs 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 position on the civil radionavigation systems mix for air, marine and land navigation. 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 the final report on the results obtained over a two year period.

John Kraemer addressed the operational requirements and described the simulation model. Norman Knable treated service outages and satellite failures, and addressed the effectiveness of clock coasting and altitude aiding to ameliorate these situations. Differential operation was treated by Janis Vilcans. Rudolph Kalafus, the Project Engineer, addressed Selective Availability and receiver performance and costs, and coordinated the writing of the document.

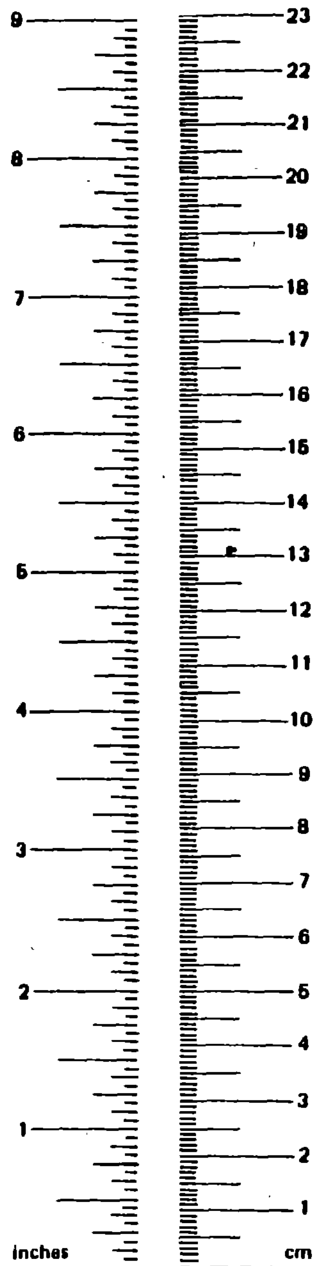
The authors wish to thank David Scull of the Office of Management and Programs, RSPA for his encouragement and guidance. Also appreciated are the contributions of Nicolas Bliamptis and LTJG James Preisig. Special thanks go to Mark Manozzi, whose tireless efforts on the word processor made it possible to complete the document in a timely fashion.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

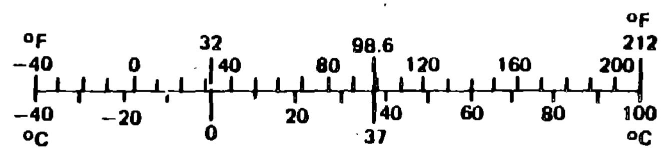
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. 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.

1.3 BACKGROUND

When the NAVSTAR Global Positioning Satellite (GPS) becomes operational, it will provide 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 not encrypted and will be available to civil users. Current plans are to have an 18-satellite configuration operational by 1988, with three additional active spares available by 1989.[1]

Navigation tests performed using the NAVSTAR GPS satellites presently in orbit have indicated C/A signal accuracies significantly better than design goals. These accuracies satisfy ocean and coastal phase marine requirements of the Federal Radionavigation Plan and most en route and terminal air requirements. They approach the stringent harbor/harbor entrance requirements. The addition of a stationary receiver measuring local position measurement drift would enable differential GPS operation that could possibly meet the harbor entrance requirements as well.

However, the accuracy of the C/A signals has posed a security problem to the Department of Defense. As a result the DOD is planning to purposely degrade the C/A signal under a program called Selective Availability. The method and magnitude of this degradation has not yet been finalized, nor has the time frame during which Selective Availability would be exercised. Enough is known, however, that the effectiveness of differential techniques can be assessed.

The U. S. Department of Transportation (DOT) is currently responsible for providing civil navigation service to the National Air System users and the marine community. The Department is charged with determining the future radionavigation system mix. To carry out this responsibility, DOT established a management structure in April 1979 under DOT Order 1120.32, to coordinate departmental planning and development efforts on future radionavigation systems. DOT and DOD implemented an Interagency Agreement which stipulated that the Departments undertake joint programs in design and testing of navigation systems.

The Federal Aviation Administration, U. S. Coast Guard, and the Research and Special Programs Administration have formulated requirements for aircraft, marine, and land-based users of NAVSTAR GPS. These requirements are presented in Volume II of the joint DOD/DOT Federal Radionavigation Plan (FRP).[2] The FRP reflects the concerns of the DOT about the issues involved in widescale civil usage of GPS receivers.

The Departments of Transportation and Defense plan to jointly issue a Preliminary Recommendation in 1983 on the civil use of radionavigation systems, including NAVSTAR GPS, followed by a Final Recommendation in 1986. From what 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 - The NAVSTAR GPS Joint Program Office has since announced the intention of providing three active spares, and locating them in such a way as to remove these outages over the conterminous U. S. (CONUS) (1) (see Section 4).

ISSUE 2: Satellite Failures

The loss of a satellite signal due to space segment failure could result in reduction of accuracy or lack of a sufficient number of available satellites to establish position during a period of time. The severity and duration of these outage periods need to be addressed.

ISSUE 3: Temporary Loss of Satellite Signal

Blockage by aircraft wings, or by buildings in the case of land receivers, can cause severe attenuation of satellite signals. It needs to be determined whether low-cost receivers can cope with this situation.

ISSUE 4: Selective Availability

The DOD plans to deliberately degrade the accuracy of C/A signal for several years for national security purposes. Depending on the type and severity of degradation imposed, many of the civil users' applications may be compromised. What is the impact?

ISSUE 5: Differential GPS, Without Selective Availability

Ionospheric and tropospheric delays and other transmission variations may limit the ability of a single-frequency, C/A code-only receiver to provide sufficiently accurate navigation information for non-precision and precision aircraft approaches, and harbor/harbor entrance ship guidance. With a nearby receiver as a benchmark reference, corrections could be made which might allow use of the GPS system for these more stringent applications. What are the performance capabilities, and what are the costs and operational complexity?

ISSUE 6: Differential GPS, With Selective Availability

If Selective Availability is imposed, Differential GPS could ameliorate its 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, policies have changed, 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 the Method of Approach, Section 4, Receiver/Processor Design Alternatives, lays the groundwork for the analysis that follows. It incorporates Issues 8 through 10, and describes some of the forms that receivers specifically designed for civil use might take. Different designs have differing abilities to handle outages, to incorporate external vertical information, and to handle transient conditions. These considerations are discussed in Section 4.

Under the new sparing strategy, there still will be geometric outages over the CONUS for some receivers when all 21 satellites (18 plus three spares) are operating. Outages will also occur as a result of satellite failures, which could result in geometric outages or reduce the number of satellites below that needed to obtain a complete solution. Section 5 is devoted to satellite outages (Issue 1): their causes, their durations, and the ability of different receiver designs to handle them. Issue 3, Temporary Loss of Satellite Signal, is treated to some extent in this section, but more work needs to be done.

The impact and likelihood of satellite failures (Issue 2) are discussed in Section 6. Selective Availability, its magnitude, its variability and the resulting navigation errors are treated in Section 7. Section 8 deals with differential operation both with and without Selective Availability (Issues 5 and 6). Receiver costs (Issue 7) are treated in Section 9.

The final section summarizes the conclusions and recommendations. Appendices provide details of the analysis and simulation tools at TSC and describes analyses to support assumptions and conclusions in the main text.

A major policy shift was recently announced by the Department of Defense which alters some of the conclusions of this report. The revised plan calls for a nominal accuracy of 100 meters (2drms) for Standard Positioning Service when the system becomes operational in 1988. The previous plan called for 500 meters, and this figure was used in the work described in this report. Footnotes indicate where figures, statements, or conclusions are altered by this change.

2. 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 segments 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 (Ref. 2).

2.2 AIR REQUIREMENTS

The two basic phases of air navigation are approach/landing and en route/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 approach fixes based on VOR in the U.S. achieve a cross track navigational accuracy of $\pm$ 100 meters (2 sigma) at the missed approach point (MAP). This accuracy is based upon the $\pm$4.5 degree VOR system use accuracy and assumes the MAP is less than 0.7 nm from the VOR facility.

The current controlled airspace navigation accuracy requirements are shown below:

Altitude	Route Width	Accuracy, 2drms
250-3000 ft	2 nm	100 meters

2.2.2 En Route/Terminal Phase

The en route/terminal phase includes all flight except that within the approach/landing phase. It includes the following sub phases:

1. Oceanic En Route
2. Domestic En Route

3. Terminal
4. Remote Area
5. Helicopter

The current controlled airspace navigation accuracy requirements for these subspaces are summarized in Table 2-1.

To facilitate aircraft operations in the en route/terminal phase, the system must be capable of being operationally integrated with the system used for approach and landing. The system used for domestic en route and terminal navigation must be suitable for non-precision approaches.

Federal Aviation Regulations specify the vertical separation required below and above Flight Level (FL) 290 (29,000 feet). The current separation requirement is 1,000 feet below Flight Level 290, and 2,000 feet at and above Flight Level 290. In order to justify the 1,000 foot vertical separation below Flight Level 290, the RSS altitude keeping requirement is $\pm$350 feet (3 sigma). This error is comprised of $\pm$250 feet (3 sigma) aircraft altimetry system error, of which the altimeter error is limited to $\pm$125 feet below Flight Level 290.

The minimum performance criteria currently established to meet requirements for the en route/terminal phase of navigation are presented in the following sections.

A. Oceanic En Route

The system must provide navigational capability commensurate with the need in specific areas in order to permit safe navigation and the application of lateral separation criteria. A 60 nm lateral separation standard has gone into effect on the North Atlantic fixed route system. The following system performance is required to achieve this separation:

(1) The standard deviation of the lateral track errors shall be less than 6.3 nm, 1 sigma (12.6 nm, 2 sigma).
(2) The proportion of the total flight time spent by aircraft 30 nm or more off track shall be less than 5.3×10^{-4}, i.e., less than 1 hour in about 2,000 flight hours.
(3) The proportion of the total flight time spent by aircraft between 50 nm and 70 nm off track shall be less than 1.3×10^{-4}, i.e., less than 1 hour in about 8,000 flight hours.

B. Domestic En Route

Domestic air routes are designed to provide as nearly direct airways as practical between city pairs that have significant air traffic. For altitudes below Flight Level 180 (18,000 feet), the airways are defined as 8 nm in width out to 51 nm from the VOR facility. Beyond 51 nm the airway increases uniformly in width on either side of the centerline, with the apex of the angle at the VOR facility.

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

For altitudes above FL 180 (18,000 feet and above), the airways consist of jet routes which have the same protected airspace as the low-altitude structure, except the VOR stations may be spaced farther apart and the route width may be as large as 20 nm. 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 ± 2 nm within 25 nm of the facility.

D. Remote Areas

Remote areas are defined as regions which do not meet the requirements for installation of VOR/DME service, or as regions in which 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 ±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.

2.3.1. Ocean Navigation

Ocean navigation is considered that phase in which a ship is beyond the Continental Shelf and more than 50 nm from land, in waters where position fixing by visual reference to land, or to fixed or floating aids to navigation is not practical. Ocean navigation is sufficiently far from land masses so that the hazards of shallow water and of collision are comparatively small.

For purposes of system planning and development, the requirements for safety of navigation in the ocean phase for all ships are given in Table 2-2. Equipment meeting these requirements must provide the master with a capability to avoid hazards in the ocean (e.g., small islands, reefs) and to plan correctly the approach to land or to maneuver in restricted waters. For operational purposes, repeatability is necessary to locate and return safely to the vicinity of a maritime distress, as well as for special activities such as hydrographic research, etc. Economic efficiency in safe transit of open ocean areas depends upon the continuous availability of accurate position fixes to enable the vessel to follow the shortest safe route with precision, and thus minimize transit time.

TABLE 2-2. CURRENT MARINE REQUIREMENTS FOR SAFETY OF NAVIGATION FOR ALL CRAFT, OCEAN PHASE

PREDICTABLE ACCURACY (2drms)	AVAILABILITY	FIX INTERVAL
2-4 nm minimum	95% full capacity	15 mins. or less desired
1-2 nm	99% fix at least every 12 hours	2 hrs maximum desirable

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 transoceanic 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 be as loose as 0.25 nm for large, economically efficient vessels. 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.

2.3.2 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 to satisfy minimum safety requirements for general navigation. These requirements are delineated in Table 2-3. Further, the total navigational service in the coastal area must provide service of useful quality, and be within the economic reach of all classes of mariners.

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.

2.3.3 Harbor Entrance

Harbor/Harbor Entrance navigation (HHE) is conducted in waters more constricted than 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 the narrowly restricted waters near and/or within the entrance to a bay, river, or harbor. The 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.

To navigate safely, the pilot needs highly accurate verification of position almost continuously, together with information depicting any tendency for the vessel to deviate from its intended track and a nearly continuous and instantaneous indication of the direction in which the pilot should steer. These requirements are given in Table 2-4. The required accuracy varies from one harbor to another. In the most restricted channels, accuracy in the range 8 to 20 meters (2drms) (predictable accuracy) is needed. The requirements for smaller vessels are currently under study but they are somewhat less stringent than for large ships. For seismic surveying, the accuracy needs are more stringent, namely from one to five meters (2drms) with a fix rate of one second.

TABLE 2-3. CURRENT MARINE REQUIREMENTS FOR SAFETY OF NAVIGATION - ALL CRAFT, COASTAL PHASE (FOR PURPOSES OF SYSTEM PLANNING AND DEVELOPMENT.)

REQUIREMENT	PREDICTABLE ACCURACY (2drms)	AVAILABILITY	FIX INTERVAL
Safety of Navigation - All Ships	0.25 nm (460 m)	99.7% Minimum	2 Min.
Safety of Navigation - Recreational Boats & Other Smaller Vessels	0.25 nm-2 nm (460-3700 m)	99% Minimum	5 Min.

TABLE 2-4. CURRENT MARINE REQUIREMENTS FOR SAFETY OF NAVIGATION HARBOR APPROACH AND HARBOR PHASES (FOR PURPOSES OF SYSTEM PLANNING AND DEVELOPMENT)

REQUIREMENTS	PREDICTABLE ACCURACY (2drms)	AVAILABILITY	FIX INTERVAL
Safety of Navigation-Large Ships & Tows	25-65 ft (8-20 m)	99.7% Minimum	6-10 Seconds
Safety of Navigation-Smaller Ships	***	99.7%	***

2.3.4 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 automatic vehicle monitoring (AVM) and site registration 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.

2.4.1 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.

2.4.2 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. No other characteristics have been determined.

TABLE 2-5. LAND RADIOLOCATION ACCURACY ESTIMATES.

APPLICATION	REPEATABLE ACCURACY (2 drms)*	COVERAGE	AVAILABILITY	FIX RATE**
Public Safety				
Urban Police, EMS***	250 ft.	Urban Area	99.7%	1 sec.
Rural Police, EMS	1000 ft.	County		1 sec.
State Police	1000 ft.	State		1 sec.
Transportation				
Urban Buses	500 ft.	Urban Area	99.7%	1 sec.
Taxi	500 ft.	Urban Area		1 sec.
Delivery Truck	1000 ft.	Urban Area		1 sec.
Truck (Hazardous Cargo)	10000 ft.	Nationwide		1 sec.
Highway Safety Planning (Traffic records Highway Inventory, Highway Main.)	100 ft.	State	99.7%	1 sec.
Resource Management	100 ft.	Nationwide	99.7%	1 sec.

* Requirement under study, values noted are current estimates.

** Fix rate of navigation system, user update rate dependent on application and characteristics of communication link.

*** Emergency Medical Service

3. 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 ones 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 have been modified at TSC. They can now 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 three or four 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 available, especially the performance history. Rather than outputting the smoothed estimate of position for a particular location at a particular time for a specific heading, as the simulation models do, TSCERR outputs the performance averaged over all geometries. It is useful for predicting what an optimal receiver would do when a satellite is faulted, or when the satellite geometry deteriorates.

While the models are useful in examining transient conditions, they are unwieldy for the investigation of system accuracies in a collective sense, because once a receiver design is defined, the accuracy is dominated by the satellite geometry. Also, with Selective Availability imposed, the intentional errors dominate all other error sources. To analyze the effects of satellite geometry and those receiver design parameters which affect satellite selection, computer programs were developed which provide GDOP measures under a variety of conditions, and which output statistical distributions.

Selective Availability is a Department of Defense program under which the SPS accuracy will be controlled, and Precise Positioning Service will be available selectively, to military and special civil users. TSC obtained segments of the signals that will be used in the satellite transmissions. They were obtained through the NAVSTAR GPS Joint Program Office from Draper Laboratory. The segments obtained are brief enough that they could not be used to reconstruct the accuracy control technique, and could thus be unclassified. Analysis consisted of statistical programs which examined the distribution of the equivalent pseudorange errors and their time deviations. This analysis is discussed in Section 7.

A costing model was adapted from two existing studies on GPS receivers. It is useful for comparing the relative costs of different receiver designs, and provides a reasonable estimate of list prices now and in the future. These models and analytical programs are described further in the next section, as well as in Appendices A through C and E.

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.

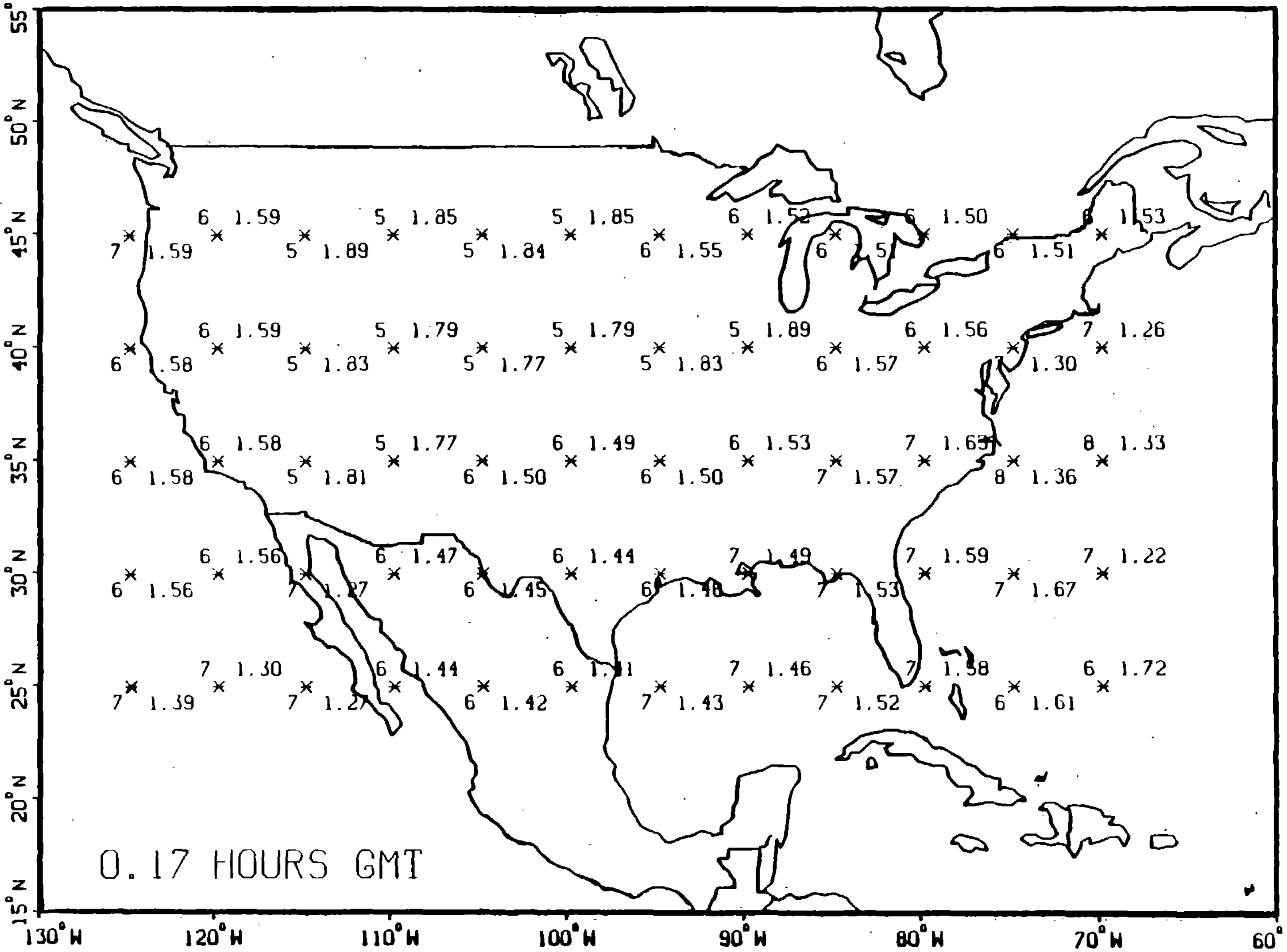

FIGURE 3-1. TYPICAL HDOP's OVER CONUS - FULL 18 + 3 SATELLITE CONSTELLATION
3 DIMENSIONAL SOLUTION, 10° MASK ANGLE

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 the full 18-satellite constellation, plus 3 spares.

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

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

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

f. Each has been modified to handle sequential receiver operation.

g. Each has a limited ability to handle three-satellite as well as four-satellite navigation solution.

h. Each incorporates antenna location and pattern effects.

i. Each accommodates vehicle roll, pitch, and heave variations.

3.3 CHARACTERIZATION OF CIVIL AIR USERS AND EQUIPMENT

The most evident civil air application of GPS is to oceanic navigation, due to its relative advantages in cost, accuracy, and coverage. The same aircraft will probably begin to use the system for high altitude domestic en route navigation as well. It will certainly be competitive with inertial systems. It is not clear that GPS can fulfill other roles of the VOR system, however. In particular, VOR sets are installed in a wide spectrum of aircraft; they are relatively inexpensive and are used in VFR as well as IFR conditions even though they are not generally required. While the VFR usage of the navigation system cannot be ignored, there are no established VFR requirements that could serve as a basis for evaluating GPS performance. Rather, the low-cost receiver processor will primarily involve IFR applications of en route, terminal, and nonprecision approach navigation. Users will range from recreational flyers to air taxi operators, and the aircraft will vary in size from two-seat trainers to 6 to 10 seat twins.

Table 3-1 shows a widely utilized user classification scheme[5]. It appears that the target population for low-cost receiver users is that of Class C. While some users may have other RNAV equipment, the investigation of this program assumed stand-alone GPS equipment except for the possible use of an encoding altimeter.

There are a number of other users who would find GPS useful, namely helicopter operators, search-and-rescue teams, agricultural operators, and survey crews. However, their dynamics and requirements are less stringent, and do not appear to pose any unusual performance problems for the GPS.

Table 3-2 shows the characteristics of the users and the flight scenarios used to address the main issues. Table 3-3 lists the receiver/processor parameters which characterize the receiver evaluated for the civil air users. In particular, the parameters listed in Table 3-3 are used as input parameters to the computer simulation called AIRGPS. They also serve to define the constraints used in the error bound simulation (TSCERR). These software tools are discussed in Appendices A and C. The receiver described in Table 3-3 is patterned after the Experimental Dual Channel Receiver (EDCR) which was recently tested by Lincoln Laboratory.[6]

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.

TABLE 3-1. CIVIL AIR USER CLASSIFICATION SCHEME

Class A

- 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).
- Equipped with dual, high quality avionics characteristic of air carrier and military aircraft.

Class B

- 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.
- Equipped with dual, high quality avionics characteristics of expensive general aviation aircraft.

Class C

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

Class D

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

Class E

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

Class F

- 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 ft/min.
	-	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.

TABLE 3-3. RECEIVER PARAMETERS - AIR

PARAMETER	VALUE	
	NAV. CHANNEL	DATA
CHANNEL		
CLOCK		
Clock Stability	1×10^{-8} (1-3 Sec.)	1×10^{-8} (1-3 Sec.)
CODE LOOP		
Type	Tau-Dither	
Order	1st	
Bandwidth	6 Hz	
Damping Factor	N.A.	
Delay Prepositioning	Yes	
Satellite Dwell Time	0.220 Sec.	
Dither Timestep	0.01 Sec.	
Dither Code Shift	±0.5 Chip	
IF Noise Filter Bandwidth	500 Hz	
CARRIER LOOP		
Type	AFC	AFC/Costas
Order	1st	1st/2nd
Bandwidth	10Hz	10Hz/20Hz
Damping Factor	N.A.	N.A.
Doppler Preposition	Yes	Yes/Yes
Satellite Dwell Time	0.220 Sec.	N/A
IF Noise Filter Bandwidth	500 Hz	500 Hz/500Hz
NAVIGATION FILTER		
Type	Kalman	
States	9	
Observables	Pseudorange	
SATELLITES TRACKED		
Satellites Tracked	4, initially (up to 7 eventually)	
Satellite Mask Angle	8°	

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 were used as input parameters to the Monte Carlo computer simulation MARINEGPS. MARINEGPS is similar to AIRGPS in that the nonlinear receiver portions of the two simulations are identical. The receiver modelled for marine applications is patterned after the Z-set. Parameters are chosen to be representative of a marine receiver. These parameters (listed in Table 3-5) also serve to define the inputs to the error bound software TSCERR.

3.5 CHARACTERIZATION OF CIVIL LAND USERS AND EQUIPMENT

Civil land use of radiolocation has been characterized by three operating regions: rural, suburban and urban. The principal applications associated with each of these regions are listed below.

Rural: The principal needs in rural regions are for location identification for emergency services, public safety, conservation and environmental protection, traffic safety data and highway data.

Suburban: The principal applications of radio location systems in suburban areas are related to automatic vehicle location of transit and public safety vehicles.

Urban: The principal applications of radio location systems in an urban area are the same as those in suburban regions, namely, transit and public safety. Urban operation is characterized by much more adverse propagation conditions due to increased electromagnetic interference (EMI) and signal blockage.

Unlike air and marine applications, no fixed set of minimum performance requirements has yet been developed for civil land uses of radio location. A tentative set of "minimum requirements" has been defined based upon current estimates. These tentative requirements fall into two application classes: those involving a static measurement and those involving significant user vehicle dynamics. The latter class is believed to represent the more demanding requirements and is the class chosen for the evaluation of GPS user set performance.

TABLE 3-4. GENERAL CHARACTERISTICS OF CIVIL MARINE USERS OF LOW-COST GPS NAVIGATION EQUIPMENT

Typical User	-	Freighter
Typical Craft-	-	50 meter length, 750 tons
Maneuvers	- -	Straight line at accelerations up to 0.05 g's Two-minute turn rate
Maximum Speed	-	15 knots Roll-15^{o} amplitude with a 6 sec. period, 5^{o} in harbor areas.
Receiver/Processor	- - - - -	C/A Code only, 1575.42 MHz Single channel, navigation data One antenna, fixed mounted Satellite tracking algorithm, best set of three Position algorithm: 2-dimensional solution.

TABLE 3-5. RECEIVER PARAMETERS - MARINE

PARAMETER	VALUE	
	NAV. CH	DATA CH.
CLOCK		
Clock Stability	1×10^{-8} (1-3 Sec)	1×10^{-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	± 0.5 CHIP	
IF Noise Filter Bandwidth	300 Hz	
CARRIER LOOP		
Type	AFC	AFC/Costas
Order	Ist	Ist/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 are given in Table 3-7.

TABLE 3-6. GENERAL CHARACTERISTICS OF CIVIL LAND USERS OF LOW-COST NAVIGATION EQUIPMENT

Typical User	-	Urban police, emergency medical service.
Typical Maneuvers	-	Straight line, constant acceleration up to 0.25 g.
	-	130 meter radius turn at 40 mph (0.25 g radial accel).
Maximum Speed	-	55 mph.
Receiver Processor	-	C/A code only, 1575.42 MHz.
	-	Two channels, Navigation and Data.
	-	One antenna, mounted on top of vehicle
	-	Satellite Tracking Algorithm: All-in-view.
	-	Position Algorithm: To be determined.

0

TABLE 3-7. RECEIVER PARAMETERS - LAND

PARAMETER	VALUE	
	NAV. CH	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	± 0.5 Chip	
IF Noise Filter Bandwidth	300 Hz	
CARRIER LOOP		
Type	AFC	AFC/Costas
Order	1st	1st/2nd
Bandwidth	10 Hz	10 Hz/17Hz
Doppler Preposition	Yes	Yes/Yes
Satellite Dwell Time	0.5 Sec.	N.A.
IF Noise Filter Bandwidth	300 Hz	300 Hz/300Hz
NAVIGATION FILTER		
Type	Kalman	
States	6	
Observables	Pseudorange	
SATELLITES TRACKED		
Satellites Tracked	4	
Satellite Mask Angle	10°	

4. 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. Receiver designs up to now have generally chosen the mask angle to be 5° or 10°. However, in Section 5.2 it will be shown that an 8° mask angle is the preferred value for 3-dimensional navigation.

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 for the planned 18-satellite-plus-3-spares constellation. The reasons for preferring different numbers of channels are 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 first three of these are discussed in Section 4.3. The others relate to the implementation of the user equipment and are discussed below.

The high-quality receivers built in Phase I of the NAVSTAR GPS program have four channels. A best-set-of-four satellite selection algorithm is employed, so each channel is devoted to one satellite. This is termed "parallel" operation. When a satellite sets, that channel is assigned to the next satellite chosen by the selection algorithm. A parallel receiver is quite insensitive to user clock drift. A marine receiver for ocean use can make use of the known altitude to operate with three satellites. Although none have been produced in this manner, a three-channel parallel marine receiver is feasible.

A lower cost receiver can be achieved by using fewer channels, and "looking at" the satellites one at a time. This is termed "sequential" operation. The Z-set [8] built during Phase I for low-dynamic aircraft use, has a single channel to receive the signals from four satellites and decode the data. One of these sets was recently modified by the U. S. Coast Guard [9] to operate with three satellites to achieve two-dimensional navigation. The update interval is about ten seconds, which is adequate for marine and most air applications, but marginal for aircraft non-precision approach navigation.

For aircraft usage the single-channel receiver has two other drawbacks that led the FAA to explore a different design:

a. Long startup period - Typical "cold-start" acquisition can take up to 30 minutes.

b. High sensitivity to satellite fading - During turns, low-lying satellites can be blocked by wing or tail, causing the set to change satellites. The abrupt change results in erratic behavior of the station.

The Experimental Dual-Channel Receiver (EDCR) was built 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]. The receiver 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° or 10°, below which satellites are not included in the navigation solution. The DOD sets use 5°, but the FAA prefers 10°. 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. The choice of mask angle affects the service outage time of a receiver, a subject discussed in Section 5. It is shown there that an 8° mask angle is desirable.

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" pseudoranges. 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).

The EDCR [10] employs an all-in-view satellite selection strategy. All satellites above the mask angle are used in the navigation solution. Each additional satellite above four serves to improve the accuracy of the solution. As a result, when one satellite fades, the solution does not change suddenly, nor is time lost in acquiring new satellites. Of course, when only four satellites are visible, the solution is identical to the best-set-of-four solution.

Figure 4-1 shows that the relative advantage of a 5° mask angle over a 10° mask angle for a receiver using a three-satellite solution is not significant. This is generally true for receivers using four-satellite solutions, which can be seen in Figure 4-2. However, there are some locations where large HDOP's occur for the 10° mask angle that do not occur for the 5° mask angle. These outages are severe enough and last long enough (1 to 10 minutes) that receiver designers should seriously consider using a mask angle below 10°. It is shown in Section 5.3 that these outages do not occur using mask angles of 8° or less.

There are several reasons generally cited for not employing satellites below some mask angle like 10°: (1) tropospheric effects, (2) higher multipath probability, (3) low signal-to-noise ratio, and (4) increased probability of blockage by terrain. In each of these the reduction of performance in using an 8° mask angle rather than 10° is small, while the advantage of eliminating outage periods is considerable. Also, there is little to be gained by going below 8°. Therefore use of a mask angle of about 8° is strongly recommended for airborne receivers and other receivers using 4 satellites in the navigation solution.

The relative advantage of the all-in-view strategy is evident in Figure 4-3. The HDOP's are about 30% better than with the best-set strategy. This is offset somewhat by the fact that the processing of additional satellites requires shorter dwell times, which means that noise-related errors increase. However, the HDOP is the dominant effect, so that accuracy improvements of 20 to 25% are reasonable to expect.

4.4 TRACKER TECHNIQUES

Tracking is performed in order to obtain user vehicle velocity estimates and smooth receiver output noise. Most trackers are first-order trackers, which means they project straight-line tracks. As a result, they estimate position to the outside of the actual track on turns. Heavy smoothing results in excellent position estimation performance under unaccelerated motion, but poor performance during accelerated motion (including turns). Reduced smoothing improves performance during accelerations, and reduces performance on straight segments of travel. In principle, second-order trackers could ameliorate this problem, but in practice the advantages are often not significant, because of the noisiness of the computed acceleration terms. In the AIRGPS simulation model, a horizontal turn state is included in the Kalman state vector.

4.5 COMPARISON OF KALMAN FILTER & ALPHA-BETA TRACKER PERFORMANCE

4.5.1 The Navigation Processor

The navigation processor filters the random errors from the measurements made to determine the user's position and estimates the position and velocity of the user vehicle. In filtering the measurements, the capability of position tracking is lessened so that a trade-off must be made, depending on the amplitude of the measurement noise and the accelerated motion of the vehicle.

The issue here is whether a simple processor like the alpha-beta tracker can be used to track a vehicle performing a standard operation, without incurring errors due to accelerated motion which exceed the bias errors in the GPS system, or whether a more complex processor like the Kalman filter is needed for the output of GPS user equipment.

Errors in the user estimated position are made when the pseudorange measurements contain errors and when there is accelerated motion. The latter is associated with the departure of the vehicle from straight line motion in the case of the alpha-beta tracker and from a dynamical model in the case of the Kalman filter. A fraction of the difference between the actual and expected measurements is used to correct the user's position estimate, the size of the fraction being determined by the confidence in the measurement.

4.5.2 The Alpha-Beta Tracker

The model used for this tracker is that of a vehicle travelling at constant velocity. Differences in position and velocity from this model, as determined by measurements, are used to correct the model estimate (usually called the propagated values) of position and velocity as follows:

$$\underline{x}_{meas}=H.\underline{R} \quad (4\text{-}2)$$

$$\underline{x}_p(k)=\underline{x}(k-1) + t\underline{x}(k-1) \quad (4\text{-}3)$$

$$\underline{x}(k) = \underline{x}_p(k) + alpha(\underline{x}_{meas}(k) - \underline{x}_p(k)) \quad (4\text{-}4)$$

$$\underline{x}(k) = \underline{x}(k-1) + (beta/t)(\underline{x}_{meas}(k) - \underline{x}_p(k)) \quad (4\text{-}5)$$

k is the number of measurement intervals from $t = 0$

H transforms the measurement vector $\underline{R}$ into the position measurement vector $\underline{x}_{meas}$

t is the measurement interval

t/beta is the response time of the alpha-beta tracker

alpha is determined from beta for damped tracking

$\underline{x}_p(k)$ is the propagated position

$\underline{x}(k)$ is the filtered position

$\underline{x}(k)$ is the filtered velocity

It can be seen from equations 4-3 and 4-4 that decreasing alpha and beta filters the measurement noise and produces a response lag to motion which departs from the model. On the other hand decreasing t tends to decrease $(\underline{x}_{meas} - \underline{x}_p)$, thus decreasing the bias errors encountered in a maneuver. Alpha is chosen to critically damp the filter output.

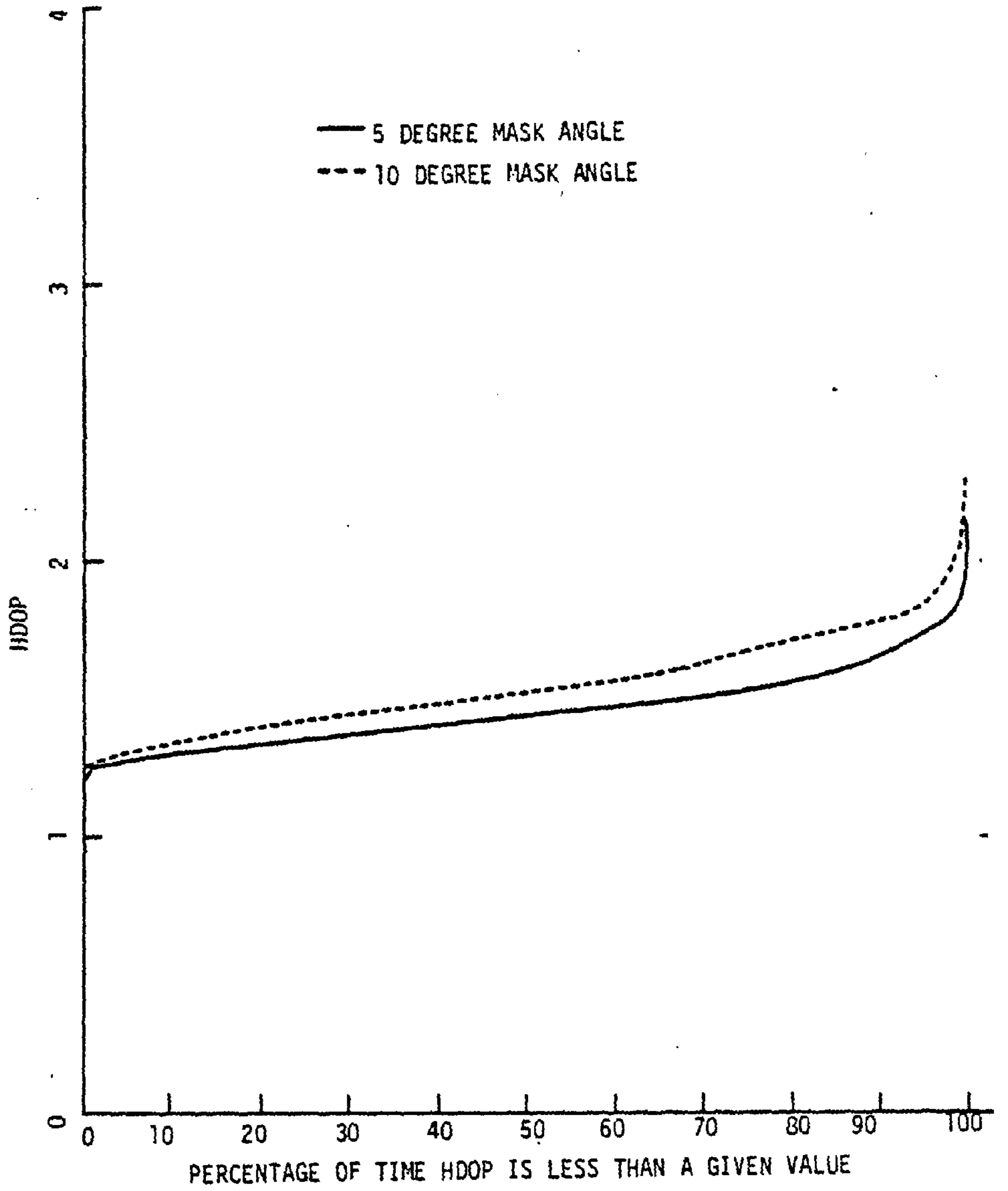

FIGURE 4-1. HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION, BEST-SET STRATE

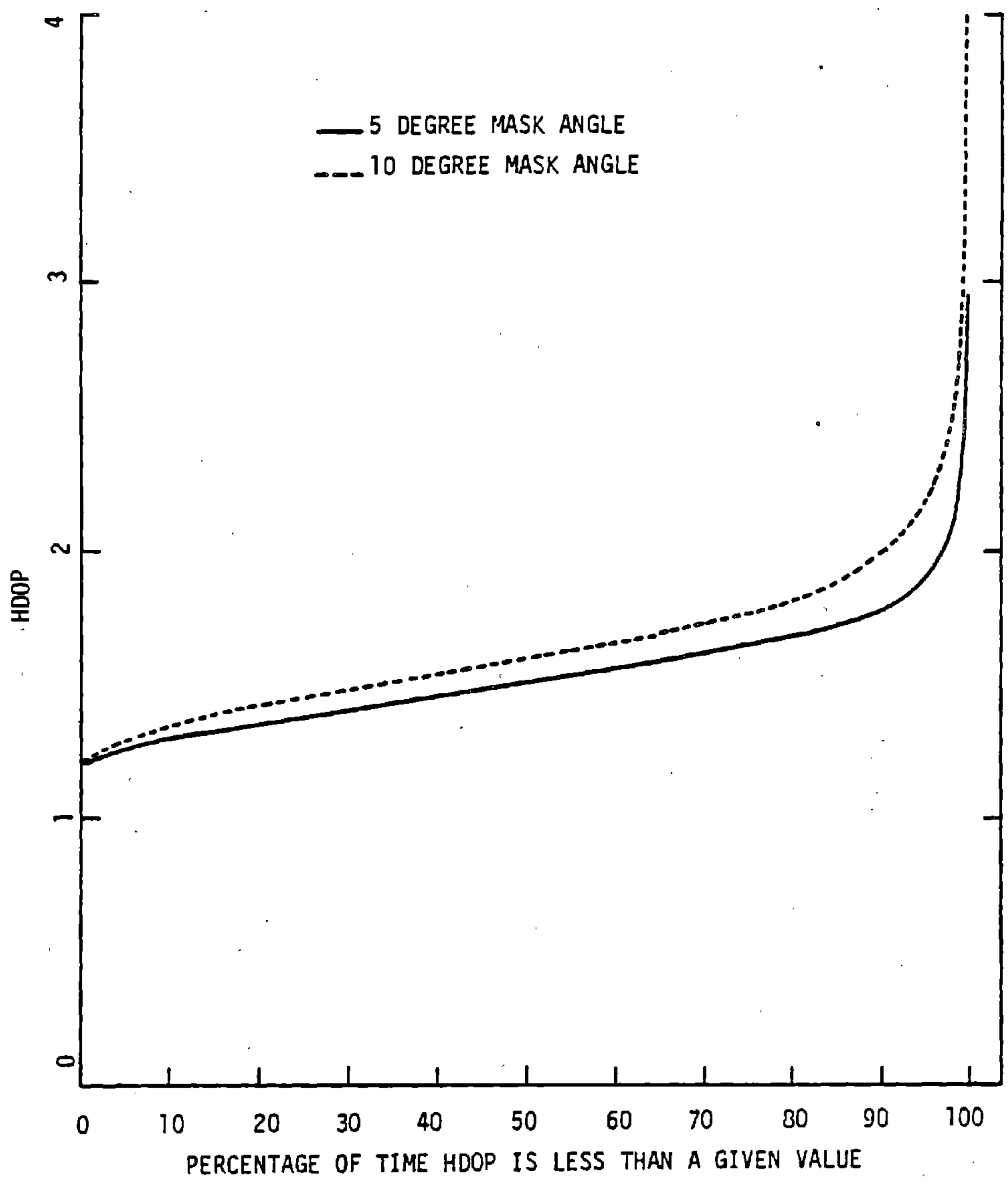

FIGURE 4-2. HDOP DISTRIBUTION, 3-DIMENSIONAL SOLUTION, BEST-SET STRATEGY

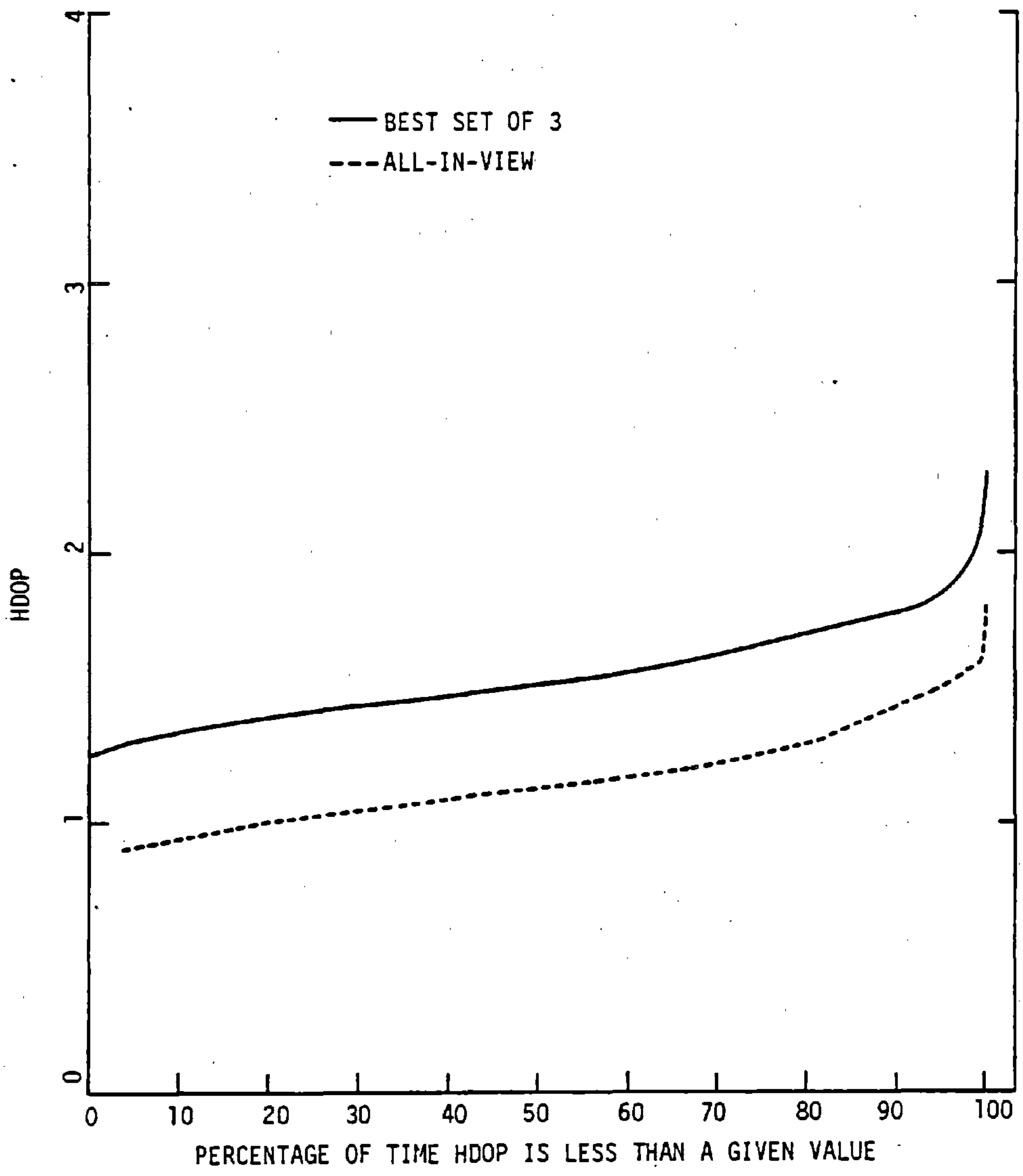

FIGURE 4-3. HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION, 10 DEGREE MASK ANGLE

this version, an acceleration sensor or measurement error threshold is used to change alpha from a low value in straight passages to 1.0 in curves, thus affecting a filtered navigation system which does not overshoot on turns.

4.5.3 The Kalman Filter

The Kalman filter can model position, velocity and acceleration states. It can also model clock errors and user trajectory errors separately from measurement errors. In the Kalman filter demonstrated here, acceleration states are not represented, but clock time and frequency states are present. A one-to-one comparison of the Kalman filter with the alpha-beta tracker here is not strictly possible, since the treatment of the two filters for use with a sequential receiver differs. The alpha-beta tracker waits to accumulate four independent measurements and then corrects its propagation estimates. The Kalman filter corrects its propagation estimates every measurement interval, essentially using four measurements of age 0, 1, 2, and 3 intervals. For the same measurement interval, this makes it more responsive to accelerations than the alpha-beta tracker.

Modification of the alpha-beta tracker to use measurements ranging in age from 0 to 3 measurement intervals should bring the performance closer to that of the Kalman filter. Use of the switched tracker should also improve performance.

4.6 SIMULATION RESULTS FOR KALMAN FILTER AND ALPHA-BETA TRACKER

Figures 4-5 to 4-8 show the performance of an alpha-beta tracker and Kalman filter on GPS receiver data taken during a simulated 900-second voyage in which a ship proceeds on a straight line course at 10 knots, begins a 90 degree turn at 540 seconds, and continues a straight line course at 631 seconds. The data for these figures are taken from a related project (Reference 32). The trajectory is shown in Figure 4-4.

Figure 4-5 shows navigation errors for an alpha-beta tracker with alpha = beta = 1. That is, course corrections are made assuming the pseudorange measurements to be error-free. The fluctuations represent pseudorange measurement errors. In essence, the tracker has been removed. The fluctuations prior to 270 seconds are transients due to the coldstart behavior of the tracker. Figure 4-6 shows the errors for an alpha-beta tracker optimized for low accelerations (alpha = .3). The tracker shows good noise-reduction during the straight legs but a large error is introduced during the turn. Figure 4-7 shows the results for a switched alpha-beta tracker in which the transient error in the turn is attenuated but a residual error due to unmodelled acceleration is present. Figure 4-8 shows the results for a Kalman filter with no acceleration states in which the measurements are incorporated into the position estimate at each measurement interval.

It appears that alpha-beta trackers can provide adequate performance for low dynamics vehicles such as ships in which accelerations are typically less than 0.05 g's.

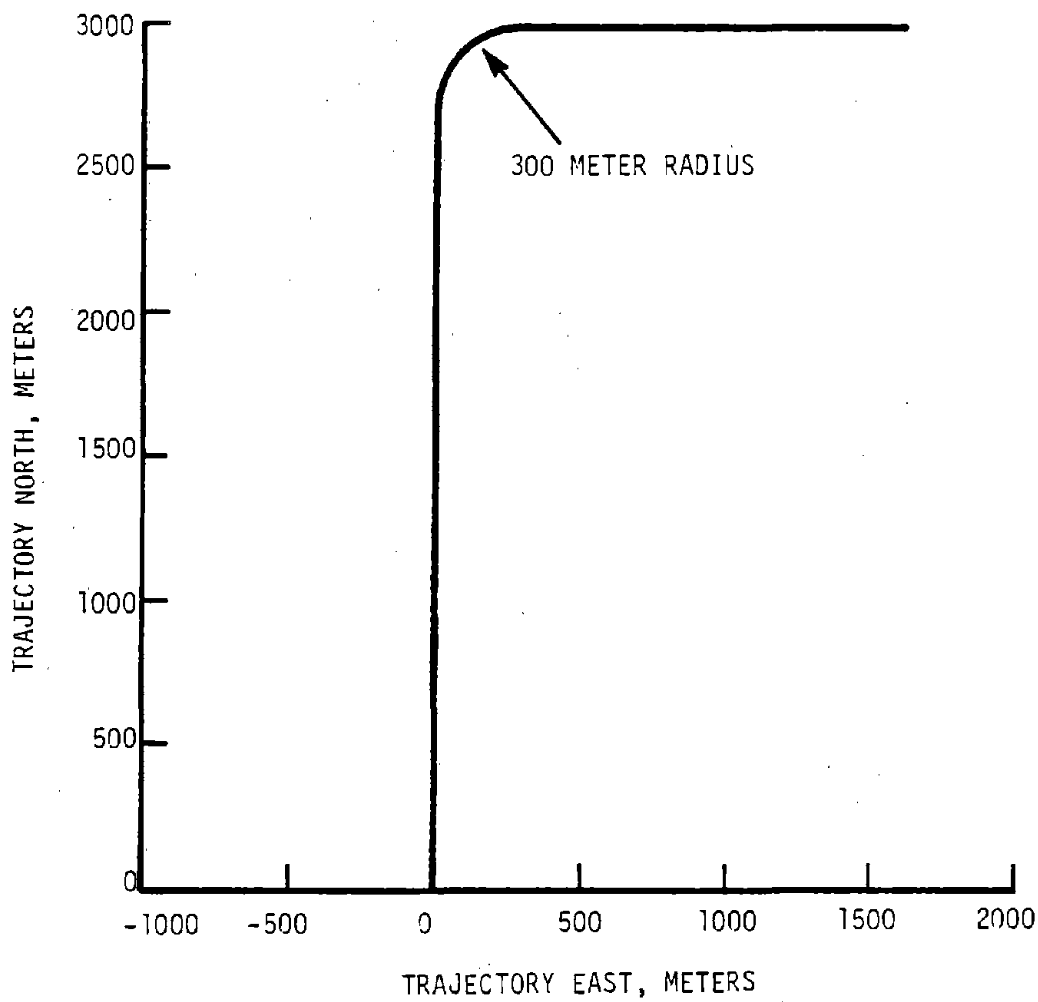

FIGURE 4-4. SHIP TRAJECTORY FOR COMPARISON OF TRACKER PERFORMANCE

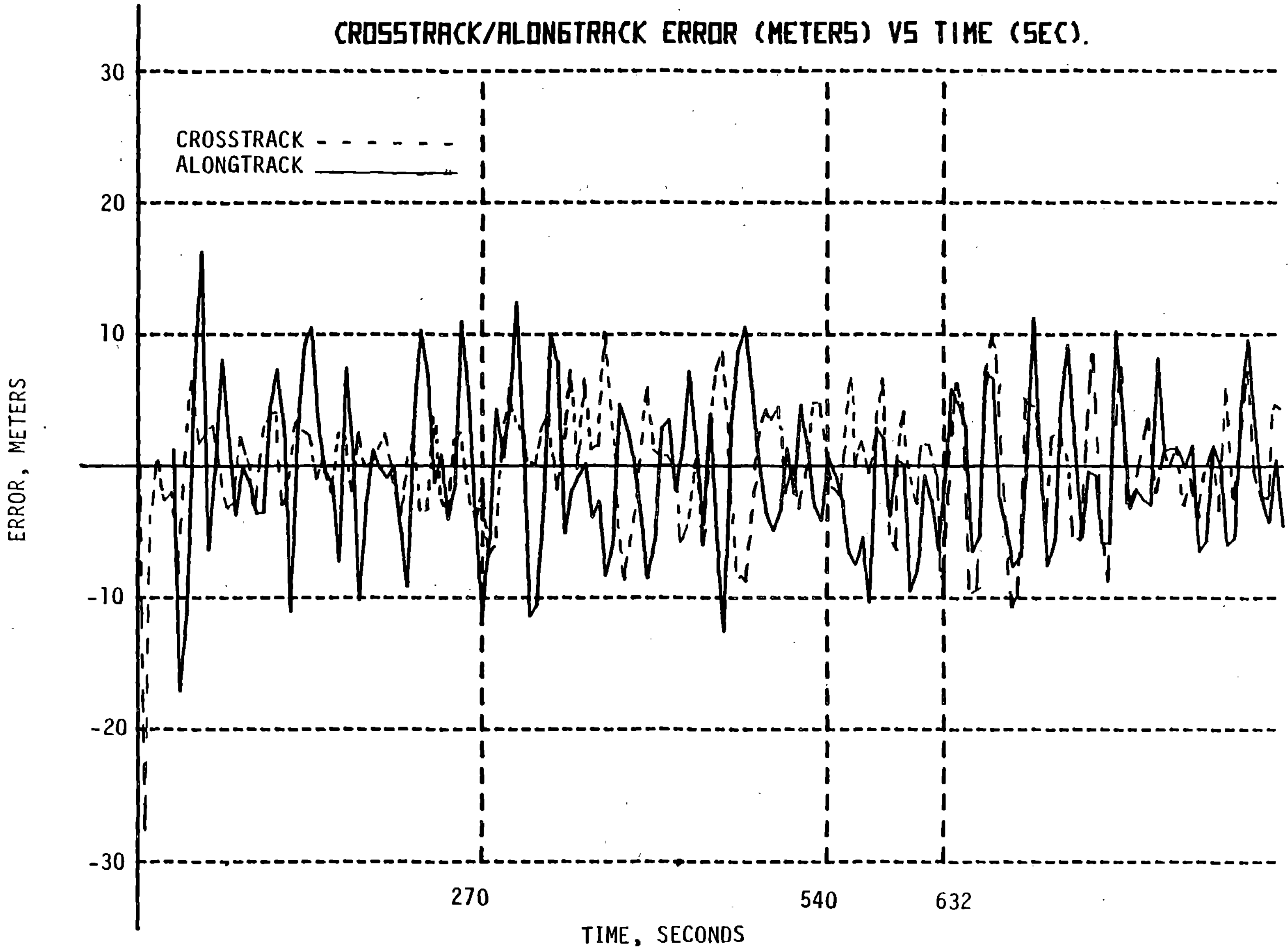

FIGURE 4-5. UNFILTERED NAVIGATION ERRORS

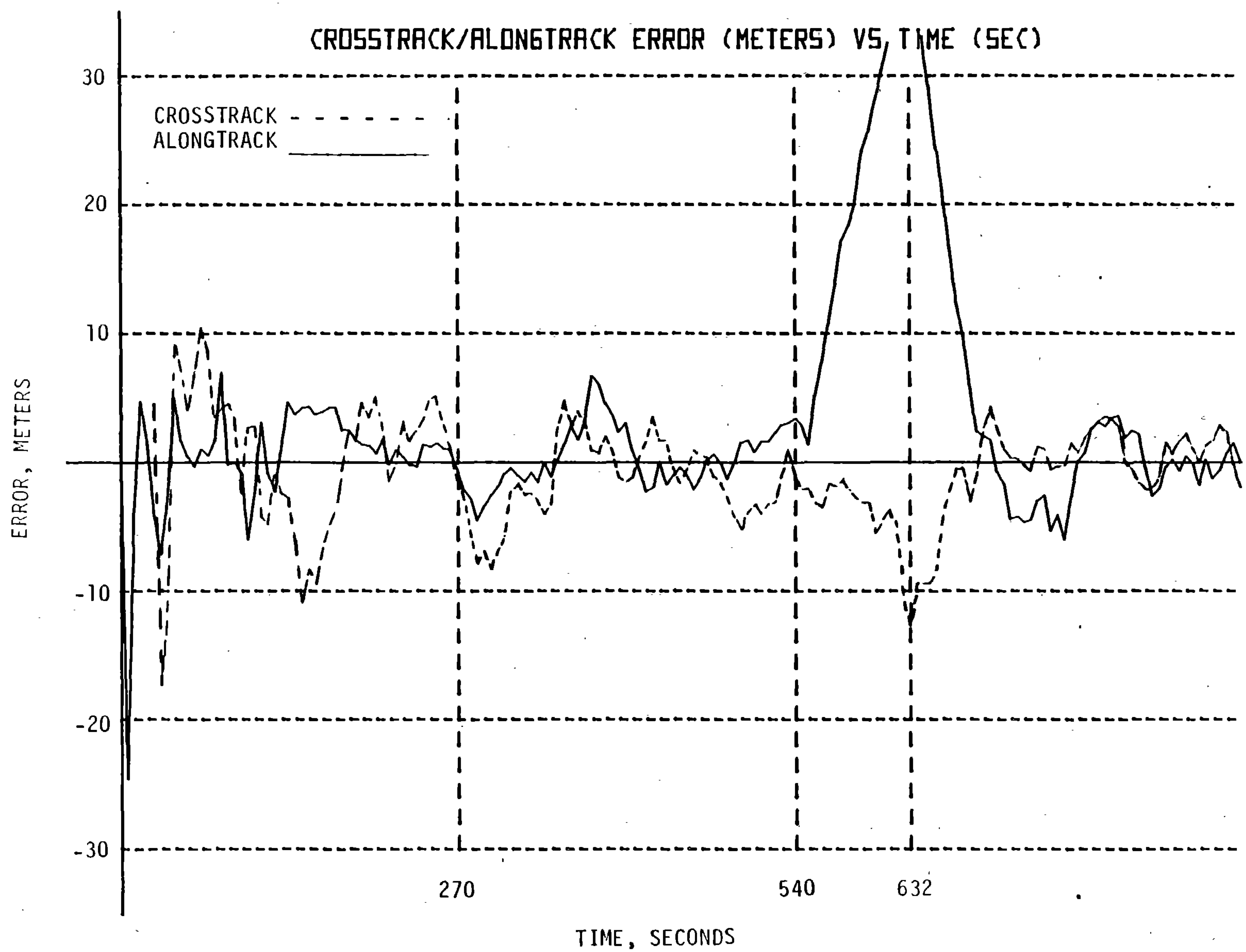

FIGURE 4-6. ALPHA-BETA TRACKER ERRORS

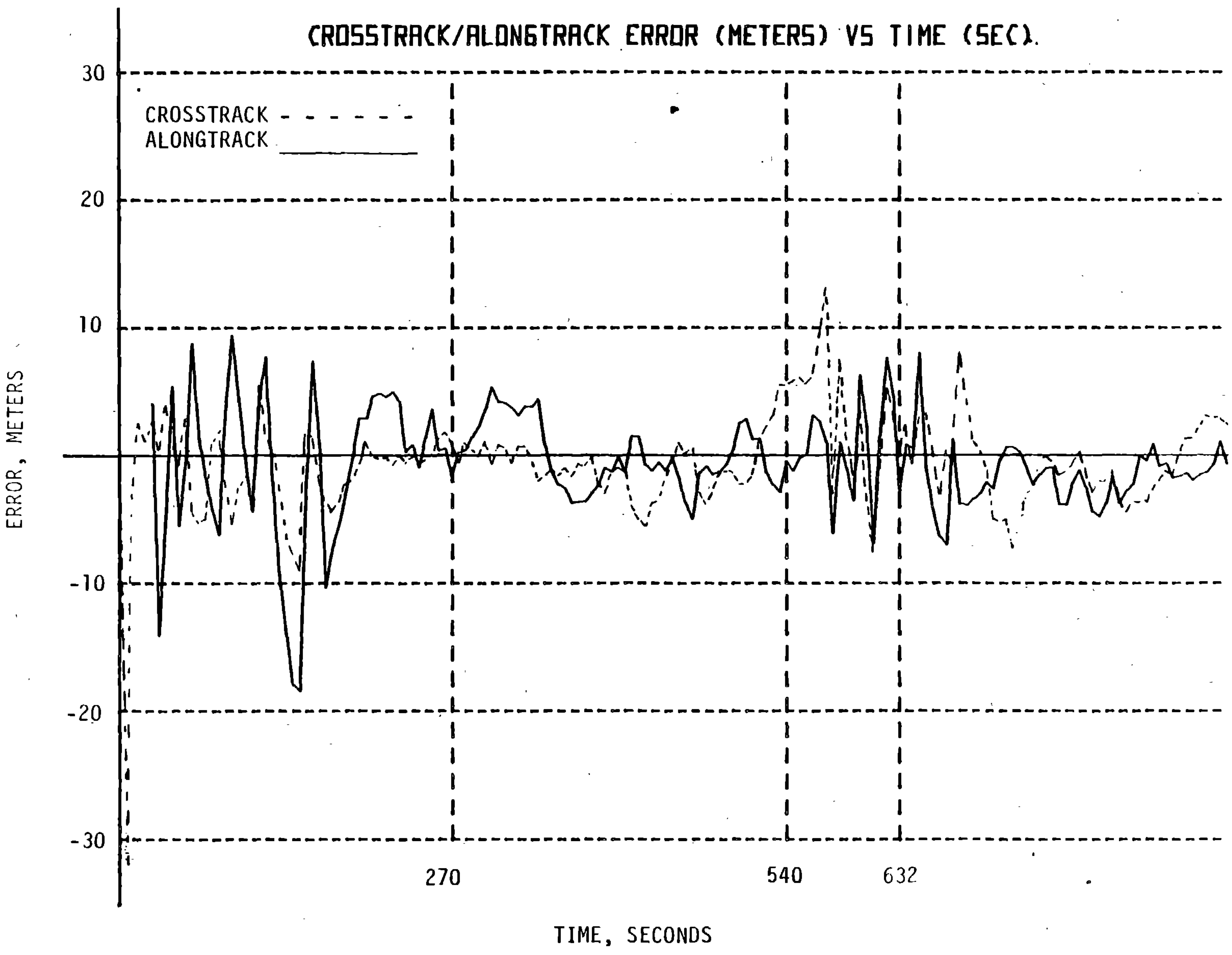

FIGURE 4-7. SWITCHED ALPHA-BETA TRACKER ERRORS

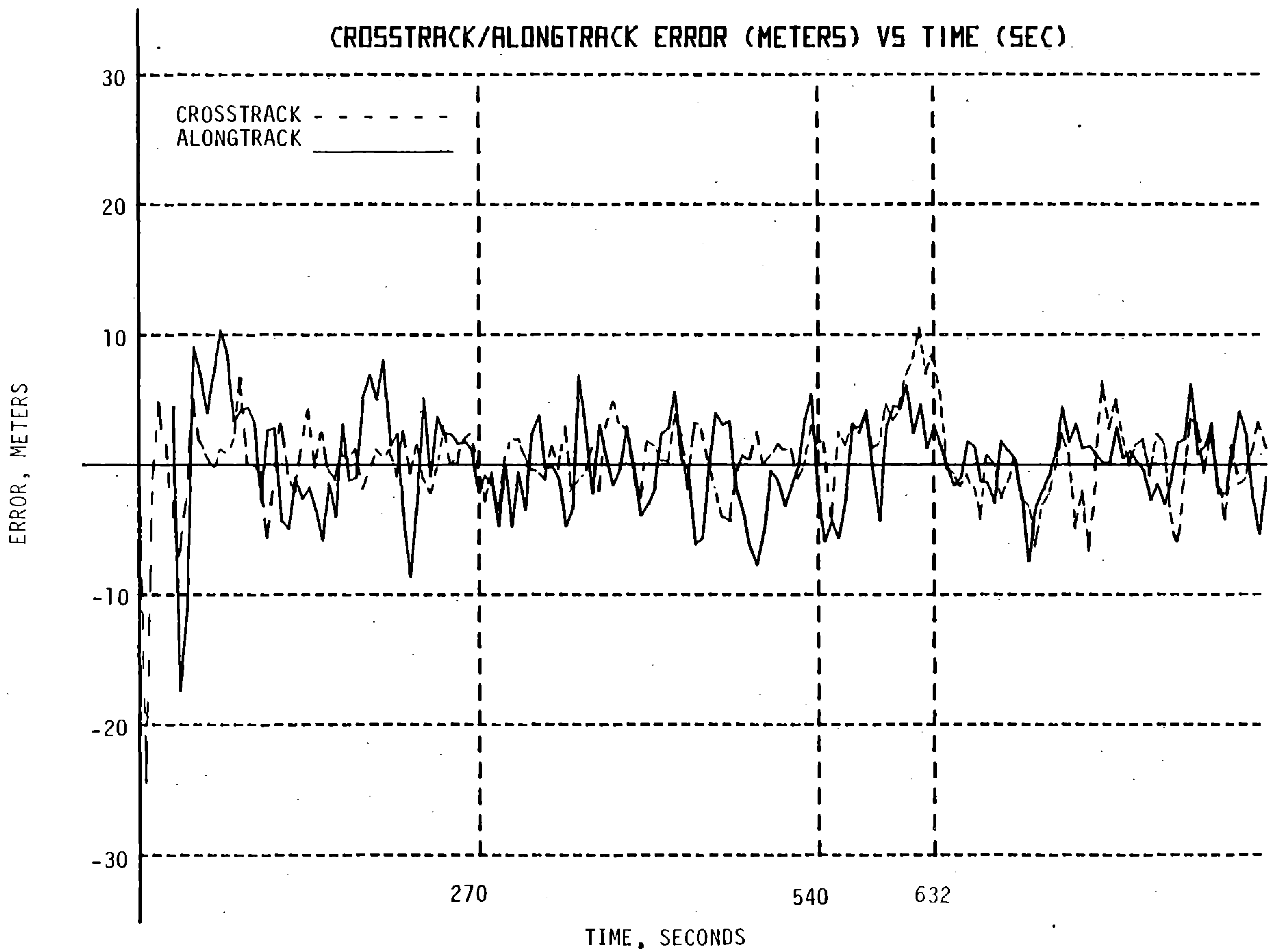

FIGURE 4-8. KALMAN FILTER ERRORS

Alpha-beta trackers are simple fixed-gain trackers, since the alpha and beta terms are selected to best match the combined effect of vehicle dynamics and measurement noise. They are considered to be less expensive than Kalman filters to implement, but this advantage is expected to disappear in future receiver designs (see Section 4.5). They can be made adaptive by adjusting the values of alpha and beta in real time. One way to do this is to have an acceleration term computed, such that when acceleration exceeds a certain threshold value, alpha and beta are set to unity (equivalent to no tracking). When the acceleration detector drops below the threshold, the terms are restored to their previous values.

The Kalman filter can be fixed or adaptive. The MARINEGPS and AIRGPS employ filter gain terms that are fixed in the sense that the expected "process" noise and measurement noise terms are not dependent on the real-time behavior of the position estimates. However, they do change with satellite elevation angle, unlike the alpha-beta tracker. Furthermore, the Kalman filter separately weights the effects of vehicle dynamics and measurement noise, again unlike the alpha-beta tracker. To be adaptive in real time, the gain terms should vary with the history of the "residuals." The Z-set navigation processor does this, and sophisticated processing includes this feature. The simulation models are adaptive only insofar as they down weight measurements which differ from predicted values by a predetermined amount. This reduces the effect of occasional bad measurements.

4.7 FUTURE RECEIVER DESIGNS

Phase I designs employed analog components to a large extent, using them to perform code-tracking, carrier-tracking, automatic gain control (AGC), and code and carrier detection functions, as well as front end radio frequency (RF) and intermediate frequency (IF) tasks of signal filtering, correlation and amplification. Phase III equipment and the EDCR perform all except RF, IF, and correlator functions digitally. Eventually IF and correlator functions will be performed by fast digital circuits as well, which will reduce costs and increase sophistication.

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 (0.01 Hz): 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 sizes: 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 cycle" exceeds 100%, and more than one microprocessor is required.

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.

TABLE 4-1. MICROPROCESSOR SPECIFICATIONS

PROCESSOR CLASS	PROCESSOR MODEL	MS micro sec	PS micro sec	MPY micro sec	DIV micro sec	CLOCK m Hz.
8/8	6502	2	.5	-	-	2
16/8	8085a-2	2.6	.8	-	-	5
16/8	68b09	2.5	.5	5.5	-	2
32/16	68000	.87	.27	4.6	10.5	15
32/32	68000/32	.87 *	.27	4.6	10.5	15

MS = time for extended address memory to register, word of bus length

PS = time for register to register instruction

MPY = time for register/register multiply

DIV = time for register/register divide

* MS time is for 32-bit register/memory instruction, 68000/32

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 4-3. MICROPROCESSOR LOADING, AVIATION APPLICATION

PROCESSOR	TASK GROUP - SECONDS				DUTY PERCENT
	1 KHZ	50 HZ	1HZ	.01 HZ	
6502	.6	2.8	1.6 .4 *	.0047	500 380 *
8085A-2	.78	2.9	1.7 .53 *	.0011	540 420 *
68b09	.75	.79	.49 .16 *	.0010	203 170 *
68000	.22	.24	.07 .019 *	.00022	53 48 *
68000/32	.22	.20	.060 .012 *	.00018	48 43 *

1. Navigation solution updated once/sec
2. 6 satellites tracked
3. 12 filter states
4. * indicates result for Alpha-Beta tracker

5. SERVICE OUTAGES

5.1 GENERAL

In this report a service outage is considered to exist when the HDOP for that user receiver exceeds 6. The horizontal measure HDOP is used, because most applications primarily use latitude/longitude information rather than altitude. It was shown in Section 4 that service outages are relatively rare. However, for some users such as aircraft operators even these rare outages can cause a problem if they last more than 5 minutes or so.

There are several conditions which can cause service outages:

1. Satellite failure.

2. Unfavorable geometry of satellite constellation with a minimum number of satellites.

3. Signal blockage due to terrain or buildings.

4. Signal blockage due to change in vehicle attitude (such as blockage by an airplane wing during a turn). This is a short-term effect.

The problem of terrain blockage could be problematic for airports in mountain valley areas. Structures causing blockage in the vicinity of airports are not likely to cause a problem because airport construction policies restrict the construction of buildings in the approach area (See Figure 5-1). For marine and land users, bridges, tunnels, and buildings can block satellite signals.

For a user who has a method of automatically informing the receiver of altitude, only three satellites are needed to obtain a position solution. Such a user is called a 2-D user, since he is using GPS to obtain 2-dimensional position information. Marine user receivers can employ models of the earth geoid to obtain this altitude input, and for some land applications this information is available. Without an independent altitude input, the NAVSTAR system must compute all three position coordinates, even though only two may be of interest to the user. These users are called 3-D users, and their receivers require four operating satellites to obtain a position measurement. If only three satellites are visible, 3-D users will experience an outage, because the HDOP is infinite; 2-D users, on the other hand, will not. Thus for 3-D users the NAVSTAR GPS must provide a mninimum of four visible satellites in a favorable HDOP geometry; similarly a minimum of three visible satellites are required for 2-D users.

When only four satellites are visible, outages may still occur for 3-D users if the satellites are almost coplanar. In such an unfavorable geometry, the HDOP becomes very high, and outages occur which can last up to 30 minutes or more. Similarly, for 2-D users unfavorable geometries occur when the three visible satellites and the user are almost coplanar.

There are three possible methods of dealing with these outages, each of which has limitations or is expensive:

1. For 3-D users an encoding altimeter can supply altitude information, in effect making them 2-D users.

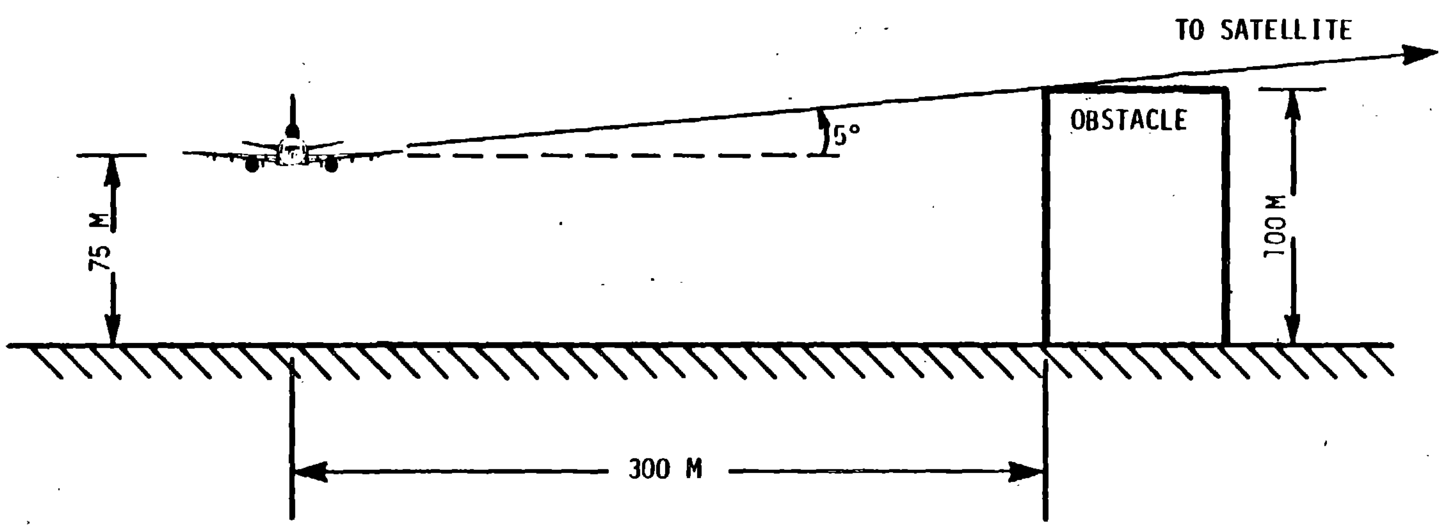

FIGURE 5-1. CLEARANCE NEEDED FOR NON-PRECISION APPROACH WITH GPS

2. A high-quality external clock can be inputted to the receiver, enabling "coasting" through long outage periods.

3. A lower mask angle can be employed, which reduces or eliminates the duration of the outage.

4. The receiver can "coast," relying on the internal clock to "hold" the time solution for a period of time.

The first two are costly, especially to general aviation or small commercial marine users. The last two have performance consequences which limit their effectiveness.

By employing a lower mask angle, a receiver will see satellites for a longer period of time, thus reducing or eliminating the outage periods. However, this advantage is accompanied with a performance loss. The receiver antenna pattern generally falls off at low elevation angles, which lowers the signal-to-noise ratio and increases the measurement uncertainty. Signal blockage and reflections of satellite signals from earth-based objects cause range errors in low elevation satellite signals. The minimum usable elevation angle (MUEA) thus depends on the environment. The imposition of a mask angle, i.e., an elevation angle below which a satellite signal is ignored, ensures that a satellite signal will not be used when it is likely to be erroneous. However, in selecting a mask angle, these considerations should be balanced against the advantages to be gained by reducing or eliminating outages.

By coasting with the clock, the position solution error will remain small until user clock drift begins to cause the solution to wander. Clearly, the better the short-term stability of the clock, the longer the coasting period will be in order to maintain a given accuracy.

This section addresses the conditions under which outages occur, the periods of the outages, the accuracy required by external altimeter or clock inputs, the user clock requirements for coasting, simulation results which demonstrate clock coasting, and the effects of mask angle variations.

5.2 SPARING STRATEGY

The recent JPO decision to rephase the three active spare satellites with the 6-plane, 18 satellite constellation will enable uninterrupted service within the CONUS for users who utilize all satellites with elevation angles greater than 8°. The configuration of 18 satellites with three active spares is detailed in Figure 5-2. Figure 5-3 shows the time variation of PDOP for the 18 satellite-only constellation for a typical observer in CONUS. Note the singularity of PDOP at approximately 2 and 15 hours for times lasting approximately one half hour. These outages arise when the visible constellation consists of 4 coplanar satellites. Figure 5-4 shows the time variation of PDOP for the 18 satellite constellation of Figure 5-2 with 3 active spares. In this case PDOP is less than 6 for the whole of the CONUS. The deployment transfers the outages to other parts of the world which will then contain time variations of PDOP similar to those in Figure 5-3.

Figures 5-3 and 5-4 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

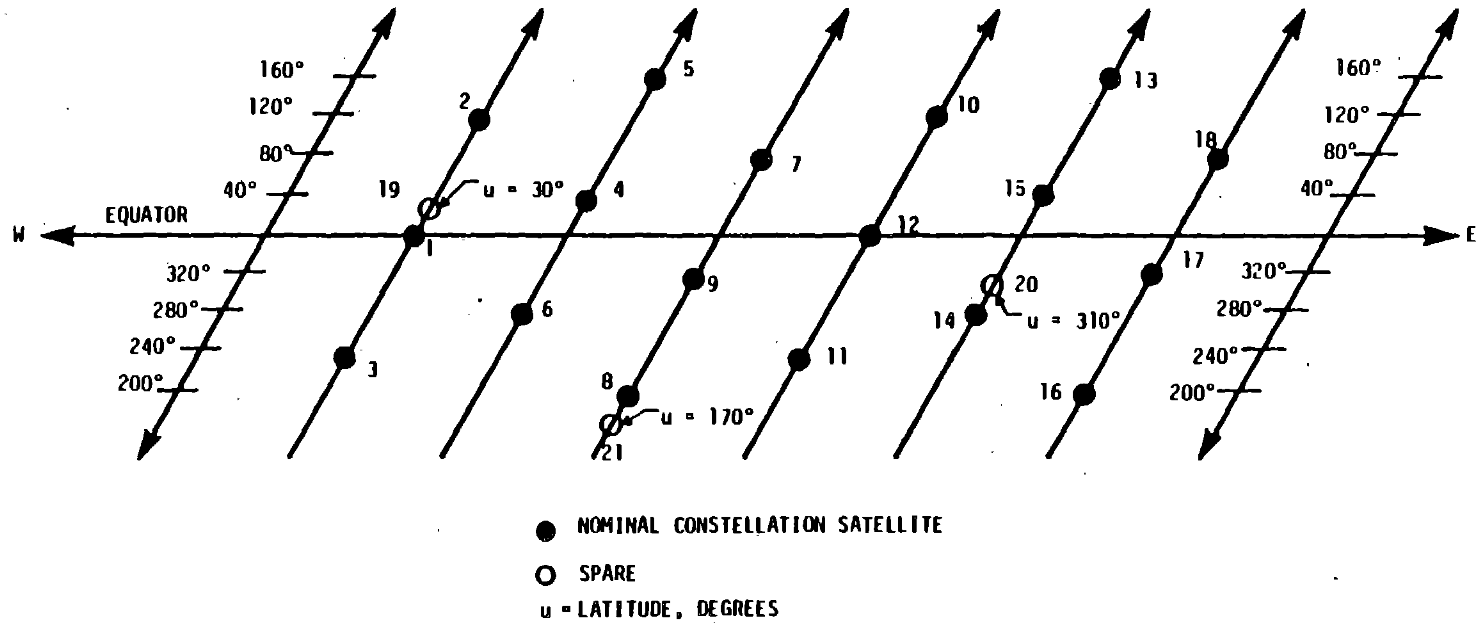

FIGURE 5-2. PLANNED SATELLITE CONSTELLATION WITH NEW SPARING STRATEGY

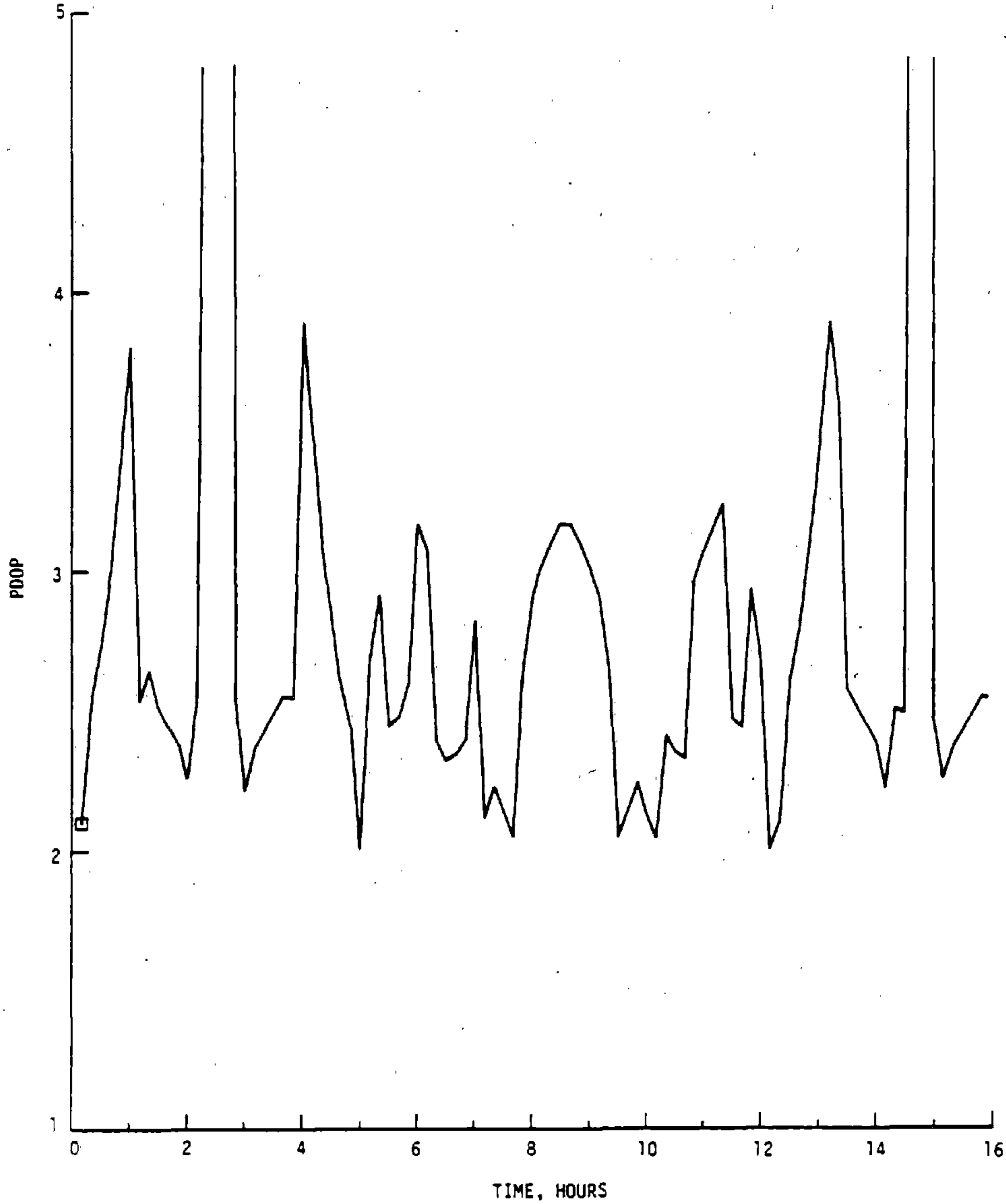

FIGURE 5-3. PDOP VARIATION - 18 SATELLITE CONSTELLATION, 3-DIMENSIONAL SOLUTION, 5° MASK ANGLE (95°W/35°N)

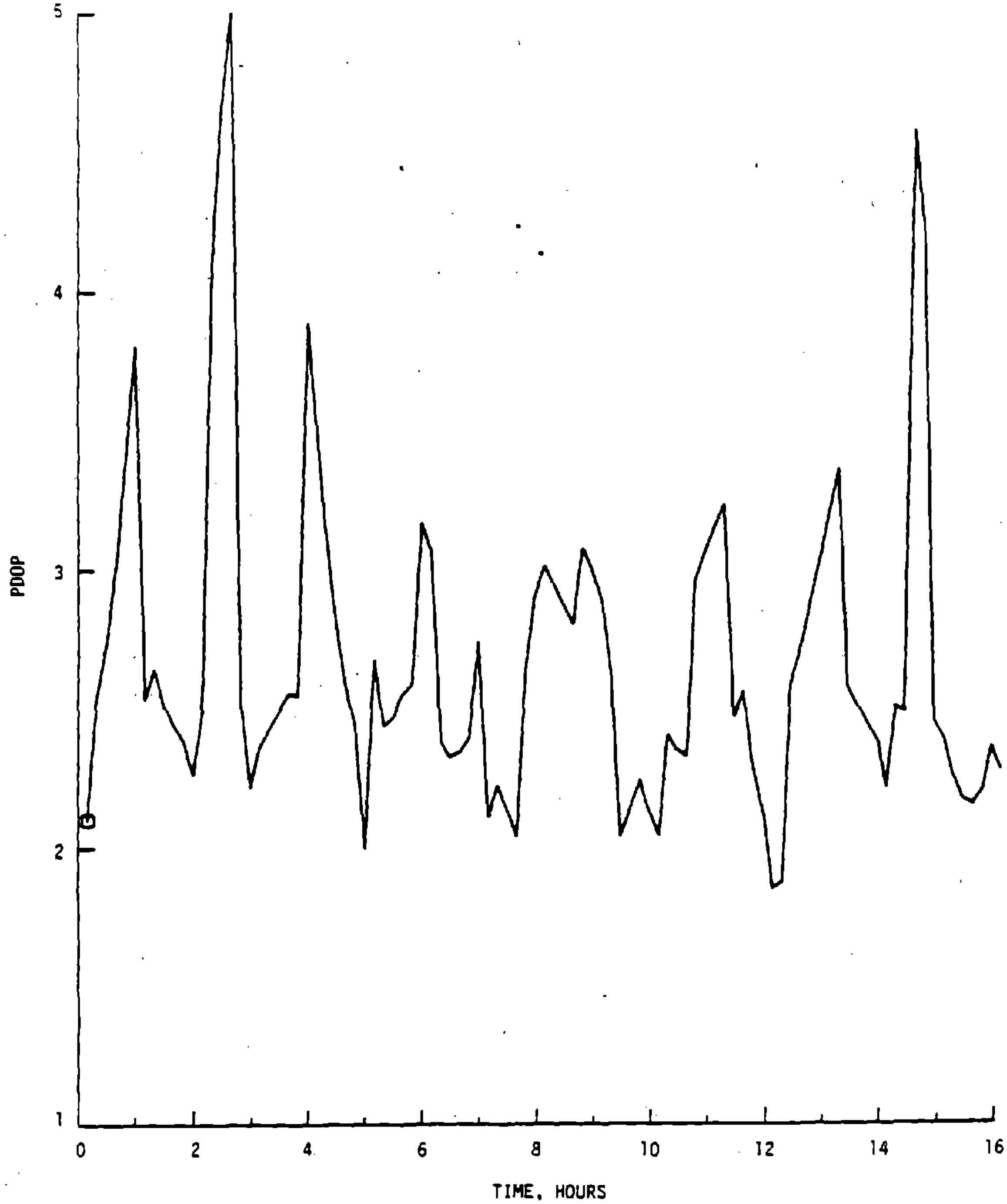

FIGURE 5-4. PDOP VARIATION - FULL 18 + 3 SATELLITE CONSTELLATION
3-DIMENSIONAL SOLUTION, 5° MASK ANGLE (95°W/35°N)

represents a typical design for an airborne receiver. If the mask angle is 10^{o}, a figure preferred by the FAA, the sparing strategy is not totally effective. Figure 5-5 shows the HDOP distributions for the two mask angles. It can be seen that there still remain outage periods for the 10^{o} mask angle receivers. A closer examination reveals there are five locations that experience outages varying in time from 1 to 15 minutes. The time variation of one of these is shown in Figure 5-6 for 50^{o} North Latitude and 85^{o} West Longitude at about 9:45 hours GPS time. Whether the receiver can "coast" through such brief outages is discussed in Section 5.4.

The outages discussed above do not apply to receivers that have independent altitude determination, i.e., either by altimeter input or by employing a two-dimensional navigation solution such as that employed by ocean-going vessels. Figure 4-1 shows that all HDOP's are below 2.5 for mask angles of 5^{o} or 10^{o}.

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 DEPENDENCE OF OUTAGE ON MASK ANGLE

The choice of mask angle in the precision design affects the length of time a receiver will experience an outage. Figure 5-7 shows the maximum contiguous outage period for a 3-D user (a 3-D navigation solution requires the use of 4 visible satellites) as a function of mask angle. It can be seen that reducing the mask angle from 10 degrees to 8 degrees reduces the maximum 3-D outage time from 20 to 0 minutes. In a fully operating system a 3-D receiver able to see satellites above 8 degrees will thus have no outages.

Figure 5-8 shows the maximum contiguous outage period for a 2-D user (a 2-D navigation solution requires the use of 3 visible satellites) as a function of mask angle. From these data it is concluded that 2-D operation for mask angles less than 12 degrees will encounter no outages.

The mask angle can be increased from 8 to 10 degrees for the 3-D user equipped with a clock having errors less than 300 nanoseconds for an outage period of 20 minutes (10^{-9} stability). Similarly, the mask angle can be increased to 15 degrees for the 2-D user equipped with a similar clock.

In summary, with a full constellation of 18 satellites and 3 active spares, outages can be eliminated by employing mask angle of 8 degrees or less for 3-D users, and 12 degrees or less for 3-D users. By using clocks with 10^{-9} frequency stability over the period of tens of minutes, receivers can coast through limited outage periods. For these receivers, mask angles of 10 and 15 degrees can be used without incurring unacceptable errors.

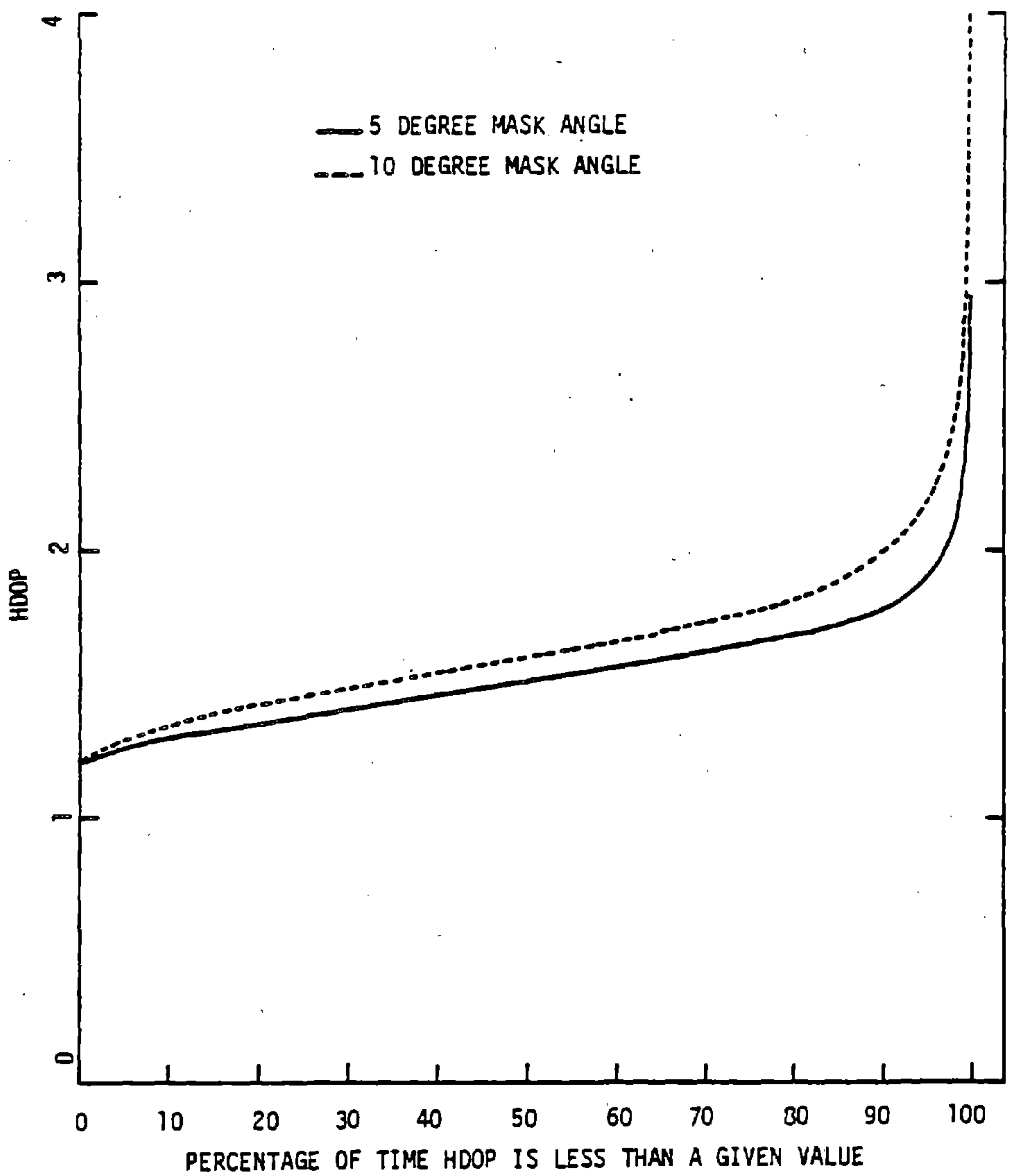

FIGURE 5-5. CONUS HDOP DISTRIBUTION - FULL 18 + 3 SATELLITE CONSTELLATION 3-DIMENSIONAL SOLUTION, BEST-SET STRATEGY

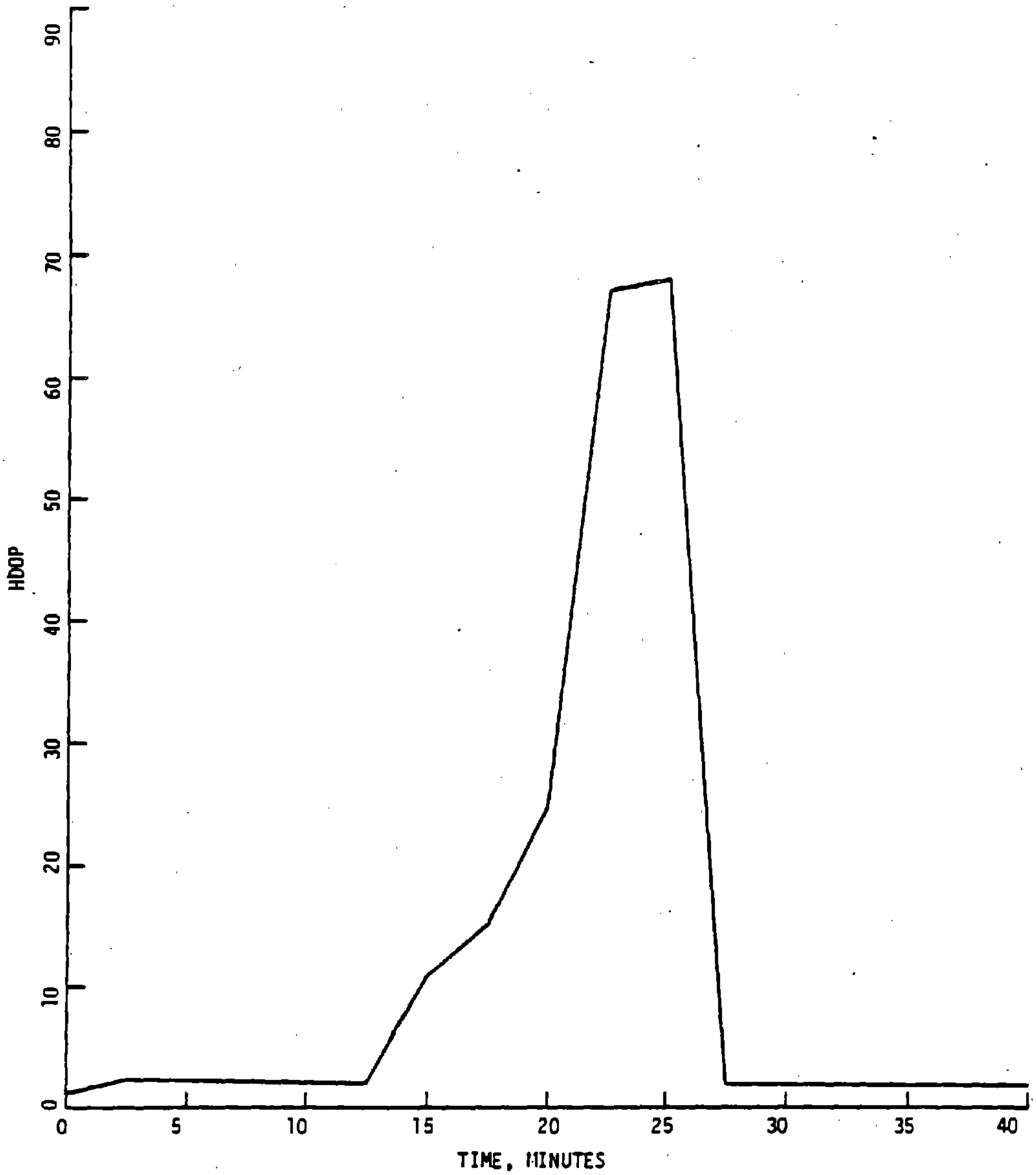

FIGURE 5-6. HDOP VARIATION DURING OUTAGE - FULL 18 + 3 SATELLITE CONSTELLATION 3-DIMENSIONAL SOLUTION, 10° MASK ANGLE

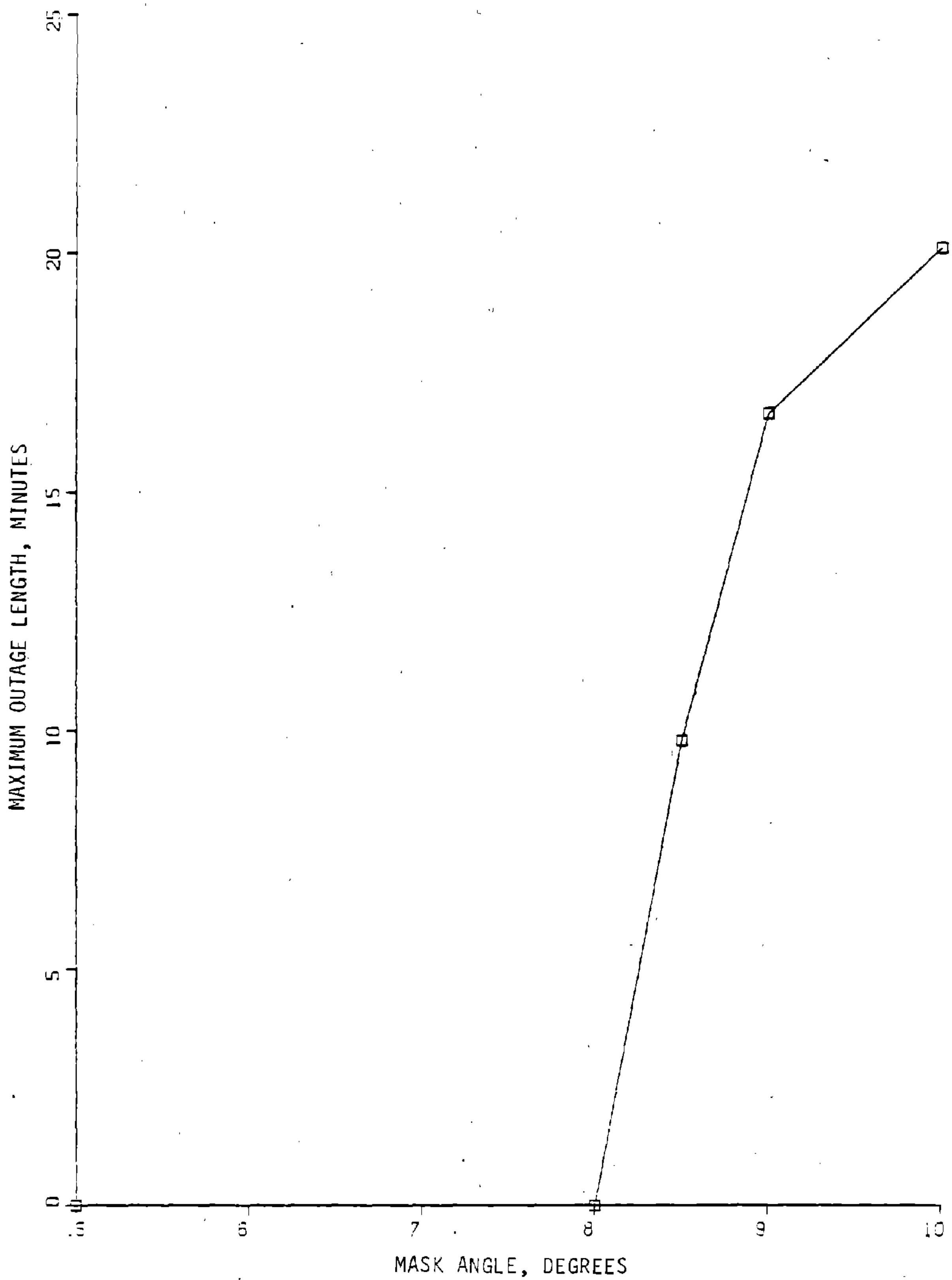

FIGURE 5-7. MAXIMUM OUTAGE TIME IN CONUS VS MASK ANGLE, 21 SATELLITES OPERATING, 3D

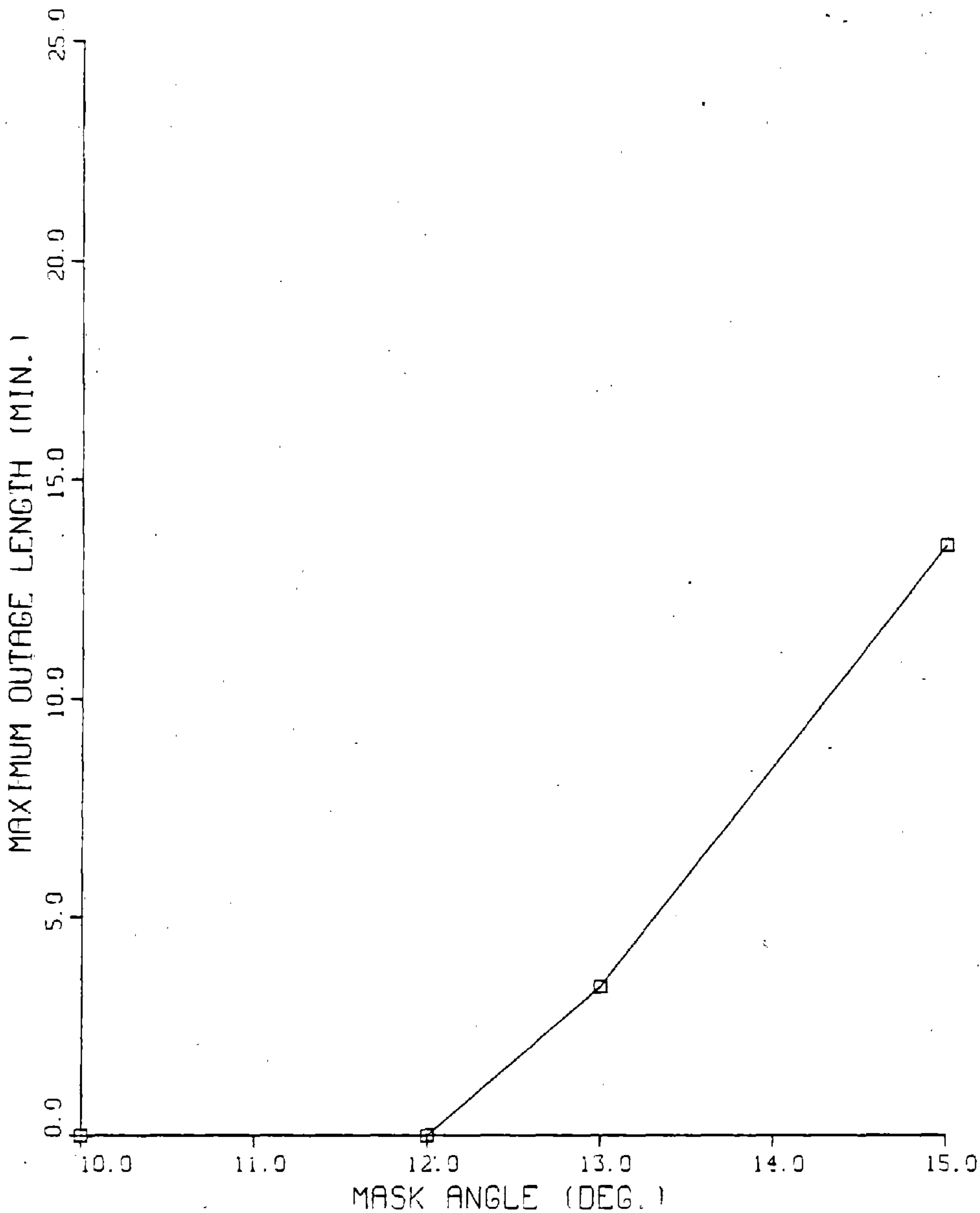

FIGURE 5-8. MAXIMUM OUTAGE TIME IN CONUS VS MASK ANGLE, 21 SATELLITES OPERATING, 2D

5.4 DEPENDENCE OF NAVIGATION ERRORS ON CLOCK ERRORS

A fixed observer may calculate his position from the four arrival times of four satellites and the known positions of the four satellites. For a four channel receiver, the changing positions in time of the satellites during the spread of arrival times (less than 0.02 seconds) can be estimated from their known velocities. During this period, the receiver clock must be able to measure time to the required range accuracy (10^{-9} sec.).

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.

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 to a 3-D user, the processor can "coast" using the clock to provide accurate system time. The clock accuracy should not exceed the sum of the contributions of range error from other sources, such as Selective Availability, during the period that only three satellites are available. The coasting 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.

Essentially, the cost of the clock is determined by the equipment used to isolate it from the environment. Some details on clocks are given in Appendix D. A clock with Allan Variance [13] better than 10^{-10} may be used for long term outages (1000 seconds). Such a clock will cost more than $2500. Thirty second outages of the type that occur during a maneuver by a civil aircraft, require a variance of the order 10^{-9}. A $250 temperature-compensated crystal oscillator satisfies this requirement. For a single satellite outage of 1200 seconds, the clock must maintain a frequency stability of 10^{-11} to maintain a position error of the order of 4 meters. An outage of 30 seconds requires a frequency stability of

$4X10^{-10}$ for a similar position error. An example is given in Appendix I for a 1000 second outage, good PDOP and a clock offset of 10^{-11} resulting in a horizontal error of 15 feet. Figure 5-9 shows the relationship of clock offset and outage time to position error during an outage with the constellation shown in Appendix H.

5.5 SIMULATION RESULTS FOR CLOCK AIDING DURING MANEUVER OUTAGE

The AIRGPS simulation was used to examine navigation filter performance under conditions of turning flight. In this situation, the filter has to cope with both turn-induced acceleration and the degraded signal quality which results from antenna pattern roll-off and airframe blockage. Four different aircraft trajectories were used. The trajectories involve both standard-rate turns and turns made at twice the standard rate. Several levels of user clock quality were used in order to observe the effect of clock stability on navigation solution accuracy. The runs also incorporated conditions of both nominal and poor GDOP.

The turn performance of the AIRGPS navigation filter was evaluated using four different flight trajectories. The first three trajectories involve racetrack patterns while the fourth begins with a descending turn followed by a descending straight-line segment. In each case the filter is initialized at the start of the run to approximate steady-state, unaccelerated flight conditions with a nominal GDOP. The salient features of the four flight trajectories are listed in Table 5-1.

TABLE 5-1. FLIGHT TRAJECTORY FEATURES

TRAJ. NUMBER	GDOP	TAS	TURN RATE	BANK ANGLE	TURN ACCEL.	RUN DURATION	ALTITUDE
1	Nominal	160 Kts	2 min	24^{o}	0.44g	200 sec	Constant
2	Nominal	160 Kts	1 min	41^{o}	0.88g	100 sec	Constant
3	Poor	160 Kts	1 min	41^{o}	0.88g	100 sec	Constant
4	Nominal	160 Kts	2 min	24^{o}	0.44g	90 sec	Variable

The navigation processor outputs for these runs (with a 10^{-10} user clock stability) are shown in Figures 5-10 through 5-13. A summary of the data is given in Table 5-2.

The data are consistent in that they show the proper navigation errors for those satellites which are blocked in the turns and the proper acceleration errors for this Kalman filter. In runs #2 and #3, the horizontal acceleration errors obscure the effects of going from a good HDOP to a poor HDOP, but the vertical errors do show the variation with VDOP. Details of these simulations are given in Appendix F.

5.6 MAINTAINING THE NAVIGATION FIX WITH ALTIMETER AIDING

It has been stated earlier that knowledge of a user's altitude from an independent source enables him to compute his position and system time from only three satellites. We wish to investigate the accuracies and cost of altitude measuring instruments and how inaccuracies in altitude, so determined, affect the accuracy of the three satellite GPS navigation fix. The GPS rms error in horizontal position resulting from an altimeter error is of the order of the altimeter error times the average HDOP.[14]

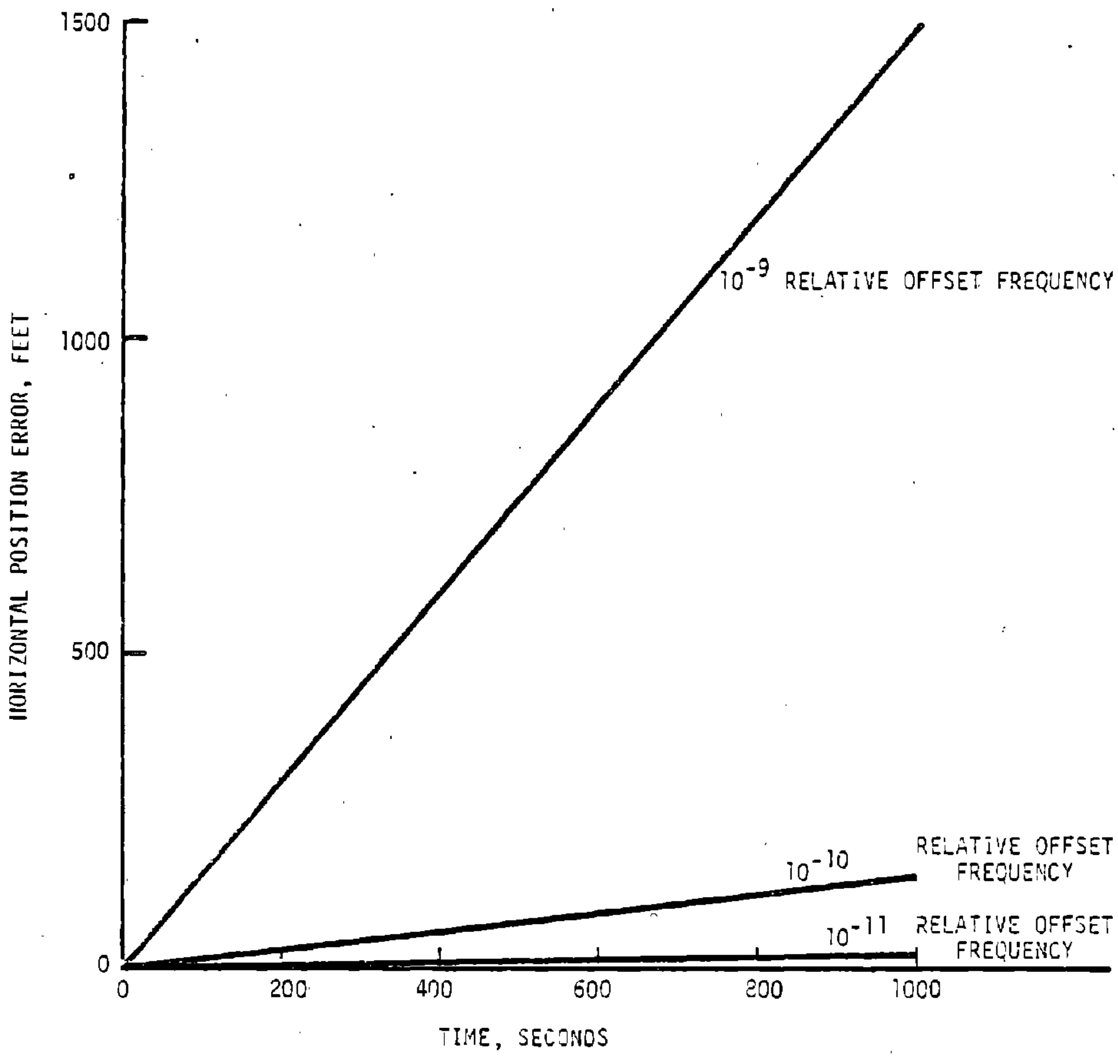

FIGURE 5-9. NAVIGATION ERRORS CAUSED BY CLOCK OFFSET FREQUENCY DURING OUTAGE

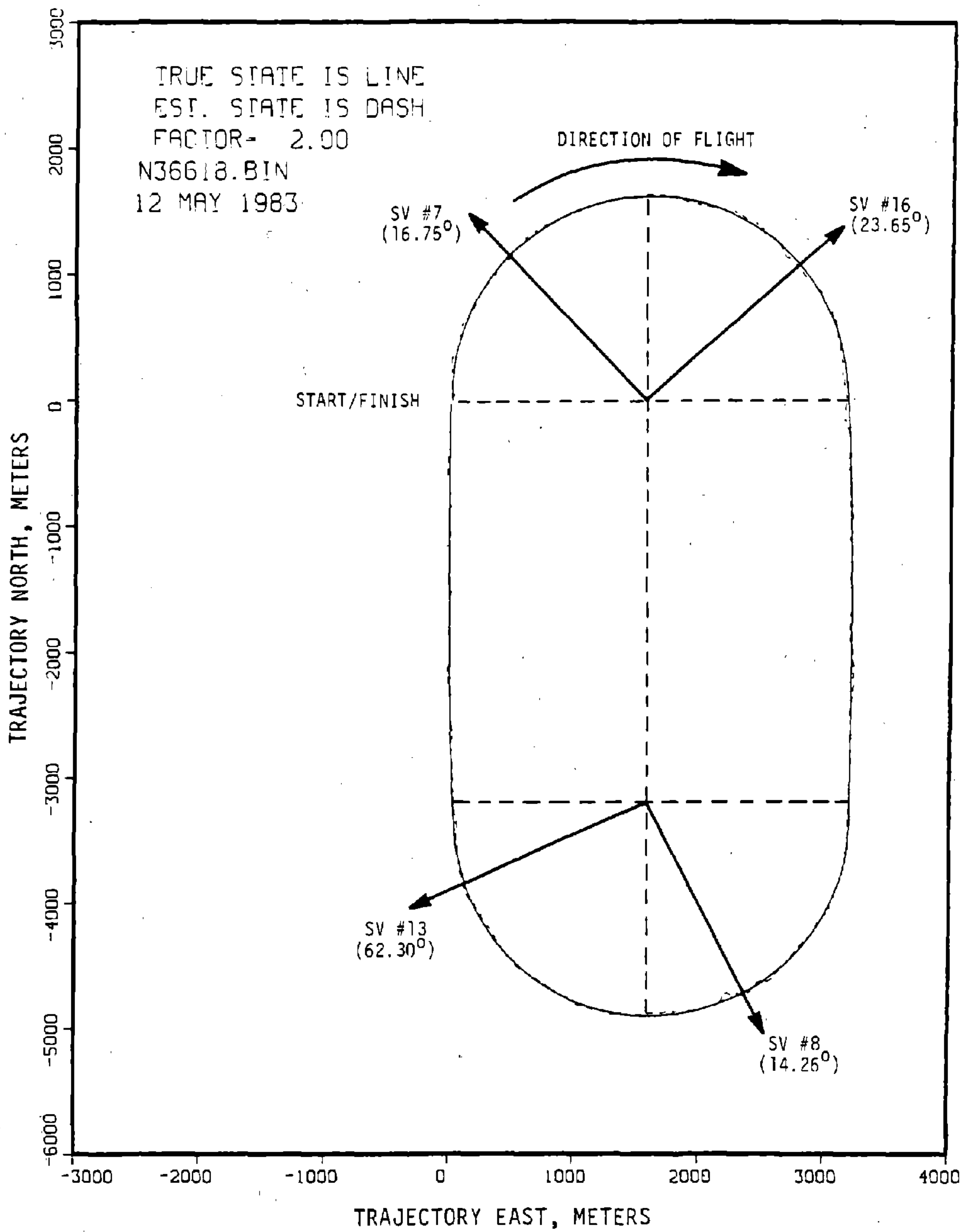

FIGURE 5-10. AIRGPS TRAJECTORY #1

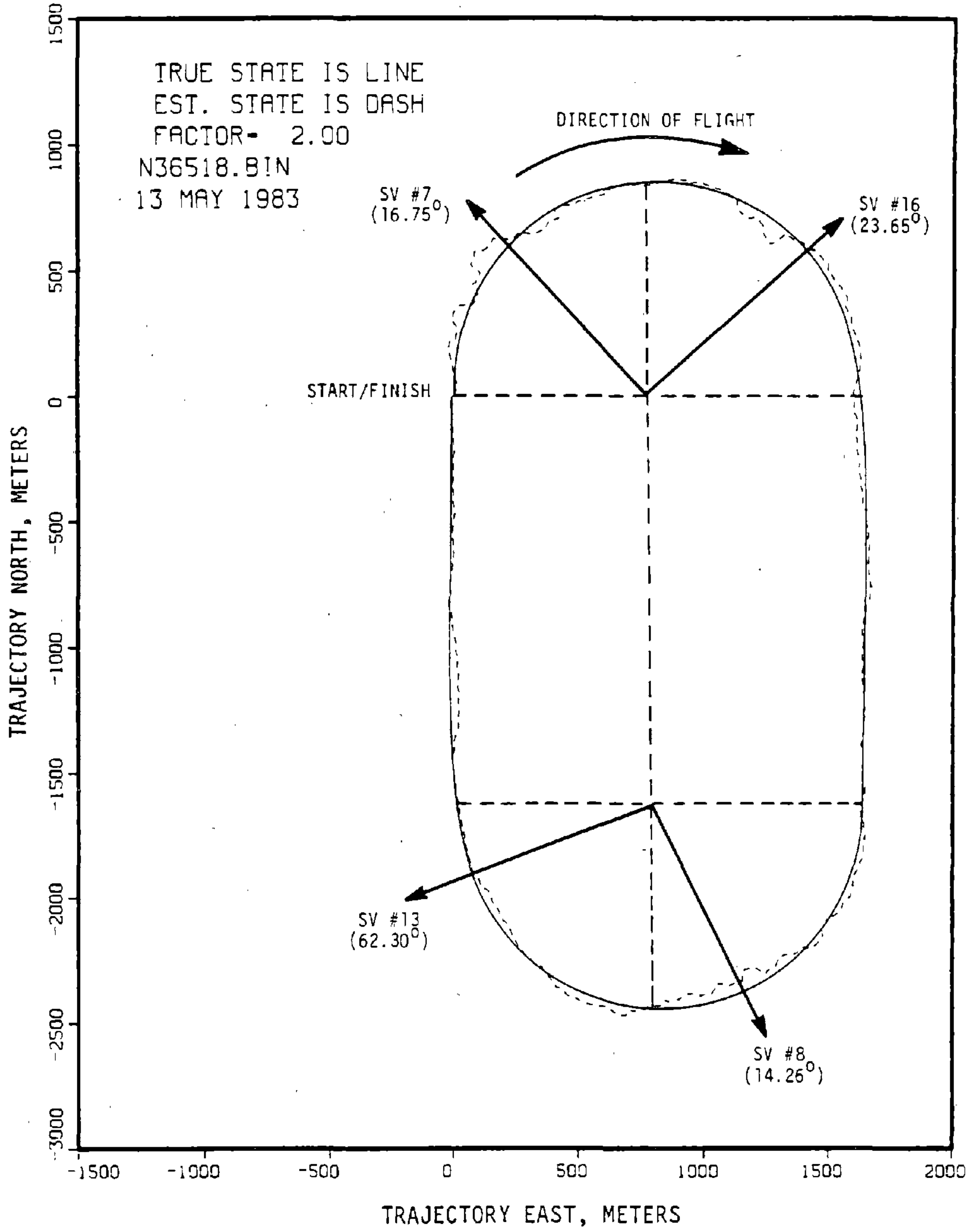

FIGURE 5-11. AIRGPS TRAJECTORY #2

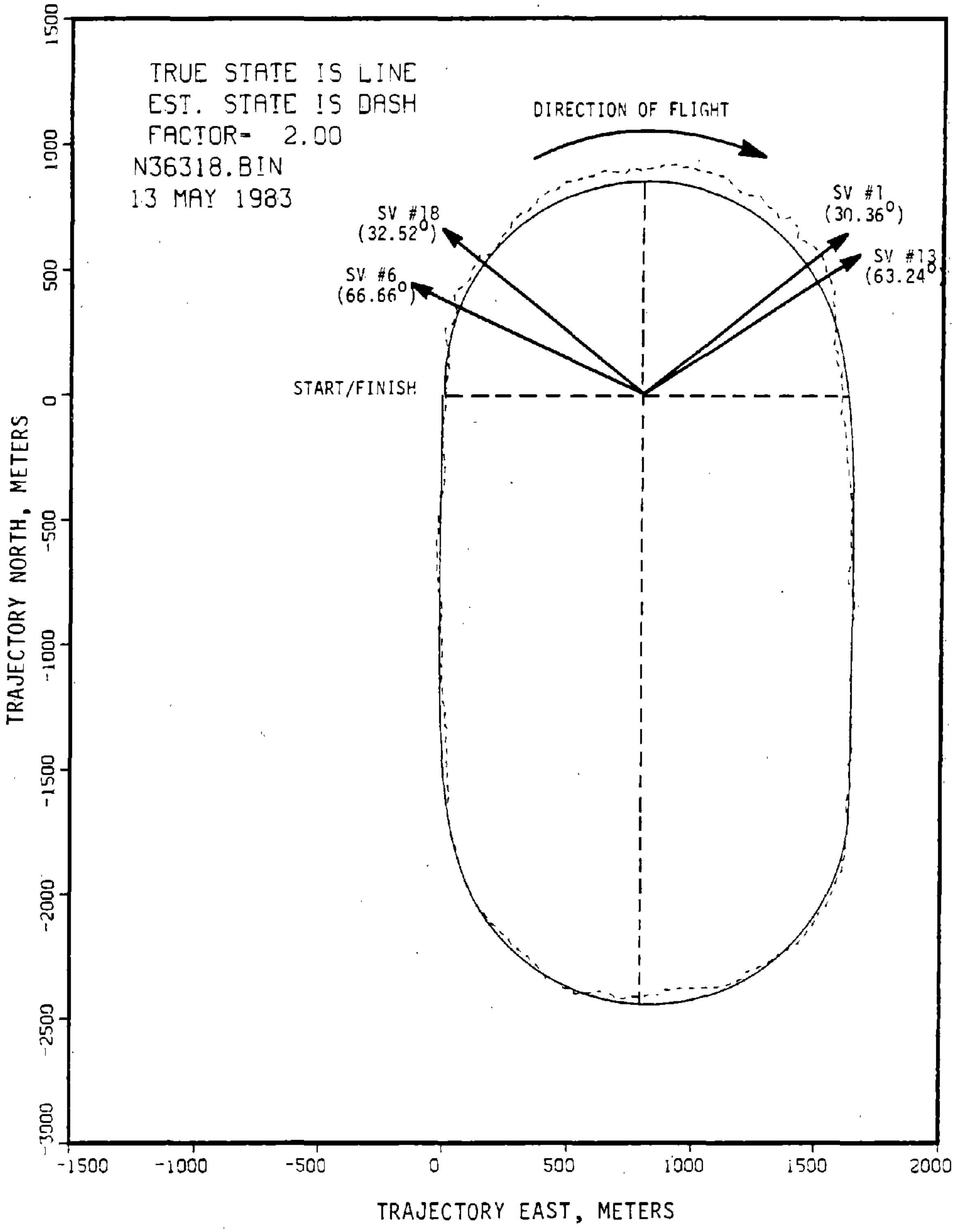

FIGURE 5-12. AIRGPS TRAJECTORY #3

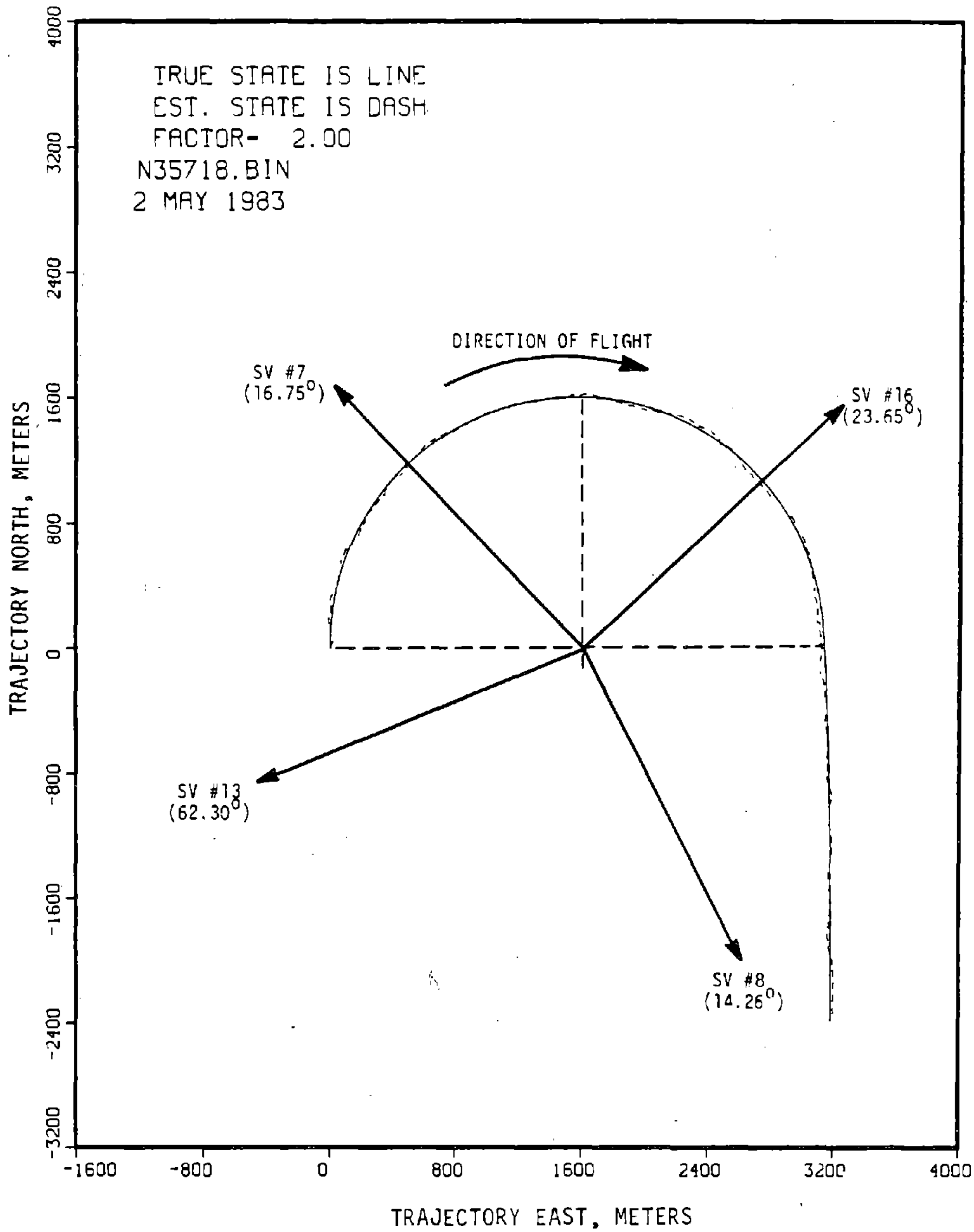

FIGURE 5-13. AIRGPS TRAJECTORY #4

TABLE 5-2

AIRGPS SIMULATION RESULTS, MANEUVER OUTAGE

CLOCK STABILITY = 10^{-10}

2DRMS ERRORS (m)

	1ST TURN	STRAIGHT	2ND TURN	STRAIGHT	TOTAL RUN
BASELINE-DIFFERENTIAL 3°/s GDOP = 2.48 HDOP = 1.29 VDOP = 2.12	15.76	13.62	14.909	10.70	13.00
6°/s GDOP = 2.48 HDOP = 1.29 VDOP = 2.12	32.82	15.90	30.70	17.18	27.00
6°/s GDOP = 21.24-15.69 HDOP = 9.76-7.23 VDOP = 18.86-13.93 HIGH C/N_0 POOR GDOP	54.92	56.84	33.74	17.82	44.00
3°/s GDOP = 2.48 HDOP = 1.29 VDOP = 2.12	16.38	14.48	-	-	15.00

2-SIGMA ALTITUDE ERROR (m)

TURN RATE					
3°/s Run 1	9.98	11.52	12.18	10.70	11.00
6°/s Run 2	17.48	6.68	12.02	8.82	12.00
6°/s Run 3	95.84	105.80	65.58	22.50	80.00
3°/s Run 4	13.22	14.28	-	-	13.00

A barometric altimeter computes the static barometric pressure from the dynamic pressure measured at the static ports of an aircraft. Aside from the errors in relating the dynamic and static pressures occurring when there are changes in aircraft altitude, and speed, the principal error in determining the aircraft altitude, using a barometric altimeter, is the variation of lapse rate (the relation of the static pressure to altitude) in time.

The mean altitude errors resulting from the variation in lapse rate are estimated to be 3% of the altitude. An aircraft at 40,000 feet may expect altitude errors of 1200 feet while an aircraft at 1,000 ft will have an altitude error of 30 ft.

A radio altimeter measures the propagation time of a signal transmitted from the aircraft, then reflected from the ground to the plan. 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 5000 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. Present costs of an encoding altimeter are about $2,000 for a barometric instrument and $3,500 for a radio altimeter.

The barometric altimeter has an accuracy at high altitudes which is far less than that necessary to produce four-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 three-satellite-fix with barometric altimeter aiding, has sufficient accuracy to be acceptable. Table 5-3 compares the expected accuracy of GPS with FRP requirements. Table 5-4 summarizes the user coverage requirements.

TABLE 5-3. CONTROLLED AIRSPACE NAVIGATION ACCURACY TO MEET CURRENT REQUIREMENTS*

Phase	Sub-Phase	Altitude (Flight Level)	Traffic Density	Route Width (NM)	Accuracy 2 drms (meters)	System Use Accuracy 2 drms (meters)	GPS Accuracy 3 Satellite + Altimeter
EnRoute/ Terminal	Oceanic	FL 275 to 400	Normal	60		12.6nm*	1024 M
	Domestic	FL 180 to 600	Low	16	2000	7,200	1537
			Normal	8	1000	3,600	1537
		500 - 18,000 ft.	High	8	1000	3,600	461
	Terminal	500 - 18,000 ft.	High	4	500	1,800	461
	Remote	500 - 60,000 ft.	Low	8 to 20	1000 to 4000	3,600 to 14,400	1537
	Helicopter Operations	500 - 5000 ft.	Low (Off-Shore)	Not Determined	1000 to 2000	3,600 to 7,200	128
		500 - 3000 ft.	High (Land)	4	500	1,800	77
Approach and Landing	Non-Precision	250 to 3000 ft. above Surface	Normal	2	100	150	77

* Reference (2)

TABLE 5-4. 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. 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, as noted in Section 5, the amount of time fewer than five satellites are in view has also been reduced. Figures 6-1 and 6-2 show that 5 or more satellites are in view at least 98% of the time. 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 fewer than four satellites are visible, or when the geometry results in high HDOP's, should be minimal. However, upon further investigation it turns out that a failure of a single satellite causes outage periods that can last as long as an hour. Shively [15] pointed this out earlier, using spare positions that had been planned prior to the recent decision.

Shively also pointed 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, 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%.

The computer analysis programs at TSC have been modified to output the DOP measures and the visible satellite count, using the new spare positions and allowing for failure of a specific satellite. In the analysis, each of the 21 satellites is faulted, and outage periods determined at a number of locations around the CONUS. Both 2-dimensional and 3-dimensional navigation algorithms were analyzed, for both 5 and 10 degree mask angles. It was found that the loss of any satellite will cause an outage somewhere in the CONUS. The outages can last up to 60 minutes.

In view of the sensitivity of GDOP to the loss of a satellite, and because of the relatively high likelihood of experiencing such a loss, the system does not appear to be adequate as a primary system for air navigation. Unlike the current VOR air navigation system, GPS does not have the capability of 100% redundancy for dealing with station faults. For most marine and land uses, the availability is adequate for all but the most stringent requirements. Also, GPS appears to be adequate as a secondary system for air navigation.

6.2 EFFECT OF SATELLITE FAILURES ON SERVICE OUTAGE PERIODS

When a satellite fails, there may be periods for some users when there are fewer than the minimum number of satellites necessary to compute a position. For example, about 2% of the time there are four satellites in view for the normal situation of 21 operating satellites and user mask angle of 10° (see Figure 6-1). This drops to 0.03% for a 5° mask angle (see Figure 6-2). If one of those four satellites suffers a failure, users attempting to obtain 3-dimensional position fixes would not be able to compute their positions. In essence, the GDOP is infinite. This is one condition for an outage.

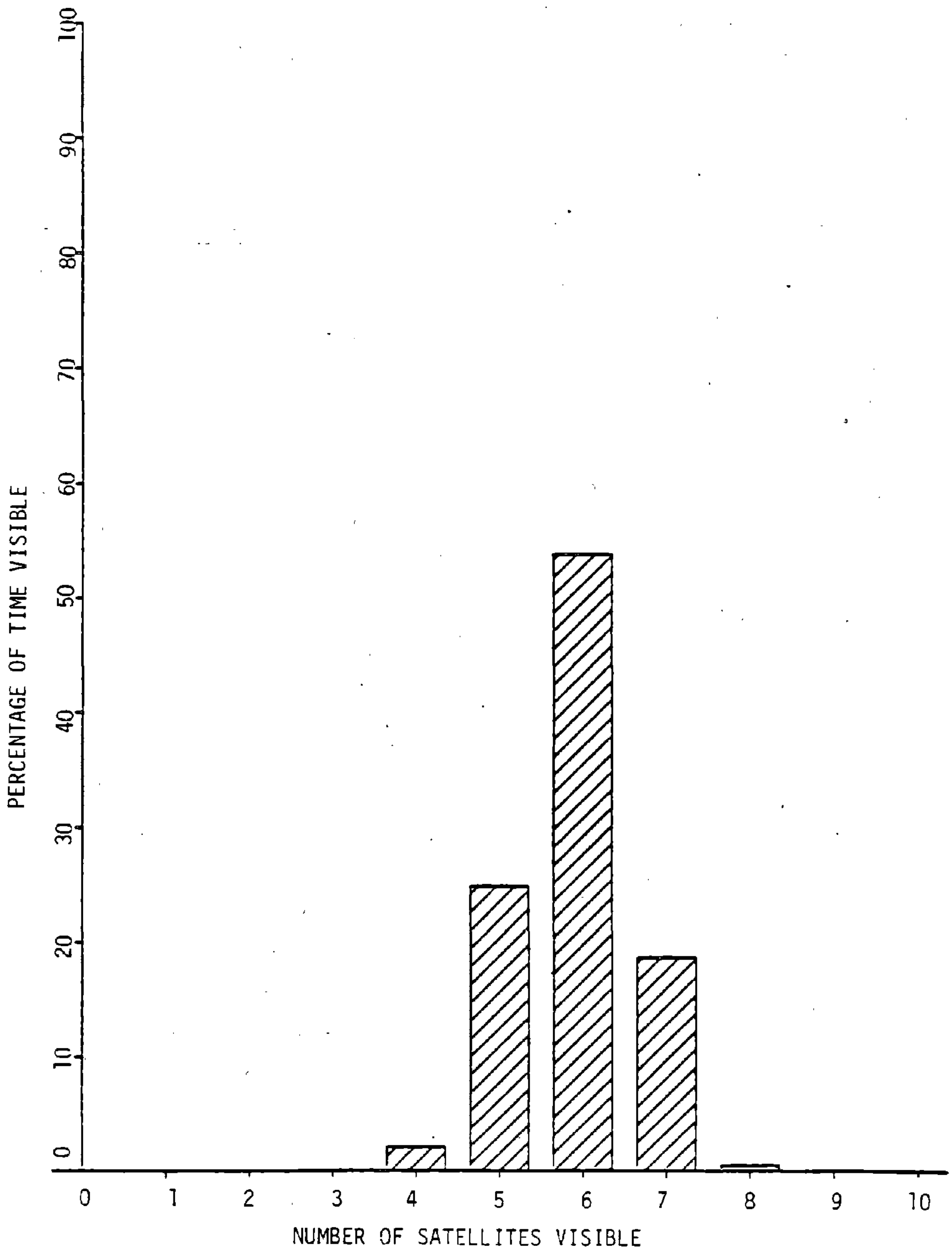

FIGURE 6-1. VISIBLE SATELLITE HISTOGRAM 10° MASK

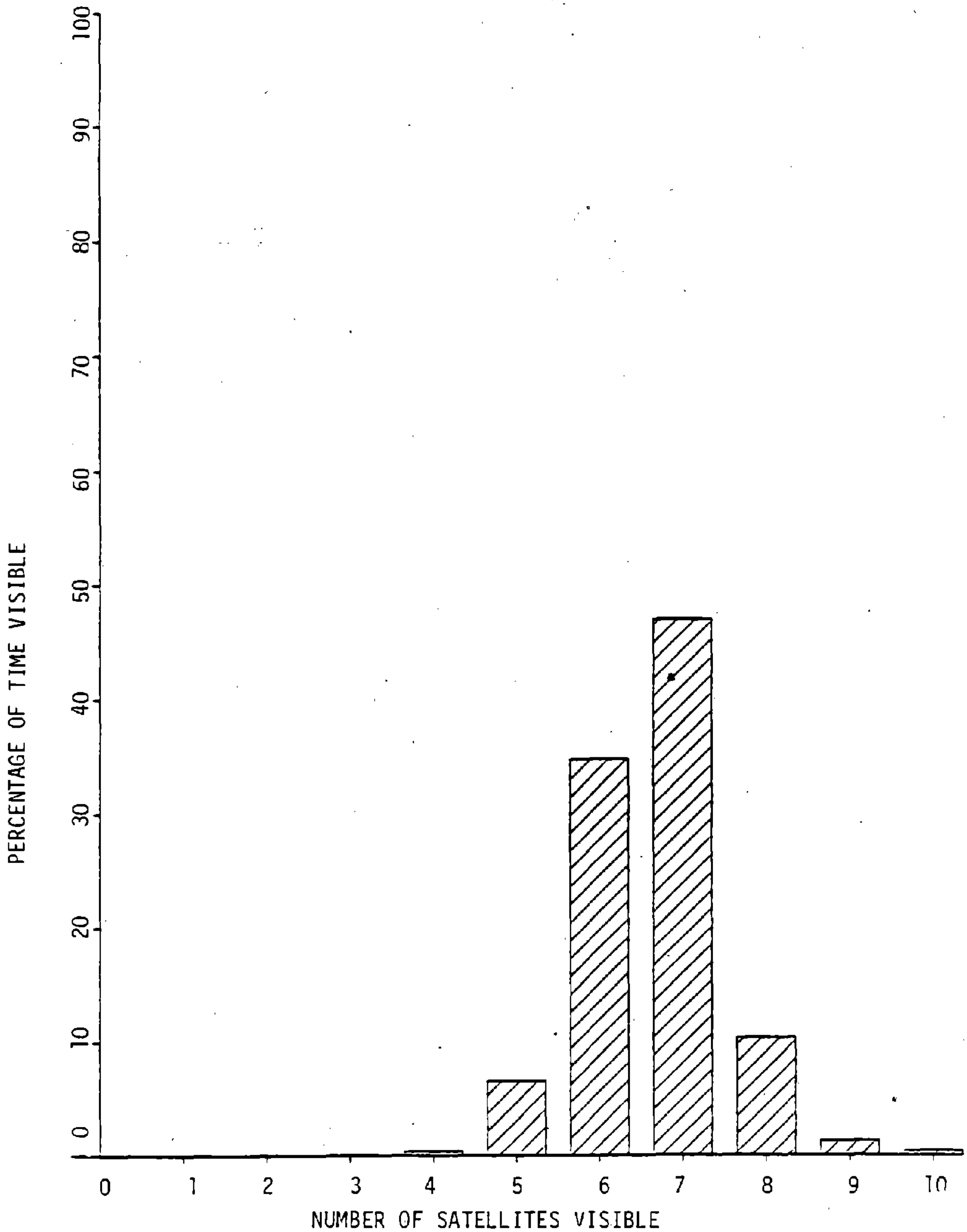

FIGURE 6-2. VISIBLE SATELLITE HISTOGRAM 5° MASK

Even if four satellites are visible for these users, they may be almost coplanar. This is the geometrical condition for the outages discussed in Section 5. For this condition, a 3-D user will experience high GDOP's. Similarly, when 3 satellites are visible, even a 2-D user can experience high HDOP's when the satellites are almost colinear.

For the purpose of this report, an outage is defined as the period during which the HDOP exceeds 6. The results are not sensitive to the number selected as the threshold value. The remainder of this section is devoted to describing the results of the analysis.

A grid was defined across the CONUS every 10 degrees in latitude and longitude. HDOP values were computed every 10 minutes for a 24-hour period at each location on the grid. Each time an HDOP value exceeded 6, a 10-minute outage time was ascribed to the location. The outages were analyzed to see if they were contiguous in time, in order to gain a measure of the maximum outage time at each location. Outage maps were generated which describe both the total outage period and the maximum outage time. These maps wee generated for each of the 21 satellites being faulted. In addition, a number of runs were made to determine the effects of different receiver mask angles, and for 2-D and 3-D navigation solutions.

Satellite failures are not uniform in their effects on CONUS outages. That is, some satellites cause more and longer outages than others. However, a failure of any satellite causes outages somewhere in the CONUS. The longest outages in the CONUS occur when satellite #2 fails (see Figure 5-1 for the satellite numbering system). Figures 6-3 through 6-5 show the total daily outage time for 3-D users with 10, 8 and 5 degree mask angles, respectively, caused by a failure of satellite #2. It can be seen that receivers employing lower mask angles are more forgiving of the satellite failure. The longest outage time for a 5 degree mask angle is only 20 minutes, while it is 60 minutes for a 10 degree mask angle. Figure 6-6 shows that the outages are nonexistent for 2-D unsers in the CONUS even for a 10 degree mask angle.

While the total outage time is significant, it is equally important to determine the length of the longest outage which a user would experience. Then the effectiveness of coasting techniques can be assessed. It also fixes the period of time that a user might be without coverage for a given mission. Figures 6-7 through 6-9 show these periods, which are termed "maximum contiguous outage times." It can be seen that these periods do not exceed 40 minutes for a 10 degree mask angle and 20 minutes for a 5 degree mask angle. These results apply for failures of other satellites as well.

The results so far have concentrated on the worst-case assumption of a failure of satellite #2. However, a failure of any satellite is equally likely. It would be desirable to determine outage times more representative of typical failures, not just those for satellite #2. In order to provide such data, outage times were computed at each grid position for a failure of each of the 21 satellites. The average outage time at each grid position was then computed. Figures 6-10 to 6-12 show the average outage times for 3-D receivers for mask angles of 10, 8 and 5 degrees. Comparison with corresponding Figures 6-3 to 6-5 shows that a failure of satellite #2 is considerably more serious than a failure of an average satellite in most locations.

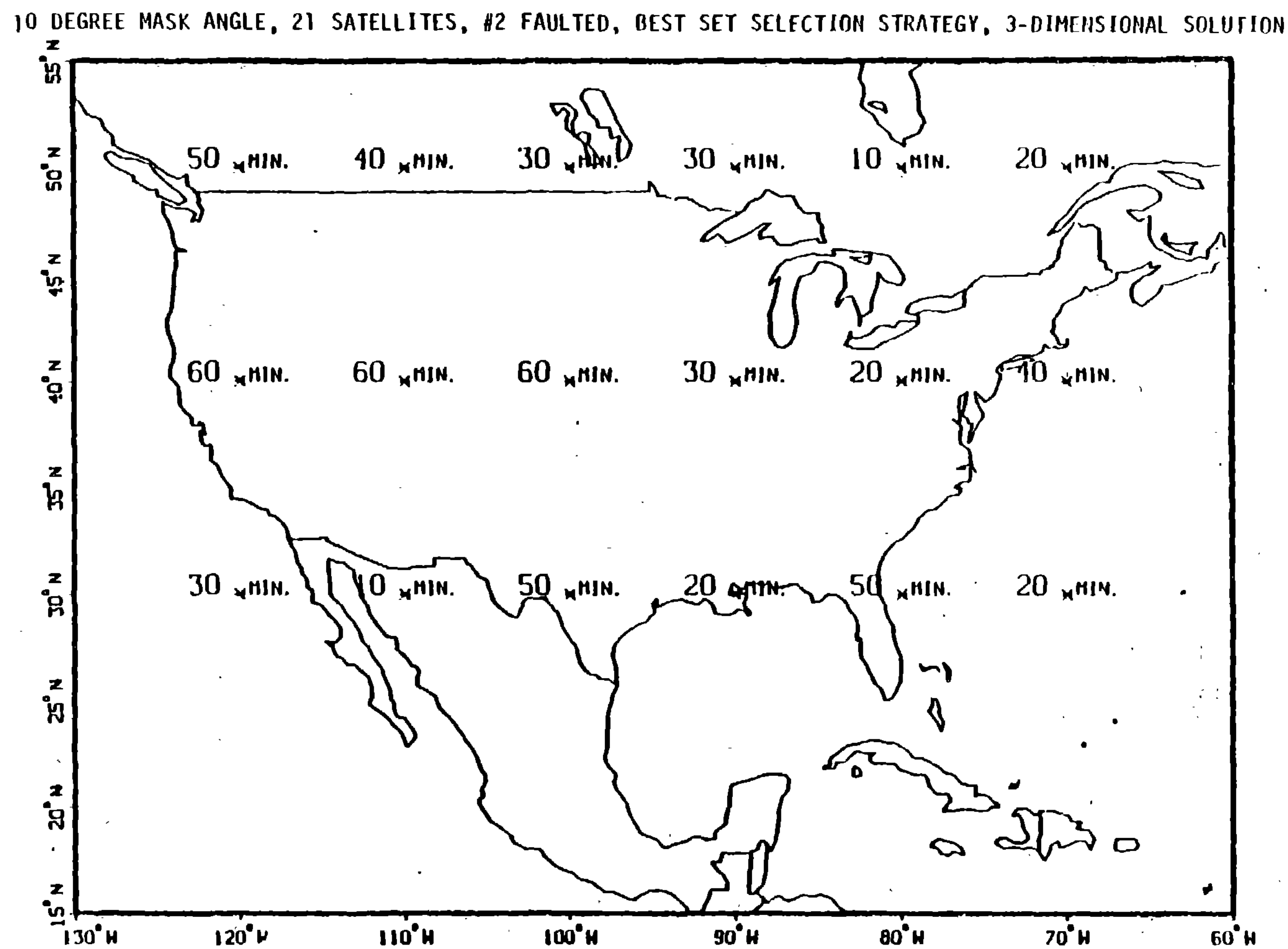

FIGURE 6-3. CUMULATIVE OUTAGE TIME, 10° MASK ANGLE, 3-D

8 DEGREE MASK ANGLE, 21 SATELLITES, #2 FAULTED, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

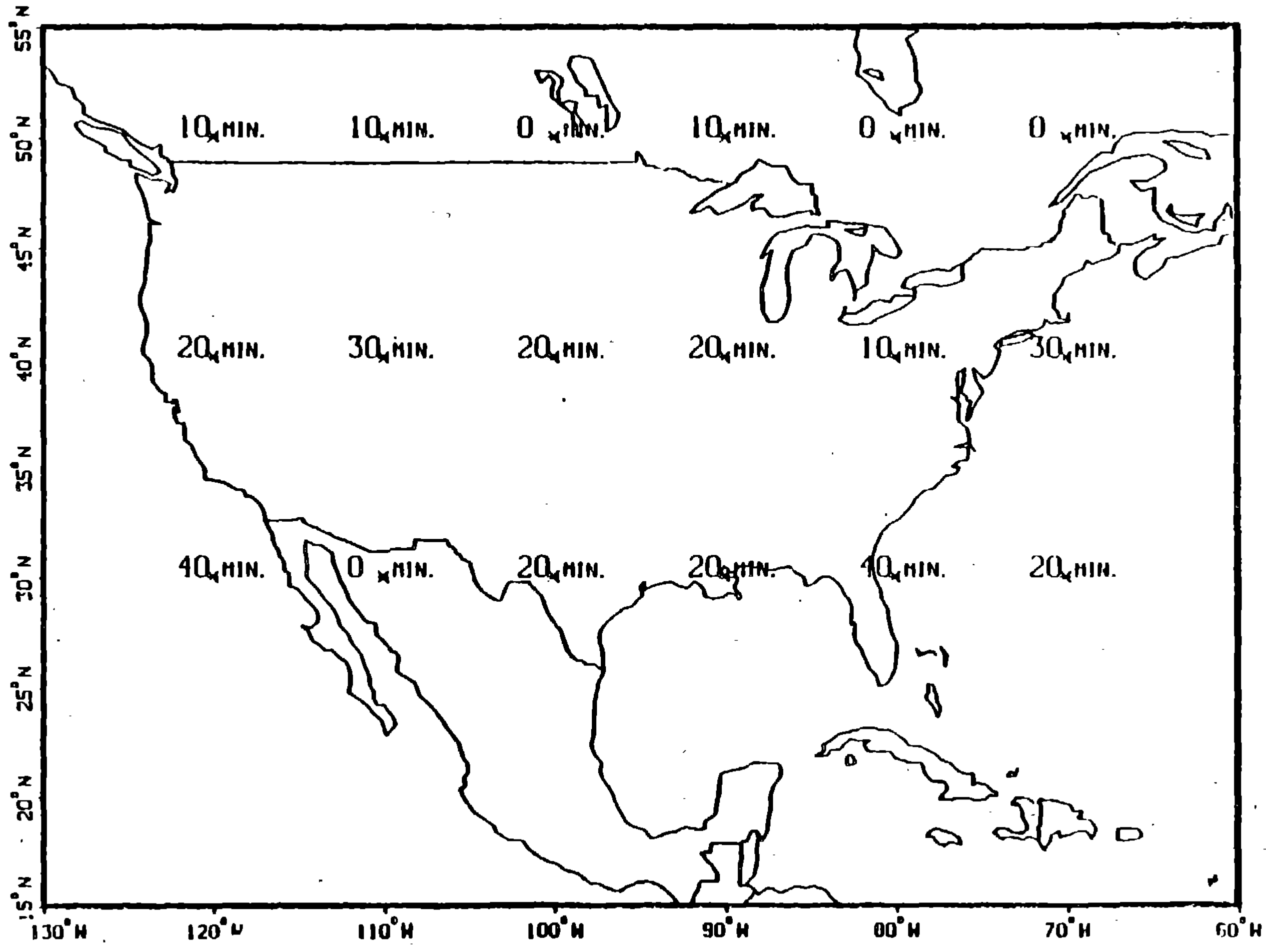

FIGURE 6-4. CUMULATIVE OUTAGE TIME, 8° MASK ANGLE, 3-D

5 DEGREE MASK ANGLE, 21 SATELLITES, #2 FAULTED, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

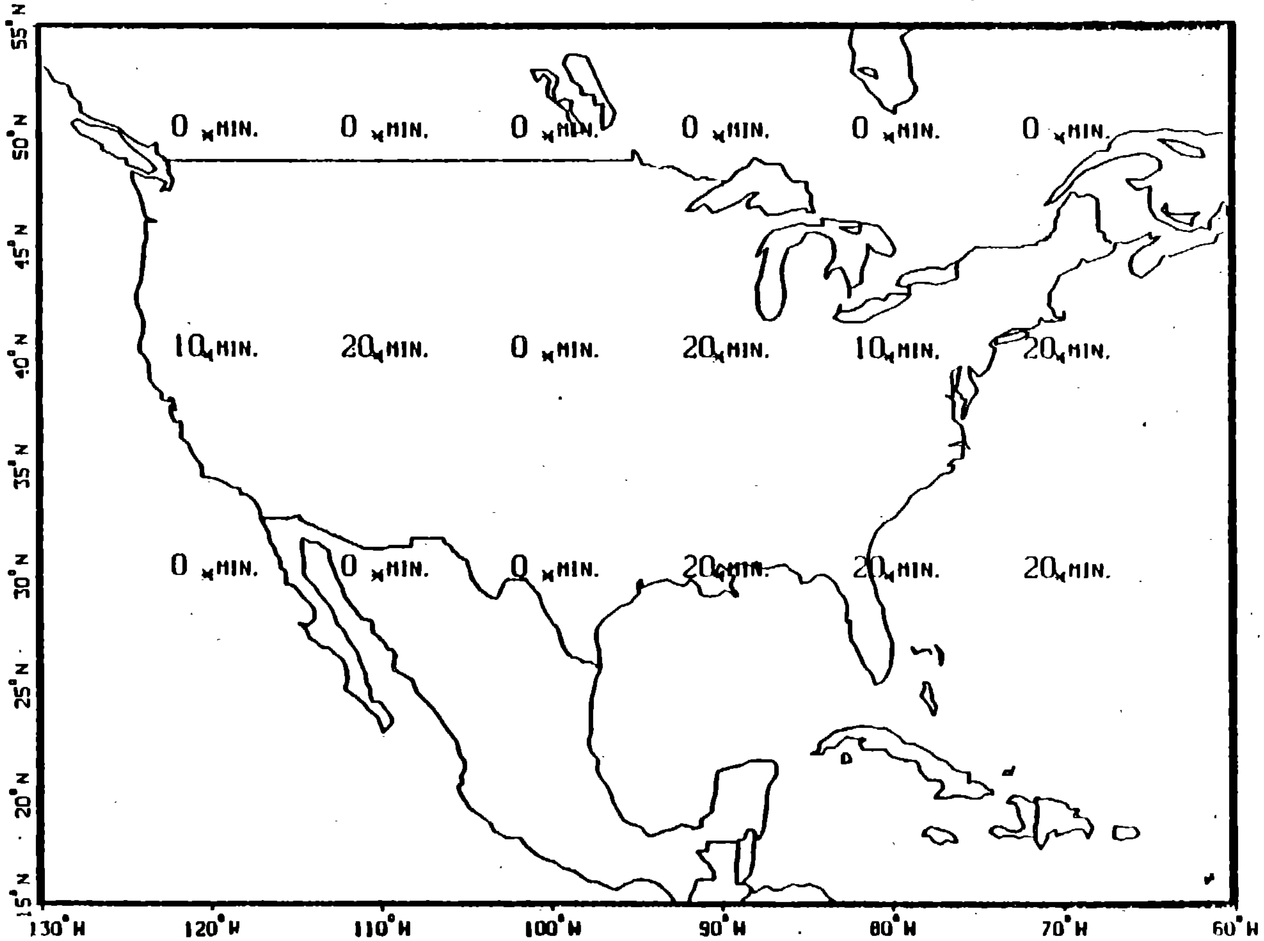

FIGURE 6-5. CUMULATIVE OUTAGE TIME, 5^{O} MASK ANGLE, 3-D

10 DEGREE MASK ANGLE, 21 SATELLITES, #2 FAULTED, BEST SET SELECTION STRATEGY, 2-DIMENSIONAL SOLUTION

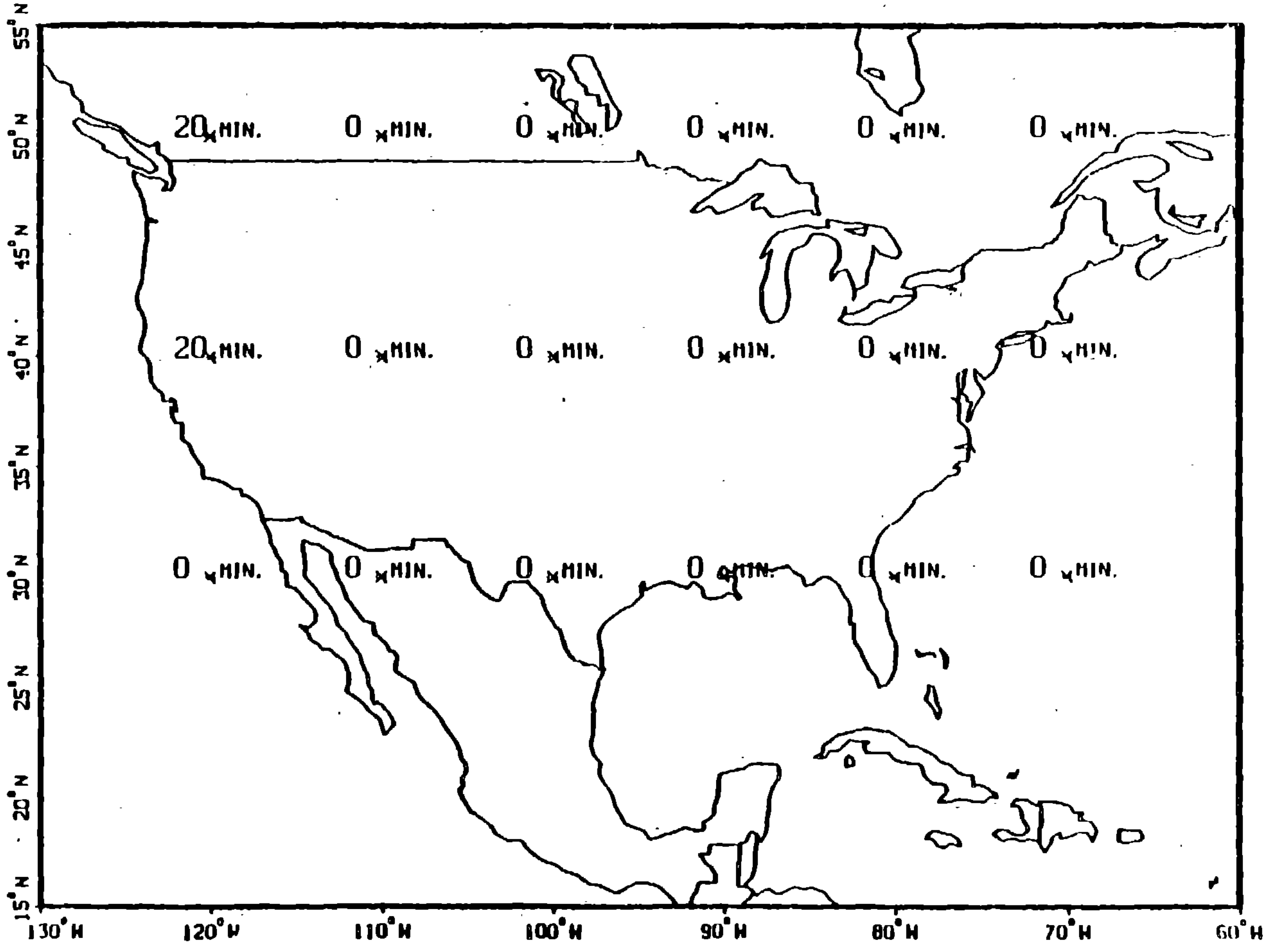

FIGURE 6-6. CUMULATIVE OUTAGE TIME, 10° MASK ANGLE, 2-D

10 DEGREE MASK ANGLE, 21 SATELLITES, #2 FAULTED, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

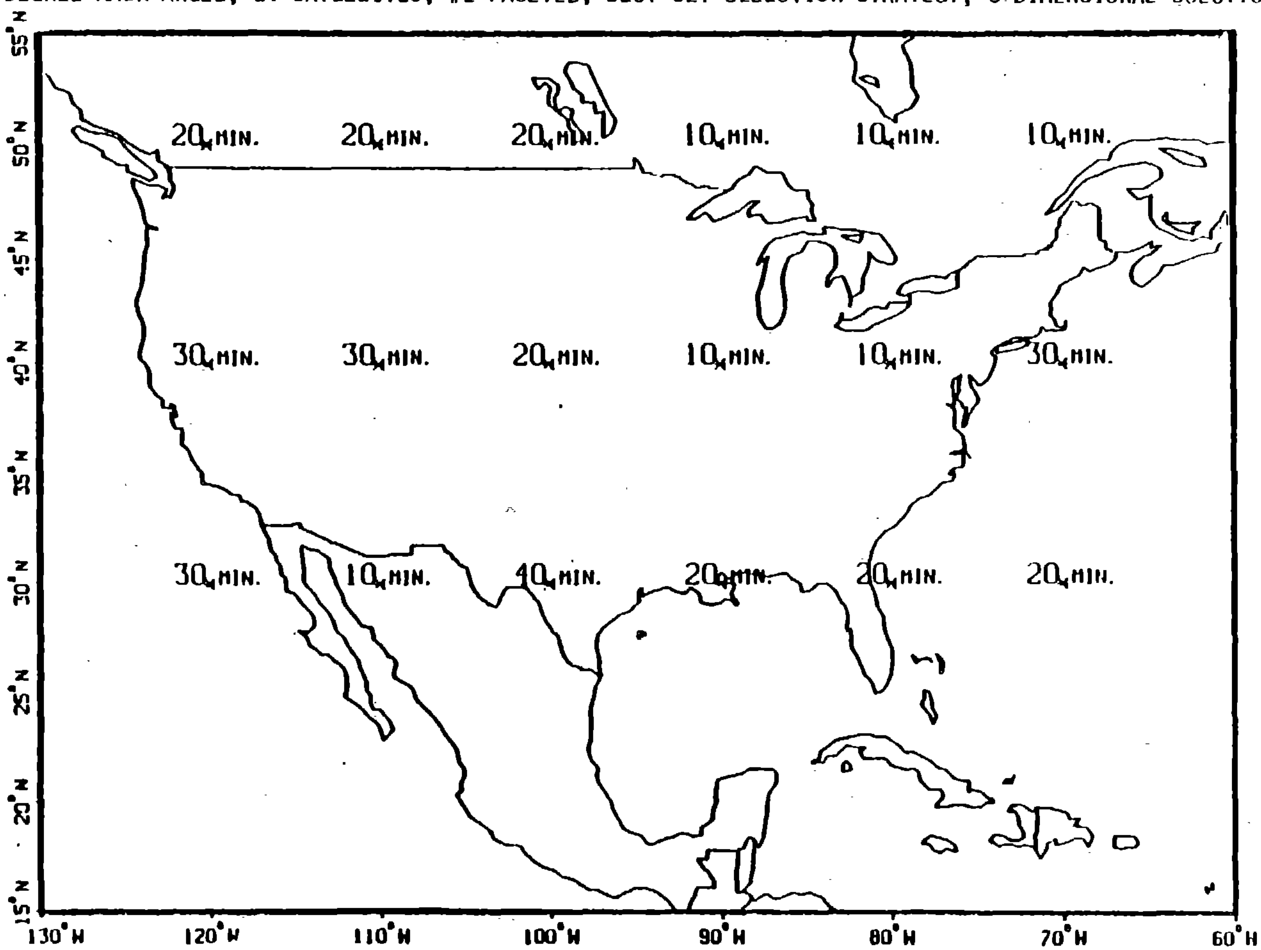

FIGURE 6-7. MAXIMUM CONTIGUOUS OUTAGE TIME, 10° MASK ANGLE, 3-D

8 DEGREE MASK ANGLE, 21 SATELLITES, #2 FAULTED, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

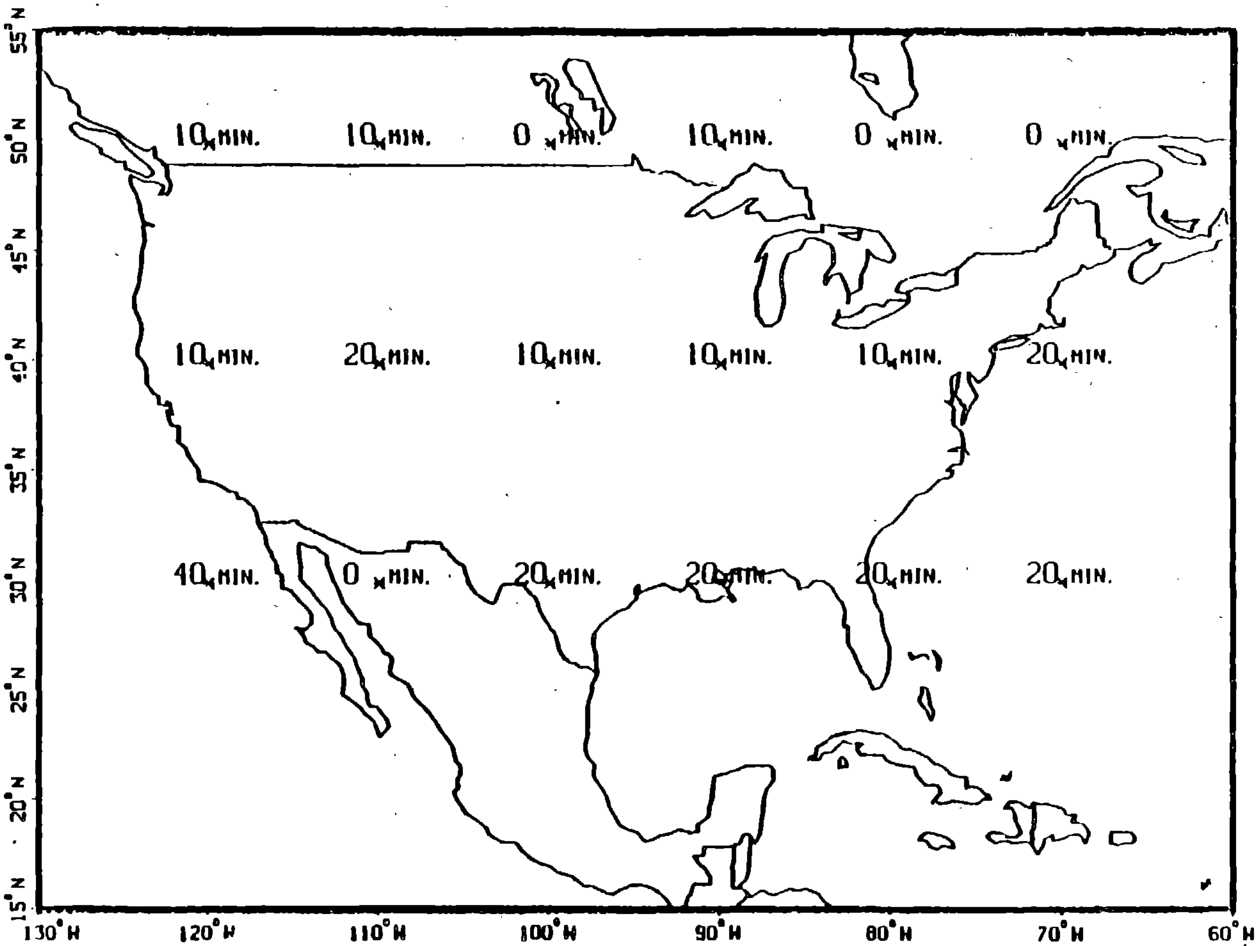

FIGURE 6-8. MAXIMUM CONTIGUOUS OUTAGE TIME, 8° MASK ANGLE, 3-D

5 DEGREE MASK ANGLE, 21 SATELLITES, #2 FAULTED, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

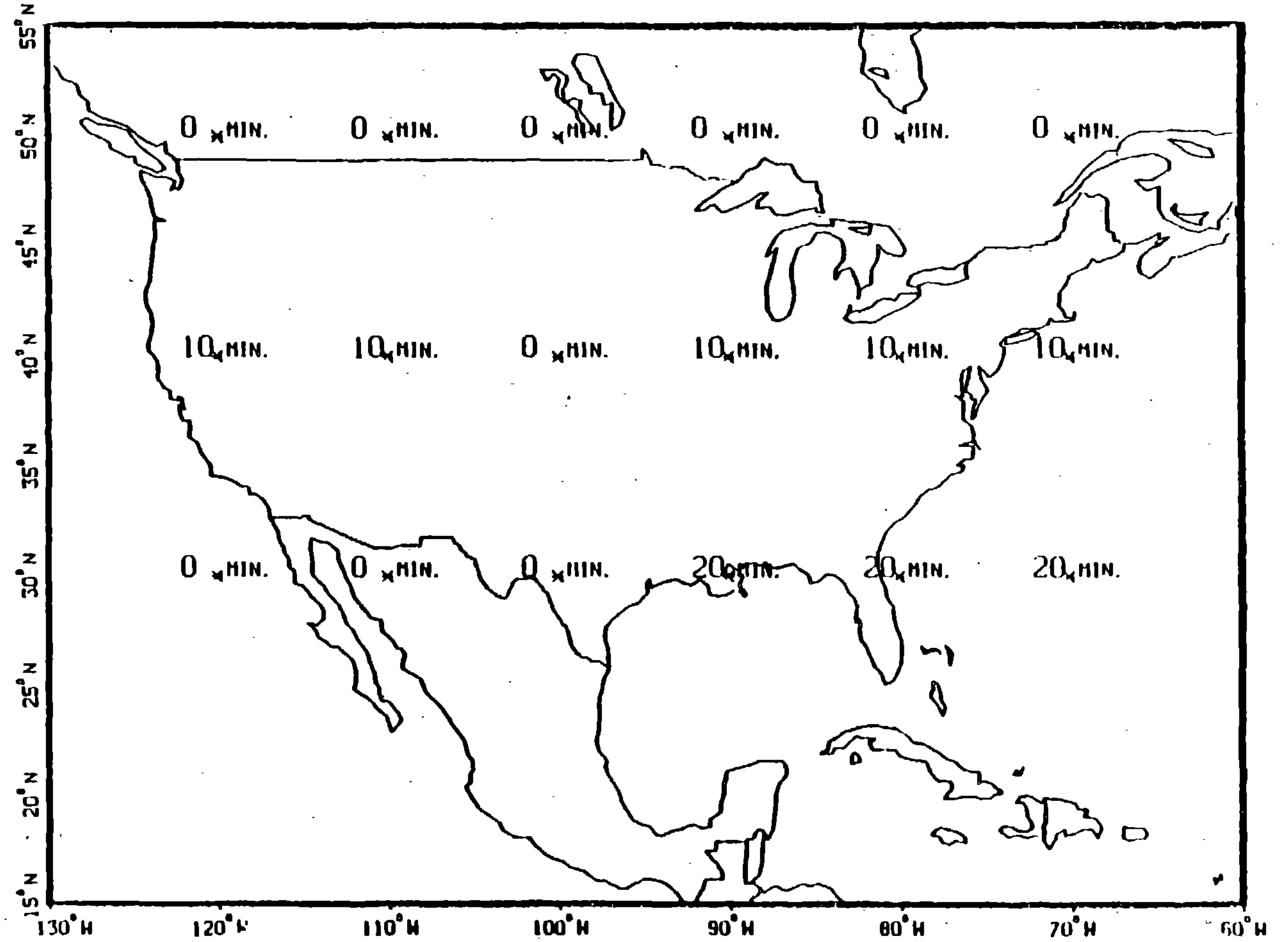

FIGURE 6-9. MAXIMUM CONTIGUOUS OUTAGE TIME, 5° MASK ANGLE, 3-D

10 DEGREE MASK ANGLE, 21 SATELLITES, SUM OF ALL FAULTS, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

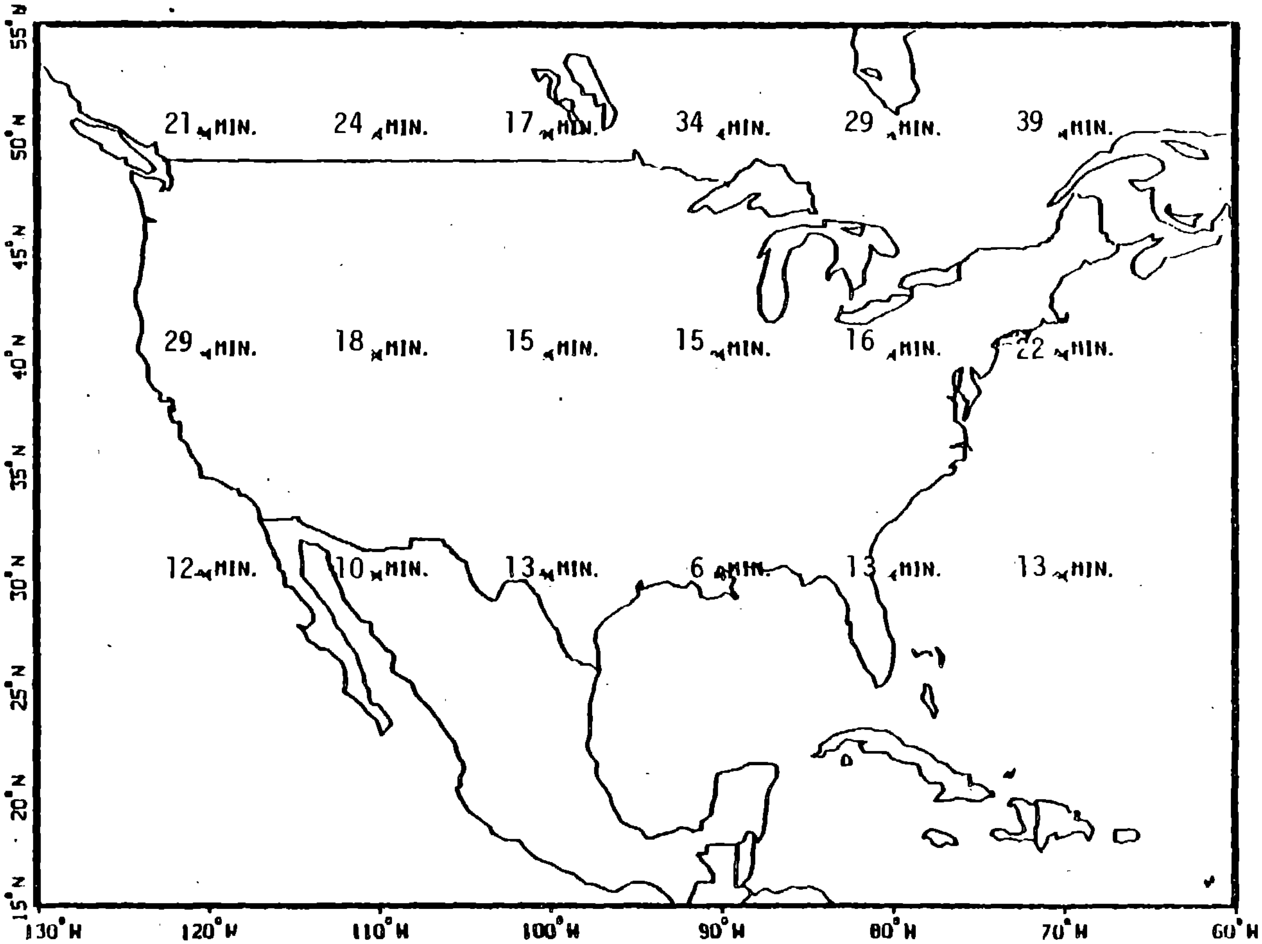

FIGURE 6-10. AVERAGE OUTAGE TIME, 10° MASK ANGLE, 3-D

8 DEGREE MASK ANGLE, 21 SATELLITES, SUM OF ALL FAULTS, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

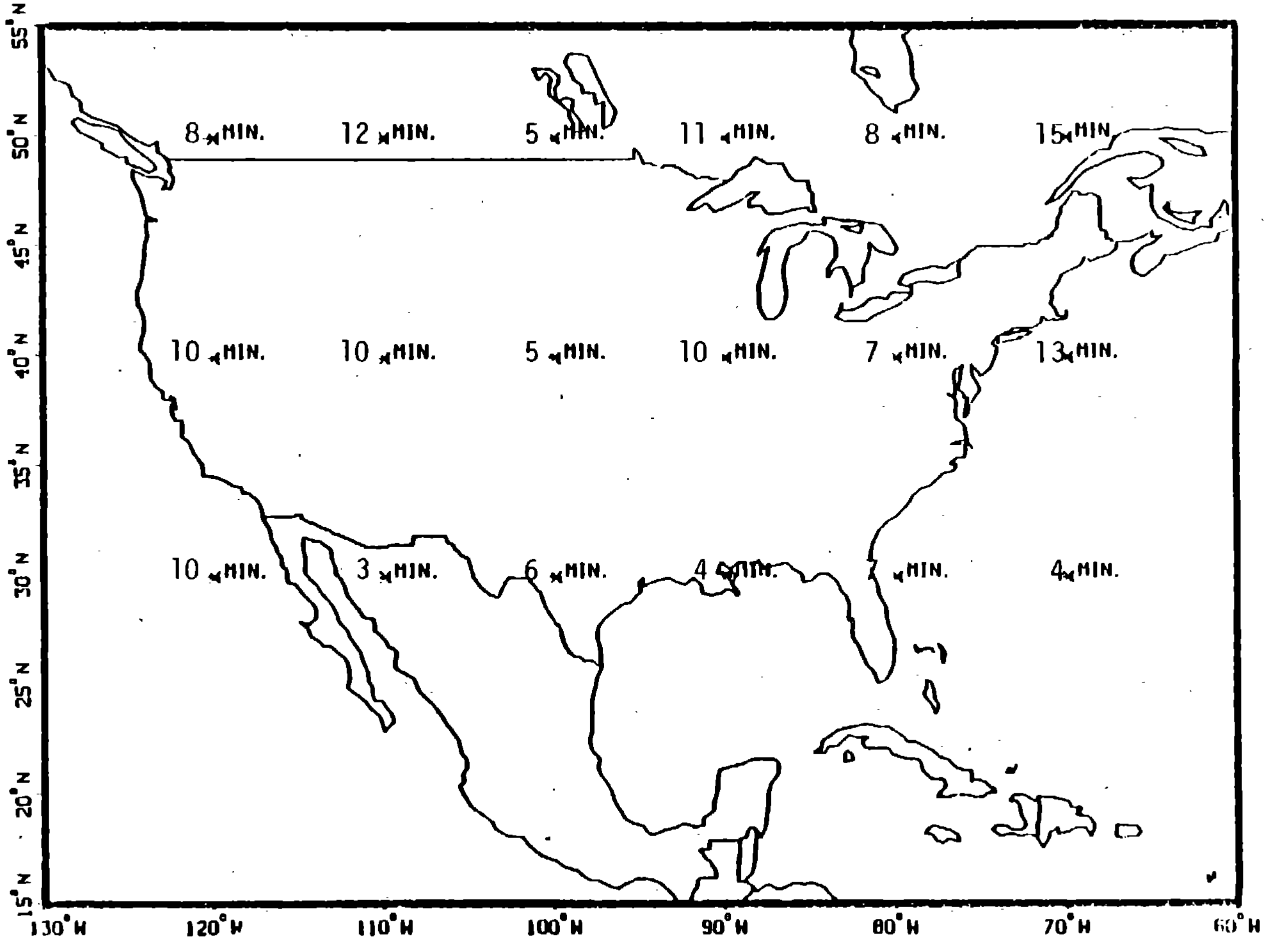

FIGURE 6-11. AVERAGE OUTAGE TIME, 8° MASK, 3-D

5 DEGREE MASK ANGLE, 21 SATELLITES, SUM OF ALL FAULTS, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

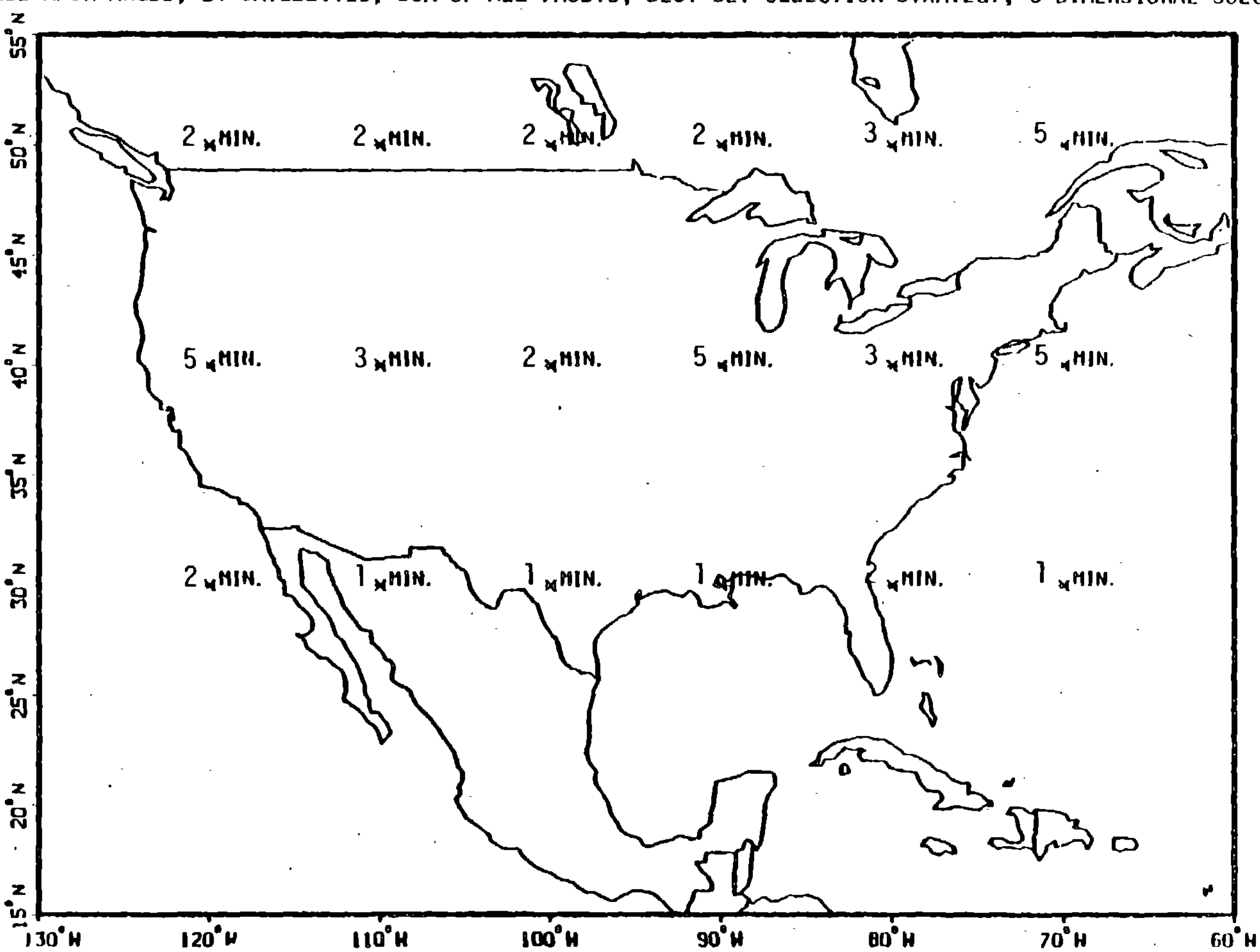

FIGURE 6-12. AVERAGE OUTAGE TIME, 5° MASK ANGLE, 3-D

The coarseness of the grid and the 10-minute time interval make it difficult to observe the patterns of outages. However, the cost of computation made five-grain analysis as contour plots prohibitively expensive. To show a local area in more detail, a grid of 2.5 degrees and 5 minutes was used for a few locations. A contour map of contiguous outage times for a local area having the longest outage time for #2 satellite failure is shown in Figure 6-13. At 30 degrees latitude, the area extends for 10 degrees latitude and 10 degrees longitude.

6.3 CONCLUSIONS

The failure of any satellite causes outages somewhere in the CONUS.

Different locations in the CONUS exhibit different sensitivities to satellite failures.

3-D users may encounter outages of up to 30 minutes from a single satellite failure.

2-D users may encounter outages of up to 20 minutes from a single satellite failure.

The failure condition may last for several days until a spare satellite can be put into covering position. For those orbital planes containing no spares, only partial covering can be provided until a new satellite can be launched and placed in orbit.

3-D users must provide clock or altimeter aiding to cope with 20- and 30-minute outages in case of satellite failure.

10 DEGREE MASK ANGLE, 21 SATELLITES, #2 FAULTED, BEST SET SELECTION STRATEGY, 3-DIMENSIONAL SOLUTION

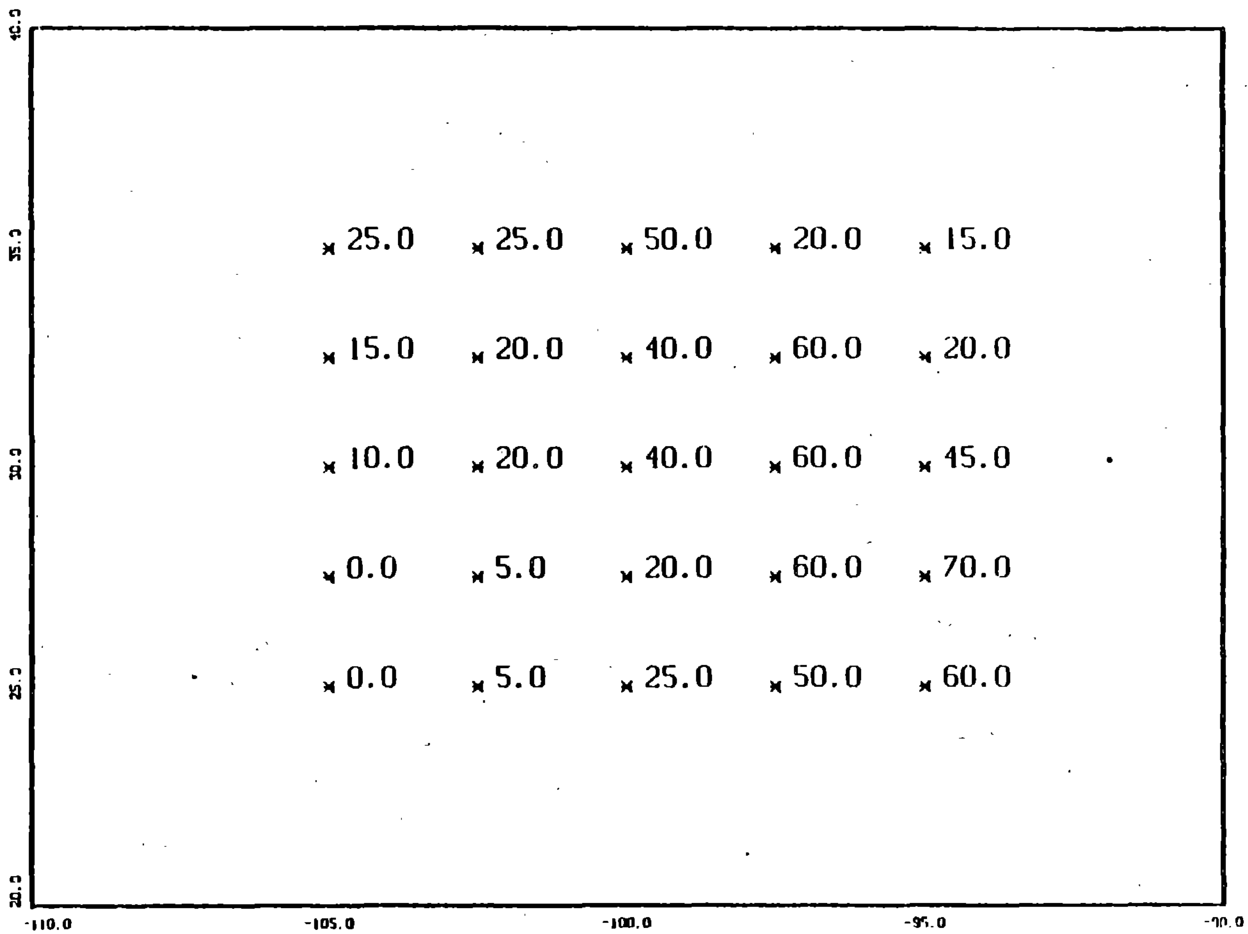

FIGURE 6-13. CONTIGUOUS OUTAGE TIMES, 10° MASK ANGLE, 3-D, CLOSELY SPACED LOCATIONS

7. 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 1988. This policy is stated in the Federal Radionavigation Plan[17]. PPS will be available to civil users only by special permission. Most users will have access to the SPS only. 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:

- Marine commercial fishing.
- Search and rescue operations
- Land survey and tracking requirements.

It is likely that Harbor/Harbor Approach navigation requirements could be met with differential operation, but this has not yet been definitely established. Commercial fishing and search and rescue operations require highly accurate repeatability of measurements, rather than high absolute (predictable) accuracy.

By comparison, LORAN-C currently meets all the Marine Ocean and Coastal navigation phase accuracy requirements where coverage is provided, which includes all of the CONUS coastline. Precise Harbor/Harbor Approach navigation is not feasible with LORAN-C without differential corrections. However, differential LORAN-C corrections are adequate only over limited regions.

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*The Office of the Secretary of Defense has recently announced a decision to provide service more accurate by a factor of 5. Thus the 500 meter nominal accuracy referred to in this section has been changed to 100 meters (2drms).

The attractive feature of differential GPS operation is that corrections are valid over large areas. A drawback is that signal characteristics of the NAVSTAR GPS satellite transmissions vary significantly with time. The ionosphere introduces a delay in the signal which changes diurnally. With Selective Availability imposed, the signal variations will be much faster, as well as much larger. Consequently GPS differential corrections must be transmitted much more frequently than differential LORAN-C would require. Differential operation is discussed at length in Section 8.

7.2 APPROACH

Selective Availability is a program for controlling the accuracy of pseudorange measurements. The user is in essence given a false location for each satellite, so that the resulting pseudorange measurement is in error by a controlled amount. The level is chosen to give navigation solutions that meet a specified accuracy under certain GDOP assumptions. While the actual time variations of the degraded signals to be employed are classified, some of the statistics of the signals are not. Through the NAVSTAR GPS Joint Program Office, the Department of Defense provided the Department of Transportation with unclassified segments of the Selective Availability cycling errors in order to enable the DOT to assess the 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 125 meters, and the HDOP were 2, the standard deviation of horizontal position error would be 250 meters, and the 2drms error would be 500 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, the marine receiver computer simulation MARINEGPS 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.

7.3 NAVIGATION ACCURACY UNDER SELECTIVE AVAILABILITY

GPS navigation accuracy under SA depends on several factors:

1. The level of SA employed.
2. The user mask angle.
3. The user satellite selection strategy.
4. The user navigational algorithm.
5. The user receiver accuracy.
6. The "coasting" characteristics of the user processor.

Of these, factors 1 through 4 are the most important: SA errors dominate, but are multiplied by the dilution-of-precision factor HDOP, which depends on factors 2 through 4. The user receiver accuracy, factor 5, is so good that it does not figure into the analysis, because SA factors predominate. Factor 6, the "coasting" characteristics of the processor, concerns the ability of the processor to handle temporary high-error states, i.e., to "coast" through them. For example, an unfavorable satellite geometry could cause a high HDOP for a few minutes. This factor is best treated by simulation, and is not addressed here.

Figure 7-1 shows the probability density and cumulative probability curves associated with SA delays, which dominate the satellite pseudorange error. The plots were derived from unclassified samples of the SA cycling errors, expressed as equivalent time delays. The data base consists of 90-second samples from four satellites, taken every hour for one week. Each 90-second segment of data is characterized by one value of pseudorange. Thus there are 24 x 7 x 4 = 672 samples in the sample set. The density function is roughly Gaussian in shape, and has a mean of 2.7 nanoseconds and a standard deviation of 485 nanoseconds. The 2-sigma value is about 975 nanoseconds. The standard deviation of the resulting pseudorange error is 145 meters.

To a first approximation the median HDOP can be used to estimate the navigational accuracy under Selective Availability by the following equation:

$$E(2drms) = 2 \times HDOP\,(median) \times \sigma\ (pseudorange)$$

where the units are meters, and σ(pseudorange) is taken to be 145 meters. Table 7-1 shows the resulting accuracies in meters and in nautical miles. This approximation is valid to the extent that the HDOP distribution is linear. An examination of Figure 7-2 shows that the assumption is quite reasonable for the two-dimensional solution. For the constellation considered here, the 3-dimensional solution distribution becomes non-linear beyond the 95% level (see Figure 7-3). This means that the accuracy figures of Table 7-1 are slightly understated for the three-dimensional solution. The accuracy figures of Table 7-1 are believed to be a good predictor of NAVSTAR GPS performance under the 500 meter level of Selective Availability. At the newly announced 100 meter level, these numbers would be smaller by a factor of 5.

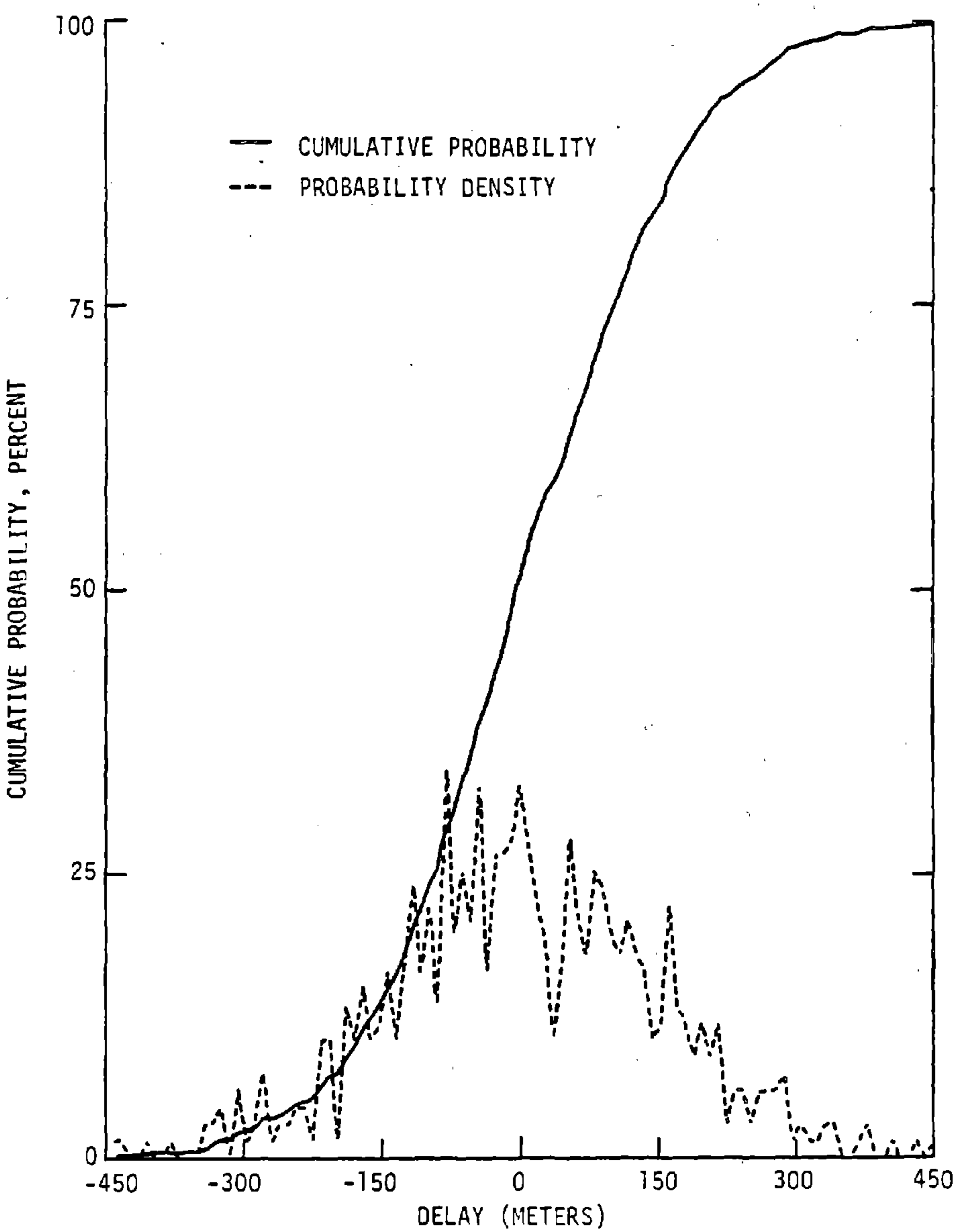


FIGURE 7-1. SELECTIVE AVAILABILITY PROBABILITY DISTRIBUTION FOR 500 METER SPS

TABLE 7-1. ACHIEVABLE ACCURACIES UNDER 500 METER (2DRMS) SELECTIVE AVAILABILITY

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

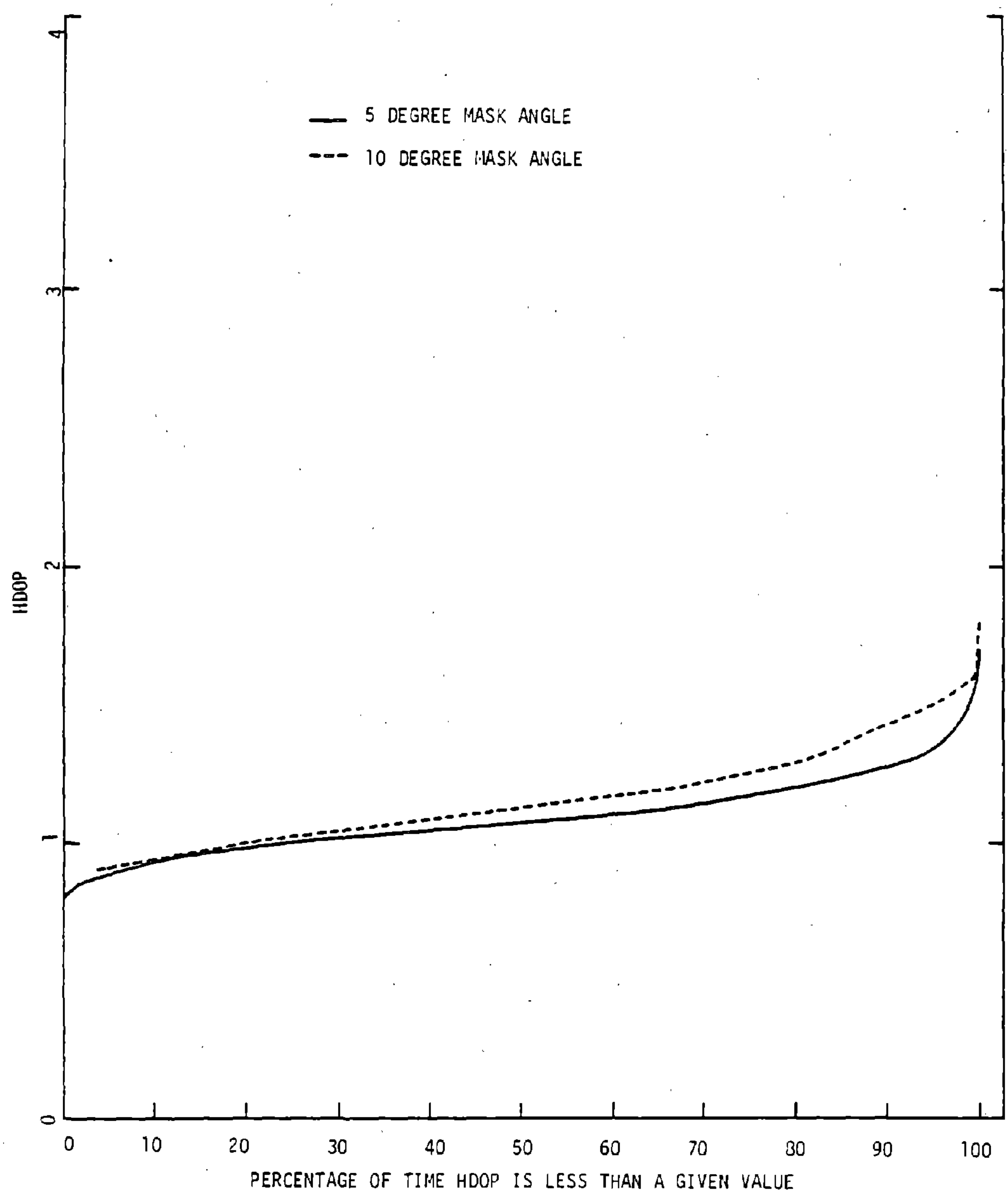


FIGURE 7-2. HDOP DISTRIBUTION, 2-DIMENSIONAL SOLUTION, ALL-IN-VIEW STRATEGY

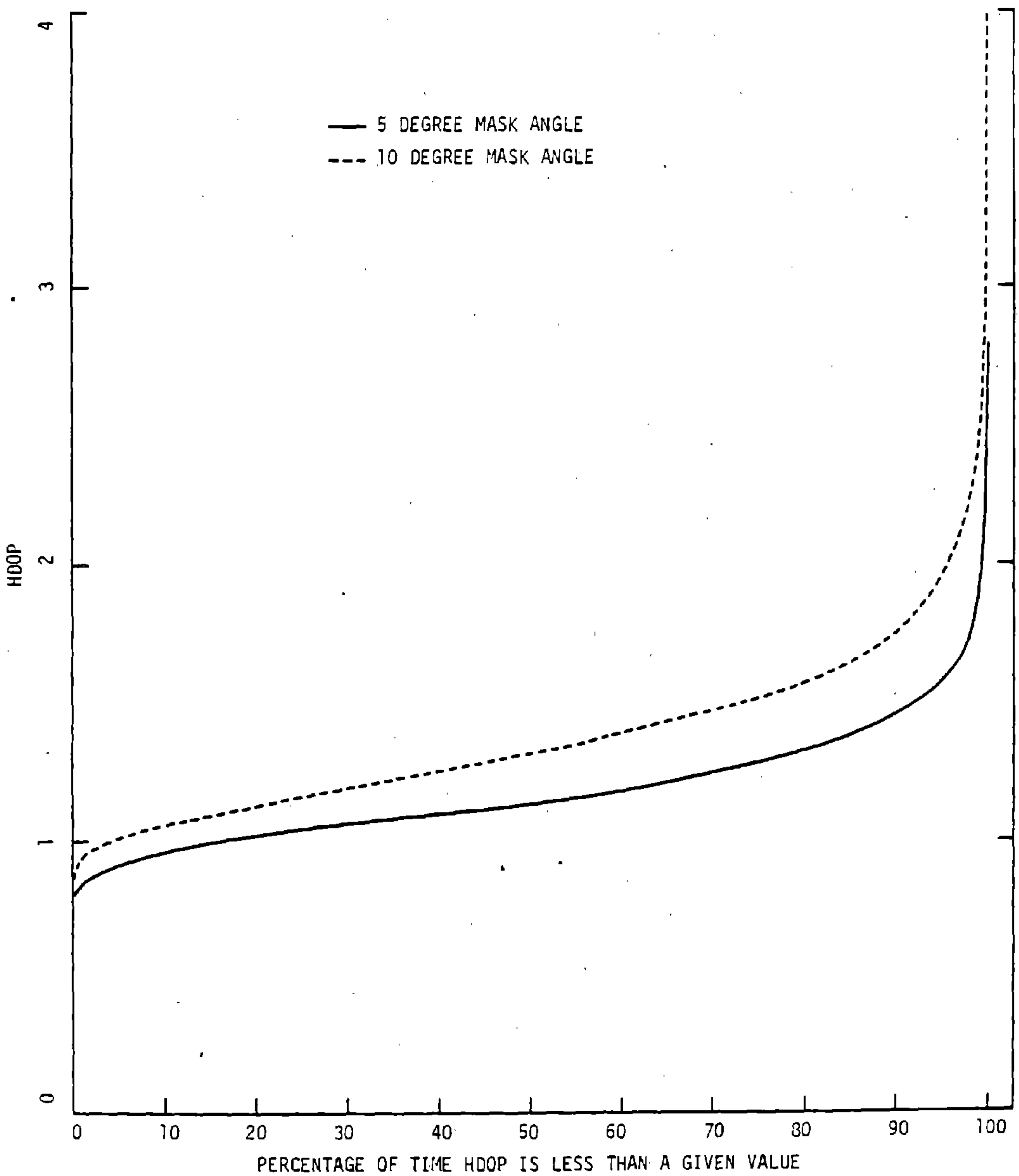


FIGURE 7-3. HDOP DISTRIBUTION, 3-DIMENSIONAL SOLUTION, ALL-IN-VIEW STRATEGY

To demonstrate the manner in which a GPS receiver/processor responds to a signal with Selective Availability, some runs were made using the MARINEGPS computer simulation at TSC. The simulation was exercised using the following conditions:

a. Best-set-of-four, four-parameter solution

b. Six-state Kalman filter (horizontal position and velocity, user clock frequency and phase)

c. Selective Availability capability

d. Sequential operation

e. Nominal satellite transmitter power

f. Antenna pattern rolloff of about 0.5 db per degree below 15°

g. A straight-line trajectory of 45 seconds, followed by a 90 degree right turn; speed is 20 knots.

h. Initial conditions of position and velocity set to actual trajectory values.

Figures 7-4 to 7-8 show the resulting estimated and actual tracks for different SA values characteristic of a 500 meter SA level. The processor is initially given the true coordinates of the vessel. Subsequently the estimated position is determined by the measurements. The navigation solution smoothly tracks the signals, which vary relatively little during the 90-second run, but the solutions are significantly offset from the true track. The effect of the initial transient is apparent: the tracker downgrades the initial measurements, because the tracker was told not to expect such large errors. The response is sluggish until the errors have become small. It can be seen that over periods of minutes, the SA errors appear as large bias-like offsets.

7.4 IMPACT OF SELECTIVE AVAILABILITY ON RECEIVER CODE AND CARRIER LOOP PERFORMANCE

As a measure of the abruptness of the changes in the equivalent Selective Availability time delay errors, each 90-second segment was characterized by a slope value, measured in nanoseconds per second, which corresponds approximately to feet per second (1 foot = 1.017 nanoseconds (ns) at the speed of light). The distribution curve derived from these values is shown in Figure 7-9. It can be seen that most values fall between $\pm$1.2 ns/sec ($\pm$0.37 m/sec).*. The receiver code loop circuits are designed to handle the Doppler shifts that are encountered with rising and setting satellites. These can result in delay rates as large as 2500 ns/sec ($\pm$0.37 m/sec) three orders of magnitude more severe. Thus the rate of change of Selective Availability errors is not a problem for the receiver code loop circuit.

*The first and second derivative of the SA time delay errors are not affected by the recent decision to reduce the SPS errors.

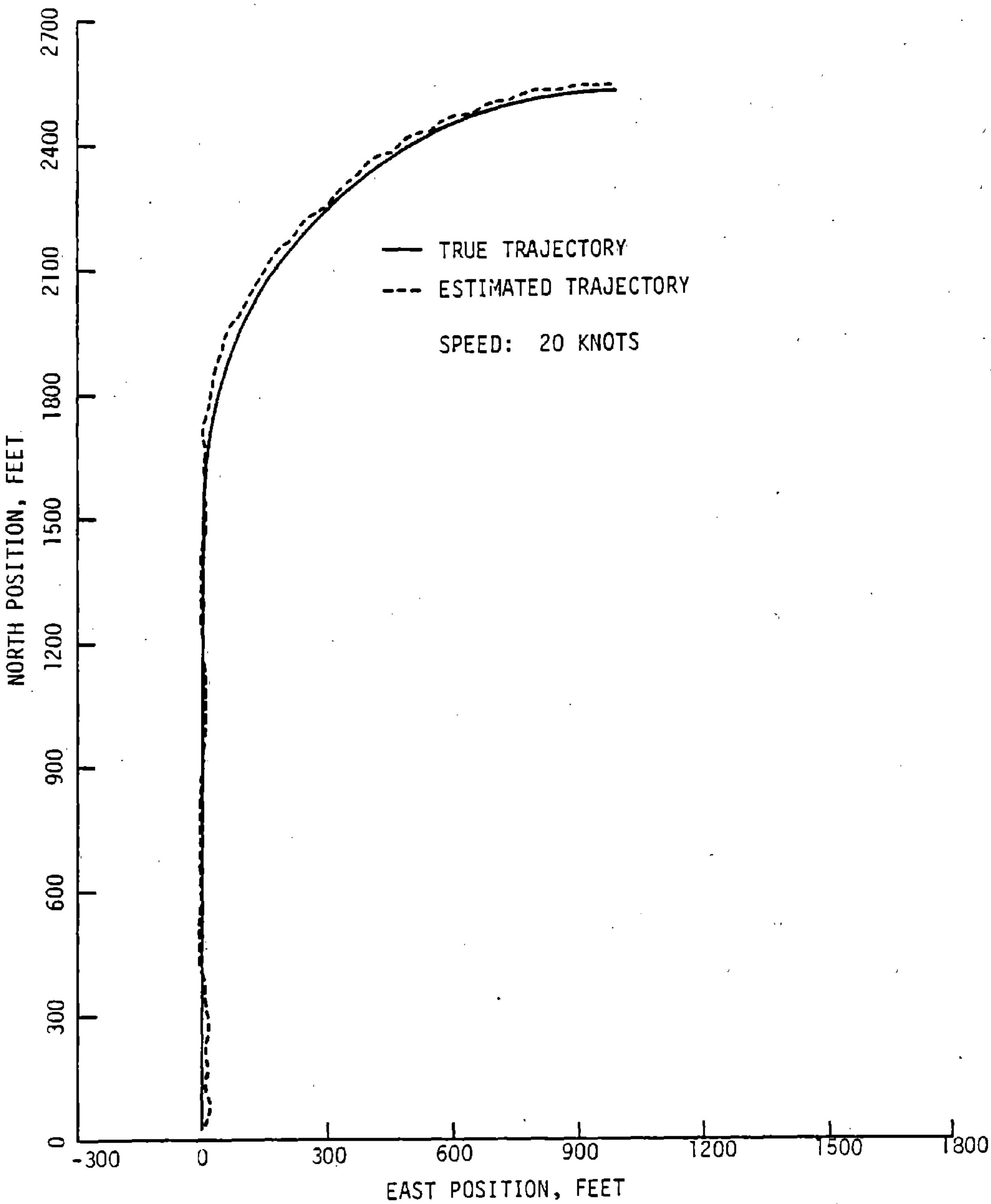
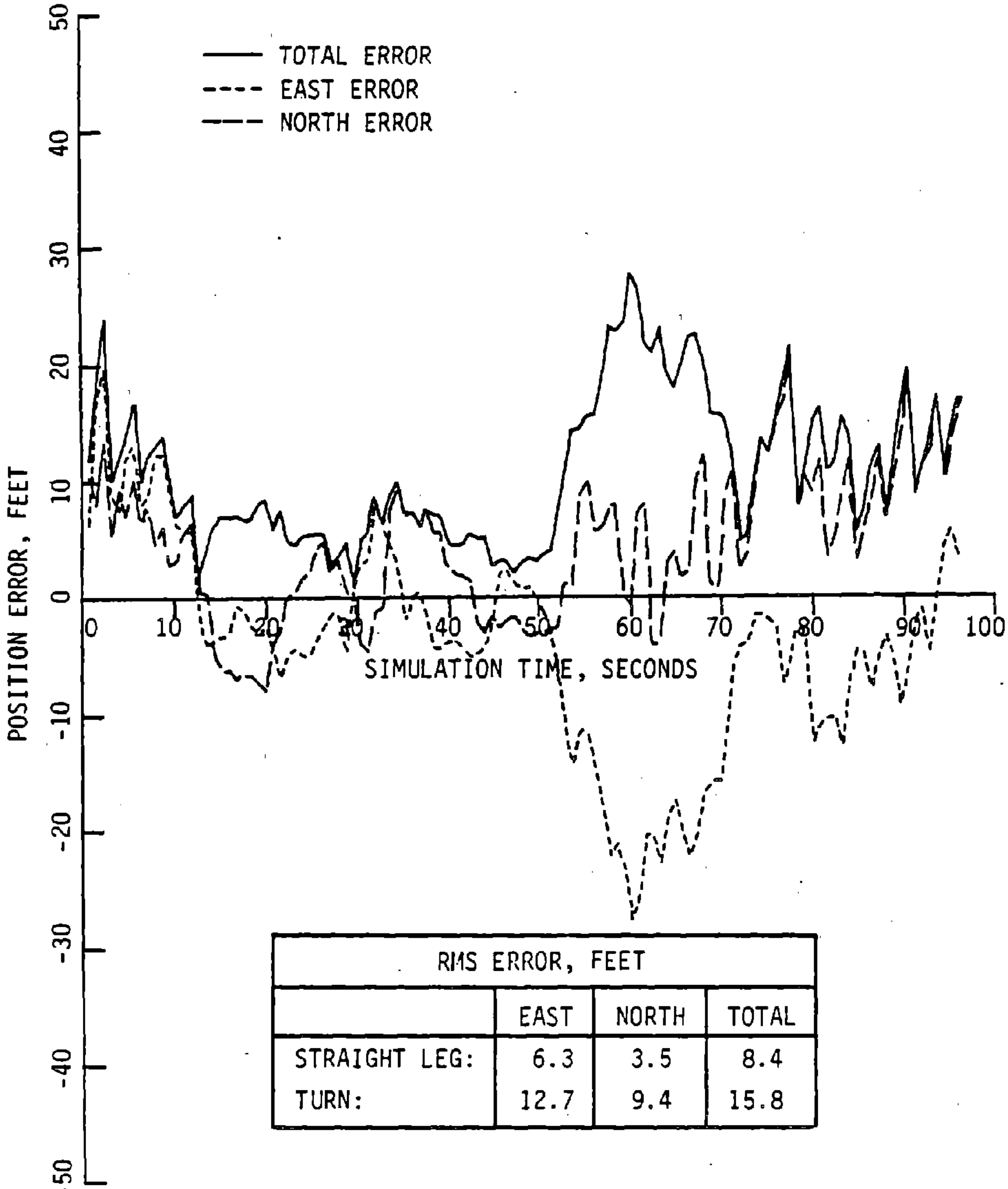


FIGURE 7-4A. ESTIMATED AND ACTUAL TRAJECTORY, NO SELECTIVE AVAILABILITY



RMS ERROR, FEET			
	EAST	NORTH	TOTAL
STRAIGHT LEG:	6.3	3.5	8.4
TURN:	12.7	9.4	15.8

FIGURE 7-4B. ERRORS, NO SELECTIVE AVAILABILITY

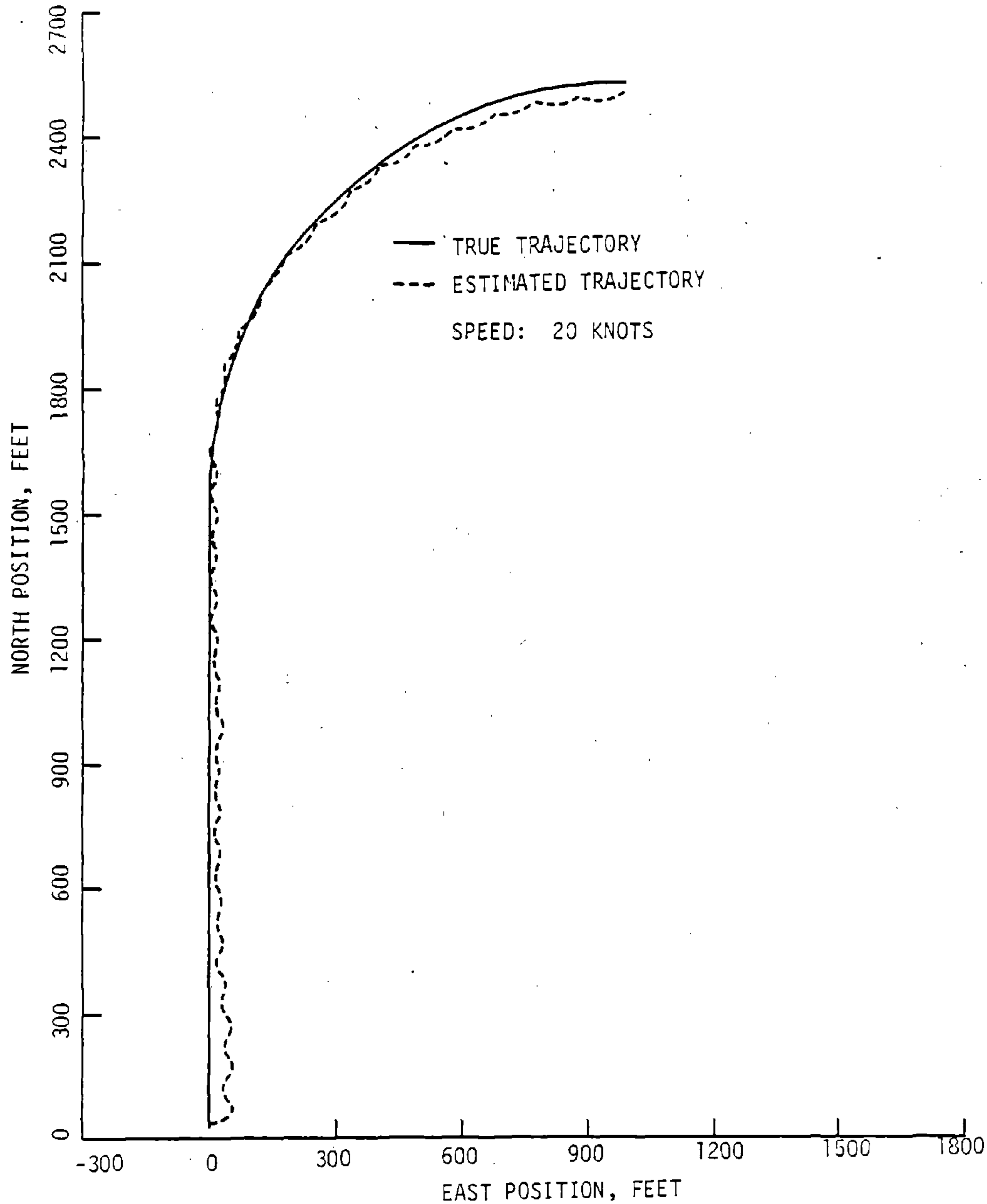
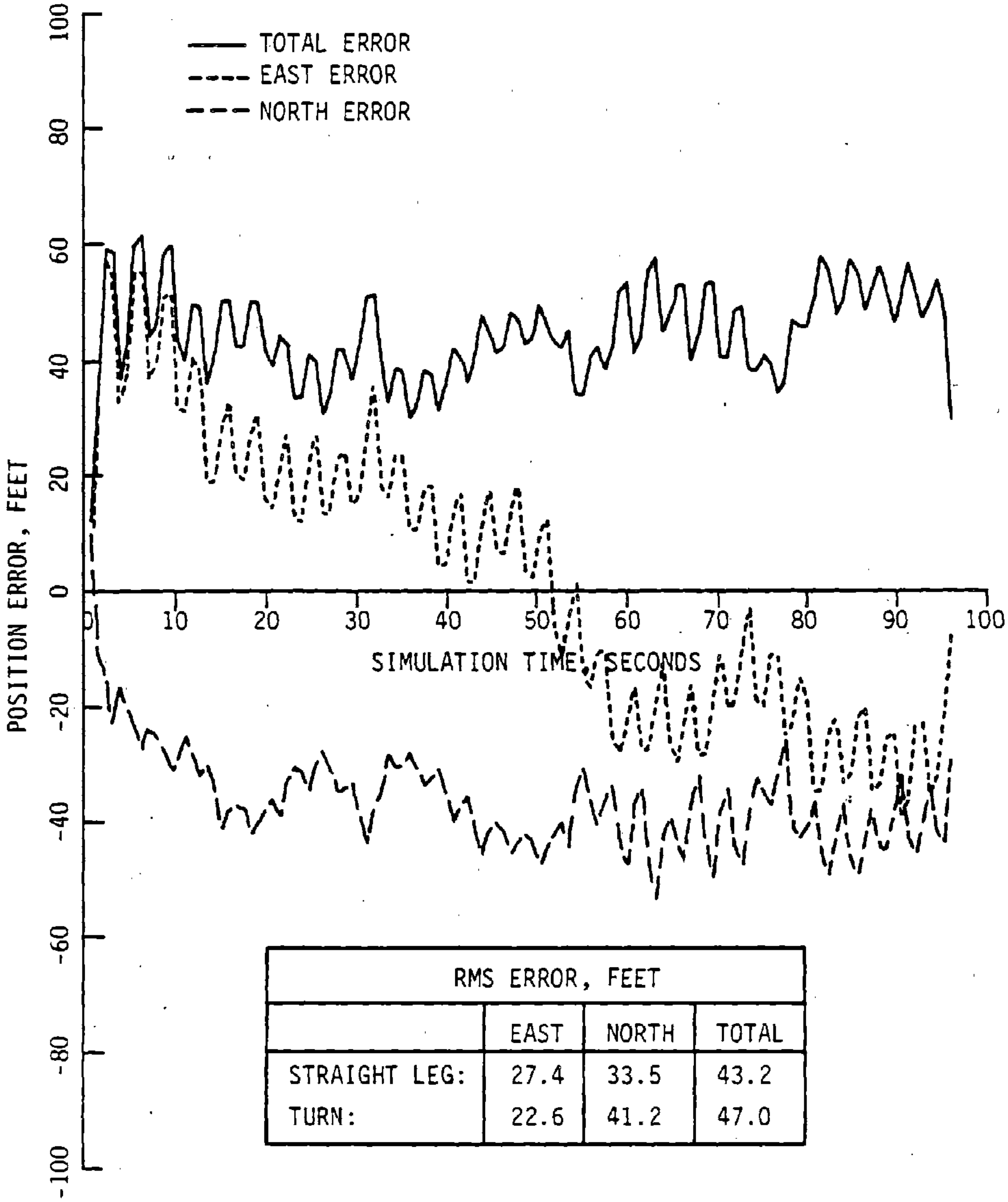


FIGURE 7-5A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 1



RMS ERROR, FEET			
	EAST	NORTH	TOTAL
STRAIGHT LEG:	27.4	33.5	43.2
TURN:	22.6	41.2	47.0

FIGURE 7-5B. ERRORS, SELECTIVE AVAILABILITY SAMPLE NO. 1.

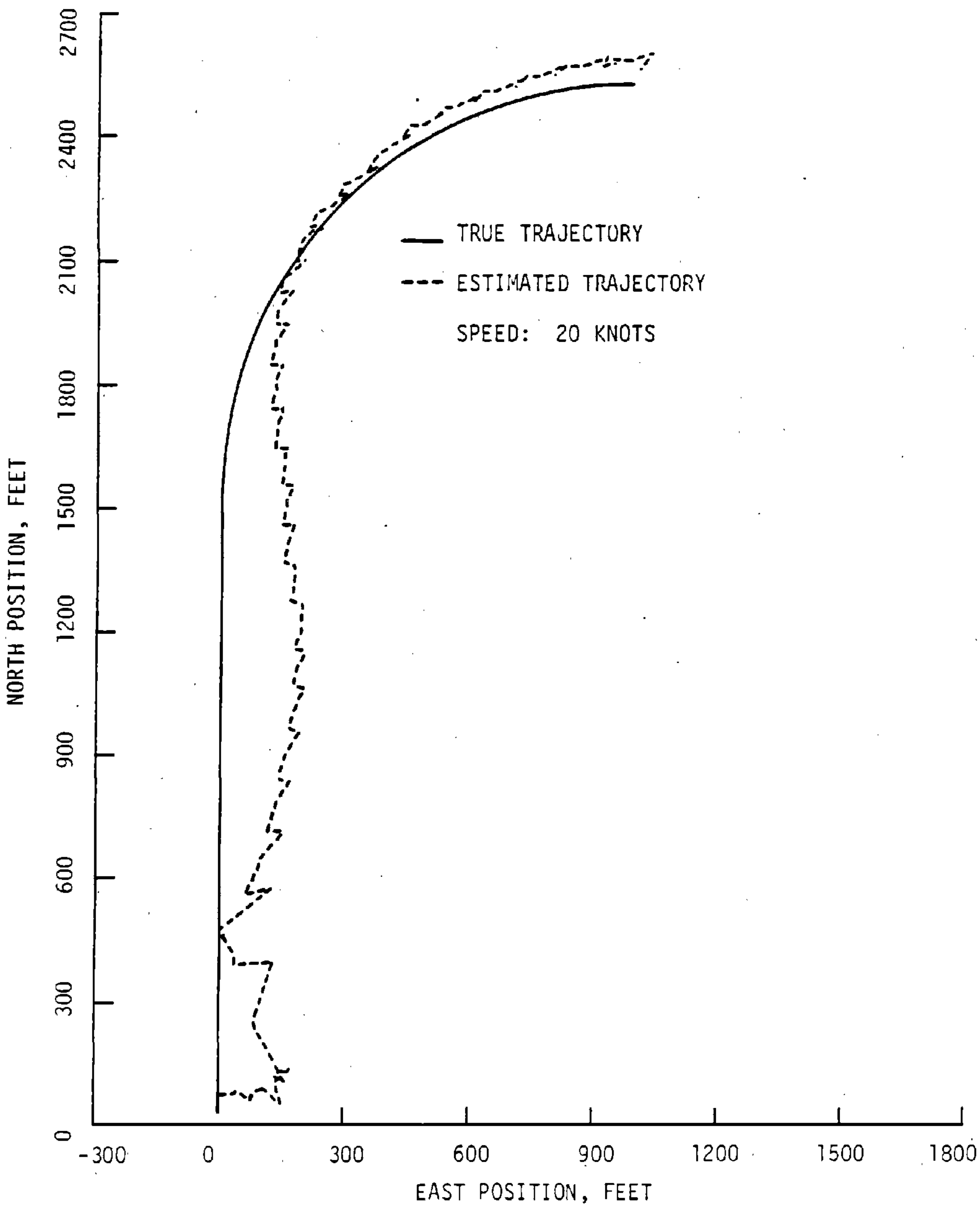
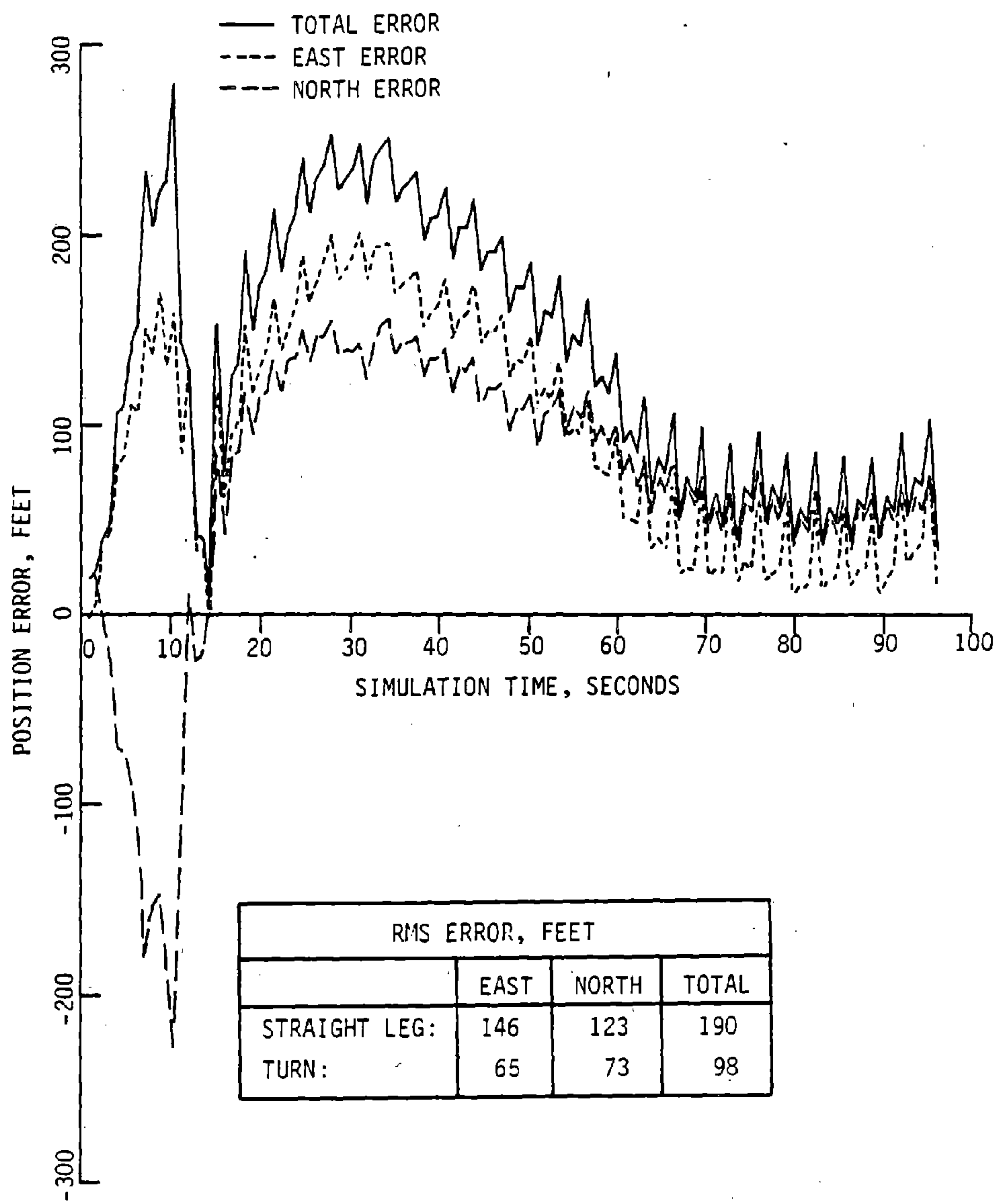


FIGURE 7-6A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 2.



RMS ERROR, FEET			
	EAST	NORTH	TOTAL
STRAIGHT LEG:	146	123	190
TURN:	65	73	98

FIGURE 7-6B. ERRORS, SELECTIVE AVAILABILITY SAMPLE NO. 2.

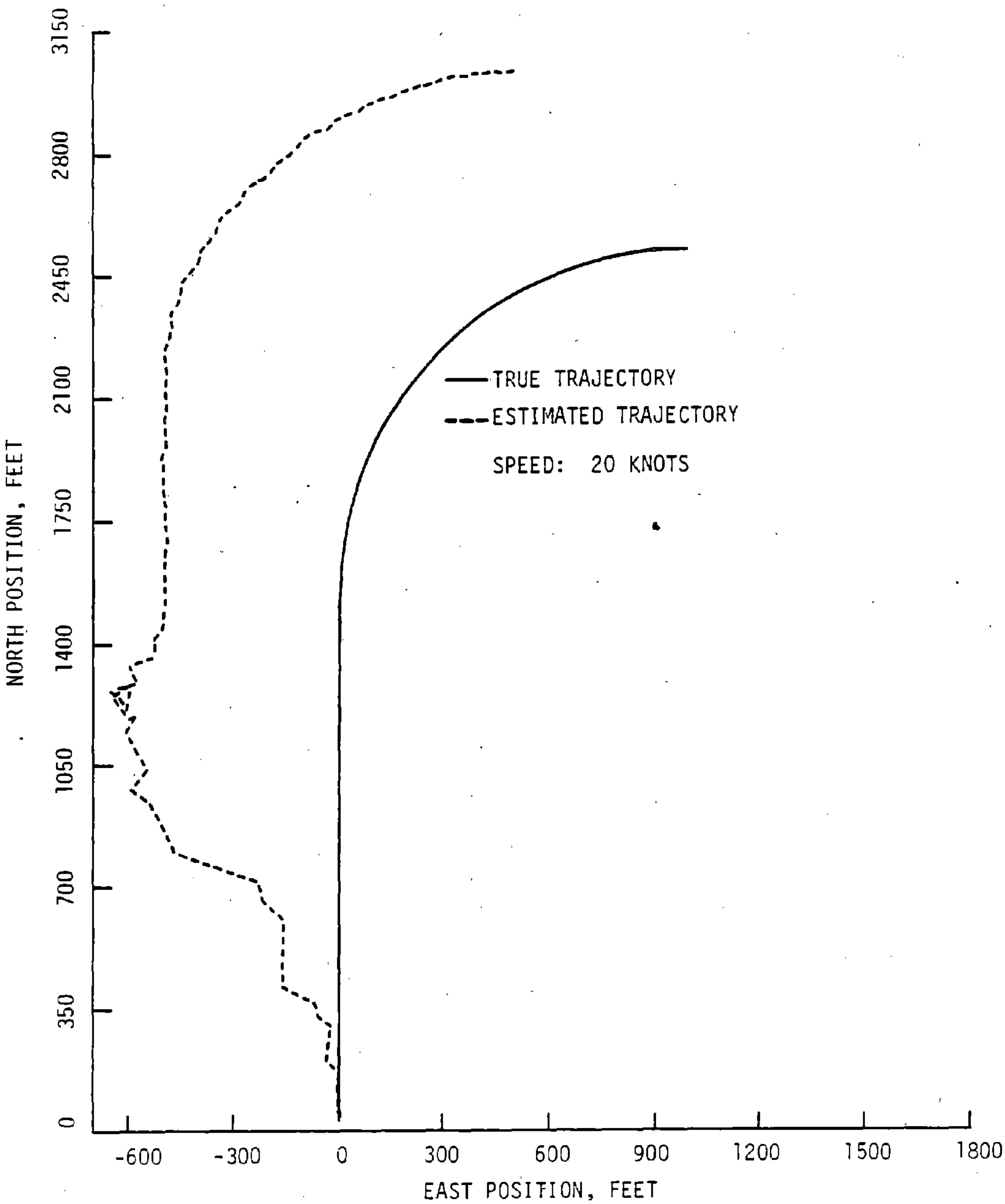
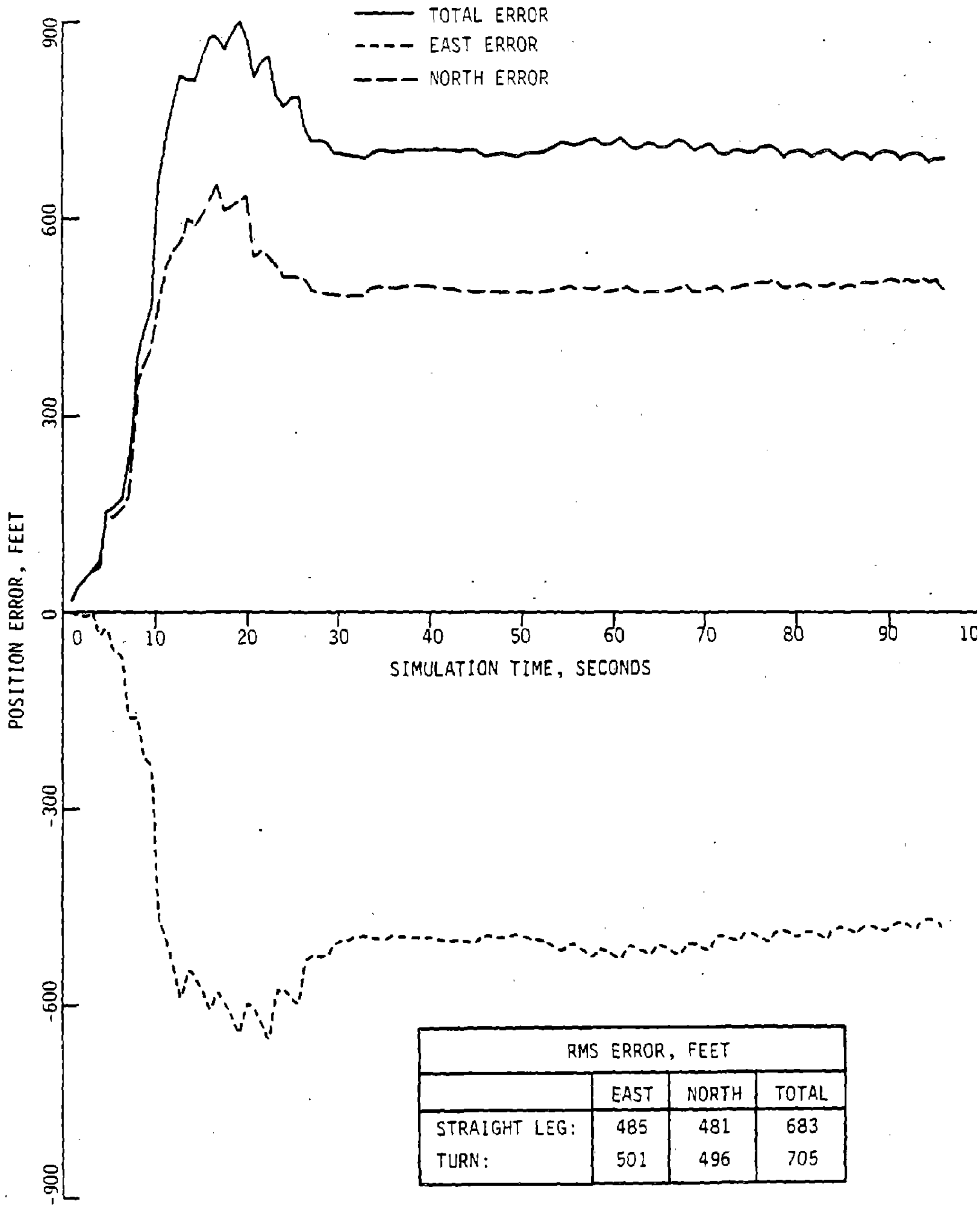


FIGURE 7-7A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 3.



RMS ERROR, FEET			
	EAST	NORTH	TOTAL
STRAIGHT LEG:	485	481	683
TURN:	501	496	705

FIGURE 7-7B. ERRORS, SELECTIVE AVAILABILITY SAMPLE NO. 3.

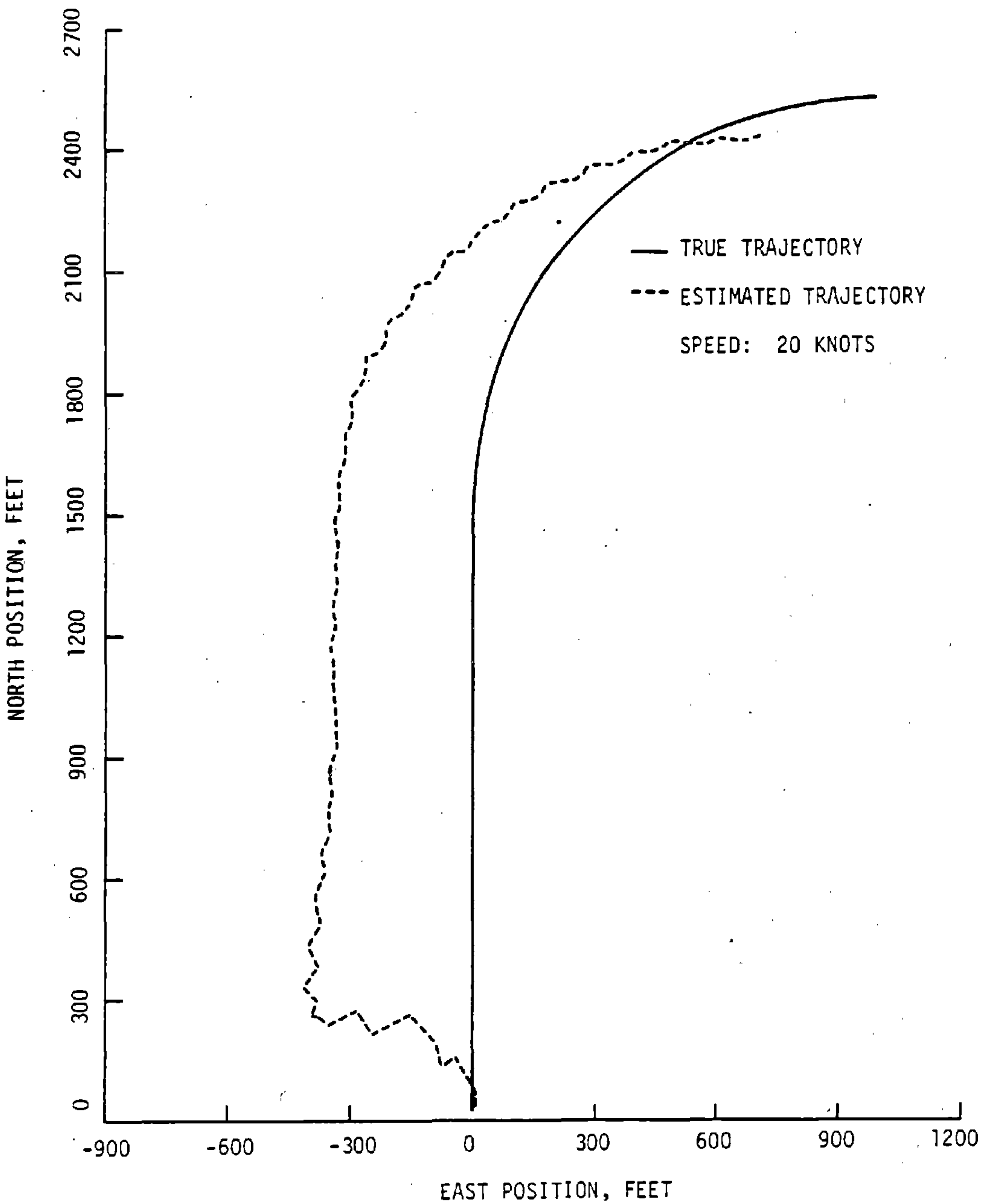
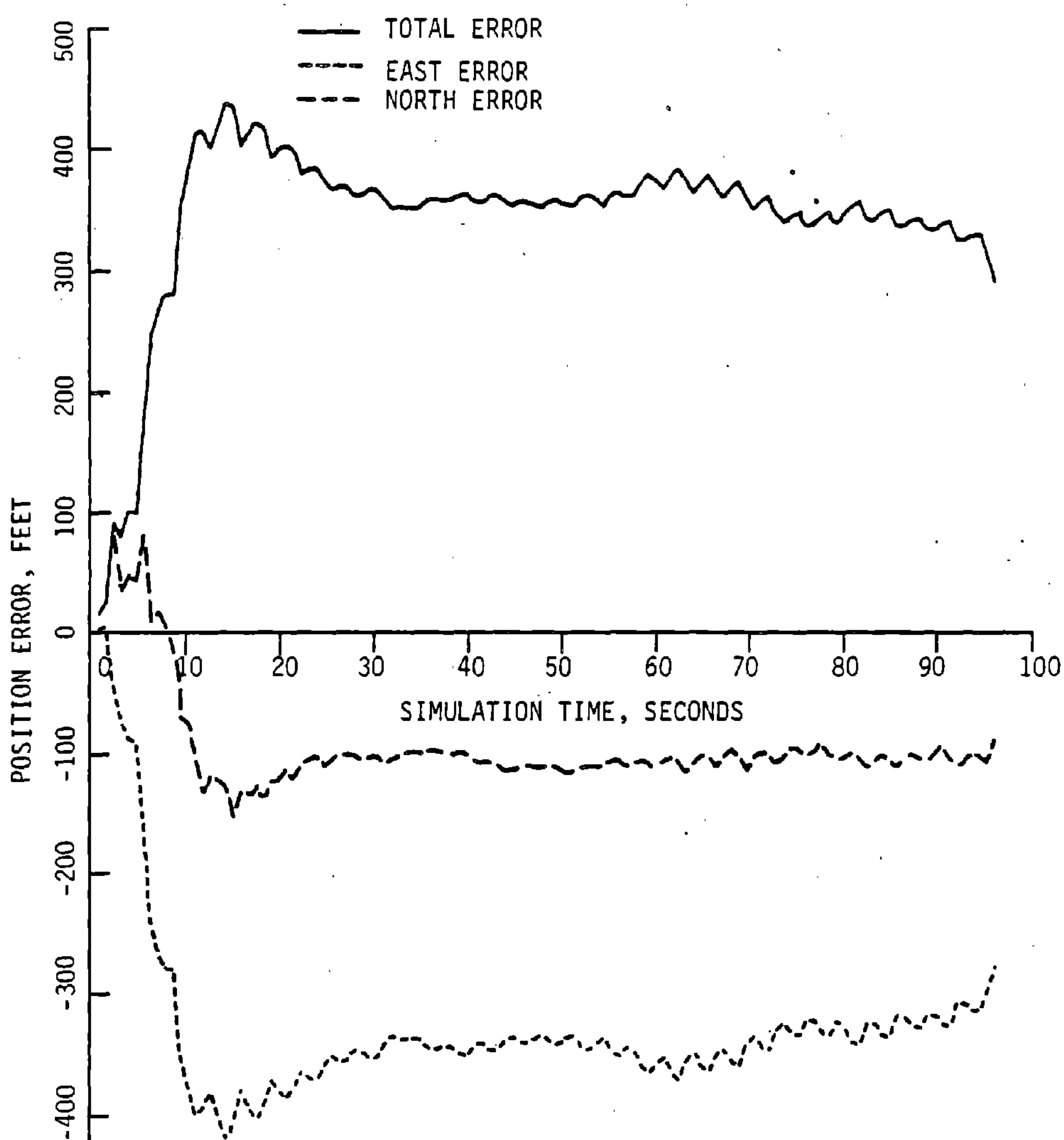


FIGURE 7-8A. ESTIMATED AND ACTUAL TRAJECTORY, SELECTIVE AVAILABILITY SAMPLE NO. 4.



RMS ERROR, FEET			
	EAST	NORTH	TOTAL
STRAIGHT LEG:	335	102	350
TURN:	337	105	353

FIGURE 7-8B. ERRORS, SELECTIVE AVAILABILITY SAMPLE NO. 4.

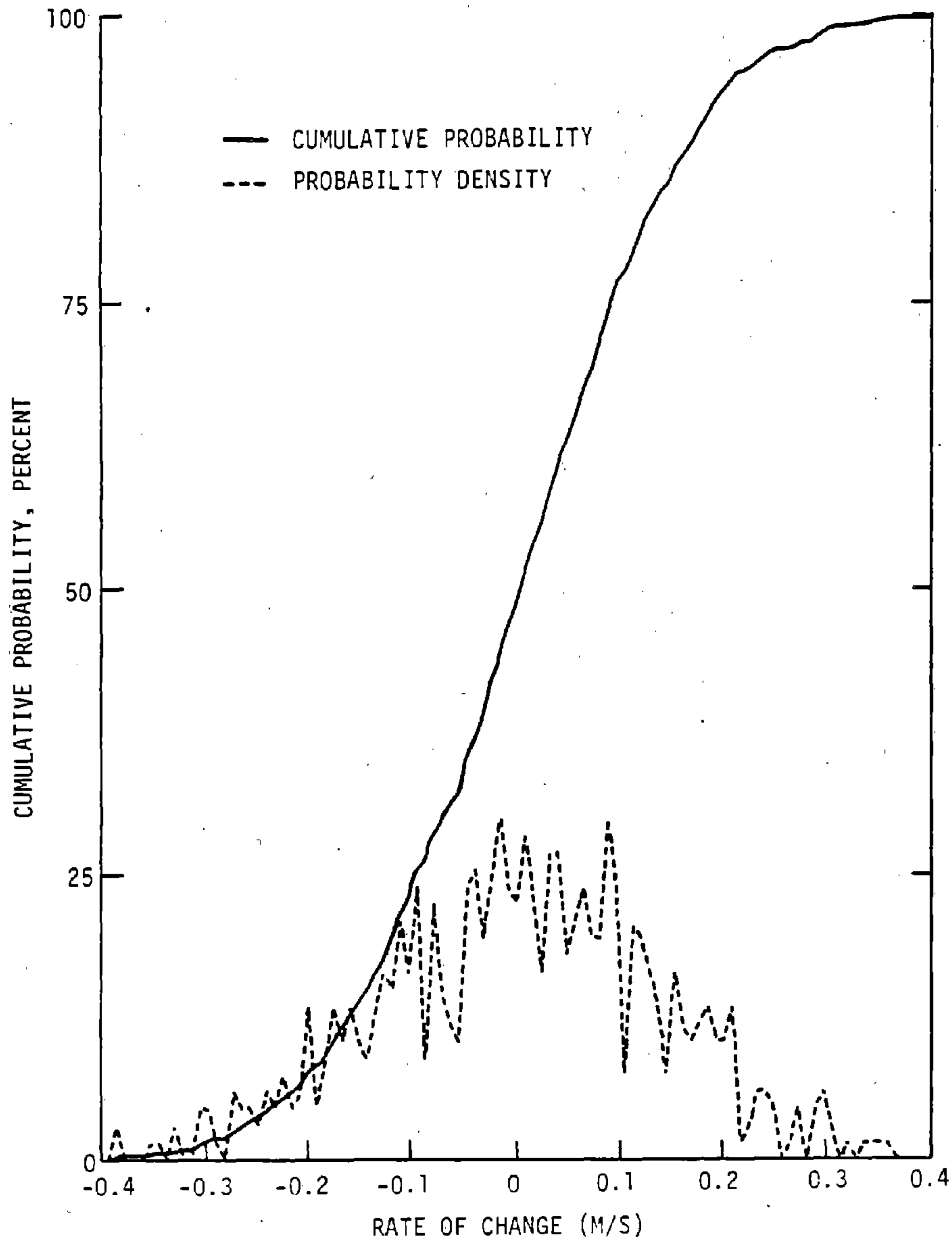


FIGURE 7-9. SELECTIVE AVAILABILITY RATE DISTRIBUTION.

A sequential receiver uses a Doppler frequency measurement to preposition the timing of the receiver code loop for the next dwell for each satellite. A linearly changing SA error will appear to the receiver as a Doppler shift, so the prepositioning will appropriately compensate for it. To the extent that the SA error variations differ from linear changes, they will not be compensated by prepositioning. It is therefore of interest to determine the shift in Doppler frequency between dwell periods of the same satellite.

Figure 7-10 shows the distribution of the second derivative of SA delay errors. It can be seen that most errors are between $\pm$0.012 ns/sec/sec ($\pm$0.0037 m/sec/sec). The longest dwell interval likely to be encountered in a practical receiver is 10 seconds. In 10 seconds the frequency shift corresponding to 0.012 ns/sec/sec is 0.2 Hz. Most receivers have carrier loop bandwidths of several Hz or more. Therefore, the SA error changes can be expected to cause no receiver carrier loop problems, either.

7.5 TRANSIENT BEHAVIOR OF NAVIGATION PROCESSOR DURING CHANGE OF SATELLITE SET

When Selective Availability delays are added to the satellite transmissions, a position error is developed in the user equipment navprocessor. This error will slowly change its magnitude and direction as the SA delays are slowly changed. When a user switches satellite sets, however, (for example, when one of the satellites has dropped below the mask angle and a new one must be selected), an abrupt change in the position estimate occurs. While the error still remains within the prescribed error limits, the abrupt change causes a transient in the measured track. Figures 7-11 and 7-12 show such a situation, using the MARINEGPS simulation. Fifty seconds into the run, satellite #7 is dropped, and satellite #5 is substituted. Each has a large positive pseudorange error. The Kalman filter position estimate undergoes a transition from one SA position error to another, each characteristic of a satellite configuration and a set of pseudorange errors. The solution changes from a northerly error to a westerly error. The response time for the transition is about 30 seconds for nominal filter parameters. In contrast, the removal of the SA delay results in transition errors that are negligible (See Figure 7-13).

In order to prevent a vehicle with stand-alone equipment from responding to such a rapid change in position estimate, it may be necessary to anticipate changes of satellite sets and lag the response of the filter or reduce the resolution of the position estimate. As long as the display resolution or control voltage threshold is not more sensitive than the prescribed GPS error, this will not be a problem.

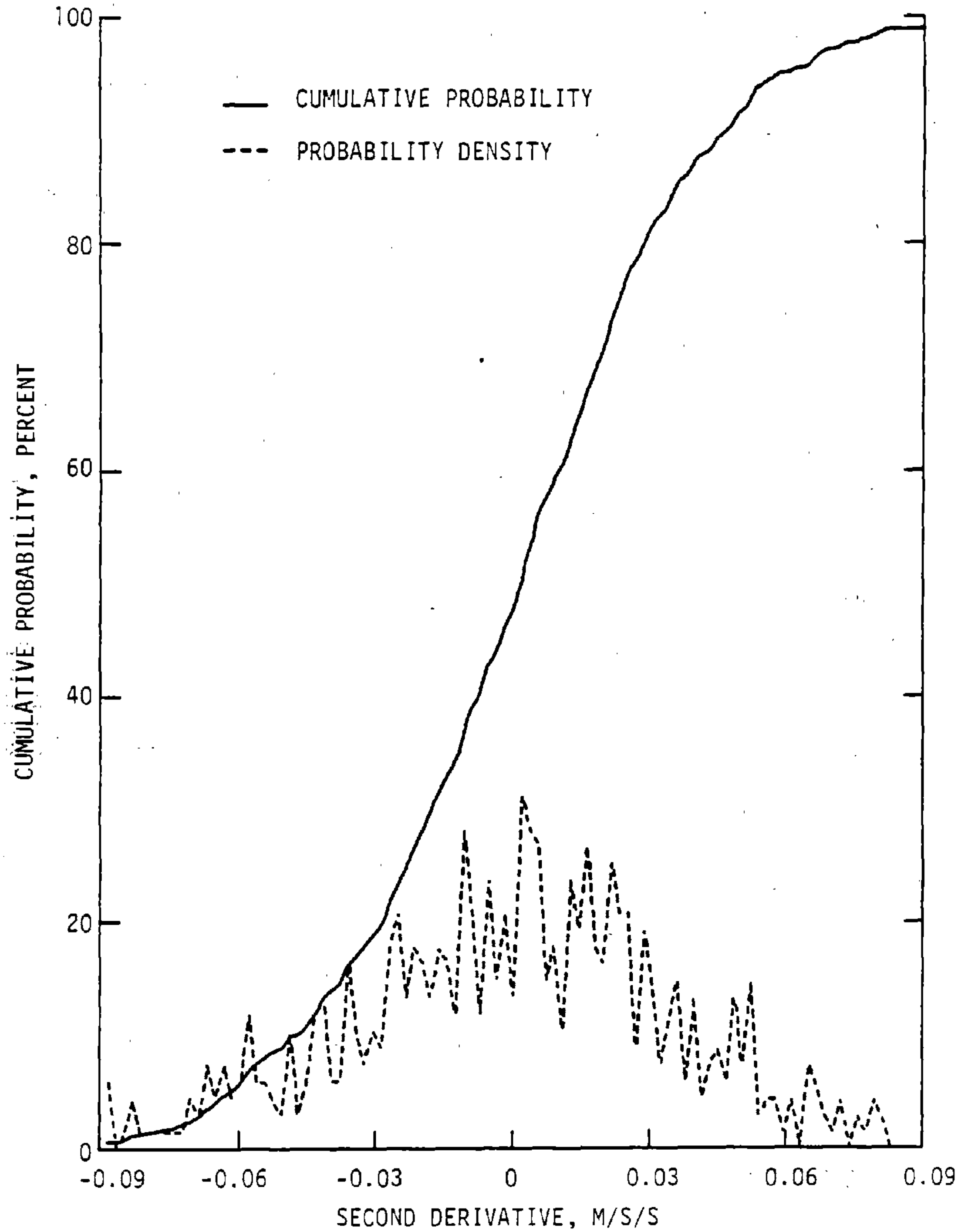
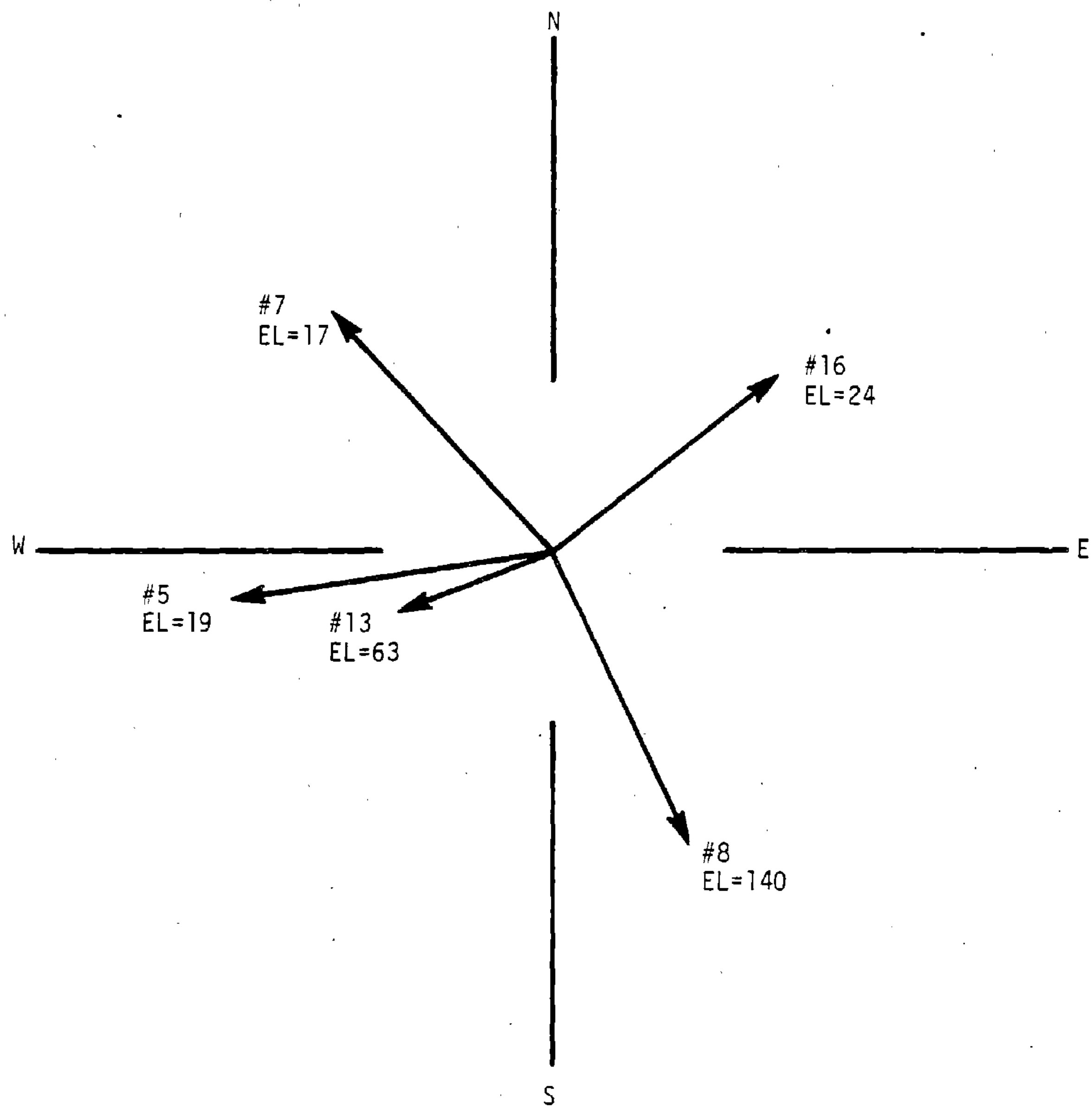


FIGURE 7-10. SELECTIVE AVAILABILITY SECOND DERIVATIVE DISTRIBUTION



SATELLITE PLAN VIEW

FIGURE 7-11. SATELLITE SWITCHING PLAN

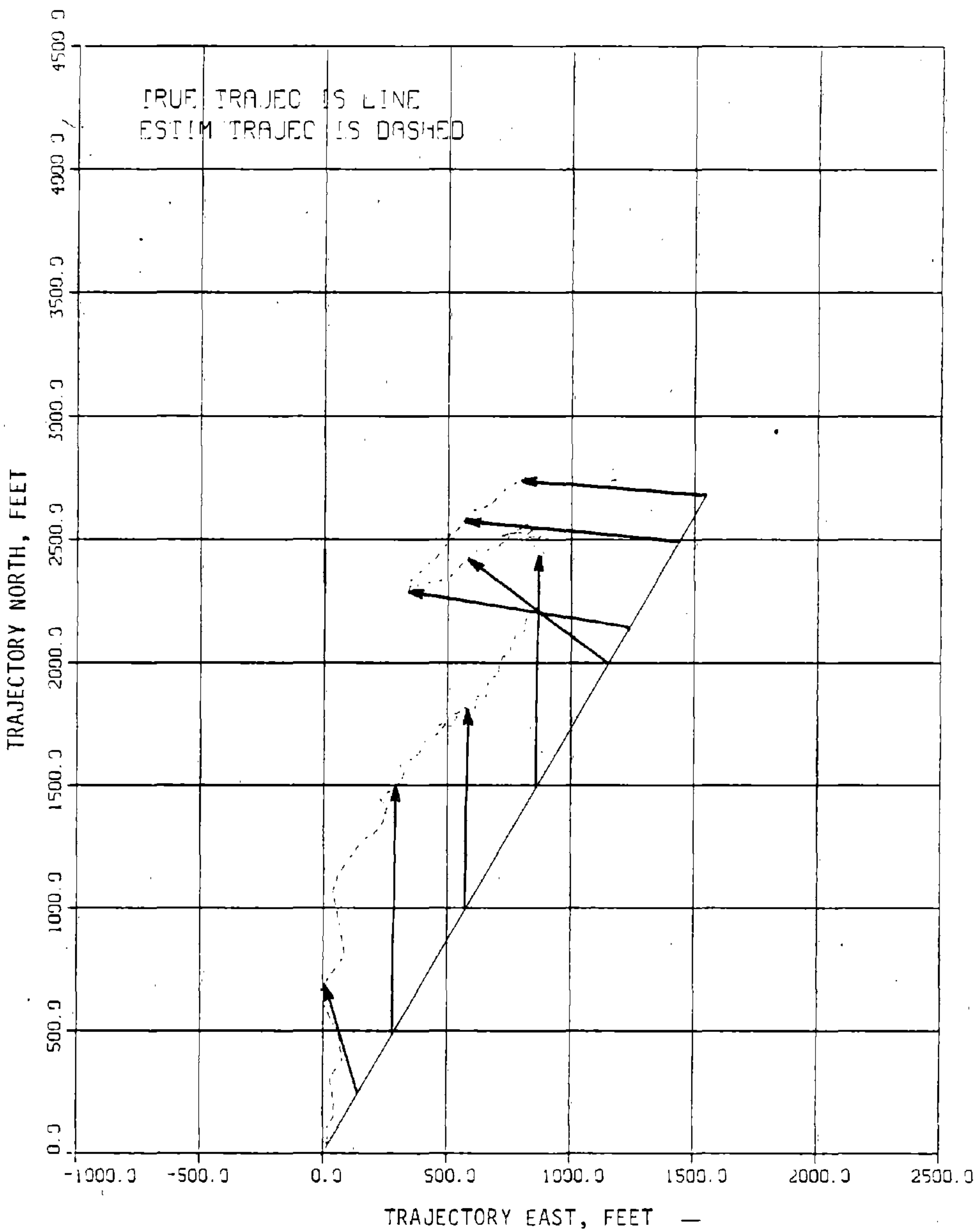


FIGURE 7-12. SATELLITE SWITCHING WITH SA DELAYS

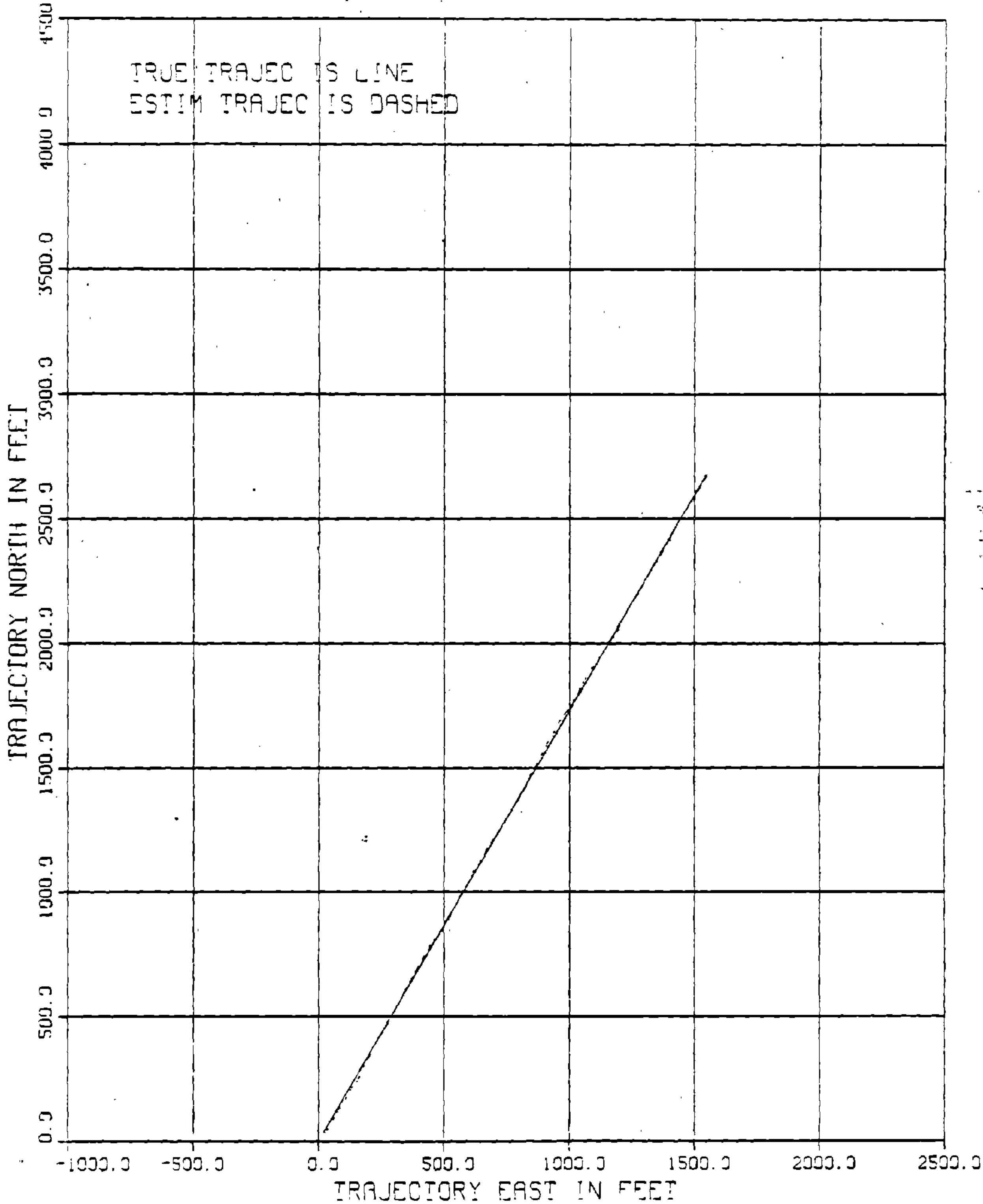


FIGURE 7-13. SATELLITE SWITCHING WITHOUT SA DELAYS

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, user dynamics 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 requirements of certain 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 pseudorange to each satellite translate into navigation errors via the Geometric Dilution of Precision (GDOP). The navigation error distribution depends on the satellite/user geometry at the time of the measurement and on the accuracy of the pseudorange measurements.

The accuracy requirements for the civil users for the radionavigation services are based upon the technical and operations performance needed for transportation safety and economic efficiency. The requirements are defined in terms of discrete "phases of navigation" and are identified in the FRP. The following summary tables (Tables 8-1 to 8-3) relate available SPS accuracy levels with the requirements met in accordance with the FRP classifications.

Table 8-1 shows requirements met over the contiguous United States (CONUS) with the 500 meter SPS specified accuracy under Selective Availability for civil users. Similar requirements are also met over localized coverage areas by existing navigation systems: VOR, DME, VORTAC, and LORAN-C.

Table 8-2 shows the requirements that would be met by NAVSTAR-GPS if Selective Availability were removed entirely. Table 8-3 shows the requirements that would be met by differential operation of NAVSTAR GPS.

*The recent OSD decision on SA reduced this to 100 meters (2drms) horizontally and 165 meters (22 sigma) vertically.

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	Required Accuracy meters (2drms)
AIR	
En Route 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)	3300

TABLE 8-2. FRP REQUIREMENTS MET UNDER SPS WITH SELECTIVE AVAILABILITY REMOVED

SPS Nominal Accuracy

Lateral: 30 m (2drms)
Vertical: 50 m (2 sigma)

Phase	Required Accuracy Meters (2drms)
AIR	
All Requirements in Table 8-1	
Approach and Landing -	
o Non-Precision	100**
MARINE	
All Requirements in Table 8-1	
Ocean Phase (Benefits)	
o Large Ships	185-460**
o Hydrography Science*	10-100*
o Search Operations	460**
Coastal Phase	
o Safety of Navigation of All Ships	460**
o Safety of Navigation of Recreational Boats and Small Vessels	460-3700**
o Benefits-Commercial Fishing & Sports	
Hydrography Science, Resource Exploitation*	1-100
Search Operations, Law Enforcement	460**
Recreational Sports, Fishing	460**
LAND	
All Requirements in Table 8-1	
o Public Safety, Urban Police, Emergency Medical	80**
o Rural Police, Medical	330**
o State Police	330**
Transportation	
o Urban Buses	170**
o Taxi	170**
o Delivery Truck	330**
Highway Safety	
o Planning	30
Resource Management	30

*Meets requirements above 30 meters (2drms)
**Also met under SPS at the recently announced SA level of 100 meters.

TABLE 8-3. FRP REQUIREMENTS MET WITH DIFFERENTIAL GPS USING SPS ACCURACIES WITH SELECTIVE AVAILABILITY

Nominal Accuracy at 50 km Range

AIR: 25.4 m (2drms)
MARINE: 15.0 m (2drms)

Phase	Required 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	
Ocean Phase - Hydrography Science* - Resource Exploitation	10-100 m
Coastal Phase - Hydrography Science* - Resource Exploitation	1-100 m
Harbor Approach and Harbor Phase - - Safety of Navigation,* Large Ships	8-20 m
LAND	
All FRP Requirements	

*Meets requirements above 15 m (2 drms).

Projecting the GPS capabilities for the civil radionavigation under SPS both with and without Selective Availability, it is clear that some FRP requirements will not be met without additional improvements. In particular, requirements for safe navigation of aircraft in precision approach and landing will not be met in the foreseeable future. Similarly, general requirements for Harbor/Harbor Entrance (HHE) (8-20 meters, 2drms) and navigation in narrow waterways (approximately 8 meters, 2drms), are not met, although some wider channels may be navigated using GPS.

There are other areas where precise navigation services could be useful, namely the remote areas, characterized by their low traffic and difficult terrain. Systems in operation today are LORAN-C, VOR, VORTAC, Omega and Nondirectional Beacon, but it has been difficult using these navigation aids to cost-effectively implement accurate, comprehensive navigation service. The reasons are either poor performance (reliability of the navigation grid is not reliable for all seasons) or high cost (multiple ground station installation requirements raise the costs). The FRP identifies these remote areas to be mountainous terrain, offshore areas and large portions of Alaska.

One of the techniques that could enable GPS service improvements is the differential mode of GPS. This approach could possibly provide navigation coverage for the civil users in the CONUS and in remote areas in a cost-effective manner. Table 8-3 summarizes the additional services that might be provided by the differential technique.

Table 8-4 shows the current and projected requirements of an important national industry, the oil exploration and production companies.(33) While SPS will meet many of the current requirements if Selective Availability is removed, differential operation can meet most of the future requirements. The relative accuracy of one meter or better required for field development and production may be met by using sophisticated differential techniques.

8.3 DIFFERENTIAL GPS IMPLEMENTATION CONCEPT

The idea of a differential mode operation is an old one. Crosschecking of one's measurements with a known reference is familiar and used in many measurement systems, but the manner of its implementation in GPS is unique.

Differential operation of GPS is achieved by reception of the satellite clear/acquisition (C/A) code signals on a single frequency at a fixed reference site. By processing these signals from all satellites in view, a pseudorange correction is determined - the difference in range between the derived satellite position (using decoded ephemeris data) and the directly measured data (corrected for the satellite clock delay). The measurement correction is broadcast at selected intervals to GPS users in the vicinity to allow users to correct their position estimates. It is assumed that errors are common to all users and are valid for specified range and time intervals. Data collection, processing and distribution are achieved in real time. Figure 8-1 illustrates a differential GPS concept consisting of three elements: reference site, data link and user.

TABLE 8-4. NAVIGATION AND POSITIONING REQUIREMENTS BY INDUSTRY SEGMENT

SEGMENT	ACTIVITY	CURRENT	1988	1992	2000
EXPLORATION	SEARCH FOR PROMISING STRUCTURES	20-40 M	10-15 M	5-10 M	3 M
APPRAISAL DRILLING	DRILL STRUCTURE AND DETERMINE IF ECONOMICALLY FEASIBLE	50 M	20 M	20 M	10 M
FIELD DEV. PRODUCTION	DEVELOP FIELD AND PROVIDE COLLECTION AND DISTRIBUTION	1 M*	0.5 M*	0.5 M*	0.5 M*
TRANSPORTATION TO REFINERY		200 M	100 M	50 M	50 M

*DESIGNATES RELATIVE ACCURACY WITHIN FIELD

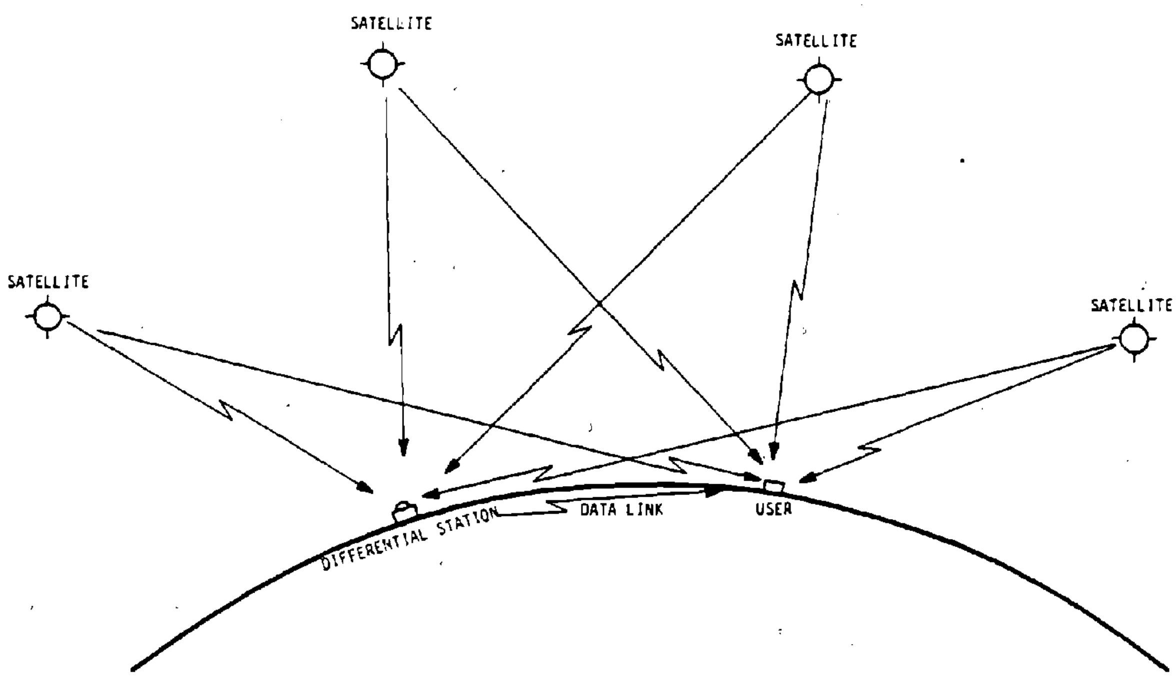


FIGURE 8-1. DIFFERENTIAL GPS GEOMETRY

8.3.1 Alternative Techniques

The manner in which the data is collected and where the data is processed distinguishes three basic differential techniques. The basic elements in all three are the cancellation of link bias errors and a priori knowledge of the reference site position location. All three techniques are shown in Figure 8-2 and can be described briefly as follows:

1. Baseline Differential GPS is a noncooperative system transmitting only the correction information derived at the ground reference site for a specified service area.

2. Centralized GPS is a cooperative system and derives its correction information by receiving the same signal from two different paths: directly and via aircraft data link. Correction information is then returned to the aircraft by an independent narrowband data link. This technique accommodates surveillance of aircraft.

3. Translator GPS is a cooperative system very similar to the centralized technique, except that the aircraft "reflects" satellite signals over a wide band data link to the ground based processor.

The baseline techniques will be discussed in greater detail as a viable candidate for implementing differential GPS operations. The centralized technique exhibits navigation performance similar to that of the baseline technique, but adds system reliability and provides surveillance. The translator technique has been analyzed, but appears to require too much bandwidth and offer too small a performance increment to justify its implementation.

8.3.2 Form of the Differential Correction Terms

The most straightforward method of implementing correction terms is to broadcast latitude and longitude (Lat/Lon) differences from the differential station. That is, the differential processor would determine the estimated position from the measurements, subtract the known Lat/Lon coordinates, and transmit the differences. The user would then subtract the same differences from his estimated coordinates. However, this is not a practical approach for the following reasons:

a. The user may employ a different navigation solution, e.g., a 2-dimensional solution rather than a 3-dimensional solution.

b. The user may employ a different mask angle or different satellite selection strategy, e.g., "all-in-view" rather than "best-set".

c. Even if the algorithms are the same, distant users may process different satellites.

Any of these conditions would result in large errors compared to the desired performance. Since there is no current restriction on the design of a civil receiver, different manufacturers may design their sets in different ways. It also turns out that Lat/Lon corrections allow no flexibility in the use of ionospheric and tropospheric models. Therefore the transmission of Lat/Lon corrections only is not a viable approach for broadcasting differential corrections.

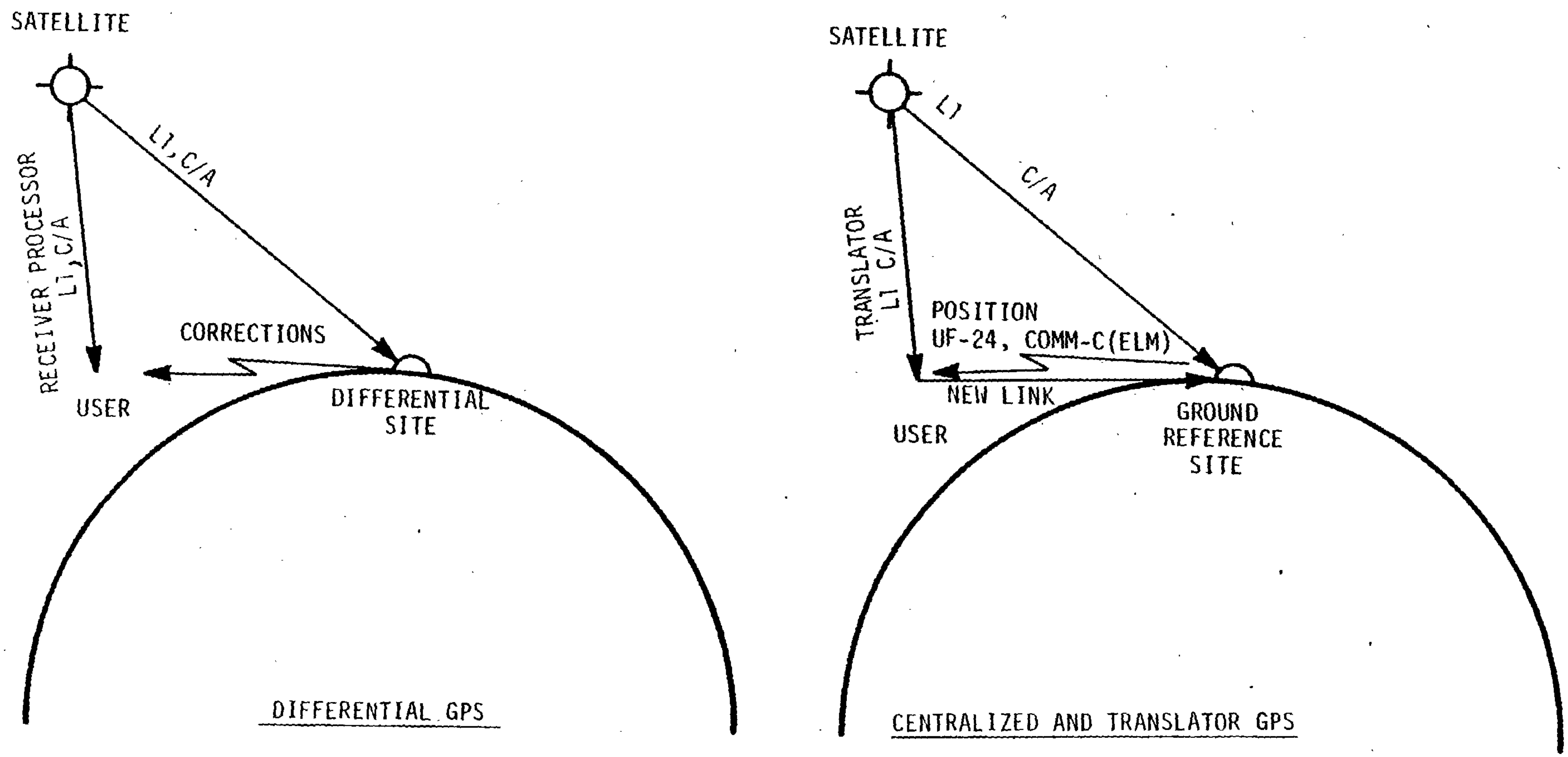


FIGURE 8-2. BASELINE, CENTRALIZED AND TRANSLATOR DIFFERENTIAL TECHNIQUES

The approach which a differential design must use is that of transmitting the pseudorange corrections for each satellite. The user processor must then subtract the correction from the measured pseudorange prior to determining the navigation solution. The data message will thus contain the station identification, plus satellite identification and pseudorange correction for each satellite in view of the station. Of course, the format must be standardized at least on a national basis, a not insignificant undertaking.

A recent workshop was held at the DOT Transportation Systems Center to begin this process. The workshop was able to partially develop a proposed signal format that appears to be quite satisfactory to a wide number of users. The proposed format is flexible and allows for considerable adaptation to particular user groups. To the extent to which the format was developed, it will be used here in this report. The format is described in Section 8.4.2.

8.3.3 Data Update Rate

Data update rate is a key parameter of a differential system. If a differential station issues pseudorange corrections periodically, users in the area can achieve momentary high-accuracy positioning by incorporating these corrections. After a period of time, however, the Selective Availability errors will change, and the users' navigation solutions will eventually 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, the standard deviation being 0.43 ns/sec. These rate values and the corresponding update rate are not affected by the recent OSD decision. This translates to a 2drms value of positional change of about 0.4 m/sec, 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 to 20 meters (2drms), which would require pseudorange measurement accuracies of 3 to 7 meters (1 sigma), assuming an HDOP of 1.5. By requiring that the differential station use a separate channel for each satellite in view and use heavy smoothing, it should be possible to achieve better than 3 meters accuracy in the pseudorange measurements. By further requiring Doppler processing of the signal carrier, pseudorange rate corrections can be generated which extend the length of time the corrections are valid.

In Section 8.5.1 it will be shown that a differential station can be expected to achieve an accuracy of 1.9 meters (one sigma) in pseudorange. Using an update period of 12 seconds from the recently proposed format, and taking advantage of the capability of a stationary receiver to do highly accurate Doppler processing on the carrier, the pseudorange corrections can be accurate to within 2.2 meters (one sigma). This can be seen in Figure 8-3, which shows the dependence of pseudorange accuracy on update rate (exclusive of receiver noise).

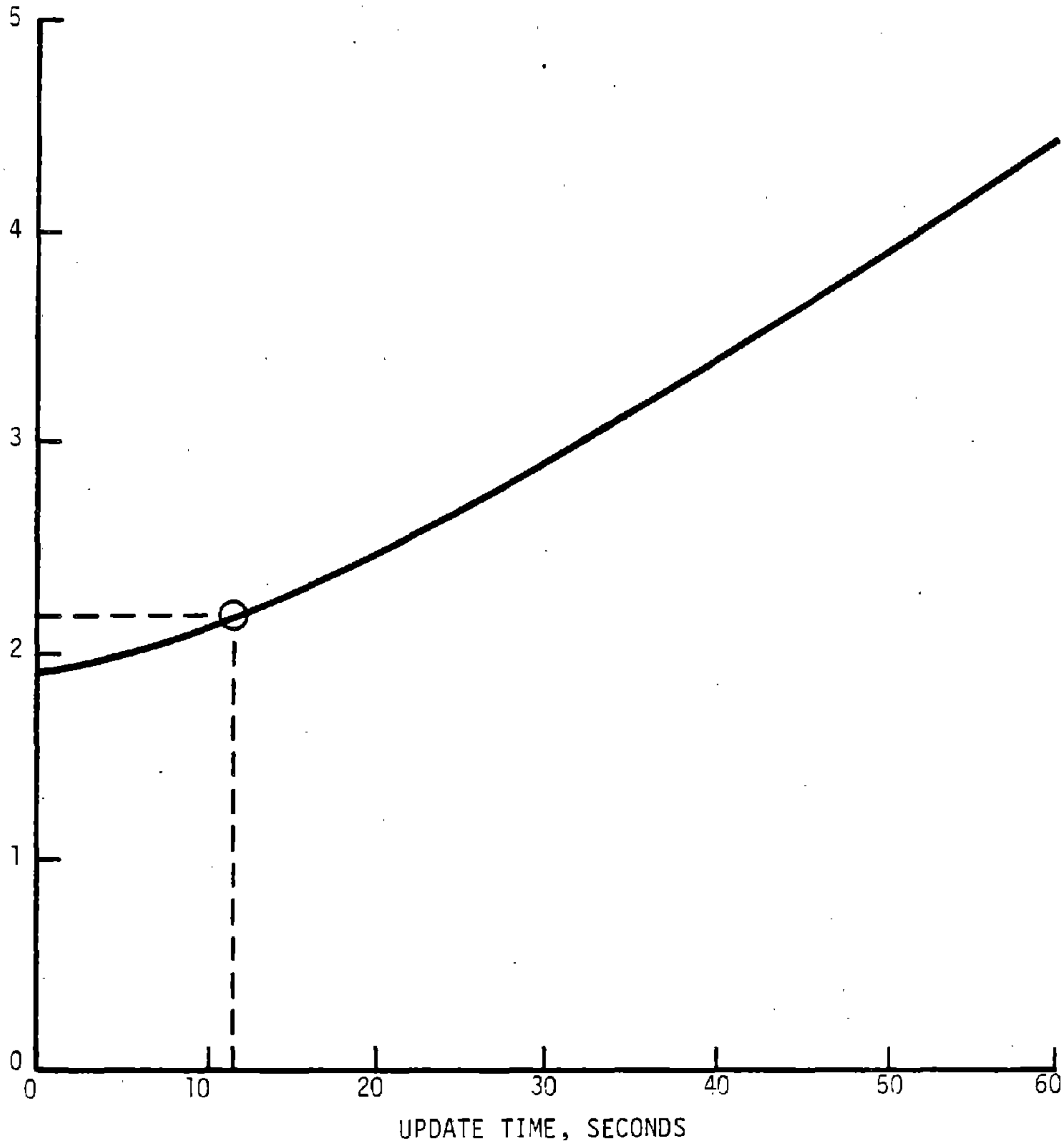


FIGURE 8-3. DEPENDENCE OF PSEUDORANGE ERRORS ON UPDATE PERIOD

Thus ignoring user receiver noise limitations, the recommended update period of 12 seconds enables reference station pseudorange accuracies of 2.2 meters, which translates to about 6 meters of positional error. A stationary receiver employing heavy filtering could achieve accuracies approaching 6.6 meters (2drms). A marine user would not be able to smooth his solution as much, and an air user even less so. Therefore, for receivers in motion the accuracy is determined primarily by the receiver measurement fluctuations. This is discussed further in Section 8.5.

8.3.4 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 GPS receiver always deals with two types of errors: "bias," a slowly varying error, which can be cancelled out by subtraction of differential corrections and "noise," rapidly varying random noise errors, which can be reduced only by filtering. Figure 8-4 shows a diagram of measurements and their relation to true range between the receiver and each satellite.

The common GPS user error sources are following:

- Ephemeris Errors - differences between the actual satellite position and the position indicated by the ephemerides provided in the satellite data message.
- Space Vehicle Clock Errors - differences between GPS system time and the satellite times indicated by the satellite data message.
- Unmodelled Ionospheric Errors.
- Selective Availability - intentional delay errors.
- User Clock Drift - most severe for sequential receivers.
- Receiver Bias Errors - due to acceleration of the vehicle
- Receiver Noise Errors.

Differential operation promises to remove most of the bias errors, but receiver noise is not affected. Also, not all bias errors are cancelled by use of a differential correction. 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 "temporal decorrelation errors." They are described below.

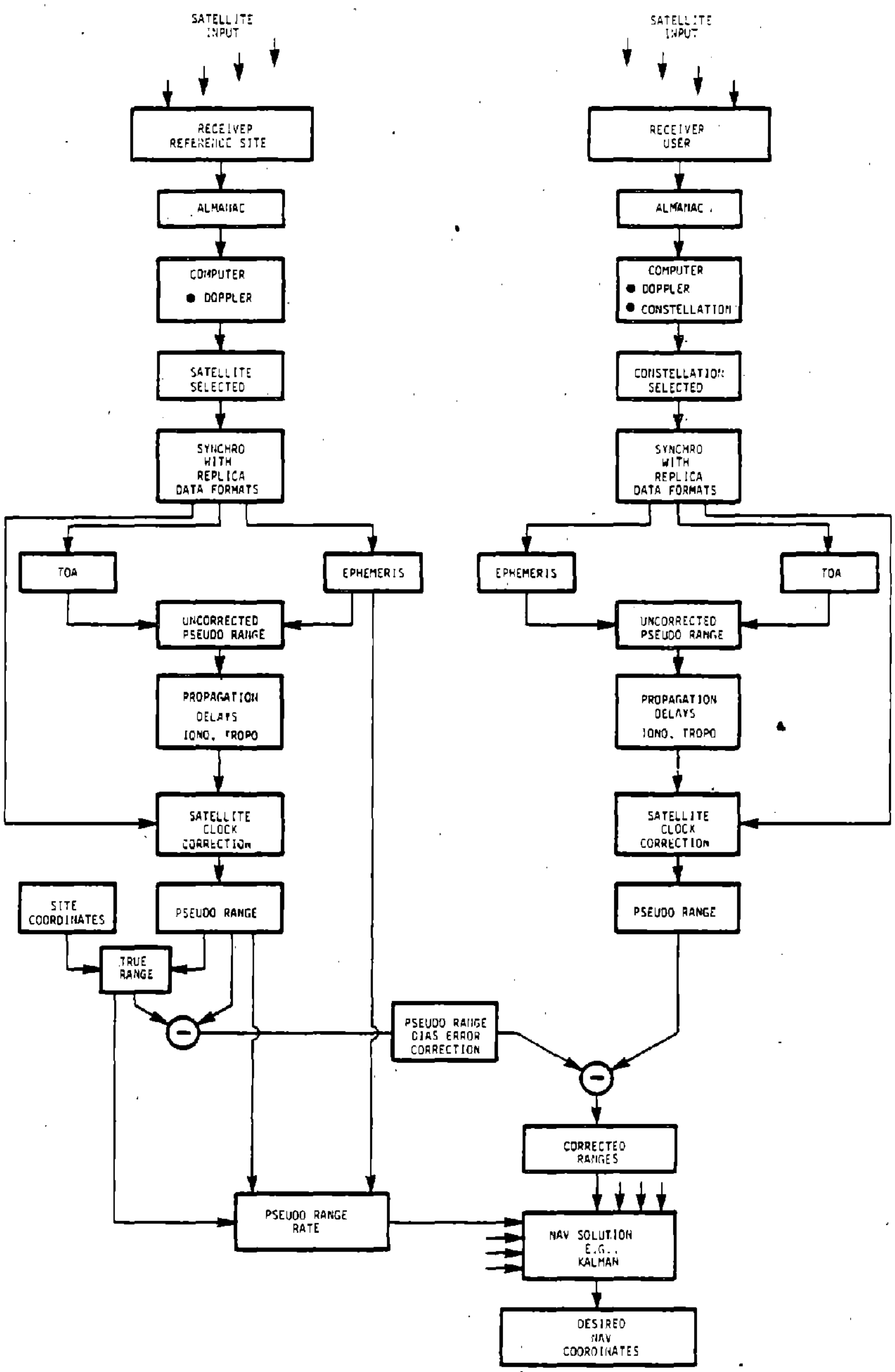


FIGURE 8-4. FUNCTIONAL FLOW DIAGRAM

a. Errors Sensitive to User/Reference Site Separation

o Ionosphere:
- Irregularities.
- Diurnal (due to different penetration points through ionospheric shell).
- Flare inhomogeneities (caused by solar flares).
- Earth Curvature (two separated receivers do not acquire a source at the same elevation angle; path length is different).
- Altitude (error in estimating the height of the ionosphere—350 km is nominal)
- Obliquity (layer thickness changes from zenith to horizon).

o Troposphere:
- Geometric Effects (thickness changes with increased path length and sharp variations in atmospheric densities).

o Selective Availability:
- Intentional delay.

o Satellite Position Error:
- Error in predicting satellite true position, which translates into a pseudorange error.

b. Time-Sensitive Errors

o Age of Ephemeris Update: error added during update, if not compensated.
o Age of Space Vehicle Clock Update: satellite clock error, if not compensated.
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 add directly 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 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, 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. For example, 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 accommodate these deviations. As a result, the signal-to-noise ratios are smaller, and less smoothing is possible for users.

8.4 BASELINE DIFFERENTIAL GPS DESIGN

8.4.1 General

In the baseline design, the differential station performs pseudorange measurements on each satellite, determines appropriate corrections and broadcasts them to nearby users. No surveillance is involved. The station receiver is not radically different from a user's receiver, except that parallel-channel operation is highly desirable, and Doppler processing should be performed to get pseudorange rate corrections as well as pseudorange corrections. These capabilities are necessary to get the greatest accuracy. The reference station navigation processor is quite different from a user's receiver, on the other hand, because the computation of position is not the primary aim of the unit. Another unique requirement of the reference station is that it must continuously receive data from each of the satellites so that it can immediately operate with the latest satellite data following a data change. These data changes occur about once per hour. With this capability the reference station data message can adjust for the fact that some users will be operating with old data. This is explained further in Section 8.4.2. A block diagram of the differential station is shown in Figure 8-5.

The differential station should be equipped with a high-quality clock, such as a double-oven-controlled quartz oscillator, which has very little drift over the period of a few seconds. The long-term stability appears to be less critical, so a rubidium or cesium standard is not necessary. The steps in the process of determining a pseudorange correction are the following:

1. Select a measurement reference time as close as possible to the next GPS subframe start time.

2. Compute the positions of all satellites at that time, and determine their actual ranges.

3. Sample the satellite pseudorange measurements and the carrier Doppler-derived pseudorange rates at the reference time and store.

4. Adjust each satellite pseudorange for ephemeris and satellite clock as determined by the satellite data messages.

5. Compute station position (as a performance check) and station time offset from GPS time.

6. Subtract actual range and station time offset from satellite pseudorange measurements to get corrections.

7. Broadcast the pseudorange and range rate corrections for the six satellites included in the subframe message.

The reference station processor should compute the error in its own position as a measure of system quality. If the error falls out of acceptable limits, the station health bits should be adjusted to warn users that the error may be higher than normal. For example, if a bad geometry existed in combination with four or five visible satellites, the station could detect this condition.

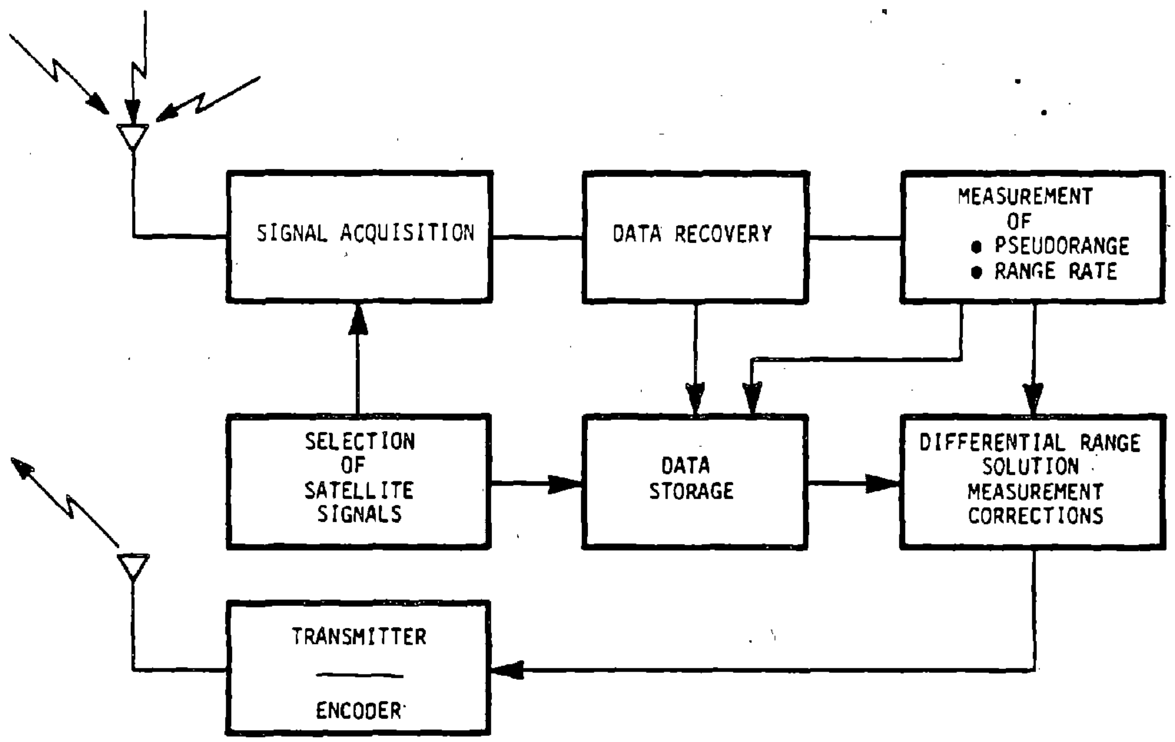


FIGURE 8-5. DIFFERENTIAL REFERENCE STATION BLOCK DIAGRAM

In addition, each pseudorange correction should be examined to see if the individual satellite corrections are reasonable. If not, the satellite health bits should reflect this condition and warn users not to incorporate particular satellites in their navigation solutions.

At least one monitor should be located near the differential station to compute position in exactly the same manner that a user would. The computed position should be communicated to the differential station to verify that the position is within bounds related to the station health bits. For example, with 2 bits there are 4 levels which can be employed, and a "level 1" indication could be used to indicate positional errors within 10 meters, "level 2" within 15 meters, "level 3" within 20 meters, and "level 4" greater than 20 meters. Unfortunately, the design of the monitor requires a single choice of satellite selection algorithm and mask angle. Probably the best way of handling this is to be conservative and choose a mask angle of 10 degrees and a best-set satellite selection strategy.

8.4.3 Differential Uplink Format

The proposed data format to be used for the communication of corrections from a differential reference station to nearby users is patterned after the NAVSTAR GPS data format. Subframes consisting of 300 bits are employed, each headed by a preamble and time indication, similar to the GPS TLM and HOW words. The proposed header identifies the start of the message, the differential station identification, station health indication, timing with respect to GPS time, and subframe identification. Figure 8-6 shows the subframes that were defined at the workshop. Up to 8 different message types are accommodated with the 3-bit subframe ID data element. The details are given in Table 8-5.

Pseudorange corrections are broadcast for each satellite, rather than latitude/longitude corrections. The pseudorange corrections use ephemeris and satellite clock data, but do not use either ionospheric or tropospheric models.

The differential corrections need to be sent out most frequently, while auxiliary data need be broadcast only every minute or so. Accordingly, the Type 1 message contains the corrections data, and consists of two subframes. Each subframe contains the pseudorange and pseudorange rate corrections, identities and health indications of up to six different satellites. This enables up to 12 satellites to be handled by a differential station. The pseudorange corrections have a resolution of 0.1 meters, and the pseudorange rate corrections have a resolution of 0.004 meters per second.

The Type 2 Message is similar to the Type 1 Message, in that 40 bits are sent for each satellite. However, instead of pseudorange and range-rate corrections, Age of Data (AOD) and "delta corrections" are broadcast. A delta correction for a satellite is equal to the difference between pseudorange corrections utilizing old and new satellite ephemeris and satellite clock data. The AOD data enables a receiver to determine whether the station is using the same satellite data as the reference station or not. If not, the receiver can further correct for the difference between the old and new satellite data by subtracting the delta correction. The Type 2 Message is broadcast approximately once for every five Type 1 Messages. It should be pointed out that the message type mix can be tailored to a particular differential station and does not have to be fixed by the format.

TABLE 8-5. DIFFERENTIAL GPS DATA

MESSAGE TYPE	PARAMETER	NUMBER OF BITS	SCALE FACTOR & UNITS	RANGE
ALL (First word)	Preamble Station ID Station Health Spare/Parity	8 12 2 2/6	(Same as GPS) 1 - -	 1-4096 4 states -
ALL (Second word)	Z-Count Subframe type Spare Spare/Parity	17 3 4 2/6	6 sec - - -	0 - 100,794 1-8 - -
TYPE 1 (corrections) Each satellite (6 satellites/ subframe)	Pseudorange Correction Range-rate correction Satellite ID Satellite Health Spare/Parity	16 8 X6 5 3 48	0.1 m 0.004 m/sec 1 - -	± 3276.8 m ± .512 m/s 1-32 8 states -
TYPE 2 (Auxiliary corrections) Each satellite (6 satellites/ subframe)	Delta Correction Age of Data Satellite ID Satellite Health Parity (Total)	16 8 5 X6 3 48	0.1 m See ICD-GPS-200 1 - -	± 3276.8 m 1-32 8 states -
TYPE 3 (Station Location)	ECEF X-Coordinate ECEF Y-Coordinate ECEF Z-Coordinate Parity Spares	32 32 32 32 96	.01 m .01 m .01 m - -	$\pm 2.15 \times 10^7$ km $\pm 2.15 \times 10^7$ km $\pm 2.15 \times 10^7$ km - -
TYPE 4 (Surveying) Each Satellite (8 satellites/ subframe)	Whole Doppler Count Fractional Doppler Ct. Satellite ID Satellite Health Parity	8 8 5 3 6	1 1/256 wavelength 1 - -	0-255 0-255 1-32 8 states -
TYPES 5-8	Optional			

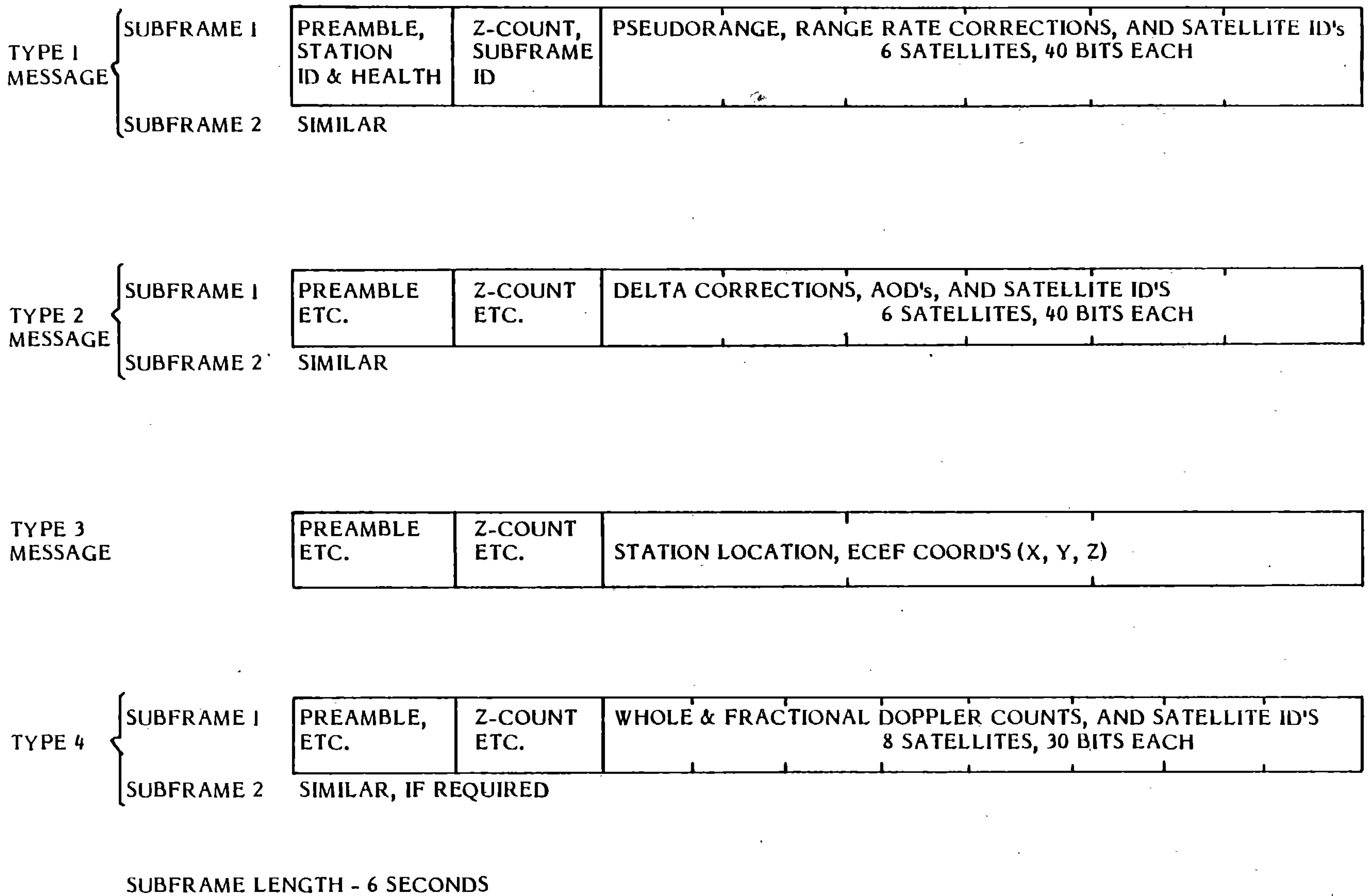


FIGURE 8-6. DIFFERENTIAL GPS MESSAGE

The Type 3 Message contains the earth-centered, earth-fixed (ECEF) coordinates of the differential station. The data is contained in one subframe. This message type need only be broadcast every two or three minutes.

A Type 4 Message was developed to accommodate the extreme precision required by some surveying applications. This message consists of satellite identity, whole Doppler cycle counts, and fractional Doppler counts, timed from the previous subframe transmission. Use of these counts enables relative location accuracies in the centimeter range.

The format can accommodate four more message types, which can be added at a later date. A message for aircraft could contain weather, runway condition data, runway threshold coordinates, tropospheric refractivity measurements, or instructions to individual aircraft, for example.

If the reference station is a pseudosatellite, the receiver passes along the data to the processor just as it passes data from the NAVSTAR GPS satellites. The processor requires no hardware changes to handle the differential data. Furthermore, the bit phase transitions are or can be synchronized to GPS time, so the range to the station can be determined. In this configuration the reference station acts as an extra satellite, and can be used to improve the accuracy of the position estimate.

The data format also accommodates an external data link. The data link itself can be at any of a number of frequencies that might be available or convenient to a particular user group. For example, Mode-S is a planned L-band data link for air-to-ground and ground-to-air communications for civil air users. It may be possible in the future to use some of the Mode-S data slots for differential corrections. Other possible aircraft bands include VOR broadcasts (108-118 MHz) and VHF communications (118-136 MHz). For marine users, the Radiobeacons (285-325 mHz) may be able to be modulated to provide the differential corrections. These signals can be received over the horizon. VHF frequencies (150-174 MHz) may be employed where line-of-sight communications are feasible. It may be possible for vehicles to use unused portions of the FM band to receive differential corrections in the future.

The only requirements placed on the data link are that the data rate be at least 50 bits per second, that it interface with a serial, asynchronous, standard RS-422 port, and that it preferably send the format data to the receiver as ASCII characters. Otherwise, the data can be transmitted as a fast data burst or a continuous stream and employ any convenient modulation scheme.

8.4.4 Data Link - Pseudosatellite

The pseudosatellite technique has been proposed as a means of broadcasting corrections to NAVSTAR GPS users at a low cost. With this approach, the ground station uplink operates at the L_1 frequency, 1575.42 MHz, and uses the same biphase modulation, chipping rate, and data rate as the GPS satellite signals. The receiver can then receive the signal, demodulate it, and process the data just as if the station were a satellite. The modifications in the receiver design necessary to accommodate the differential format would be software changes -- no hardware changes or separate antenna would be involved. From the system design perspective this approach would make differential NAVSTAR GPS a self-contained operation. No interfaces with existing facilities would be required, and no non-GPS frequencies would be involved.

There is another significant advantage to pseudosatellite operation as well. By tying the ground station into GPS system time, the signals can provide ranging from the station. In effect, the ground station can serve as another "satellite", thus improving the PDOP (and hence the positional accuracy) and reducing the susceptibility of the NAVSTAR GPS to satellite faults or service outages.

The differential workshop held at the Transportation Systems Center this year (34) established that a 50 bps data rate would be adequate for accurate differential operation. Thus, the pseudosatellite technique, which is constrained to 50 bps, has a high enough data rate to support differential operation.

However, the major problem with the pseudosatellite technique is that it may cause interference with other GPS receivers in the area, and could even jam differential receivers. In the GPS design the satellite antenna patterns are tailored to provide a fairly constant signal to receivers on the earth. Since the signal power received by a user falls off as the square of the distance from the receiver, large variations of signal will occur with a differential transmitter. Users close to the station would experience a large signal, which could cause interference with the satellite signals and could even cause false lock, or saturate the RF amplifier. Several techniques have been proposed to alleviate the situation, but none appear to be entirely satisfactory. Time multiplexing looks to be quite promising, wherein the ground station transmits only 1 millisecond out of 20. However, if those transmissions coincided with satellite data bit phase transitions, data could be lost which might not be reacquired for up to 30 minutes. Frequency multiplexing does not appear to substantially reduce interference, while the use of a separate frequency in the GPS band would require a separate IF section, which would be expensive.

There are other problems as well. For aircraft usage, a bottom-mounted antenna might be required for satisfactory signal reliability; this would add considerable expense for an airborne user. For applications where users might be blocked by terrain from line-of-sight reception of the ground station transmissions, there is no method of relaying the signal or of using multiple transmitters. Such users would just lose the signal. This consideration makes the pseudosatellite look less feasible for marine applications in harbors and inland waterways, where experience with VHF communications has established the considerable difficulties with providing coverage in such areas.

If the difficulties can be surmounted, pseudosatellite operation appears to be very attractive for a large number of users. The station clock should then be a high-quality clock with good long-term stability as well as short-term stability. A rubidium or cesium standard should be employed. The transmitter antenna should be designed to give good low angle coverage down to about 3 degrees to cover aircraft approaches to airports. The antenna design should exhibit a rapid falloff in antenna pattern below 3 degrees to reduce multipath. Multipath would reduce the effectiveness of the station by increasing the error in range to the station. The contradictory requirements of low-angle coverage and low multipath make it difficult for surface users to be accommodated by the pseudosatellite.

8.4.5 Data Link - External Communications

For applications where a pseudosatellite is not applicable, it will be necessary to broadcast the corrections on a separate data link. This link could be devoted to differential corrections, or could be shared with other services. There are several types of communications that could be employed.

1. Line-of-sight (e.g., VHF, L-band, microwave), wherein the transmitter tower must be strategically located and tall enough to be visible to the users in the coverage area.

2. Ground-wave (e.g., radiobeacons), wherein the frequency is low enough to reach targets beyond the horizon.

3. Satellite relay, whereby signals are transmitted to a satellite relay station, and retransmitted to earth.

Satellite relay communications do not appear to be attractive because of the expense of the user equipment and the leasing of time on the satellite. Line-of-sight and ground-wave communications appear to be the most likely candidates, but each has its limitations. Earth curvature limits line-of-sight communications between station and surface users to 15 to 20 miles. Thus, several transmitting stations would be required to cover an area such as Delaware Bay. In principle, ground-wave propagation using low frequency (LF) and medium frequency (MF) bands could be used to increase the range, since such signals can be received by users beyond the horizon. However, competition for radio spectrum allocation is severe. One possibility is to use marine radiobeacons in the 275-335 kHz band.

Some of the advantages and disadvantages of different communications bands and existing broadcast facilities are discussed below:

1. LORAN-C - The 100 kHz band is ideal for broadcasting over-the-horizon signals. Three or four stations could serve the entire eastern coast of the U.S., for example. LORAN-C transmitters can and have been modified to transmit data, but it does not appear that this approach is feasible. If a non-LORAN modulation is used, it will interfere with LORAN-C. Using LORAN-C modulation requires a costly data receiver, which is not desirable.

2. VHF Communications - VHF is a likely communication medium for line-of-sight applications. Both air and marine users have assigned bands that could conceivably be used for differential broadcasts. The accessibility of these frequency bands for navigation use is considered to be more problematic than other techniques, so that this should be explored further only if other means are not available.

3. Radiobeacons - The LF and MF bands used by air and marine radiobeacons appear ideal for providing over-the-horizon coverage. The technical problems involved with modulating the radiobeacon transmitters appear to be quite tractable, and the resulting communications receivers would be quite inexpensive. Differential OMEGA corrections are currently being broadcast by radiobeacon units in Southern Europe, and these units are under evaluation by the U.S. Coast Guard for use in Puerto Rico.[35] Ranges of 100 km are possible

in principle, but most radiobeacons are more limited in range as they are currently employed.

4. Satellite Communications - Satellite broadcast of differential GPS corrections is considered to be unlikely for many users due to the weak signal and directional antenna requirements. It was noted that oil exploration companies might implement such a system through INMARSAT for some applications. It was also noted that it might be possible for a country or continent to provide a special satellite to augment GPS coverage while providing differential GPS signals.

5. Mode-S - The Mode-S transponder system for airborne air traffic control use incorporates a data link. The specifications for this data link are now being developed. It is expected that most aircraft will have these transponders in the early 1990's. It would be convenient to have the data link message from the ground include differential GPS corrections.

In summary, the external data link can be implemented in a variety of ways using any of several different frequencies. The problems lie in selecting the best implementation techniques and obtaining the necessary institutional acceptance.

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.

8.4.6 Receiver Design Implications

Civil usage of differential NAVSTAR GPS service will include commercial, research, search-and-rescue, and pleasure modes of operation. Receiver designs may differ significantly, so the differential service provided must allow for these differences. Mask angles, the number of satellites used in the navigation solution, and the algorithms used can differ. Some receivers may be single-channel, others dual-channel, and still others may have multiple-channel parallel operations. The dual-channel design, for example, offers some significant performance advantages for aircraft: redundancy, all-in-view satellite capability, quick startup, and smoother navigation during satellite transitions. A dual-channel experimental receiver has recently been developed and demonstrated by M.I.T. Lincoln Laboratory for the FAA [16].

Since the user makes use of corrections determined at the differential site, a data link receiver is required as well as a navigation receiver. If the system incorporates a pseudosatellite, this receiver is realized by channel management software--no separate communications interface is needed. The software generates the appropriate "satellite" code for the receiver, directs the data management software to interpret the data differently than usual, and instructs the navigation processor how to treat the data. If the system requires a separate data link, however, a communications interface and communications receivers must be added to the user equiment. The channel management software must also be modified to handle this differential data.

8.5 PERFORMANCE ESTIMATES

8.5.1 General

Performance estimates derived in this section are intended to predict performances and to present a comparison of the navigation accuracies of a variety of users. Numerical values are based on computed or predicted performance estimates. Field tests conducted on the pseudorange measurements by others are compatible with our predictions. While the performance predictions are made in absolute terms, emphasis should be placed upon the relative accuracy of one system as compared to that of another. Both systems are compared under a common set of assumptions wherever possible.

Several noise and bias components enter into the positional error determination of a user's receiver. Although noise components are assumed to be stationary random processes some discretion is used in estimating bias and noise errors during the short intervals when measurements are being taken. The following are the typical sources of errors in the measurements.

RECEIVER NOISE - code tracking loop error due to thermal receiver noise.

UNCERTAINTY IN THE REFERENCE SITE MEASUREMENTS - the noise error component associated with the reference receiver; it is seen by the user as a bias in the measurements.

EPHEMERIS - residual error in the ephemeris correction; it increases linearly with separation of user and reference site. In the absence of Selective Availability, this term is negligible.

USER CLOCK NOISE - Phase noise in the user clock, appears as receiver noise.

RANGE QUANTIZATION - noise error in pseudorange due to limited code tracking resolution of a particular receiver design. A unit designed for differential use would use enough resolution to reduce this to negligible levels.

IONOSPHERIC BIAS - bias error due to different paths being traversed by a satellite signal to the user and the reference site. By proper use of models, this can be limited to the differences caused by ionospheric inhomogeneities, which are usually less than a meter.

IONOSPHERIC NOISE - Noise error due to short term ionospheric fluctuations. This is small and is considered negligible.

TROPOSPHERIC BIAS - Bias errors in the correction estimates for receivers at different altitudes and distances from the reference site. This error is zero near the reference site, and can be estimated fairly well with models. Fluctuations in temperature and humidity leave a residual error.

TROPOSPHERIC NOISE - Noise error in the measurement due to tropospheric fluctuations.

MULTIPATH - Noise error caused by reflections of the satellite signals from terrain and buildings.

MULTIPLE ACCESS INTERFERENCE - Interference from other satellites; up to 1 db interference noise in the receiver.

These noise sources and their magnitudes are discussed in Appendix K.

In addition to the performance of the differential station, the performance of three classes of user receivers was analyzed based on their unique service requirements. The three classifications are:

1. Marine navigation receiver.
2. Airborne receiver.
3. Marine/Land navigation receiver.

The performance estimates for these different users are given in Sections 8.5.2 - 8.5.4. The performance of the baseline differential station is estimated below.

In a differential system, it is somewhat arbitrary whether errors are ascribed, to the user or to the reference station. In this report, all errors will be ascribed to the user except for the uncertainty attributed to the differential station measurement. The differential station uncertainty is caused by receiver noise, multipath, range quantization, and surveying error. The last two are assumed to be negligible.

Multipath is site-dependent, varies with satellite elevation angle and differs in azimuth. With proper siting, large multipath errors can be avoided, leaving effects of surface reflections, which are significant only at low angles, i.e., below 10 to 15 degrees elevation. A value of one meter (one sigma) uncertainty is budgeted for multipath.

Receiver noise depends on the code loop band width, any navigation program smoothing, and a number of design options such as tracking technique, employment of "prompt" correlation, and code loop detection technique. Assuming a parallel-channel receiver with coherent detection, and a code loop bandwidth of 0.1 Hz, errors due to receiver noise can be limited to 1.6 meters (one sigma). The variation of the delay caused by Selective Availability limits the amount of smoothing that is effective. That is, further resolving of the code loop bandwidth would result in loss of lock, and smoothing by a navigation filter would not be effective.

Therefore, the uncertainty of the reference station is estimated from the multipath (1 meter) and receiver noise (1.6 meters) to be 1.9 meters (one sigma). This uncertainty is passed along as a bias error to the users, whose correction estimate for each satellite obtained from the differential station has this error in it.

8.5.2 Marine Receiver Performance

The sources of error for a marine receiver are those cited in 8.5.1. The total potential error is dominated by the receiver noise, and the amount of smoothing that is allowed by dynamics of the vessel. A vessel on the open ocean would experience considerable pitch, roll and heave variations. A Kalman filter designed for such an environment would look quite different from one designed for navigation in harbor or inland waters, where wave and wind actions would be less severe. Since there is no need to obtain the accuracies enabled by differential operation for ocean or coastal phases of navigation, differential operation should be employed with a Kalman filter designed around the more benign harbor environment vessel dynamics. It will be assumed here that noise variations can be smoothed during differential operations. A code loop bandwidth of 0.3 Hz is assumed. Other parameters are given in Table 3-5.

The error sources and their effects are estimated as follows for a marine receiver 50 km from the reference station (one-sigma values are used):

Receiver noise error	-	5.2 meters
Multipath error	-	1.0 meters
		Total noise error - 5.3 meters
Differential Station Uncertainty	-	1.9 meters
Ephemeris bias due to SA	-	1.2 meters
SA error growth after 12 seconds	-	1.1 meters
Ionosphere, troposphere	-	0.5 meters
		Total bias Error - 2.6 meters

The noise error for a sequential receiver can be reduced further by smoothing by a factor of 2, to 2.65 meters. This gives a total pseudorange error of 3.7 meters (one sigma). With a median HDOP of 1.5, this corresponds to a positional error of 11.1 meters (2drms).

The performance can be improved by using more expensive receivers. If a parallel-channel receiver is used, the smoothing can reduce the noise by a factor of 3, which would give pseudorange errors of 3.1 meters, equivalent to a positional error of 9.4 meters (2drms).

Therefore, it appears that GPS is a promising candidate navigation system for providing Harbor/Harbor Entrance guidance. These estimated performance figures compare well with the 8 to 20 meters cited as a requirement in Table 2-4.

8.5.3 Airborne Receiver Performance

An airborne receiver must operate in a much more dynamic environment than one for marine usage. A sequential, dual-channel receiver is assumed, having the design characteristics shown in Table 3-3. By virtue of the 6 Hz code-loop bandwidth, the noise error is considerably higher than for a marine receiver. The wide bandwidth is needed to accommodate the short satellite dwell time of the receiver (220 milliseconds).

The error sources and their estimates are given below:

Receiver noise error	-	19.3 meters (one sigma)
Multipath error	-	1.0 meters
		Total noise error-19.4 meters
Total bias error	-	2.6 meters (from 8.5.2)

Smoothing by the navigation filter can reduce the noise error considerably. A factor of 2.5 is assumed here, based on experience with simulations. This gives a noise error, after smoothing, of 7.7 meters (one sigma). Combined with the bias errors of 2.6 meters, gives an estimate of 8.1 meters for the total one sigma error. With an HDOP of 1.3 (median value for an all-in-view receiver), the horizontal position estimate is thus 21.1 meters (2drms). The altitude computed using GPS would have about a 32 meter error (2 sigma), assuming a VDOP of 2.0.

Parallel-channel operation would provide considerable improvement, enabling 1 Hz code-loop bandwidths to be employed in the receiver, although further smoothing would not be as effective.

While the accuracy is far better than that provided by existing FAA navigation facilities, it does not provide Category I guidance, which calls for 9 meters lateral and 3 meter vertical accuracies. It is close enough, however, that improved techniques may eventually provide at least the lateral precision required.

8.5.4 Land Receiver Performance

A land receiver would employ a design similar to a marine receiver. It would probably be of an inexpensive, sequential design. Table 3-7 shows a set of typical parameters for a land receiver. With a code-loop bandwidth of 1 Hz, the error sources and their effects for a land user 50 km from the reference station are estimated as follows:

Receiver noise error	-	9.5 meters
Multipath error	-	1.0 meters
		Total noise error - 9.5 meters
Total bias error (from 8.5.2)	-	2.6 meters

Smoothing by a navigation filter would provide some smoothing, but not as much as for a marine user. A factor of 1.5 is assumed. This gives a total pseudorange error of 6.8. For an HDOP of 1.6, based on a 10-degree mask angle and a best-set-of-four satellite selection algorithm (Table 7-1), this implies a 2drms error of 21.9 meters.

With this accuracy, land vehicles could in principle identify the block in a city or town in which they are located. Most homes and buildings could be uniquely identified by GPS location. The possible uses of this precise positioning accuracy have yet to be explored.

9. 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 does not 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. Some differences would be expected, but we have no explanation for these differences. 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 patterns. These subcomponents are:

Antenna
Microwave Circuits - preamp, local oscillator, RF mixers
Precision Oscillator (Clock)
Analog Signal Processing - filters, IF amplifiers, mixers
A/D Converters - analog to digital
Random Logic - gates, buffers, shift registers
Memories, Program and Data - includes ROM and RAM
Software - cost of programming
Microprocessor
Power Supply Regulators and Converters
Enclosure and Chassis
P. C. Boards
Display and Controls

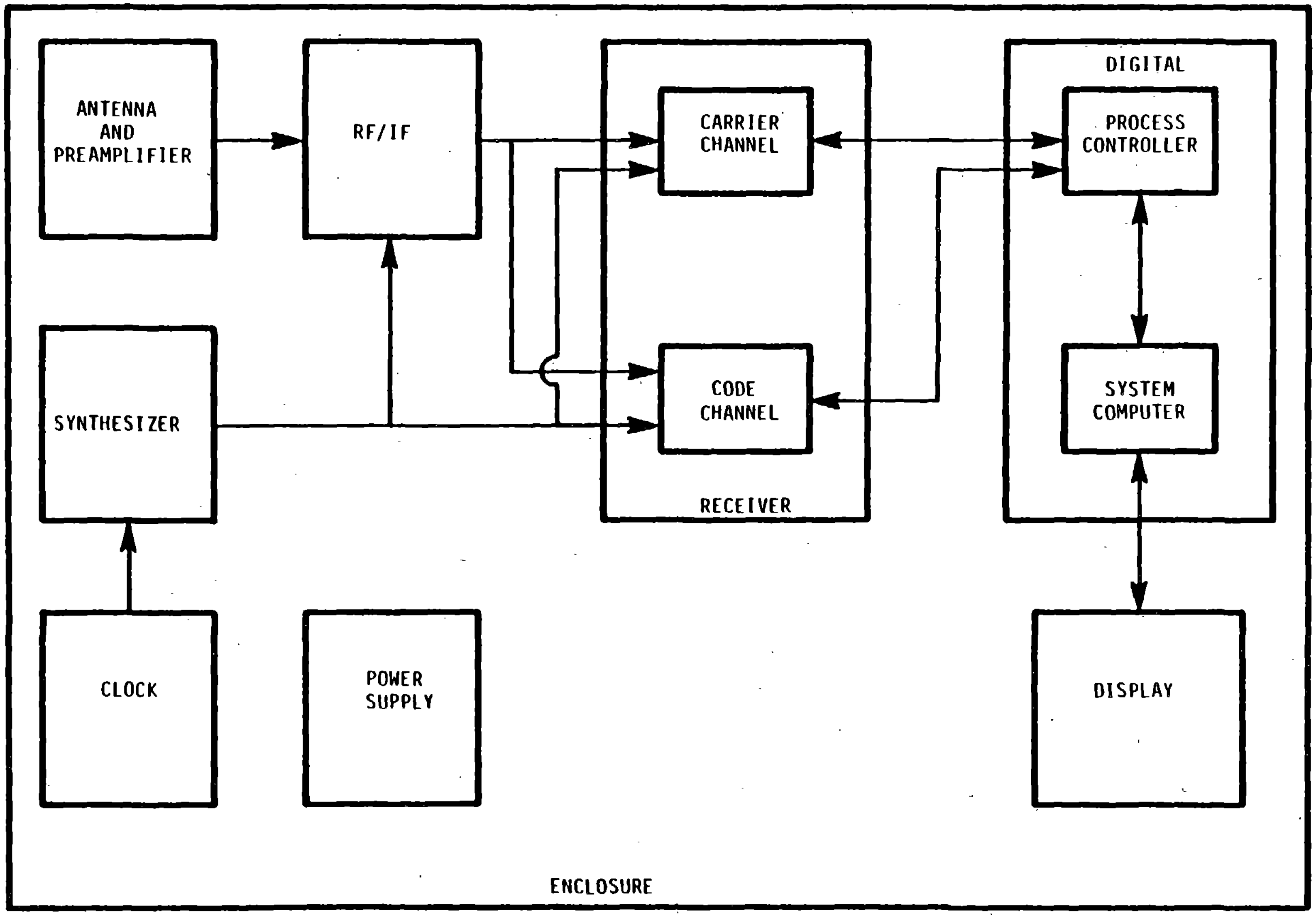


FIGURE 9-1. COSTING MODEL BLOCK DIAGRAM FOR SINGLE CHANNEL RECEIVER

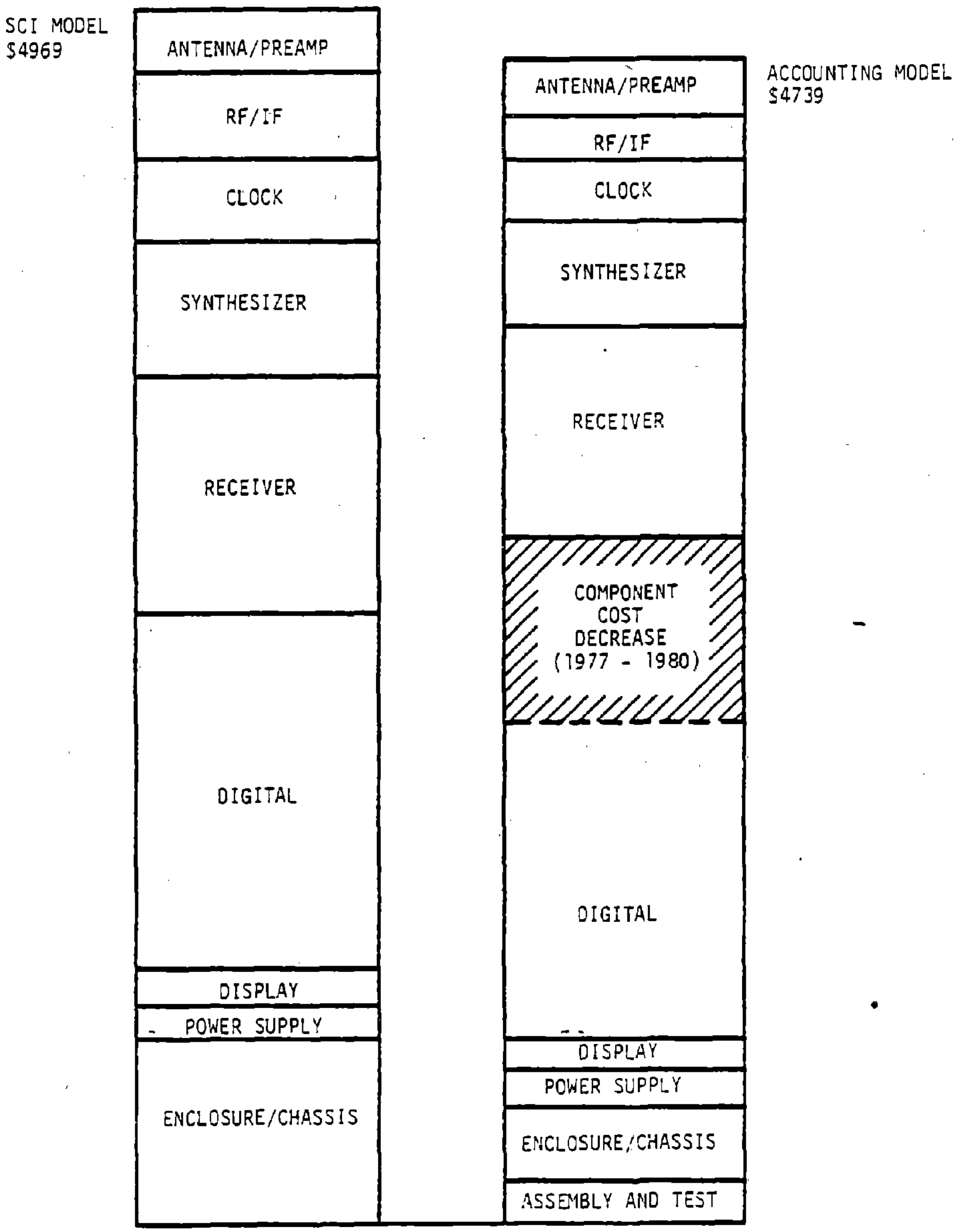


FIGURE 9-2. GPS RECEIVER COST ESTIMATE, TWO MODELS (1982 DOLLARS)

Each function of Figure 9-2 uses a definable number of these subcomponents. By using SCI's costs for the base year, and the predicted trending equations, receiver costs can be estimated for any desired future time. The trending equations involve either one or two exponentials; if one, they have the form $\exp((t-t_b)/T)$, where t is the future time, t_b is the base time, and T is the trend parameter. After T years, the price is predicted to reduce to 1/e = .37 of its base year price. This is explained further in Section 9.3.

Using the subcomponent costs and trend parameters of SCI's model, the predicted prices of single-channel GPS receivers are the following (using 1982 dollars):

1980 - $4969
1990 - $2850
2000 - $2160

Appendix E shows a similar chart, but using 1980 dollars. The method used to obtain 1982 prices from 1980 prices separates the labor and material costs. In Section E-2 of the Appendix it is noted that material costs of equipment appear to track variations of the Producer Price Index (PPI), 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 fewer 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 receiver price in 1990 and 2000. Since doubling the cost-halving period implies a slower rate of price decrease, the effect is to increase the price. The process is then repeated by assuming a cost-halving period of half the original and observe the resulting cost decrease. Figure 9-3 shows the results for 1990, and 9-4 shows the similar results for the year 2000.

For example, the figures show that the big-leverage items are the analog signal processing, the random logic, and the enclosure subcomponents. Inaccurate predictions of costs for these items have a more serious impact on the error in predicted receiver price than do the other subcomponents. It is apparent from the figures that the impact of erroneous predictions for any of the subcomponents will change the price by less than 8%. In fact, if all subcomponent trend predictions were simultaneously optimistic (or pessimistic), the price difference would be 25% (-20%) for 1990, and 30% (-26%) for 2000.

These figures can serve as a measure of uncertainty of the predictions. By bracketing the expected error in trends by assuming the cost-halving periods are accurate within a factor of two, the price of a low-cost receiver should be $2290 to $3585 in 1990, and $1628 to $2830 in the year 2000.

9.4 DUAL CHANNEL RECEIVER

To estimate the dual channel receiver costs, the same basic receiver architecture is used as for the single-channel receiver of Figure 9-1. Adding a second channel, shown in Figure 9-5, involves adding a base-band receiver with its code and carrier channels, plus a process controller for the second channel. The system computer is considerably more complex, especially if a single-channel backup mode is required, whereby the healthy channel takes over both navigation and data functions in case of a channel failure. Thus, the number of subcomponents associated with the receiver function is doubled, and more memory and processing capability is required, increasing both digital and software "subcomponents" by about a factor of two. Enclosure and power supply costs are also increased. The result is shown in Figure 9-6.

The increase in cost over a single-channel receiver is about 45%. A large 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 also to reduce the cost ratio. As a rough estimate, dual channel receivers wil probably cost about 25% to 30% more than single-channel receivers.

9.5 IMPACT OF POSSIBLE CHANGES

9.5.1 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 iononspheric/tropospheric path, the inherent precision of the C/A signal is the same as the P-code, namely in the 5 to 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.

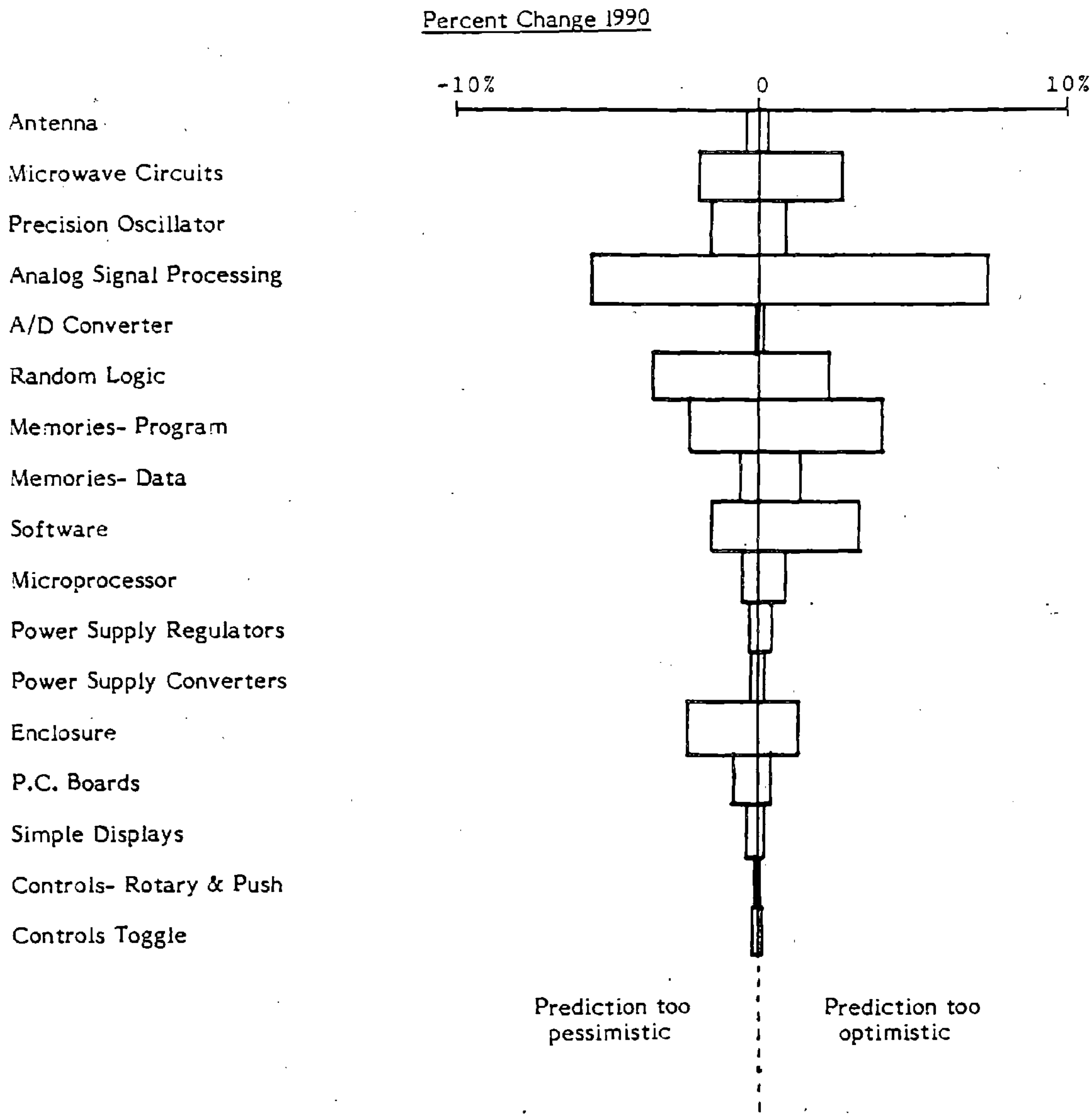


FIGURE 9-3. SENSITIVITY OF RECEIVER COSTS TO PREDICTION ERRORS IN TRENDS - 1990

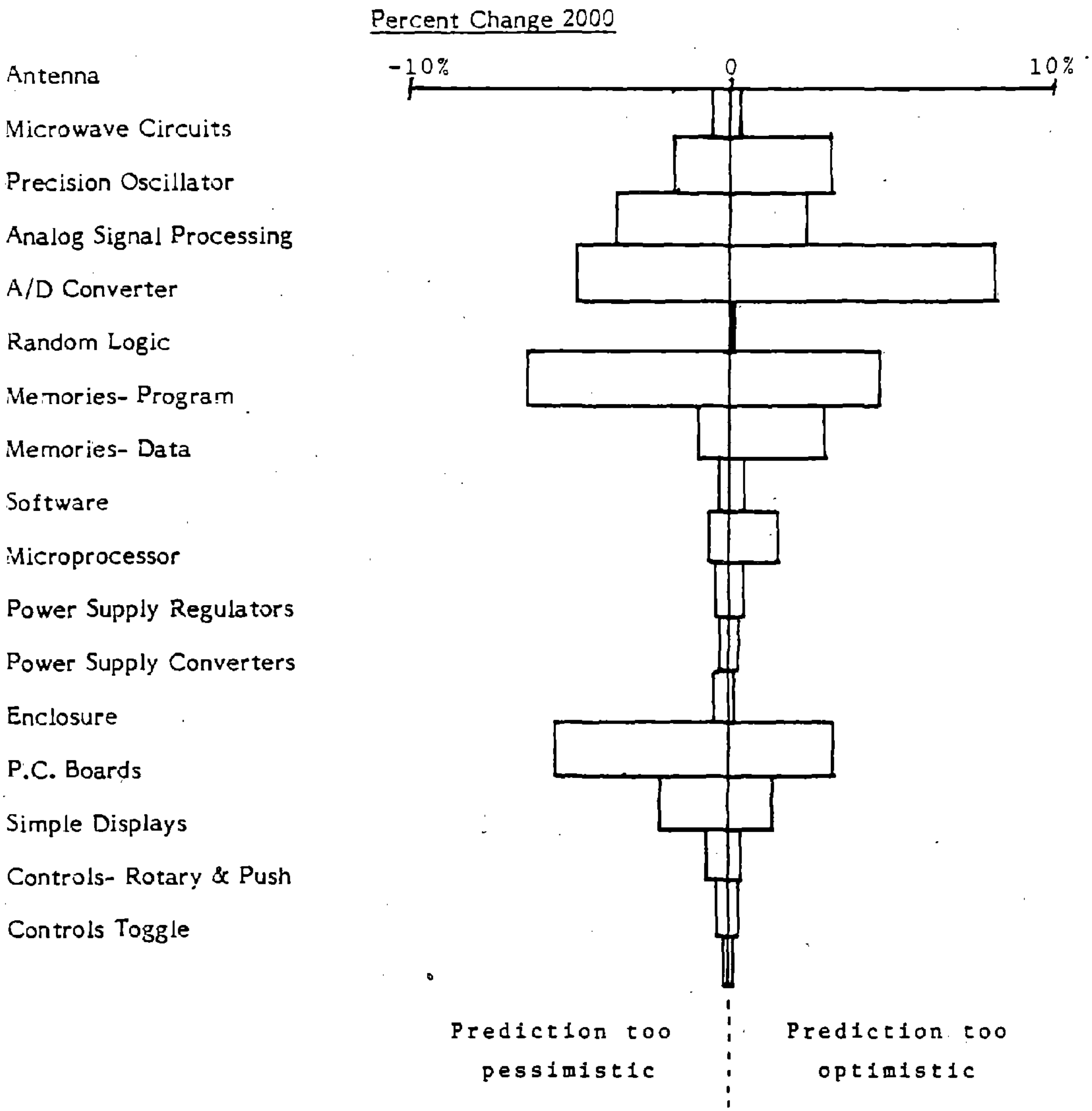


FIGURE 9-4. SENSITIVITY OF RECEIVER COSTS TO PREDICTION ERRORS IN TRENDS - 2000

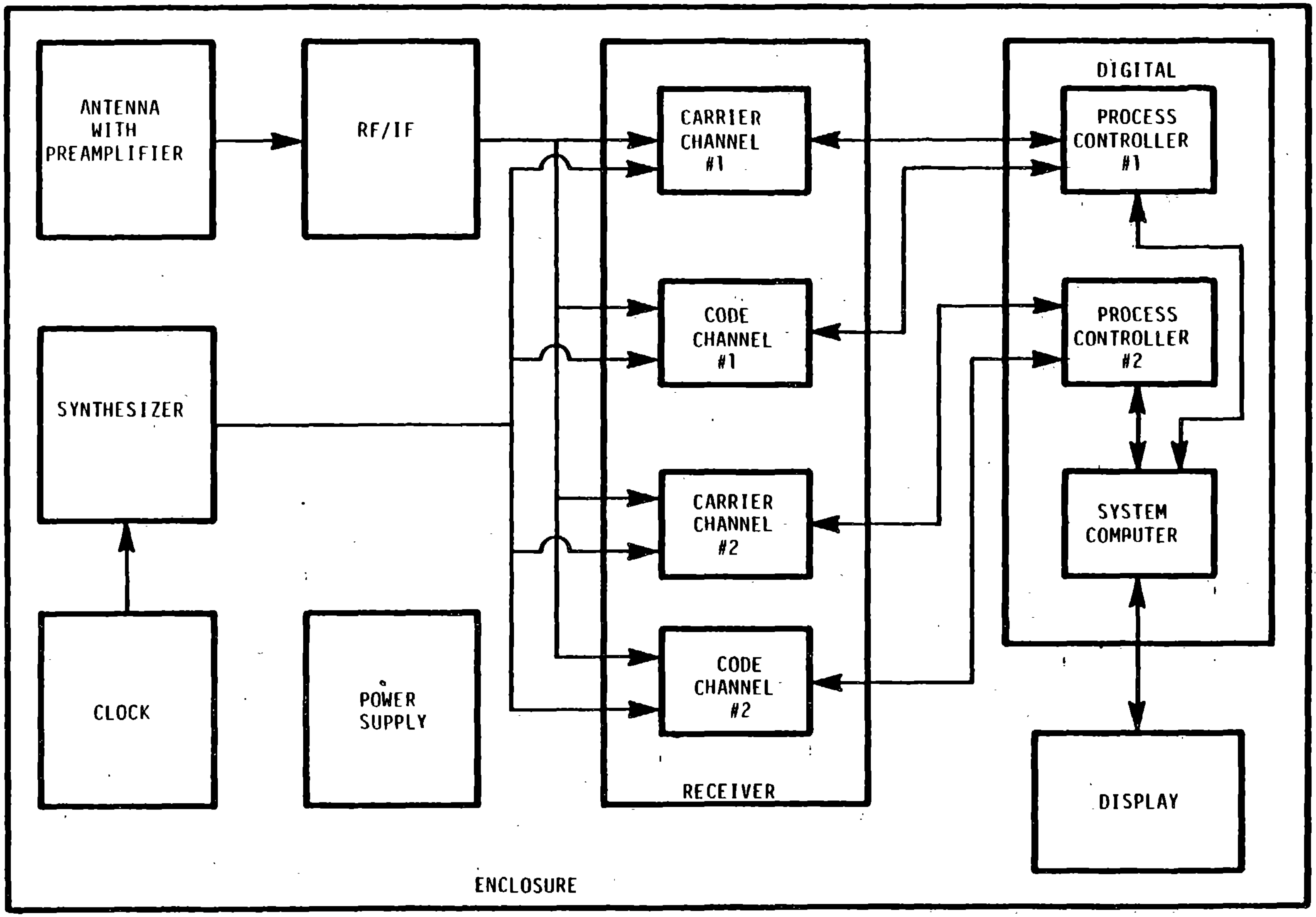


FIGURE 9-5. COSTING MODEL BLOCK DIAGRAM FOR DUAL CHANNEL RECEIVER

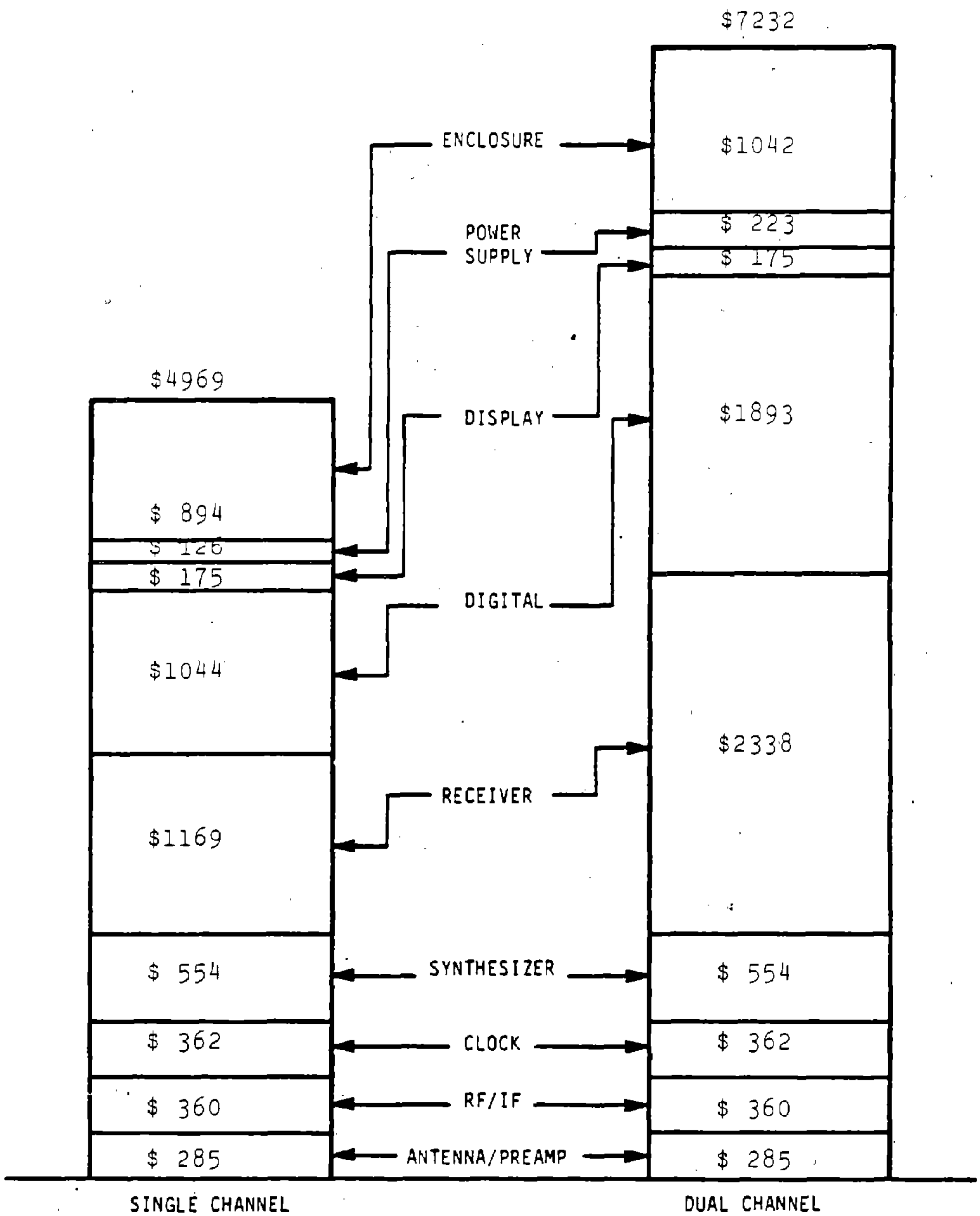


FIGURE 9-6. GPS RECEIVER COST ESTIMATE, DUAL CHANNEL RECEIVER

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 pseudosatellite, 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.

The first would be required by a user who did not already have a data link capability. It would entail the expense of a data link receiver, installation of a separate antenna, the communications interface in the GPS unit, and software to accommodate the correction terms. These would be added to the basic cost of the GPS receiver. The implementation would require a data link frequency allocation by the provider of the service.

The second would be required by a user who already owned a data link receiver. It might have to be modified to output the differential corrections to the receiver. It would entail a communications interface and software over and above the GPS receiver. The provider of the service would have to negotiate the use of the data link for this purpose.

The third is associated with the pseudosatellite approach. It is the least expensive option for the user, since changes are necessary only in the channel management and navigation software. Interference to GPS users near the transmitting station may preclude this option, however.

These alternatives are currently under evaluation from both the performance and cost standpoints.

9.5.2 <u>Selective Availability</u> - The Department of Defense currently plans to provide a nominal 500-meter accuracy service to civil users, called Standard Positioning Service (SPS). While the accuracy possible using the C/A code is closer to 30 to 50 meters (2drms), national security considerations have led the DOD to implement a program called Selective Availability (SA). Under SA there may be several years during which the signal will be degraded to 500 meters accuracy, or be subject to periods of this degraded accuracy. This is, while the signal might be more accurate, users of SPS could not depend on it.

Since any signal degradation imposed will be undetectable by the user, no direct impact on receiver costs is anticipated. Indirectly, however, there could be 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.

9.5.3 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.

9.5.4 Improved Technology - There are a number of areas of technology where developments are occurring frequently, and which have applications to GPS receiver/processors. It is well known that computer-related components are rapidly increasing in speed, memory size, and capability; they are also decreasing in power requirements, physical size, and cost. While such developments have the direct effect of lowering the cost of imlementation of a given design, at some point they enable a qualitatively different design approach to be used. Some of these technological areas are now discussed, approximately in order of their expected realization times.

A. Digital Baseband Receiver - There appear to be no compelling reasons for performing code-tracking, carrier-tracking and carrier-tracking with analog components any longer. The Experimental Dual Channel Receiver (EDCR), which recently was tested by Lincoln Laboratory [10] for the Federal Aviation Administration, met design goals and works quite nicely. The baseband signal is sampled at 2kHz, and all the code-tracking, carrier tracking, data demodulation, AGC and lock detection are performed in software. The carrier error variable drives a numerically controlled oscillator (NCO) to achieve frequency tracking, but code tracking is performed digitally. Thus, this technology is available today.

B. 16/32-bit Microprocessor - New experimental receivers are beginning to incorporate 16-bit microprocessors. The EDCR has a separate 16-bit Zilog 8000 microprocessor for each channel. Another 16-bit processor (LSI-11) is used for the navigation and channel management functions. There are several advantages in the new generation of 16-bit microprocessors: (1) they can be run at higher clock rates (5 to 15 MHz), (2) they are more efficient in addressing and arithmetic operations, and (3) some, at least, obviate the need for auxiliary floating point processors. It appears to be possible for one 16-bit microprocessor to perform all the channel management and navigation tasks, as well as the data demodulation and carrier/code tracking requirements of a single-channel digital baseband receiver.

C. High-Speed Digital Circuitry - The next generation of GPS receivers is expected to replace analog correlation with digital correlation techniques. Thus, for example, 20 MHz sampling of the signal at IF allows the C/A code to be matched against ten different codes, while maintaining the full information in the C/A signal for each code. Lincoln Laboratory [10] terms this the "virtual channel" 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. 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.

D. 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.

9.5.5 Large Volume Sale of Receivers-If an extensive consumer market develops for NAVSTAR GPS receivers, the price of inexpensive receivers could drop to the $500 level by the year 2000, if not well before then [36]. Such receivers would make use of custom LSI technology: for example, each receiver channel might be a separate chip, and the navigation processor and channel management functions might be on a single chip. Such custom devices might find use in commercial equipment. If not, at least many of the basic masks would be usable for the development of integrated circuits. The effect would certainly be to significantly reduce the cost of commercial receivers.

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. Under the recently announced policy of 100 meters (2drms) accuracy for SPS, non-precision approach requirements will be met. This makes the system attractive for oceanic en route 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 at airports where a VOR facility is installed. With differential operation, non-precision approach guidance accuracy is readily achieved.

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

c. Availability - The seriousness of this problem area for NAVSTAR GPS, is not yet clear, and may not be until the system is operational. With the new satellite spare-location strategy, outages caused by satellite alignment have been eliminated for receivers with mask angles of five degrees. However, the FAA believes that a ten-degree mask angle is necessary to guarantee accuracy for low-lying satellites. At low elevation angles, multipath can be more of a problem, since the antenna pattern discrimination against reflections is not as strong, and since the reflection coefficients of land and water are maximum there for vertical polarization (the antenna polarization is essentially linear near the horizon). When an airplane banks, the antenna discrimination against multipath decreases and antenna polarization has an increased horizontal component. In addition to multipath, low-lying satellite signals have a higher noise content. How serious these problems are in practice has not yet been determined. The technique of "clock coasting" appears to be promising, but the studies are not conclusive.

d. Reliability - It is this category where primary and secondary usage have different requirements. A primary system must have high reliability, while for a secondary system the requirement is not as stringent. As a secondary system which provides good guidance when the service is available, GPS has more than adequate reliability. The satellites are designed to have an MTBF of about 7 years.

As a primary system, the reliability must be extremely high, or incorporate a universally-employed backup that requires no significant procedural changes. For example, a backup system that required a sudden change from great-circle to point-to-point flight paths would not be acceptable. The VOR/DME system is highly redundant, in that loss of a station is not serious. Loss of a satellite, however, can cause outages of 20 to 60 minutes at some locations in the U.S.

NAVSTAR GPS may in fact prove adequately reliable in practice, but this will have to be demonstrated. However, serious consideration should be given to augmenting the 21-satellite GPS in order to provide backup in case of satellite outage.

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, and enables fishermen to return to favorable fishing spots. The SPS provides nominally 500 meters (100 meters under the new policy). 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 to 10 meters (2drms) is cited as a requirement for HHE [2], and even with SA turned off, the expected accuracy of GPS is 20 to 40 meters, which would be adequate for navigation in less stringent harbor areas. With differential operation, 10 to 15 meters appears to be achievable. Since this is the middle of the 8 to 20 meter estimated requirement, it appears that the usefulness 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, 2 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 (100 meters under the new policy) under Selective Availability.

c. Availability - Outages that occur for airborne receivers can be avoided for marine receivers by proper choice of receivers, i.e., those that require only three satellites to obtain a navigation solution. Such receivers do not experience the same geometric outages, and are less vulnerable to the loss of a satellite. Operationally the availability requirement is much less severe for most marine applications. Oceanic and coastal navigation require only periodic fixes. Inland waterway and harbor area navigation during periods of low visibility do require continuous operation.

The availability of NAVSTAR GPS appears to meet these requirements and the ones formally stated in Section 2.3.

d. Reliability - Reliability requirements are not as stringent for ships as for aircraft. Only for HHE and Inland Phases of navigation is continuous service required. Even these brief outages could be dealt with if they were predictable, since the master could avoid navigating narrow channels at those times. The likelihood of a satellite going out during a maneuver is miniscule. Furthermore, the absence of one satellite rarely causes a problem. The likelihood of a problemmatic outage occuring during a low-visibility situation is rare indeed. Notices to Mariners would incorporate any long-term satellite faults and describe the area and time of day where any outages might occur.

It appears that NAVSTAR GPS reliability is adequate for marine users.

10.3 ABILITY OF NAVSTAR GPS TO MEET LAND APPLICATIONS REQUIREMENTS

The land-based usage of NAVSTAR GPS could well prove to be the most extensive in the long run, especially if receiver costs could be reduced enough to be within reach of the consumer market. However, it is difficult to define formal requirements for land uses, because there is no federal mandate to set safety requirements in this area, and because there is very little experience with land navigation at all.

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 not 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 (100 meters under the new policy) 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.

10.4 RESOLUTION OF THE ISSUES

The ten issues identified in Section 1.4 were addressed in this report, but not in the order listed there. In order to provide a concise account of the relation of the work to the issues, the following sections summarize the conclusions by issue.

10.4.1 ISSUE 1: Satellite Outages

At the time the project began, it was planned to provide 18 satellites in the NAVSTAR GPS constellation. In this constellation, outage periods of 5 to 25 minutes would occur twice a day in several regions of the country. Since then the Joint Program Office announced the intention of providing three active spares, and locating them in such a way as to remove these outages over the CONUS.

In this report it was shown that the outages would indeed be removed for receivers utilizing a mask angle of 5 degrees, but outages still would occur for receivers with 10-degree mask angles. Further study showed that the outages disappear with 8-degree mask angles. Based on this, it is recommended that 8 degree mask angles be employed for civil users requiring 3-dimensional navigation data.

For users requiring only 2-dimensional navigation or positioning data, only 3 satellites are required for establishing a solution. For these users the outages do not exist even for the 18 satellite constellation, so there is no outage problem.

10.4.2 ISSUE 2: Satellite Failures

In general, once satellites have been launched and satisfactorily operated for a time, failures are usually not catastrophic. More typical are performance reductions, such as reduced power and reduced clock stability. However, it is difficult to develop a figure of merit to describe such a situation. Furthermore, there is a threshold of performance which renders the satellite signal unusable for some applications. The approach used here thus assumes the loss of a satellite and involves a computation of the resulting dilution of precision measures over the CONUS.

In the analysis, one satellite at a time is removed and the resulting locations, times, and durations of outages over the CONUS are determined. Assuming an equal likelihood that any particular satellite might fail, some locations are more likely than others to be affected by a satellite fault. Resulting outage times vary from 10 to 60 minutes per day. While some satellites faults cause more serious and extensive outage periods than others, the faulting of any satellite will cause outages somewhere in the CONUS during the day.

10.4.3 ISSUE 3: Temporary Loss of Satellite Signal

Simulations run using the AIRGPS receiver model indicate that temporary loss of a satellite signal does not significantly degrade the accuracy of the navigational solution if a medium-quality clock (one with a short-term stability of one part in 100,000,000) is incorporated in the receiver. The effect of a poor-quality clock (short-term stability of one part in 10,000,000 or more) is evidenced by larger errors. Medium-quality clocks can be obtained in small numbers for less than $100. For any application requiring continuous high accuracy, such as terminal-area aircraft guidance, receivers should be equipped with such clocks.

It should be noted that it is necessary to have enough satellites in view when a set is turned on in order to establish a good time estimate. Subsequent brief periods where only three satellites are in view can then be accommodated.

10.4.4 ISSUE 4: Selective Availability

If the current plan of the Department of Defense is carried out, namely to provide 500 meter (2drms) service (100 meters under the new policy) for Standard Positioning Service (SPS) when the system becomes operational, there are a number of navigation functions which NAVSTAR GPS cannot provide. Non-precision approach guidance service, for example, calls for 100-meter (2drms) accuracy. Search and rescue marine operations and harbor navigation guidance would be compromised. Repeatable accuracy needed by commercial fishermen would not be provided, even though it is currently available from LORAN-C.

The Office of the Secretary of Defense recently announced [37] that the level of service to be provided by SPS will meet that of any other federally managed navigation system. While not definitive, it strongly suggests that an accuracy level closer to 100 meters (2drms) may be offered when the system becomes operational. If this occurs, GPS will support non-precision approaches, search and rescue operations and navigational guidance in a number of harbor areas. This is now official policy.

10.4.5 ISSUE 5: Differential GPS, Without Selective Availability

Ignoring Selective Availability, differential corrections would remove errors caused by inadequacies in the ionospheric and tropospheric models used by a receiver. In the absence of SA, these are the dominant error sources. A receiver near the differential reference station could achieve accuracies limited only by his receiver noise, i.e., 10 meters or less. Receivers further away from the reference station would incur errors due to inhomogeneities in the ionosphere and troposphere, typically on the order of a meter or less. Errors due to altitude separation between user and station, due to elevation angle differences, or due to ionospheric shell spatial variations, can be modelled out by the user receiver who desires the additional accuracy.

By employing carrier Doppler measurements, it may prove possible to make sub-meter measurements for stationary receivers, which could have significance for surveying, geodesy, and charting applications. Special differential messages would need to be broadcast for these applications.

10.4.6 Differential GPS, With Selective Availability

The imposition of Selective Availability adds relatively large errors in the position determination of conventional receivers. The time variations of Selective Availability also dominate the time variations of the satellite ranging signals. However, with differential operation these deliberate errors can be counteracted in a local area. The broadcast of these corrections poses no security problem.

The corrections virtually cancel the effects of SA (as well as those of the ionosphere and troposphere) for users near the reference station, immediately after the corrections are applied. After a few seconds the positional accuracy begins to degrade. For marine applications, it appears that 10 to 15 meter accuracy can be attained with correction updates every half minute.

In a recent workshop at TSC, a strawman format was developed for the broadcast of differential corrections, which enables updates every 12 seconds. In addition to broadcasting pseudorange corrections, the format calls for broadcasting range rate corrections as well, which further improves the accuracy between updates. It thus appears that the accuracy achievable with differential operation is limited by the noise limitations of the user's receiver. This in turn depends on the dynamics of the user platform. The more benign the accelerations involved, the more precisely the user can determine his location.

10.4.7 ISSUE 7: Receiver Cost vs. Level of Service Provided

Using the technology of 1979, the cost of a general aviation or small commercial marine receiver is estimated to cost about $5000 in 1982 dollars. Such a receiver would employ a sequential design and have one channel. It would lose accuracy during aircraft maneuvers. To achieve the next increment of performance for an aircraft receiver, a dual channel design would probably be employed, which would increase the cost by about 40 to 45%, or $7000 to $7300. By the year 2000, the price of a similar design would be expected to drop to about 40%, or about $3000.

However, receiver technology is changing rapidly to take advantage of the dramatically reduced costs of digital circuitry, which is paced by military and consumer markets. This could bring the receiver costs down further by a factor of two or more.

10.4.8 ISSUE 8: "All-In-View" Position Computation

Use of an "all-in-view" satellite selection algorithm can increase accuracy by about 25 to 30%. It is expected to improve the accuracy of position fixes during maneuvers as well, although simulations have not yet been run on this project to verify this. The cost implications for a receiver in the next few years are that the more expensive dual channel receiver design must be employed. However, the use of monolithic integrated circuit techniques is expected to bring the cost of additional channels down significantly, so that the cost increment can be expected to drop by the early 1990's.

10.4.9 ISSUE 9: Kalman Filter vs. Alpha-Beta Tracker

Kalman filters show improved performance over alpha-beta trackers, especially during maneuvers, although alpha-beta trackers can be improved by using adaptive techniques. In addition, alpha-beta trackers are much less complex computationally. The issue is whether a Kalman filter design can be employed in a low-cost receiver without adding significantly to the cost.

While previous processor microprocessor technology has required multiple processors to accommodate Kalman filter algorithms, it now appears that current microprocessors using high clock rates can enable sizable increases in program sizes and computational complexity without requiring multiple processors. Thus, for future receiver designs the computational complexity added by a Kalman filter is not expected to be a significant cost item.

10.4.10 ISSUE 10: Aiding

Aircraft GPS receivers can be aided by encoded altimeter inputs, which reduce the number of satellites necessary for a position determination by one. This would eliminate the problem caused by a single satellite fault. However, altimeter errors result in horizontal positional errors. If the errors in the Standard Positioning Service are 100 meters or more, the aiding will improve the solution. In differential operation, on the other hand, an altimeter input will actually reduce the accuracy of the system, and should thus be avoided.

10.5 RECOMMENDATIONS

In summary, the NAVSTAR Global Positioning System will provide navigation service to air, marine, and land users over the CONUS with an accuracy available only in limited areas by other navigation systems. Differential operation will provide even higher accuracies using SPS regardless of the level of Selective Availability employed. While outages of 20 to 30 minutes could occur for certain air users, these can be dealt with by proper receiver design. Satellite failures could cause outage periods that could not be avoided by these users, and could cause outages for other users as well. Thus, the system is susceptible to the failure of a single satellite.

Therefore, it is recommended that further work be performed to ascertain whether the addition of a few more satellites to the GPS constellation could alleviate this susceptibility.

Other recommendations are the following:

1. Tests shall be run with aircraft receivers employing mask angles of 8 degrees or less to establish whether civil aircraft can obtain adequate accuracy using the low lying satellite below 10 degree elevation. If so, there is no outage problem with a full constellation.

2. DOT should explore the means of monitoring the GPS satellite signals and estimate the associated costs. The means and timeliness required for the monitors to alert users of any problems should also be considered.

3. The various multipath, blockage, and signal attenuation mechanisms that can reduce GPS accuracy should be enumerated and assessed, with special emphasis on land user scenarios.

4. DOT should support further efforts to develop a standard for the broadcast of differential corrections.

APPENDIX A. "AIRGPS", AIRCRAFT RECEIVER SIMULATION MODEL

AIRGPS is a Monte Carlo simulation of a generalized receiver architecture operating in a 3-D environment. A simulated aircraft trajectory can be specified in terms of a number of waypoint-defined constant-velocity or constant-acceleration segments. A nominally hemispherical coverage antenna pattern model, which includes lever-arm effects, permits simulation of signal attenuation and blockage associated with aircraft roll during maneuvers. Receiver operation is simulated through the use of one of two available receiver demodulator models driving a navigation processor. One to four parallel "hardware" channels can be modeled. Channel assignment is flexible, permitting a given channel to be sequenced over a number of satellites in an arbitrary manner. Antenna motion effects are also included. A nine-state Kalman filter provides position, velocity and turn rate estimates as well as estimates of the user clock phase and frequency states.

The nonlinear receiver model in AIRGPS provides for detailed receiver simulation, including operation in the nonlinear region where thresholds and break-lock effects can be observed. It is primarily intended to provide data on receiver performance over relatively short flight segments in which the receiver is highly stressed.

A simplified receiver model is also contained in AIRGPS for use in providing input data to the navigation processor over longer duration flight trajectories. The simplified model provides noise-corrupted pseudorange samples to the navigation filter. The variance is determined from Hartmann's [26] equation for the noncoherent tau-dither loop, using signal-to-noise ratios based upon satellite location and user antenna pattern orientation. The simplified receiver model will be used in locating specific flight segments which require more careful evaluation using the nonlinear receiver model. The simplified model is cheaper to run by about a factor of 10.

Nonlinear Receiver Model

The nonlinear receiver is a generalized receiver model capable of simulating a variety of receiver architectures. Code tracking is simulated through the modeling of a noncoherent tau-dither loop. Either Costas or AFC carrier tracking can be simulated. Code and carrier tracking loop orders up to third-order can be selected. Loop and noise filter bandwidths are operator selectable.

Simplified Receiver Model

The function of the simplified receiver model is to provide noise statistics representative of the tau-dither code loop. In essence, the model is represented by an algebraic equation for the variance of the tracking error of a noncoherent tau-dither loop. Hartmann's analysis [26] is based upon a linear code loop model and assumes square-law envelope detection. Hartmann's analysis deals only with output tracking error variance due to noise. Consequently, the simplified receiver model does not simulate bias-like effects such as dynamic tracking errors due to vehicle acceleration. The simplified receiver model serves only to replace the nonlinear code and carrier loop demodulators in AIRGPS.

APPENDIX B. "MARINEGPS", MARINE RECEIVER SIMULATION MODEL

MARINEGPS is a Monte Carlo simulation of a generalized receiver architecture operating in a 2-D marine environment. It also employs both a simplified code loop model and the simulated hardware portion of the receiver (AGC and tracking loops, lock indicators, user clock, and channel management) that is identical to the one contained in AIRGPS. The environment, user trajectory generator, antenna model and navigation processor are different, being representative of a marine simulation.

Unlike AIRGPS, the MARINEGPS environment module contains both a direct path and a multipath propagation model. The multipath model is a simple specular model in which scattering loss at the surface is specified by the operator. Polarization effects are neglected. MARINEGPS contains a relatively simple antenna model which is generally hemispherical in coverage but does include gain falloff at the horizon and a simple backlobe structure. Antenna lever arm effects are simulated in order that both translational and rotational effects be modeled.

The user vehicle trajectory is modeled by a series of waypoint-specified constant velocity or constant acceleration segments. Roll, pitch and heave are modeled by simple harmonic motion with amplitudes, periods and phases specified by the operator. The MARINEGPS navigation processor contains a six-state Kalman filter which provides estimates of user position, velocity, and clock states. Pseudorange inputs to the Kalman filter are provided by the code loop. Doppler information derived from the carrier loop is not used by the navigation processor.

APPENDIX C. "TSCERR", ERROR BOUND MODEL

TSCERR is a software tool used to calculate a lower bound on the rms position error achievable by a GPS receiver/processor. The bound is calculated under constraints on the number of correlators (hardware channels), user clock quality and external aiding (if any) available to the receiver. TSCERR is distinguished from Monte Carlo simulations such as AIRGPS in that it does not involve a deterministic aircraft trajectory defined in terms of heading, speed, altitude, etc. The bound is calculated for a particular location in space as a function of time and is averaged over an ensemble of aircraft with random headings and accelerations. The bound is typically calculated over a twenty-four hour period at time increments chosen to allow significant changes in GDOP to occur between sequential runs. This provides a measure of potential receiver performance for conditions of varying GDOP. The bound serves to evaluate system performance over relatively long time intervals (through sampling) as well as conditions of highly varying GDOP, such as those associated with particular geographic locations. TSCERR will also permit a comparison of the relative performance of a particular receiver/processor architecture as simulated with AIRGPS to the system's performance potential.

APPENDIX D. SUMMARY OF OSCILLATOR PROPERTIES

Available clocks for user equipment can be divided into 2 classes:

1. Atomic clocks - These consist of quartz-controlled oscillators having their average frequency (averaged over one second periods) stabilized by hyperfine structure transitions in one of three atoms: cesium, rubidium, or hydrogen. These are all fairly expensive oscillators.

2. Crystal-controlled clocks - These are oscillators which are referenced only to a quartz crystal so that mechanical and thermal stability of the crystal determine the oscillator performance. We can further divide these oscillators into two subclasses: low cost and expensive.

    1. Low cost - Conventional simple mechanical supported crystals, temperature thermostatically controlled.

    2. Expensive - advanced resonator design for mechanical isolation, minimal aging characteristics.[27]

Atomic Clocks

The atomic clocks basically develop an aggregation of atoms in a non-equilibrium population of energy states. The aggregation can absorb microwave radiation over a very narrow frequency range thus serving as a reference frequency for an external oscillator.

The center frequency and spectral width of the absorption line are determined by the internal magnetic moments and magnetic fields within the atom and have been chosen from long-lived atomic states so as to have narrow line widths and to be relatively non-interacting with outside systems.

The center frequency and line widths are perturbed, however, by collisions of the atoms with each other or other gases, and with container walls and by external man-made magnetic fields. The ultimate stability of the clock is determined by the amount of isolation the atomic aggregation can be afforded. Thus, low densities of gas and low temperatures and suitable container wall coatings serve to minimize collisions, and proper routing of electric currents and suitable magnetic shielding further isolate the system.

The atomic clock is limited to the same short-term frequency errors as the crystal-controlled clock since they both have the same oscillator sources. The atomic clock has the advantage that for periods larger than about 100 seconds, thermal and mechanical perturbations do not contribute to clock errors.

For the most part, the frequency stability and absolute accuracy of an atomic clock suitable for use in user equipment are determined by the degree to which the clock can be isolated from thermal changes, mechanical shock, and strong magnetic fields.

The least expensive atomic clock (at present) is the rubidium clock, which can produce a frequency stability of 1 part in 10^{11} for long periods (greater than 100 seconds) for normal operating temperature variations and the 1/2 g accelerations characteristic of the environment for a civil aircraft. These can be purchased in quantities for under $5,000.[28]

Crystal-Controlled Clocks

The frequency-determining element in this type oscillator is a piezoelectric quartz crystal whose resonant frequency is dependent on temperature, oscillator drive level, pressure of the surrounding gas, and variations in external coupling through physical support structures.

Many ingenious methods have been devised to make the quartz crystal oscillator stable, but the fact remains that the cost of such an oscillator employing elaborate ovens, mechanical isolation and reactance compensation, rivals that of the atomic oscillator. Recently, advances in crystal resonator design have made it possible to construct crystal oscillators with 20-minute frequency accuracies to 10^{-11}, and there is reason to believe the costs for this type of oscillator would be much reduced from that of an atomic clock[29].

The least expensive crystal oscillator will, however, be more sensitive to temperature and acceleration so that a frequency stability of 10^{-8} may be achieved. It will be shown that this is sufficient to provide accurate satellite ranging in a sequential receiver but not sufficient to remember satellite synchronization time in the event of less than minimum satellite coverage.

Present estimated costs of user clocks are listed below and in Table D-1.

Rubidium Clock - $5000
High Accuracy Crystal Clock - $2500

TABLE D-1. TYPICAL QUARTZ CRYSTAL OSCILLATORS

TYPE	FREQUENCY STABILITY		EST. COST
	1 SEC AV.	30-1000 SEC AV.	
Clock Oscillator	1×10^{-8}	$\pm 3 \times 10^{-6}$	$ 45.00
Temperature-Compensated Crystal Oscillator	1×10^{-9}	$\pm 1 \times 10^{-7}$	150.00
Single Oven-Controlled Crystal Oscillator	3×10^{-11}	$\pm 5 \times 10^{-9}$	350.00
Double Oven-Controlled Crystal Oscillator	5×10^{-12}	$\pm 5 \times 10^{-10}$	900.00

APPENDIX E. RECEIVER COST MODELS

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

E.1 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.

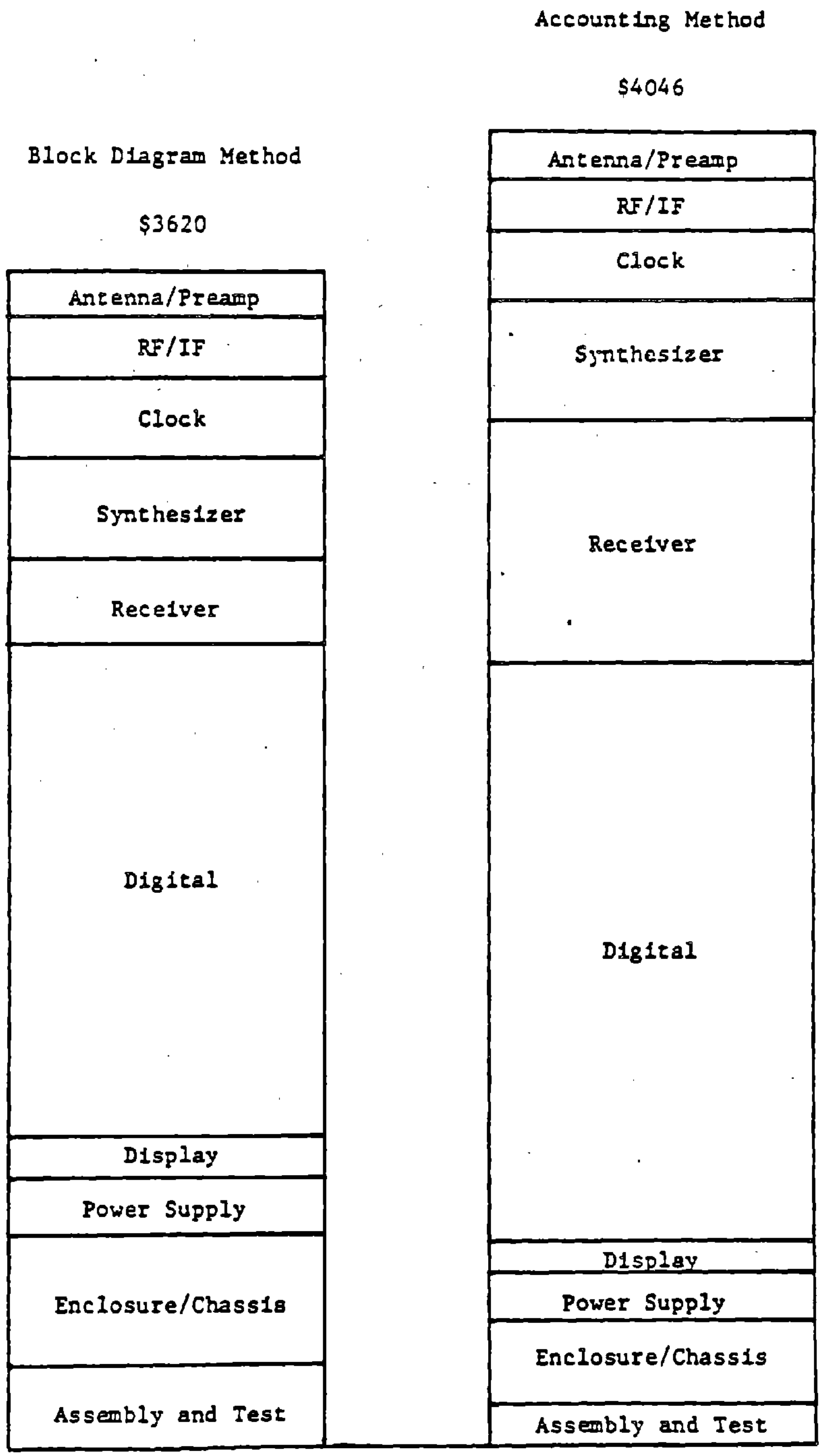


FIGURE E-1. RECEIVER COST ESTIMATE - ARINC MODELS
LIST PRICE, 1978 DOLLARS

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 expected to follow the same price units is not obvious. Within these assumptions the method does provide a reasonable way of comparing the costs of different navigation system user equipments, both now and in the future. The method is also traceable, and new trend data can be readily incorporated. The Z-set was one of several sets used to derive the data; the Texas Instruments and Rockwell International receivers were also used.

By grouping the subcomponents according to function, the costs can be disaggregated in a manner similar to Figure E-1. Figure E-2 shows this breakout for the SCI costing. It cannot be directly compared with the ARINC study values of Figure E-1 because the SCI study uses 1980 dollars.

Some relevant features of the study are the following:

1. The model allows grouping of subcomponents by function.

2. A "production base adjustment" factor is used to distinguish materials costs for the various classes of user equipment.

3. A "unit cost" and "unit count" for each subcomponent is employed to give the cost-to-manufacture for each subcomponent.

4. A production base of 3000 is assumed.

5. The cost-to-manufacture is multiplied by a "grade-level-multiplier" (less than 1), a volume discount factor (about 1) and a dealer margin/cost factor (3 to 4) to obtain a list price.

6. The ratio of list-price to cost-to-manufacture for the low-performance unit is about 295%.

7. The list-price to materials-cost ratio is about 5.4:1.

8. The trend curves lump labor and materials together.

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

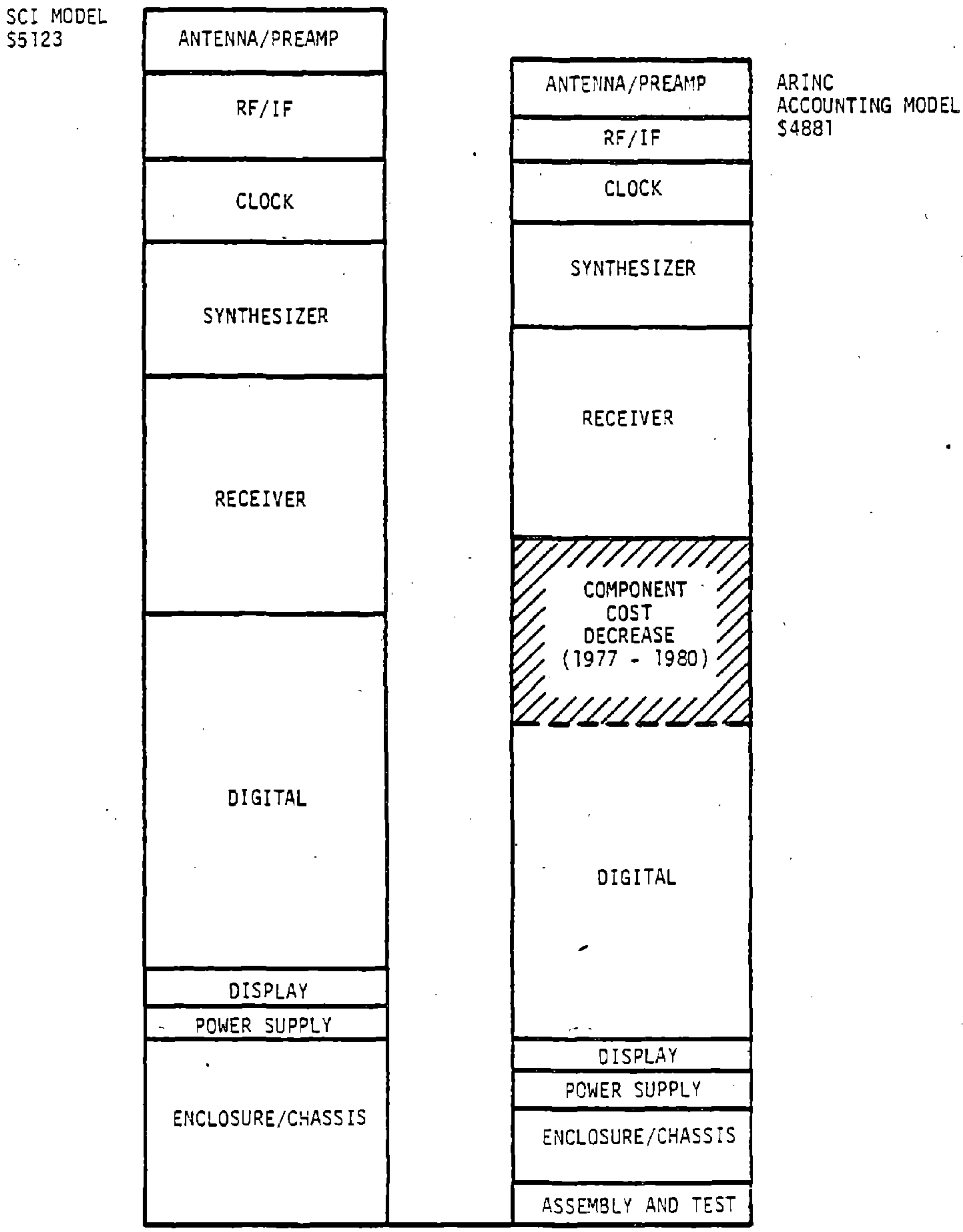


FIGURE E-2. RECEIVER COST ESTIMATE - ARINC AND SCI MODELS LIST PRICE, 1980 DOLLARS

Comparison of the Two Studies: The studies are aimed at addressing somewhat different issues, and this is reflected in the methodologies employed. The ARINC study aimed to develop a well-justified method for costing current GPS avionics equiment. At any time it is applied, it should provide credible results. The SCI study attempted to predict the cost of current and future receivers of a variety of navigation systems, so that comparative costs between systems could be estimated. The large number of estimating factors that are used, and the lack of justification given for the particular estimates selected, reduce overall confidence in the model. However, the results using this method are very similar to the results of the ARINC approach.

Figure E-2 shows a comparison of the two methods, where the ARINC numbers were adjusted to reflect higher labor and material costs. Not included are price decreases that have, in fact, occurred due to improved technology and volume purchases of the subcomponents. The shaded portion of the ARINC chart shows how much digital parts have come down in price between 1977 and 1980. With these adjustments, the prices are remarkably similar. Especially notable are the similarities in the relative costs of the functional components. Of course, the ARINC model treats avionics, while the SCI model treats marine equipment, so one would expect some differences to show up (for example, in the enclosure costs).

E.2 TRENDS

ARINC Study: "Impact of Technology on Avionics Cost Trends," ARINC [24].

This study, recently completed, looks at the trends in navigation avionics costs over the last 10 to 20 years, and makes projections for the next 10 to 20 years. There were no GPS receivers considered, of course, but some of the conclusions are equally applicable to them. Among the conclusions drawn, the following are pertinent to our interests:

1. Material costs tend to follow the Producer Price Index (PPI) rather than the Consumer Price Index (CPI).

2. The CPI is increasing at a more rapid rate than the PPI. This is due primarily to the sensitivity of the CPI to costs of housing and food, factors that do not 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:

1. How does the cost of a dual-channel receiver compare to that of a single channel receiver?

2. What is the cost of a digital receiver, compared to an analog receiver?

3. When will 16-bit microprocessors become cost-effective?

4. When will high-speed digital circuits become cost-effective for multiple-channel "simultaneous" tracking, or for replacing the second down-conversion stage of IF?

5. When will VLSI become cost-effective for these relatively low-production units?

6. Will the new developments decrease the cost ratio between GPS and other navigation system receivers?

7. How will costs behave in future years?

We can certainly use the SCI trends to project costs and address some of these questions. There are two reasons why applying them in their present form is not completely satisfying: (1) the trends are largely based on engineering judgment; (2) labor and materials trends are not separated. The first can be addressed by reviewing trends projected in trade journals. The second is more troublesome. ARINC goes to some effort to detail the trends of materials vs. labor, and the trends of capital-intensive vs. labor-intensive processes. It would be desirable to incorporate these trends into projections of future subcomponent costs for various GPS receiver designs. By grouping the labor and materials trends together, such information is lost. The SCI position does have a certain logic, in that if highly-leveraged components were dominated by labor costs, good business practice would dictate searching for capital-intensive alternatives. Thus there is a compelling reason to try to keep the ratio of labor to materials costs constant. Following this line of reasoning, it would be expected that the labor cost trend for a given subcomponent would qualitatively follow the trend of the materials cost. Quantitatively, it would be desirable to establish a line of reasoning which incorporates the labor/materials trend noted by ARINC.

APPENDIX F. AIRGPS SIMULATION OF AIRCRAFT MANEUVERS

F.1 INTRODUCTION

The AIRGPS simulation was used to examine navigation filter performance under conditions of turning flight. In this situation, the filter has to cope with both turn-induced acceleration and the degraded signal quality which results from antenna pattern roll-off and airframe blockage. Four different aircraft trajectories were used. The trajectories involve both standard-rate turns and turns made at twice the standard rate. Two levels of user clock quality were used in order to observe the effect of clock stability on navigation solution accuracy. The runs also incorporated conditions of both nominal and poor GDOP.

F.2 NAVIGATION FILTER PERFORMANCE

The turn performance of the AIRGPS navigation filter was evaluated using four different flight trajectories. The first three trajectories involve racetrack patterns, while the fourth begins with a descending turn followed by a descending straight-line segment. In each case the filter is initialized at the start of the run to approximate steady-state, unaccelerated flight conditions with a nominal GDOP. The salient features of the four flight trajectories are listed in Table F-1.

TABLE F-1. SALIENT FEATURES OF FLIGHT TRAJECTORIES

TRAJ NUMBER	GDOP	SPEED	TURN RATE	BANK ANGLE	TURN ACCEL.	RUN DURATION	ALTITUDE
1	Nominal	160 Kts	2 min.	24°	0.44 g	200 Sec.	Constant
2	Nominal	160 Kts	1 min.	41°	0.88 g	100 Sec.	Constant
3	Poor	160 Kts	1 min.	41°	0.88 g	100 Sec.	Constant
4	Nominal	160 Kts	2 min.	24°	0.44 g	90 Sec.	Variable

The first trajectory serves as a baseline and is intended to simulate filter behavior under nominal flight conditions. The run involves level standard rate turns, and performance is compared to that obtained with the following two runs which use twice the standard turn rate.

The second trajectory constitutes a rigorous run in which the filter has to cope with a fairly harsh turning environment (twice the standard rate turn), accompanied by significant antenna rolloff (reaching 18 dB in two instances).

The third trajectory permits examination of the effects of poor GDOP on filter behavior. Note that the poor geometry should be reflected in the "size" of the state covariance matrix, which in turn determines the Kalman gain and hence the relative weighting of the measurement vs. the projected state estimate.

Trajectory number four introduces two levels of descent rate (2,000 ft/min and 848 ft/min), the more rapid of which is combined with a standard rate turn. The descending turn is intended to simulate a portion of a procedure turn while the straight-line segment simulates a standard 3° glideslope final approach.

Receiver Parameter Selection

All runs were made using a simplified linear model of a single-channel sequential receiver employing a "best-set-of-four" satellite selection algorithm. The parameters used for the linear receiver model are based upon the design of a civil receiver developed for the FAA by the MIT Lincoln Laboratory. Table F-2 contains a list of the relevant receiver parameters used in the simulation. All runs were made using a nominal carrier-to-noise power spectral density ratio of 40 dB-Hz.

Navigation Filter Parameters

The navigation filter parameters used in the simulation were selected to give the best overall performance on the fourth trajectory. The intent was to adjust the filter to give its best performance during the landing phase of flight. The descending standard rate turn followed by a three-degree glideslope (used in trajectory number four) is felt to be a reasonable approximation to what might be encountered during a landing approach. The parameters were chosen with the user clock modeled as having a long-term (30 minute) frequency stability of 1.01×10^{-10} (one sigma) while the filter assumes a frequency uncertainty of 0.97×10^{-8} (one-sigma).

Two sets of navigation filter parameters were used in making the runs described in this appendix. The sets differ only in the values chosen for two filter parameters which are associated with the frequency stability of the user clock. Runs made using the "good clock" employ the parameters described above. For those runs which use the "poor clock," the following changes have been made:

The frequency standard deviation was increased from 3.0 m/sec to 300.0 m/sec.
The frequency correlation time was reduced from 1800.0 sec to 10.0 sec.

These values are consistent with those used to model the "poor clock" and they provide a good model match between the filter and the clock.

Aircraft Characteristics

The aircraft dynamics parameters used in the simulation are (with one exception) those of a 6-10 seat twin turboprop business aircraft, the Beechcraft C90. An exception was made in the case of the roll time constant. The AIRGPS aircraft trajectory generator produced an unwanted oscillation when using the 0.25 sec. roll time constant of the C90 and consequently the value of this parameter was increased to 1.0 seconds.

The simulation employs an antenna gain pattern which approximates the measured pattern from a model of a Beechcraft Baron. The Baron is a 4-6 seat, twin-engined aircraft, somewhat smaller than the Beechcraft King Air C90, but having the same general external configuration. Figure F-1 shows the model used for the antenna pattern measurement. The antenna location (for the AIRGPS simulation) is indicated by the numeral 2 shown on the figure.

Satellite Geometry

Figure F-2 depicts the satellite locations for the "nominal GDOP" situation characteristic of trajectories number 1, 2 and 4. The satellite's elevation angle is indicated by the length of the radius vector as scaled along the vertical axis. The various dilution-of-precision measures listed on the figure are the initial values appropriate to the start of each run. Since the satellite geometry is relatively good and the run durations short, they can be assumed to be representative of an entire run.

TABLE F-2. RECEIVER PARAMETERS

PARAMETER	VALUE
CLOCK	
CLOCK STABILITY	VARIABLE
CODE LOOP	
TYPE	TAU-DITHER
ORDER	IST
BANDWIDTH	6 Hz
DAMPING FACTOR	N/A
DELAY PREPOSITIONING	YES
DOPPLER PREPOSITIONING	NO
SATELLITE DWELL TIME	0.220 SEC.
DITHER TIMESTEP	0.01 SEC.
DITHER CODE SHIFT	± 0.5 CHIP
NOISE FILTER BANDWIDTH	500 Hz
NAVIGATION FILTER	
TYPE	KALMAN
STATES	9
OBSERVABLES	PSEUDORANGE
SATELLITES TRACKED	
SATELLITES TRACKED	BEST SET OF FOUR
SATELLITE MASK ANGLE	8^{o}

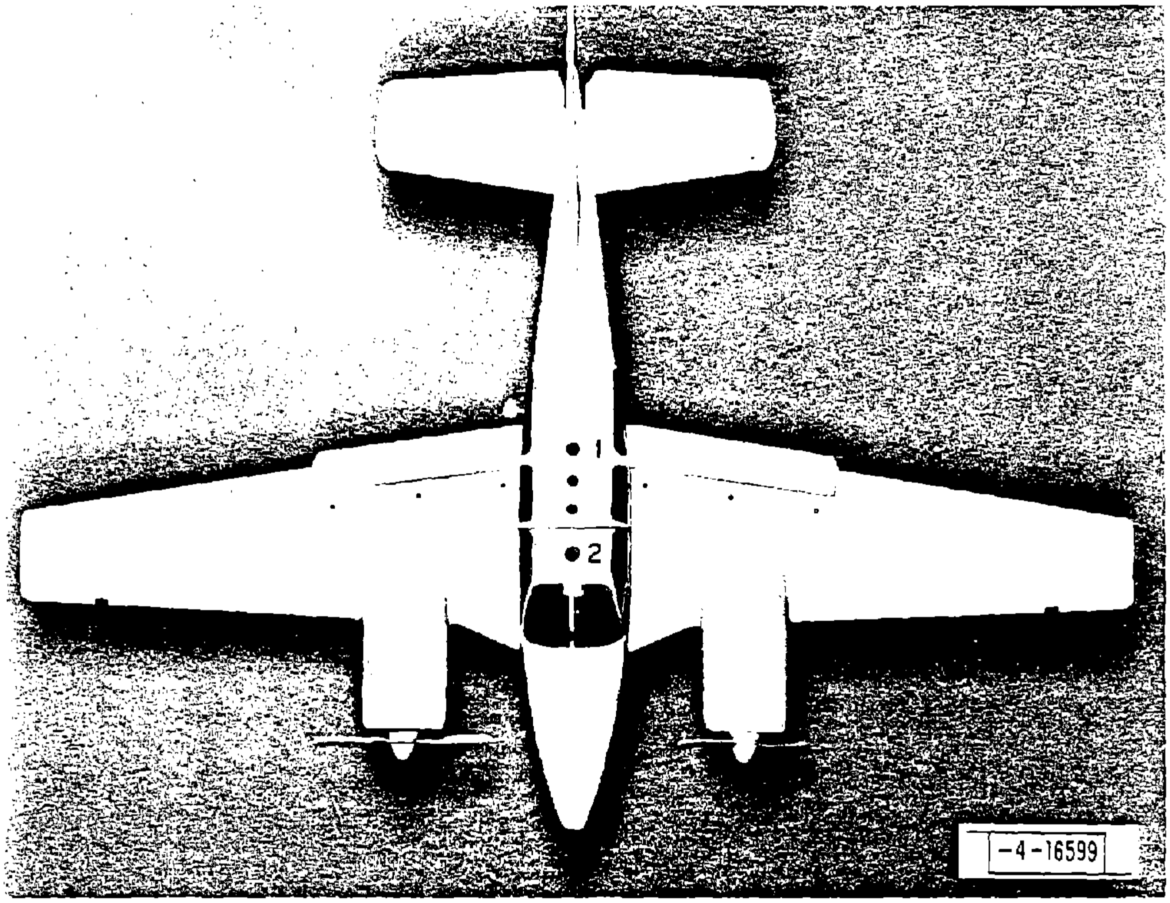


FIGURE F-1. BEECHCRAFT BARON ANTENNA POSITION

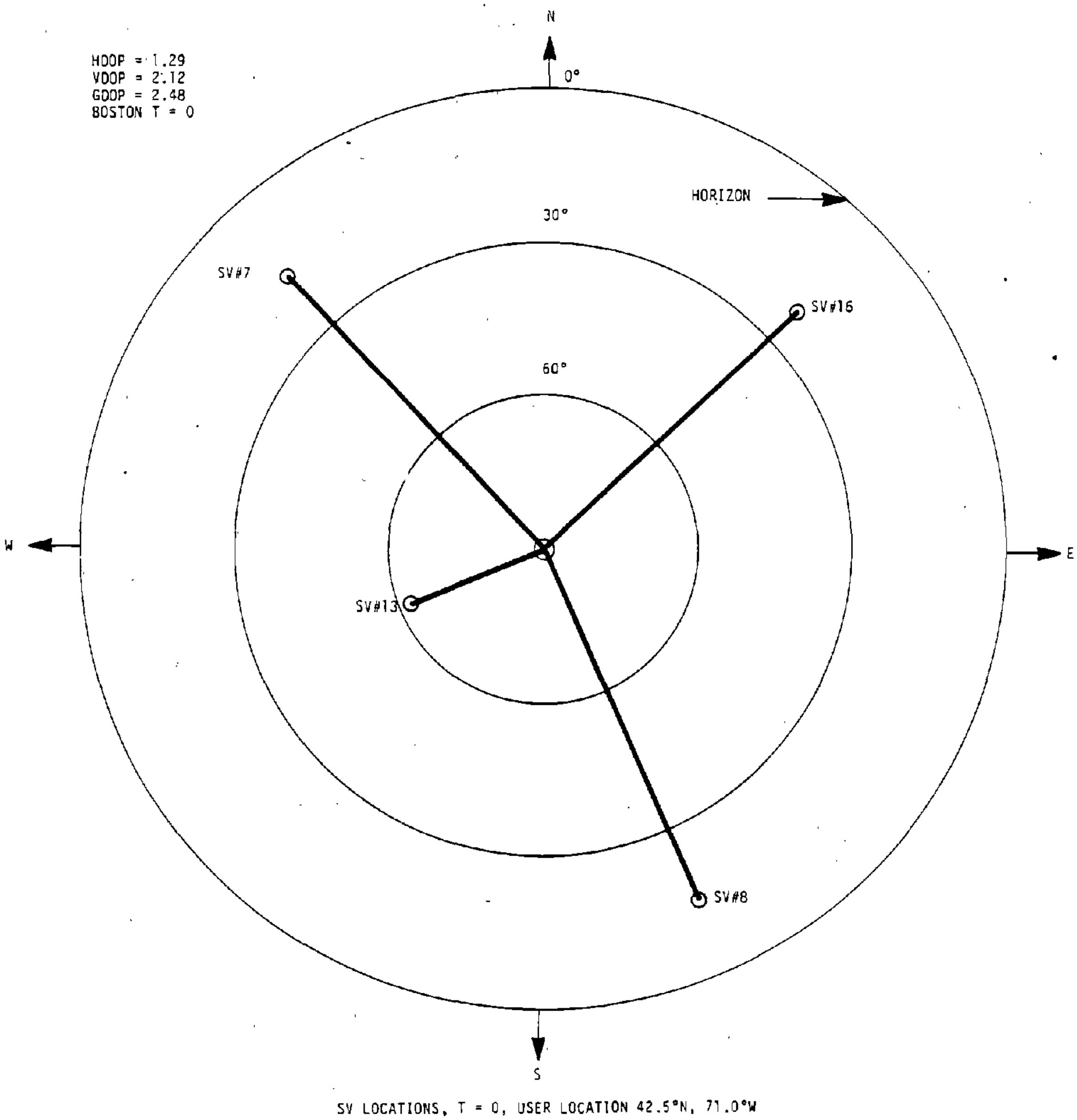


FIGURE F-2. SATELLITE LOCATIONS FOR NOMINAL GDOP

The satellite geometry for the poor GDOP situation associated with trajectory number 3 is depicted in Figure F-3. The notes on the figure give the initial dilution-of-precision (DOP) measures. In this case the DOP values are changing rapidly, spanning the following ranges during the duration of the run:

GDOP	=	21.24-15.69
HDOP	=	9.76-7.23
VDOP	=	18.86-13.93

User Clock Stability

For the purposes of the AIRGPS simulations described herein, user clock stability is generally of interest over three time intervals: typically one second, ten seconds, and 10 to 30 minutes in duration. Short-term variations involving time intervals on the order of one second are of interest, since this is comparable to the time (880 ms) it takes the receiver to scan the four satellites. One might view the problem as that of bringing four sequential measurements to a common reference time in order to form a solution. Clock stability over time intervals in the order of ten seconds is also of interest. This is approximately the duration of the periods of low signal quality which result from airframe blockage during turning maneuvers. The third time interval, that of 10 to 30 minutes, is typical of the durations of periods of high GDOP. This situation occurs when only four satellites are visible and they approach or pass through a co-planar geometry. Clock stability over this longer interval affects the ability of the receiver to form a navigation solution using only three satellites, while depending on the clock's frequency stability to maintain a nearly constant clock bias.

This appendix deals primarily with effects of relatively short-term (1 second and 10 seconds in duration) clock instabilities. Although data are presented for conditions of poor GDOP, run durations are limited to less than two minutes. Runs are made at two levels of clock quality: good (frequency stability equal to 1.01×10^{-10}) and poor (1.01×10^{-6}). The runs made with the good clock use a frequency correlation time of 1800 seconds while those made with the poor clock use a frequency correlation time of 10 seconds. The shorter correlation time places greater stress on the receiver/processor since, for a given level of frequency uncertainty, it results in a proportionally faster rate of frequency drift.

F.2.1 Trajectory No. 1 (Two Minute Turn Rate, Nominal GDOP)

This trajectory serves as a baseline and consists of a level racetrack pattern employing standard rate turns. Figure F-4 shows the pattern with the satellite locations (azimuth) indicated by the arrows. The corresponding satellite elevation angles are contained in parentheses. As noted on the figure, the aircraft's true position is indicated by the solid line, and the estimated position by the broken line. Since the errors are generally small in comparison to the dimensions of the plot, the error has been overstated by a factor of two. This is indicated by "FACTOR = 2.00" in the notes on the plot. The error scaling is implemented by computing the estimated state as the true state plus the error state multiplied by the scaling constant FACTOR. As a consequence, the actual errors in position are only 50% of those shown in the plot. A similar convention holds for all other trajectory plots.

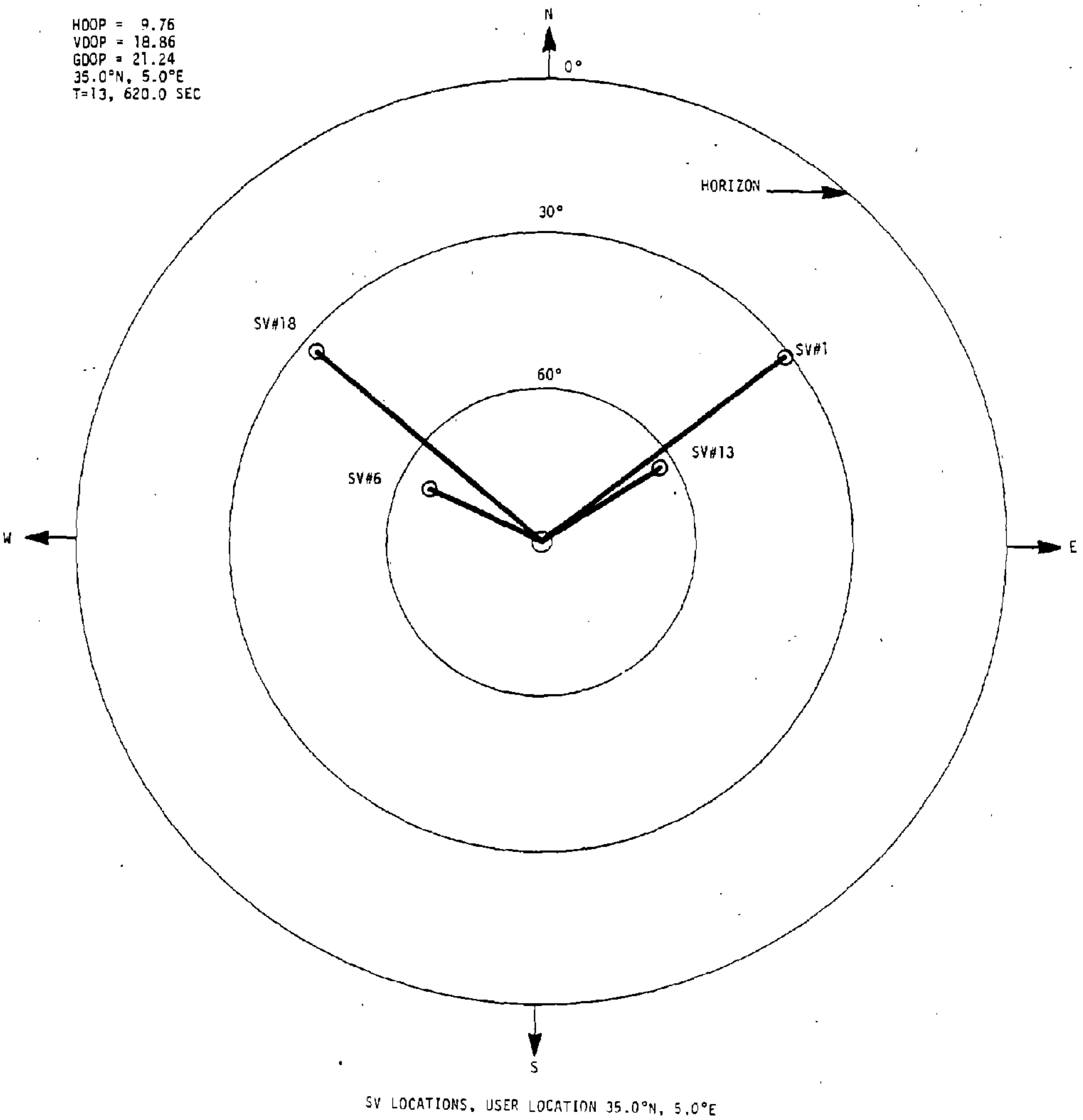


FIGURE F-3. SATELLITE LOCATIONS FOR POOR GDOP

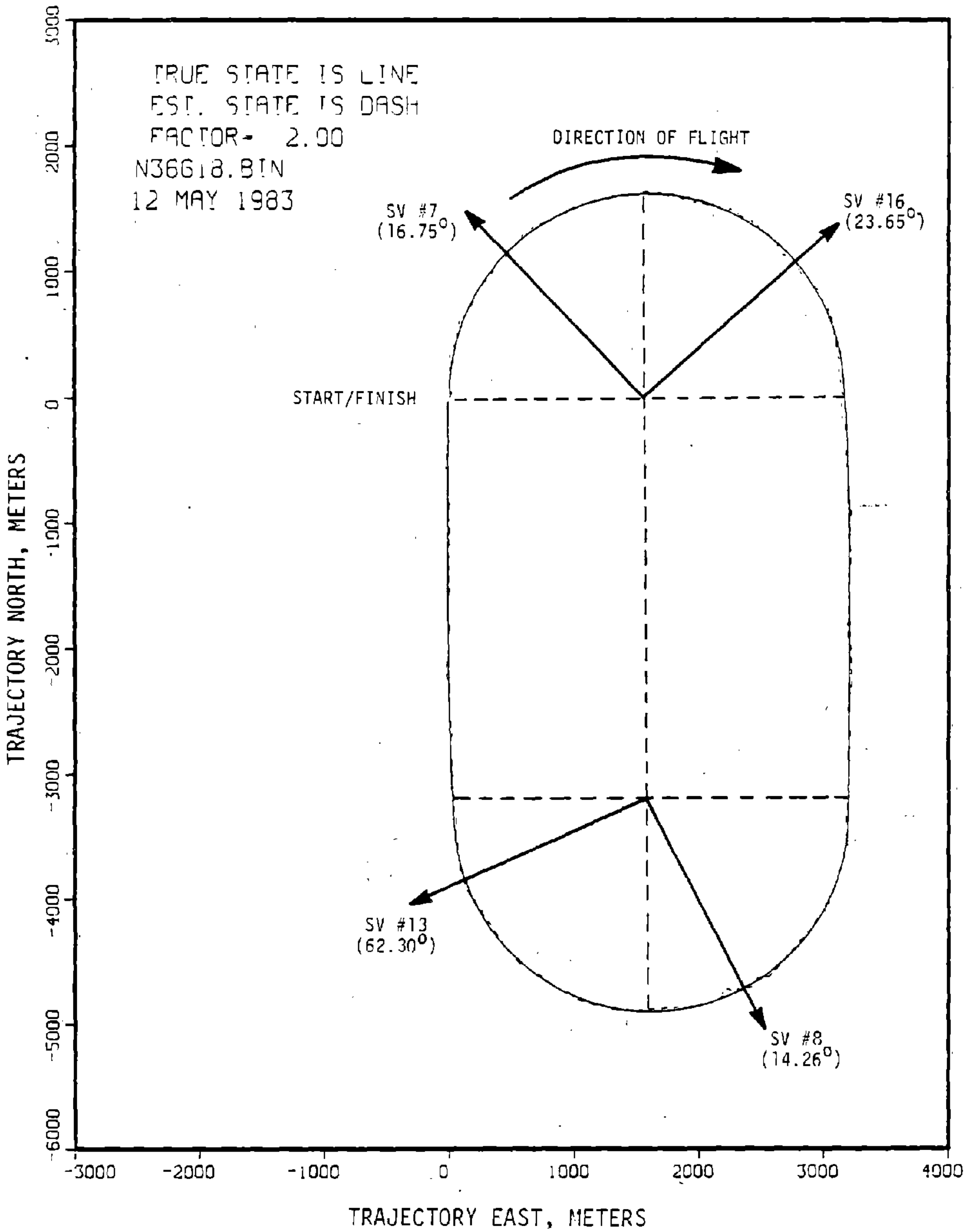


FIGURE F-4. ERROR PLOT, RUN 1, TRAJECTORY #1, GOOD CLOCK

Run 1, Trajectory No. 1, Good Clock

The position/error plot for Run 1, used as an example of Trajectory No. 1, is shown in Figure F-4. As can be seen from the plot, filter performance during the turns is little different from that obtained during the straight-line segments of the run. The position errors averaged over various portions of the run are:

HORIZONTAL POSITION ERROR 2DRMS (m)	ALTITUDE ERROR 2 SIGMA (m)	SEGMENT
16.22	9.82	1st turn (top of page)
12.60	12.00	east leg (A/C heading 180°)
14.28	12.72	2nd turn (bottom of page)
9.18	12.74	west leg (A/C heading 360°)
13.82	11.76	total run

Run 1 gives an example of filter performance obtained with a high-quality user clock. AIRGPS models the user clock frequency error as a first-order Gauss-Markov process of the form

$$x(k) = x(k-1)\, \varepsilon^{-\Delta t/\tau} + \left[1.0 - \varepsilon^{-2\Delta t/\tau}\right]^{1/2} \sigma_f \, G_f(0,1)$$

where:

Δt = measurement time step (s)
τ = correlation time (s)
σ_f = standard deviation of frequency error (R/sec)
$G_f(0,1)$ = Zero-mean, unit-variance Gaussian random variable (ND).

The user clock phase error is modeled as the integral of the frequency error plus a white noise term and may be expressed as

$$\Delta\phi(k) = \left[x(k) + x(k-1)\right] \Delta t/2 \; + \left[N_\phi \Delta t\right]^{1/2} G_\phi(0,1)$$

where N_ϕ = power spectral density of phase noise (R^2/sec)
$G_\phi(0,1)$ = zero-mean, unit-variance Gaussian random variable (N.D.).

For the clock model used in Run 1, the corresponding values of the parameters are:

Δt = 0.22 sec
τ = 1800 sec
σ_f = 1.0 R/sec
N_ϕ = 57.0 R^2/sec

The corresponding frequency stability is 1.01 X 10^{-10} which is equivalent to an rms velocity error of 0.031 m/sec, and the random phase error component is equivalent to an rms position error of 0.11 m.

Run 2, Trajectory No. 1, Poor Clock

Run 2 demonstrates the effect of poor clock stability when using the baseline trajectory. The clock parameters are:

Δt = 0.22 sec
τ = 10.0 sec
σ_f = 10,000.0 R/sec
N_ϕ = 57.0 R^2/sec

The corresponding frequency stability is 1.01 X 10^{-6} which is equivalent to an rms velocity error of 310.0 m/sec. Figure F-5 shows a position/error plot for Run 2. As can be readily seen, the plot is essentially the same as that shown in Figure F-4 for Run 1 which uses a good clock. The position errors for Run 2 averaged over various portions of the run are:

HORIZONTAL POSITION ERROR 2DRMS (m)	ALTITUDE ERROR 2-SIGMA (m)	SEGMENT
18.52	12.54	1st turn (top of page)
12.70	15.76	east leg (A/C heading 180°)
16.20	21.06	2nd turn (bottom of page)
9.64	18.92	west leg (A/C heading 360°)
15.36	17.40	total run

A comparison with the results from Run 1 shows that the rms horizontal position errors suffer a maximum degradation of 14% while the two-sigma altitude errors increase by a maximum of 66%.

F.2.2 Trajectory No. 2 (One Minute turn rate, nominal GDOP)

This trajectory, shown in Figure F-6, subjects the filter to a combination of heavy turn-induced acceleration (0.88 g) and periods of poor signal quality (C/N_o = 22 dB-Hz). The satellite geometry is unchanged from that of Trajectory No. 1. Signal quality is severely degraded at three times during the run. During the first turn, the aircraft is banked away from the two low-lying satellites to the north. A roll angle of 41° places SV#7 approximately 24° below the "horizon" of the aircraft's antenna pattern early in the turn. Similarly, SV #16 drops to approximately 17° below the antenna "horizon" later in the turn. The signal loss due to antenna pattern roll-off reaches peak values of 18 dB and 16 dB for SV #7 and SV #16 respectively. In a similar way, SV #8 suffers an 18 dB signal loss about one-third of the way through the second turn. The signal from the high elevation satellite, SV #13, is relatively unaffected since it never falls below 21 degrees (above the "horizon") on the aircraft's antenna pattern.

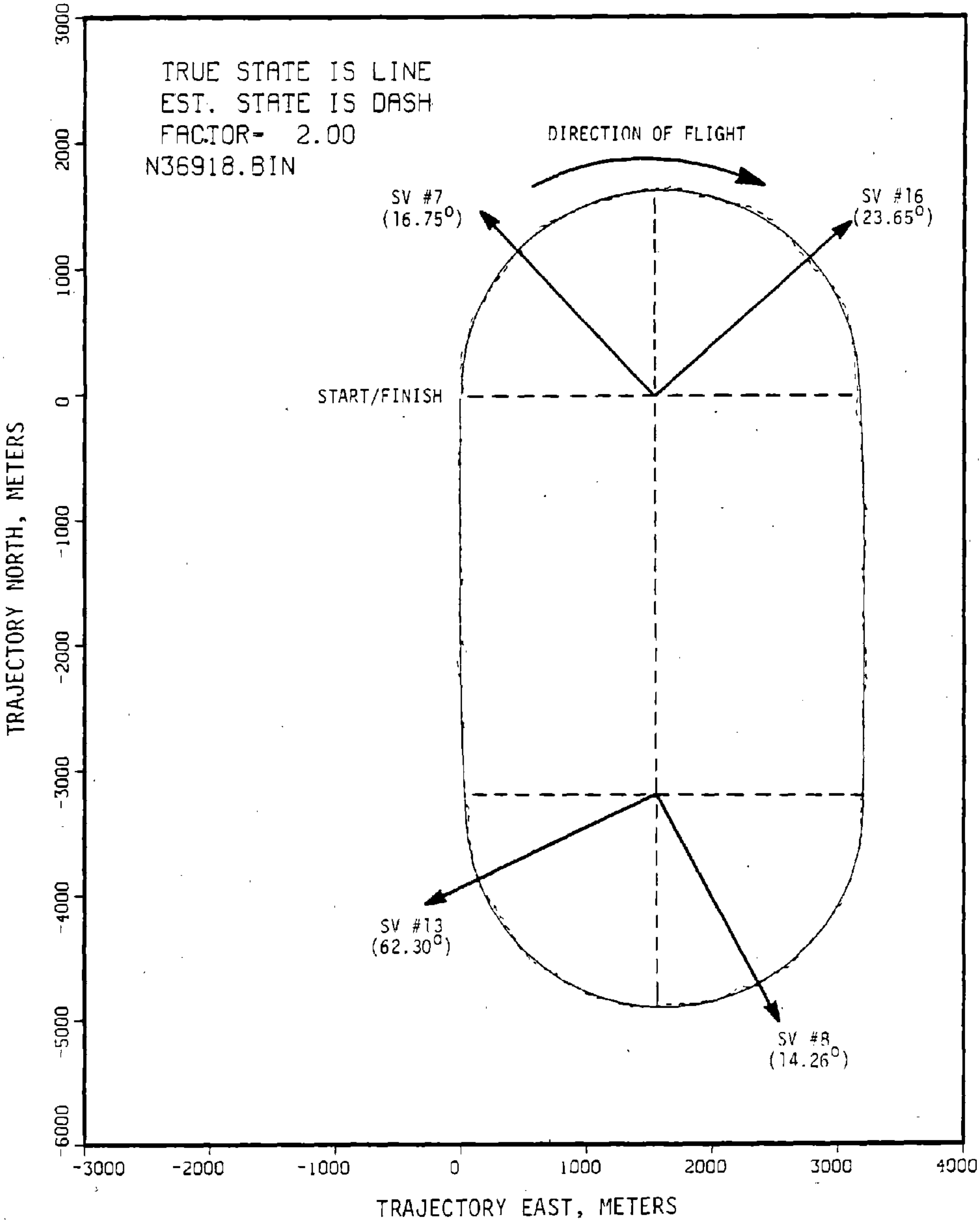


FIGURE F-5. ERROR PLOT, RUN 2, TRAJECTORY #1, POOR CLOCK

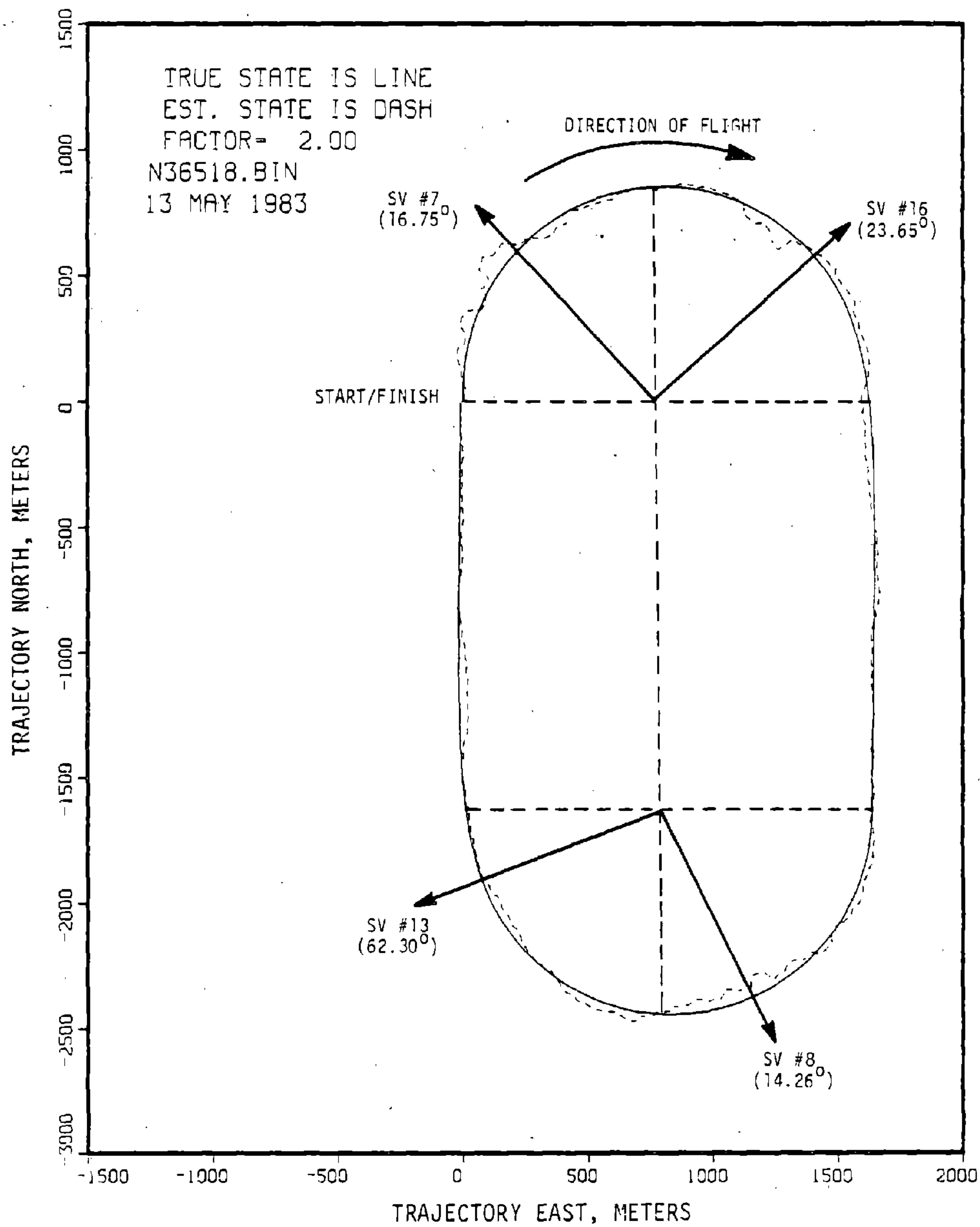


FIGURE F-6. ERROR PLOT, RUN 3, TRAJECTORY #2, GOOD CLOCK

Run 3, Trajectory No. 2, Good Clock

The position/error plot used to illustrate the features of the second trajectory (Figure F-6) shows the results obtained during Run 3. The error behavior shown in the plot is generally consistent with expectations. At the onset of each turn the estimated position tends to fall on the outside of the aircraft's true trajectory. This behavior is to be expected, since the filter's estimate of horizontal turn rate is small before the turn begins. At the start of the first turn, for example, the filter is initialized with a horizontal turn rate of less than 0.06°/sec and an east velocity error of only 0.1 m/sec. As the aircraft progresses through the turn, the estimated position tends to fall on either side of the true trajectory, as would be expected as the filter obtains a better estimate of the turn rate. Similarly, one would anticipate some overshoot (to the inside of the turn) as the aircraft rolls out of the turn and follows a straight-line path. This overshoot appears to be present at the end of the first turn and to a lesser extent at the end of the second turn.

The magnitudes of the position errors (magnified by a factor of two in the plot) are generally consistent with the degradation of signal quality experienced as the aircraft turns away from the low-lying satellites. Note the relatively large errors which seem to be associated with SV #7, SV #16 and SV #8 as compared to those which occur elsewhere during the run.

The position errors for the various segments of Run 3 are:

HORIZONTAL POSITION ERROR 2drms (m)	ALTITUDE ERROR 2 sigma (m)	SEGMENT
32.82	17.48	1st turn (top of page)
15.90	6.68	east leg (A/C heading 180°)
30.70	12.02	2nd turn (bottom of page)
17.18	8.82	west leg (A/C heading 360°)
27.10	12.80	total run

The user clock stability remains at 1.01×10^{-10} as in Run 1.

Run 4, Trajectory No. 2, Poor Clock

Figure F-7 shows the position/error plot for Run 4. The clock and navigation filter parameters for this run are the same as those used in Run 2. As can be seen by comparing Figure F-7 with Figure F-6 for Run 3, both plots are essentially the same. The position errors for Run 4 averaged over various portions of the run are given below.

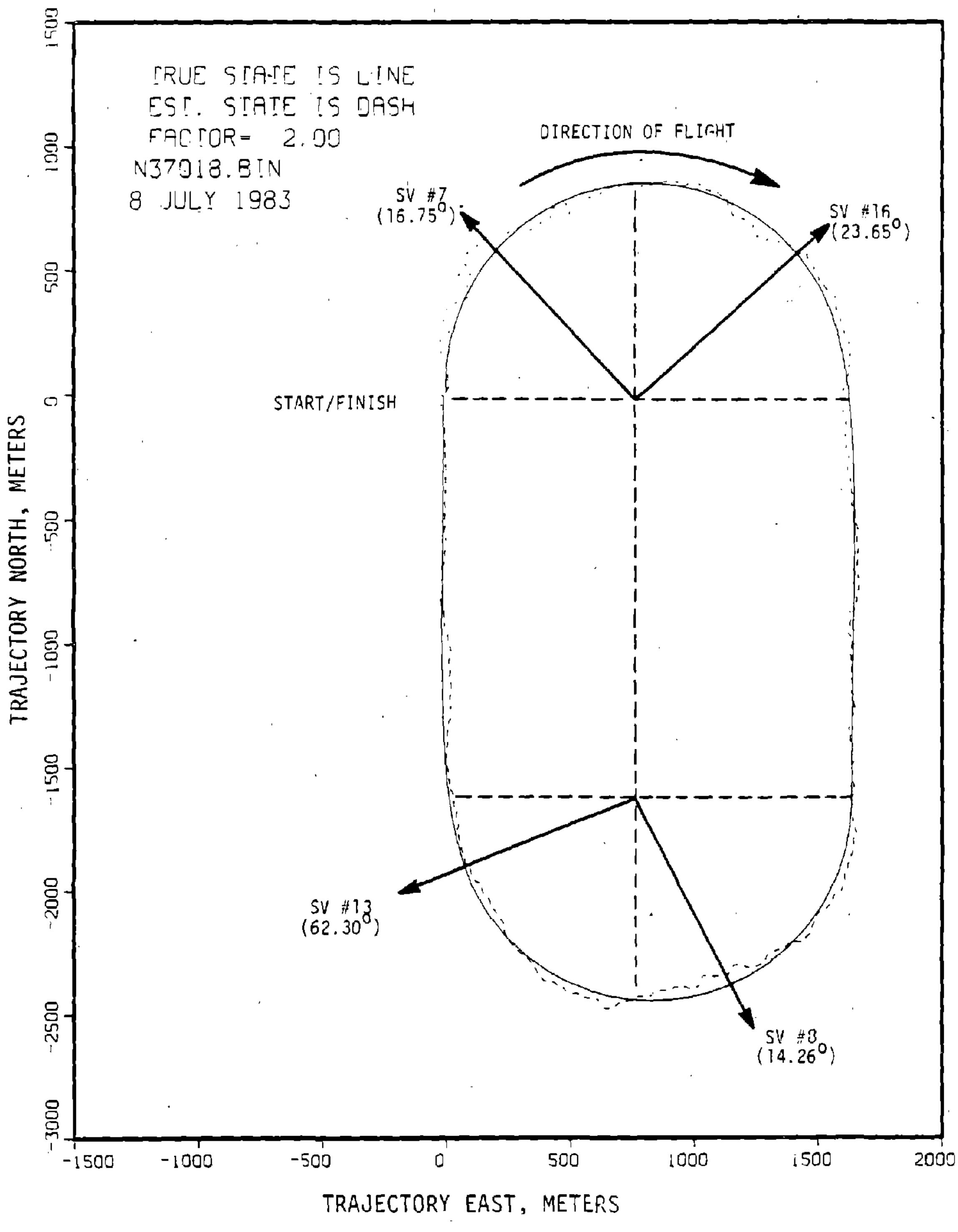


FIGURE F-7. ERROR PLOT, RUN 4, TRAJECTORY #2, POOR CLOCK

HORIZONTAL POSITION ERROR 2drms (m)	ALTITUDE ERROR 2 sigma (m)	SEGMENT
32.88	20.88	1st turn (top of page)
16.36	11.10	east leg (A/C heading 360°)
32.20	21.86	2nd turn (bottom of page)
17.86	16.80	west leg (A/C heading 360°)
27.78	19.00	total run

A comparison with the corresponding values for Run 3 shows that the rms horizontal position errors for Run 4 are larger by less than 5%. The altitude errors for Run 4 are larger by from 19% to 90% as compared to those for Run 3.

F.2.3 Trajectory No. 3 (One Minute Turn Rate, Poor GDOP)

Trajectory No. 3 is the same as Trajectory No. 2, except that the GDOP is materially worse (21.24 to 15.69 vs. 2.48). Figure F-8 shows the orientation of the satellites with respect to the path of the aircraft. All four satellites lie to the north; two at about 30° elevation and two at about 65° elevation. Degradation of signal quality due to shadowing and antenna pattern roll-off reaches peak values of 11 dB and 13 dB for SV #18 and SV #1 respectively. Peak signal fading is approximately 5 dB less severe for ths trajectory as compared to that of Trajectory No. 2.

Run 5, Trajectory No. 3, Good Clock

Figure F-8 shows the position/error plot for Run 5. In this situation, the filter must contend with large (0.88 g) turn-induced acceleration and high GDOP. It is interesting to note that although the GDOP is considerably worse than in Run 3 (21.24 to 15.69 vs. 2.48), the signal quality is better. This results from the fact that the lowest elevation satellite is at 30.36° in Run 5 vs. 16.75° in Run 3.

The position errors shown in Figure F-8 tend to follow expectations. The generally east-west orientation of the satellites in pairs should provide a better measurement of position in the east-west direction than in the north-south direction. As can be seen in Figure F-8, the results of Run 5 seem to confirm this expectation. The overshoot at the beginning and end of each turn is also consistent with expectations based upon horizontal turn rate estimation. Examination of the error components in latitude and longitude (not shown) reveals that while the east-west component has a relatively small mean, the north-south component has a relatively large mean. The filter picks up a large north error component early in the first turn. This error bias continues throughout the remainder of the turn and persists throughout the east leg of the pattern. The error bias is pretty well eliminated during the second turn (at the bottom of the page) and remains small throughout the second straight-line leg of the pattern. Although the north-south error bias along the east leg of the pattern cannot be seen in Figure F-8, its presence is evidenced in the error statistics. The 2drms errors for the various segments of Run 5 are:

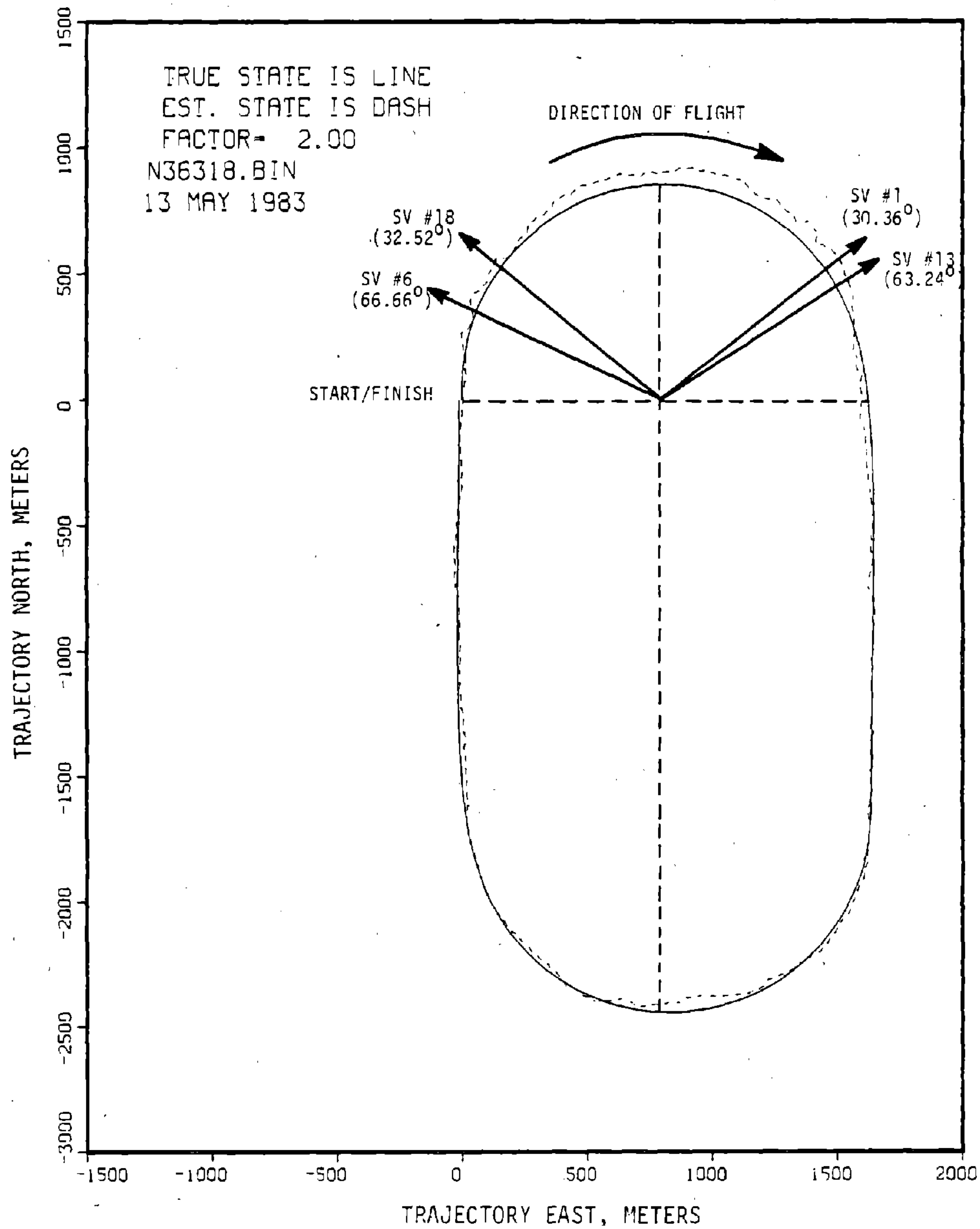


FIGURE F-8. ERROR PLOT, RUN 5, TRAJECTORY #3, GOOD CLOCK

HORIZONTAL POSITION ERROR 2drms (m)	ALTITUDE ERROR 2 sigma (m)	SEGMENT
54.92	95.84	1st turn (top of page)
56.84	105.80	east leg (A/C heading 180°)
33.74	65.58	2nd turn (bottom of page)
17.82	22.50	west leg (A/C heading 360°)
44.40	80.16	total run

The user clock for Run 5 is unchanged from that of Run 1 and Run 3 having a frequency stability of 1.01×10^{-10}.

Run 6, Trajectory No. 3, Poor Clock

Run 6 combines high acceleration (a turn rate of 6 deg/sec) with poor GDOP and poor clock stability. Figure F-9 shows the position/error plot for this run. The relevant statistics for Run 6 are:

HORIZONTAL POSITION ERROR 2drms (m)	ALTITUDE ERROR 2 sigma (m)	SEGMENT
44.50	80.46	1st turn (top of page)
38.12	60.20	east leg (A/C heading 180°)
55.18	108.26	2nd turn (bottom of page)
47.56	89.94	west leg (A/C heading 360°)
47.56	88.62	total run

A comparison of the results for Run 6 (poor clock) with those obtained previously for Run 5 (good clock) reveals the following:

1) Both runs develop relatively large north position error biases at the onset of the first turn. These north position error biases persist throughout the first straight-line segment on each of the runs.

2) The north position error bias is largely eliminated in the second turn of Run 5, having been reduced to only a few meters by the end of the turn.

3) The north position error bias is driven rapidly through zero and becomes a south position error bias during the second turn of Run 6. This error bias is essentially reduced to zero during the second straight-line segment of Run 6.

4) Runs 5 and 6 both exhibit significantly larger north-south (and altitude) errors than east-west errors.

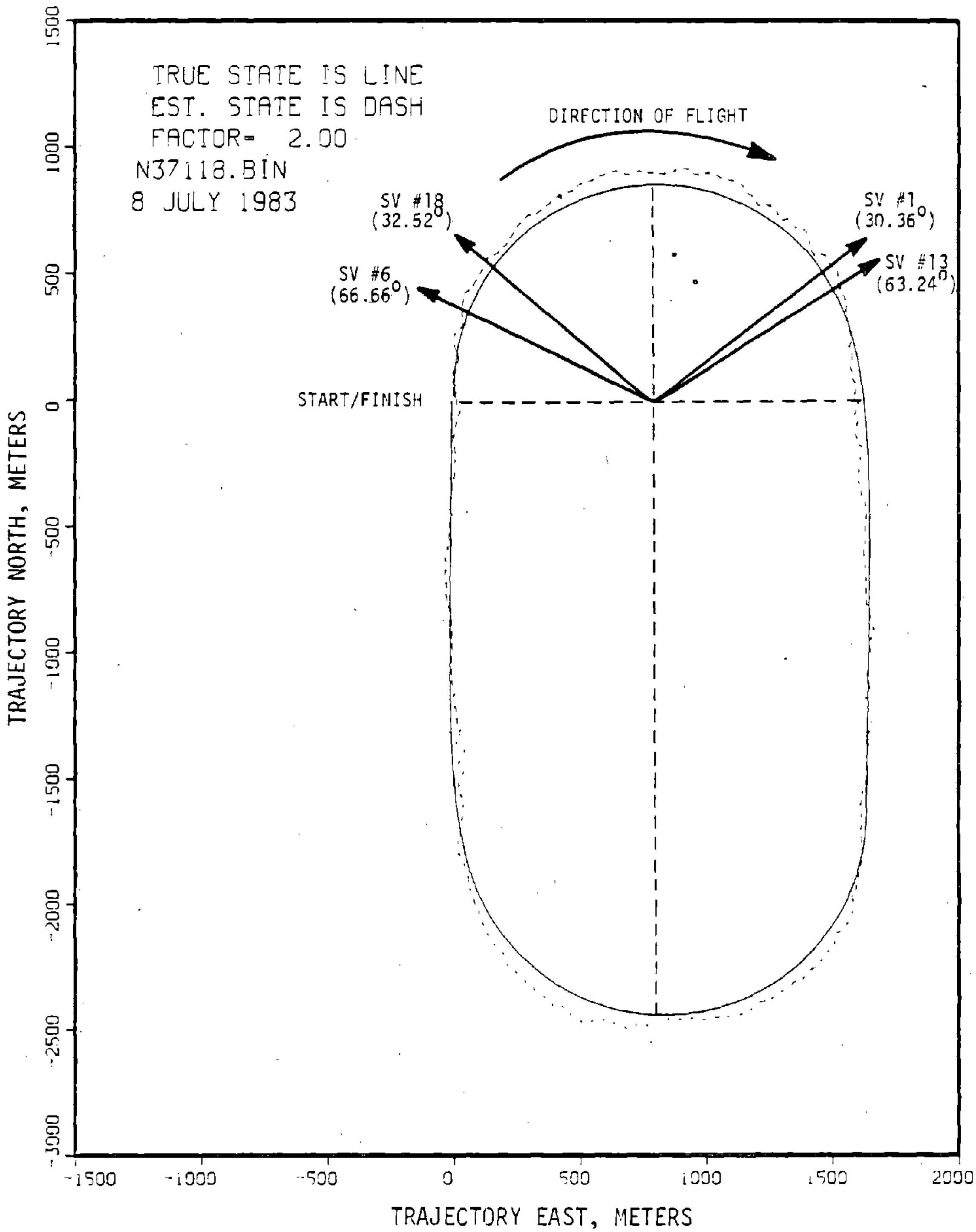


FIGURE F-9. ERROR PLOT, RUN 6, TRAJECTORY #3, POOR CLOCK

Some of the observed error characteristics seem consistent with what one might expect. Since the satellite geometry has rough east-west symmetry, we can expect clock-induced errors to roughly cancel in this direction. A comparison of the straight-line (north-south) segments of Runs 5 and 6 (Figures F-8 and F-9) shows this to be approximately the case. Note also that the satellites are favorably situated to the making of an east-west position measurement and errors in this direction are relatively small. Conversely, the satellites are poorly situated to the making of north-south position measurements and errors in this direction are relatively large and tend to persist. Clock-induced altitude errors cannot be expected to cancel and altitude error plots (not included here) tend to bear this out. The plots show a significant difference between the altitude errors of Runs 5 and 6. Run 6 exhibits a large negative altitude error (exceeding 50 meters in amplitude) during much of the second turn. No such errors are present in Run 5.

F.2.4 Trajectory No. 4 (Two Minute Turn Rate, Nominal GDOP)

This trajectory, shown in Figure F-10, is intended to indicate the level of performance that might be expected during a non-precision approach. The trajectory begins with a descending standard rate (2 minute) turn of 180°. The nominal descent rate in the turn is 2,000 ft/min. As the aircraft completes the turn, the descent rate is reduced to 848 ft/min providing a 3° glideslope on the straight-line segment of the pattern. Aircraft speed is maintained at 160 knots throughout the pattern.

Run 7, Trajectory No. 4, Good Clock

Figure F-10 shows the horizontal error performance obtained in Run 7. The performance is very similar to that obtained over the first portion of Run 1, which uses the same turn rate (3 deg/sec) and the same clock stability (1.01×10^{-10}) and GDOP (2.48). Clearly the introduction of descent rates of 2,000 ft/min and 848 ft/min has little effect on horizontal error in this example. The run statistics are:

HORIZONTAL POSITION ERROR 2DRMS (m)	ALTITUDE ERROR 2 SIGMA (m)	SEGMENT
16.38	13.22	1st turn (top of page)
14.48	14.28	east leg (A/C heading 180°)
15.80	13.56	total run

A comparison of the statistics of the comparable portions of Runs 1 and 7 shows that the horizontal position errors are within 4% over the turn and 6% over the straight-line segment. The corresponding altitude errors compare to within 32% and 24% over the turn and straight-line segments respectively.

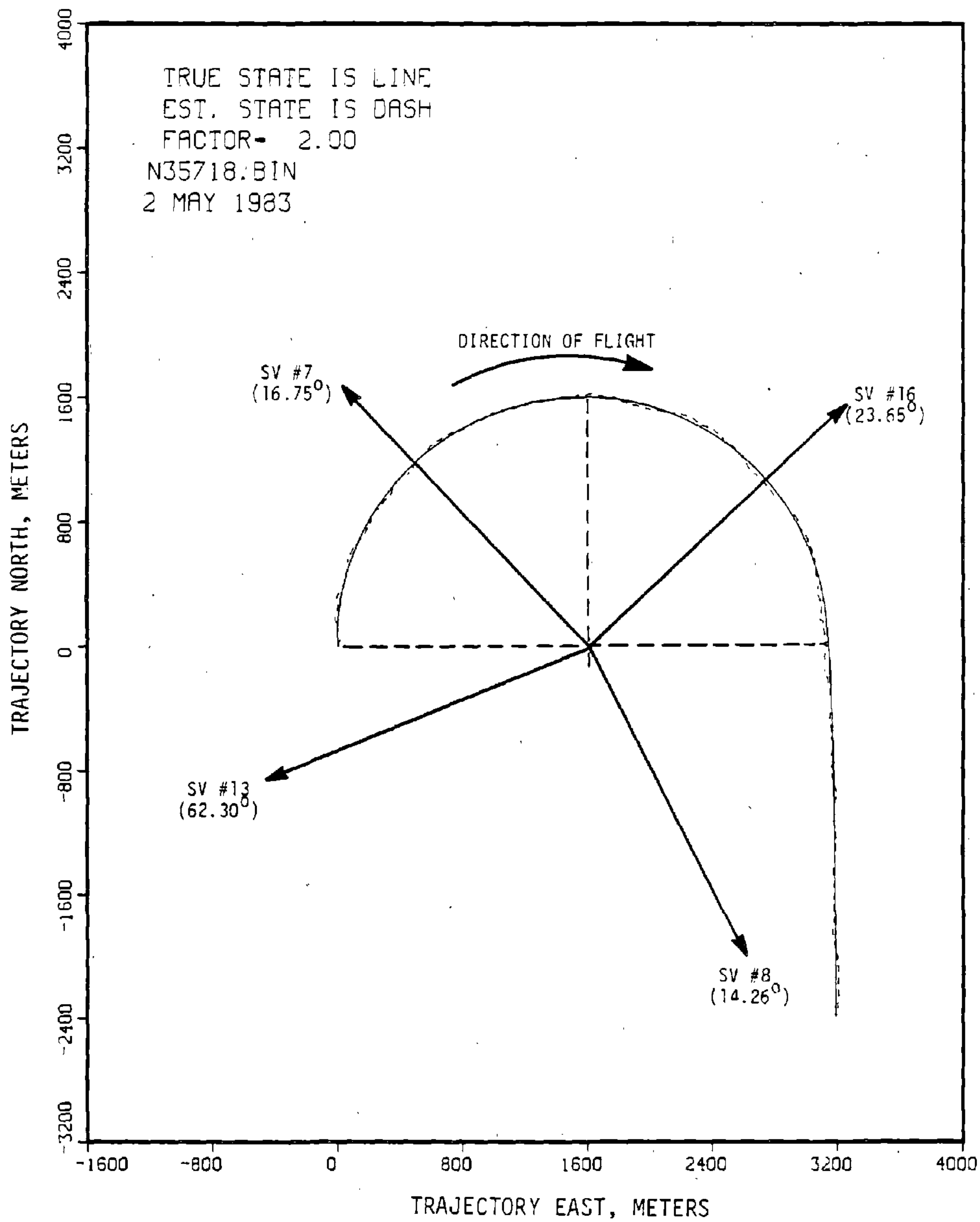


FIGURE F-10. ERROR PLOT, RUN 7, TRAJECTORY #4, GOOD CLOCK

Run 8, Trajectory No. 4, Poor Clock

This run shows the effect of a poor clock on the trajectory used to approximate the conditions of a non-precision approach. As in the case of the baseline trajectory (Runs 1 and 2), the poorer clock has a relatively small effect. The position/error plot for Run 8, shown in Figure F-11, is essentially the same as that shown in Figure F-10 for Run 7. The relevent error statistics for Run 8 and given below are not too much different from those for Run 7.

HORIZONTAL POSITION ERROR 2DRMS (m)	ALTITUDE ERROR 2 SIGMA (m)	SEGMENT
19.12	20.06	1st turn (top of page)
14.74	18.56	east leg (A/C heading 180°)
17.86	19.60	total run

In particular, the 2drms horizontal position errors are only increased by a maximum of 17% over those of Run 7, while the 2 sigma altitude errors are increased by a maximum of 52%.

F.3 SUMMARY

The AIRGPS simulation runs were intended to answer the following two questions:

1) What is the likely impact of temporary satellite blockage and turn-induced acceleration on navigation processor performance as a result of aircraft turning maneuvers?

2) What is the likely impact of poor user clock frequency stability on navigation processor performance during maneuvers which involve satellite blockage and turn-induced acceleration?

F.3.1 Turning Flight

The AIRGPS simulation results support the view that NAVSTAR GPS can provide suitable accuracy for non-precision approaches. Temporary satellite blockage and turn-induced accelerations had only a modest impact on navigation processor performance under conditions of nominal GDOP.

The performance of the receiver/processor was evaluated over four trajectories containing turns. Standard rate (3 deg/sec) and twice standard rate (6 deg/sec) turns were included, as were conditions of nominal and poor GDOP and changes in altitude. Table F-3 contains a summary of the 2drms position errors. When averaged over the total run, the 2drms errors range from 13.82 meters (baseline trajectory, good clock) to a worst case of 47.56 meters (twice standard rate turn, poor GDOP and poor clock). The maximum 2drms error occurred during

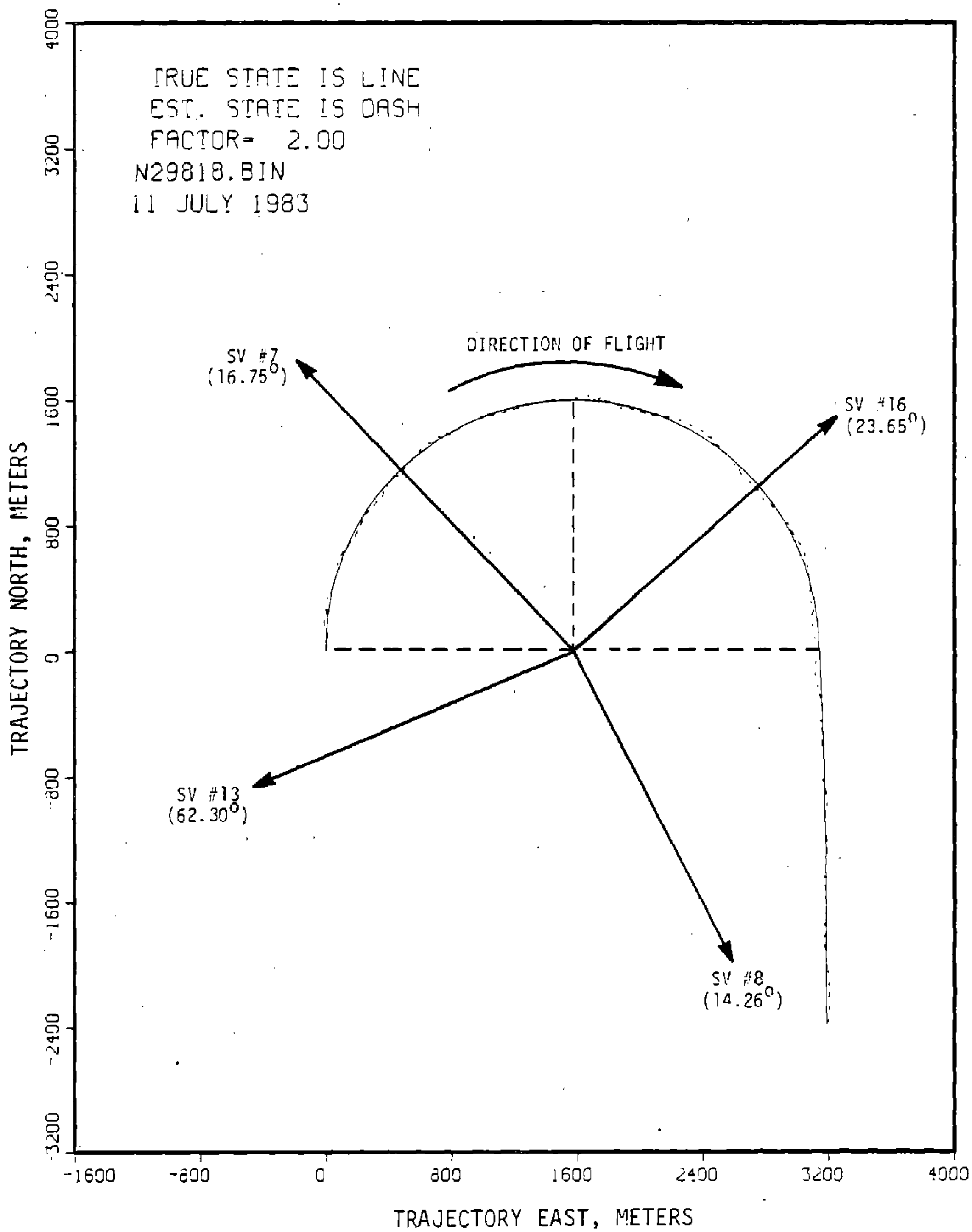


FIGURE F-11. ERROR PLOT, RUN 8, TRAJECTORY #4, POOR CLOCK

TABLE F-3. SUMMARY OF HORIZONTAL POSITION ERRORS

2DRMS ERRORS

RUN	TURN RATE (DEG/S)	HDOP (N.D.)	CLOCK STABILITY (N.D.)	1ST TURN (M)	STRAIGHT (M)	2ND TURN (M)	STRAIGHT (M)	TOTAL RUN (M)
1	3	1.29	1.0×10^{-10}	16.22	12.60	14.28	9.18	13.82
2	3	1.29	1.0×10^{-6}	18.52	12.70	16.20	9.64	15.36
3	6	1.29	1.0×10^{-10}	32.82	15.90	30.70	17.18	27.10
4	6	1.29	1.0×10^{-6}	32.88	16.36	32.20	17.86	27.78
5	6	9.76-7.23	1.0×10^{-10}	54.92	56.84	33.74	17.82	44.40
6	6	9.76-7.23	1.0×10^{-6}	44.50	38.12	55.18	47.56	47.56
7	3	1.29	1.0×10^{-10}	16.38	14.48	N/A	N/A	15.80
8	3	1.29	1.0×10^{-6}	19.12	14.74	N/A	N/A	17.86

the first straight-line segment of Run 5 (twice standard rate turn, poor GDOP and good clock). When restricted to a standard rate of turn and nominal GDOP (2.48), all errors remained below 20.0 meters 2drms. This performance compares favorably with the 100.0 meter, 2drms accuracy requirement given in the Federal Radionavigation Plan for non-precision approach. Altitude errors ranged from a low of 6.68 m 2 sigma in the first straight-line segment of Run 2 to to a high of 1087.26 m 2 sigma during the second turn of Run 6.

F.3.2 User Clock Stability

Poor user clock frequency stability does not appear to impose a significant burden on navigation processor performance during turning maneuvers under nominal GDOP conditions. Even under poor GDOP conditions, navigation processor performance was within that required by the Federal Radionavigation Plan for non-precision approaches.

A comparison of the data summarized in Table F-3 indicates that user clock stability was seldom a dominant factor. When averaged over the total run, the maximum increase in horizontal position error due to a poor clock was only 13% (Runs 7 and 8). When comparing the statistics for individual segments, only in the case of poor GDOP was there much more than about a 20% increase in error. The largest fractional increase occurs in the final straight-line segments of Runs 5 and 6. In this case, the 2drms horizontal position error increases from 17.82 meters to 47.56 meters, a factor of 2.67. We should point out, however, that although these results are based upon a very poor clock, they involve relatively short time intervals lasting for less than two minutes. Longer runs would be required to determine the effects of user clock stability in trying to "coast" the clock through periods of high GDOP for example.

APPENDIX G. SHORT-TERM CLOCK ERROR

In the case of short-term clock error, we are concerned with the problem of accuracy in measuring the time of arrival of signals from four satellites with a sequential receiver. If the time spread of measurements is 3 seconds, and the periods of fluctuation in the clock are of a similar magnitude, we can investigate the magnitude of the position errors based on the 3-second spread.

The navigation processor can model the clock errors and decrease their effect, but only within the period that characterizes the accelerated motion of the vehicle.

The long-term frequency offsets of the user clock will be compensated for by the Kalman filter, but the frequency shifts and phase fluctuations occurring with periods less than a second will result in errors of predicted position.

The fundamental equations of the multilateration system are:

$$(x_j-x_A)^2 + (y_j-y_A)^2 + (z_j-z_A)^2 = c^2(t_j-t_o)^2$$

from which we obtain:

$$(x_j-x_A)(\Delta x_j-\Delta x_A) + (y_j-y_A)(\Delta y_j-\Delta y_A) + (z_j-z_A)(\Delta z_j-\Delta z_A) = c^2(t_j-t_o)(\Delta t_j-\Delta t_o) \quad \text{(G-1)}$$

where x_j, y_j, z_j are coordinates of the j^{th} satellite.

$\Delta x_j, \Delta y_j, \Delta z_j$ are errors in position of the j^{th} satellite.

x_A, y_A, z_A are coordinates of the user position.

t_o is the time of satellite transmission.

t_j is the time of arrival of the signal from the j^{th} satellite.

Δt_j is the error in measurement of the j^{th} TOA.

Δt_o is the error in system time.

$\Delta x_A, \Delta y_A, \Delta z_A$ are errors in user position.

c is the speed of light in vacuo.

It will be convenient to use the following vector notation:

$$\underline{\Delta x_A} = \begin{bmatrix} \Delta x_A \\ \Delta y_A \\ \Delta z_A \\ c\Delta t_o \end{bmatrix} \qquad \underline{\Delta t} = \begin{bmatrix} \Delta t_1 \\ \Delta t_2 \\ \Delta t_3 \\ \Delta t_4 \end{bmatrix} \qquad \underline{\Delta x_j} = \begin{bmatrix} \Delta x_j \\ \Delta y_j \\ \Delta z_j \end{bmatrix}$$

In the following treatment we may calculate $\underline{\Delta x_A}$ from estimates of errors $\underline{\Delta t}$ or $\underline{\Delta x_j}$ or, in the case of fewer than four satellites, errors in measuring z_A or t_o using outside instruments are additional sources of error in estimating the remaining position coordinates.

Equation (G-1) can be written:

$$a_{j1}\Delta x_A + a_{j2}\Delta y_A + a_{j3}\Delta z_A + c\Delta t_o = c\Delta t_j \tag{G-2}$$

or

$$[A]\ \underline{\Delta x_A} = \underline{c\Delta t} \tag{G-3}$$

where a_{j1}, a_{j2}, a_{j3} are the direction cosines of the j^{th} satellite and $a_{j4} = 1$. $\underline{\Delta t}$ is the source of error (as in the case of short-term clock errors).
Similarly,

$$\underline{\Delta x_A} = [A^{-1}]\ \underline{c\Delta t}. \tag{G-4}$$

We represent the elements of A^{-1} as $\overline{a_{ij}}$.

An accepted measure of the GPS errors in estimated position is the rms value of estimated position averaged over the distribution of errors in measuring the satellite TOA's. Thus

$$\overline{\Delta x_A^{\ 2}} = \overline{\overline{a_{11}}^2\Delta t_1^{\ 2} + \overline{a_{12}}^2\Delta t_2^{\ 2} + \overline{a_{13}}^2\Delta t_3^{\ 2} + \overline{a_{14}}^2\Delta t_4^{\ 2} + 2\overline{a_{11}}\,\overline{a_{12}}\Delta t_1\Delta t_2} \tag{G-5}$$

$$+ \ ....$$

for which, if we assume Δt_j's represent measurement errors randomly distributed with zero, means:

$$\overline{\Delta t_i \Delta t_j} = \sigma^2 \delta_{ij} \tag{G-6}$$

where σ is the mean deviation of the error in satellite range measurement.

The measures HDOP, VDOP, and PDOP have been defined as follows:

$$HDOP = [\overline{\Delta x_A^2 + \Delta y_A^2}]^{1/2} / \sigma$$

$$VDOP = [\overline{\Delta z_A^2}]^{1/2} / \sigma$$

$$PDOP = [\overline{\Delta x_A^2 + \Delta y_A^2 + \Delta z_A^2}]^{1/2} / \sigma$$

In the short-term clock case for the sequential receiver, the satellite ranges are measured at approximately one-second intervals. The TOA errors are caused by clock frequency shifts induced by mechanical vibrations, which result in random phase shifts of the user clock such that the satellite TOA errors are not correlated, and Equation (G-6) prevails.

The short-term clock errors produce errors as follows:

Δs = HDOP $(\sigma_c)(c)$

Δv = VDOP $(\sigma_c)(c)$

where Δs is the rms horizontal position error estimate.

Δv is the rms altitude error estimate.

σ_c is the rms short term phase variation of the clock in seconds.

σ_c^2 is the Allan variance[30] of the clock for a one second sampling interval.

APPENDIX H. LONG-TERM CLOCK ERROR

We consider a sequential receiver making a 3-D navigation fix with 3 satellites and a good clock, operating in the coasting mode. If the period for which the clock must be used is 20 minutes or longer, the principal source of error will be clock frequency drift. Referring to the notation of Appendix G we let the TOA errors

$\Delta t_j = 0$

and the user clock error, $\Delta t_o = T$

where $T = \Delta f t / f_o$.

$\Delta f / f_o$ is the fractional frequency offset of the clock and t is the time elapsed since last there was a 4-satellite fix, which could be used to calculate f_o.

Equation (G-1) of Appendix G becomes

$$cT + a_{j1}\Delta x_1 + a_{j2}\Delta y_1 + a_{j3}\Delta z_1 = a_{j1}\Delta x_A + a_{j2}\Delta y_A + a_{j3}\Delta z_A.$$

Now $a_{j1}\Delta x_j + a_{j2}\Delta y_j + a_{j3}\Delta z_j = \underline{v}_j \cdot \underline{r}_j T$

where $\underline{v}_j$ is the velocity of the j^{th} satellite.

Since $|\underline{v}_j| << c$, the expression becomes

$$cT = a_{j1}\Delta x_A + a_{j2}\Delta y_A + a_{j3}\Delta z_A.$$

Equation (G-1) becomes

$$\begin{bmatrix} A_3 \\ \\ \\ \end{bmatrix} \underline{\Delta x}_A = \begin{bmatrix} cT \\ cT \\ cT \end{bmatrix}$$

where A_3 is the 3-satellite LOS matrix version of Appendix G and $\underline{\Delta X}_A$ is the 3-element user-position vector.

$$\underline{\Delta x_A} = \begin{bmatrix} A_3^{-1} & & \\ & & \\ & & \end{bmatrix} \begin{bmatrix} cT \\ cT \\ cT \end{bmatrix}$$

$$\Delta x_A = [\overline{a_{11}} + \overline{a_{12}} + \overline{a_{13}}]\ cT$$

and $$\Delta x_A{}^2 = [\overline{a_{11}}{}^2 + \overline{a_{12}}{}^2 + \overline{a_{13}}{}^2 +$$

$$2\overline{a_{11}}\,\overline{a_{12}} + 2\overline{a_{11}}\,\overline{a_{13}} + 2\overline{a_{12}}\,\overline{a_{23}}]\ c^2\ T^2.$$

Averaging over all possible satellite configurations of the constellation, we arrive at:

$$\overline{\Delta x_A{}^2 + \Delta y_A{}^2 + \Delta z_A{}^2} = [\overline{HDOP^2 + VDOP^2}^{\,\text{Constellation}}]\ c^2 T^2$$

and $$\Delta s = [\overline{HDOP^2}^{\,\text{Constellation}}]^{1/2} \cdot cT = KcT = Kct(\Delta f/f_o) = K\lambda\Delta ft,$$

where t is the time since 4-satellite coverage was last obtained and λ is the wavelength of the clock. K is the rms value of HDOP averaged over the constellation. From Figure 5-4, K = 1.5.

Example:

t = 1000 sec., $f_o = 1.5 \times 10^9$, $\lambda = 2/3$ ft.

If $f/f_o = 10^{-9}$,

$\Delta ft = 1500$

$\Delta s = 2250\lambda = 1500$ ft.

If $f/f_o = 10^{-11}$

$\Delta s = 15\lambda = 15$ ft.

Navigation errors are described in the foregoing page in terms of average HDOP's. In the following, we examine the errors of a specific three-satellite constellation in the coasting mode.

Figure H-1 shows the constellation considered. In this notation:

θ_j is the polar angle of the satellite with respect to zenith.

ψ_j is the projected angle in the horizontal plane of the LOS vector.

$\theta_1 = \theta_2 = 90°$, $\theta_3 = 0°$

$\phi_1 = 0$

$\phi_2 = 90°$

$\Delta = t\Delta f/f_o$.

If only clock errors are significant, Equation (H-1) becomes:

$$\Delta x_A + 0\Delta y_A + 0\Delta z_A = \Delta$$

$$0\Delta x_A + \Delta y_A + 0\Delta z_A = \Delta$$

$$0\Delta x_A + 0\Delta y_A + \Delta z_A = \Delta$$

$$\therefore \Delta x_A = \Delta y_A = \Delta z_A = \Delta$$

$$\Delta s = \sqrt{2}\Delta = \sqrt{2}ct\Delta f/f_o.$$

The HDOP for this configuration is $\sqrt{2}$.

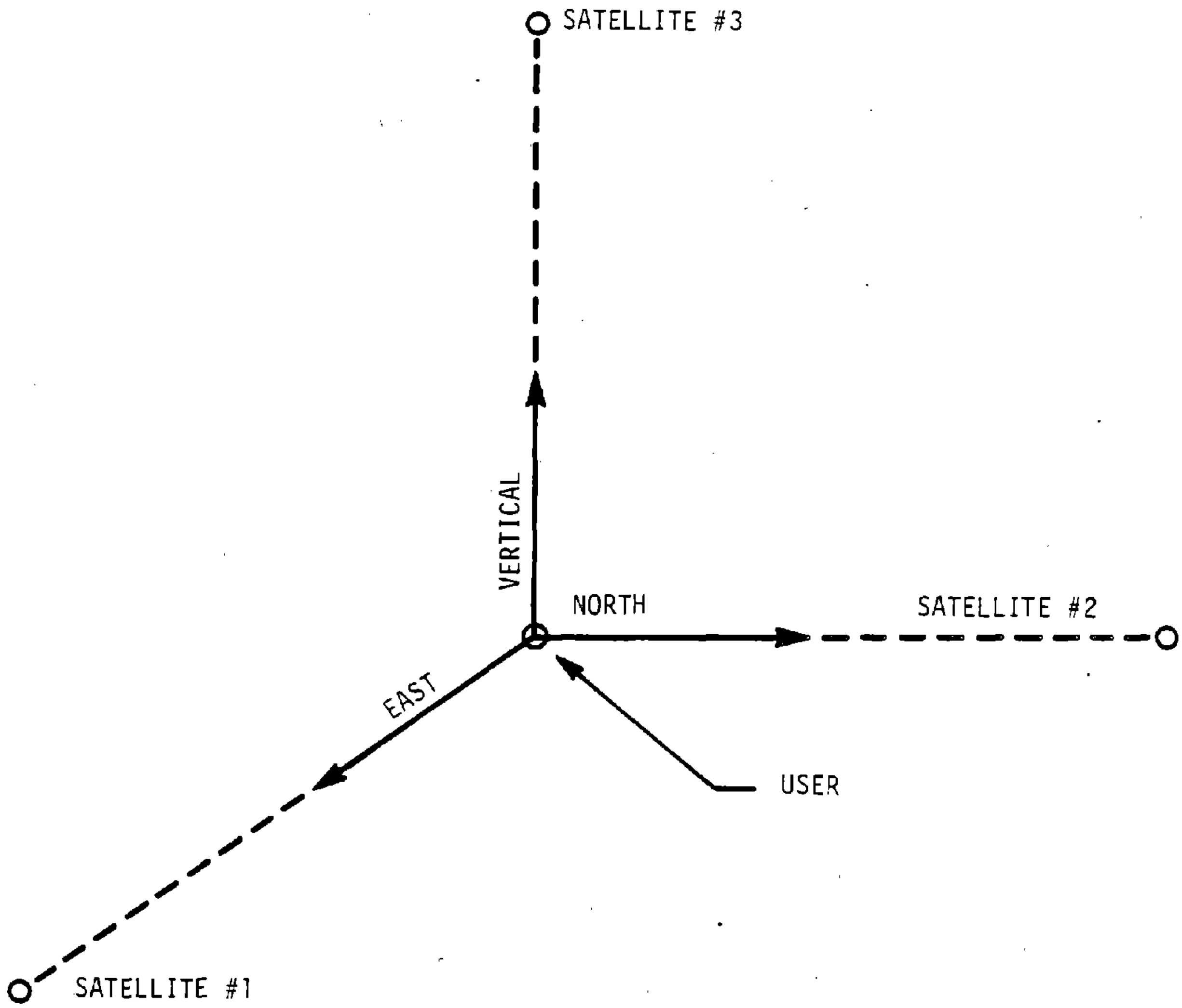


FIGURE H-1. SATELLITE CONFIGURATION FOR CLOCK OR ALTIMETER AIDING

APPENDIX I. ERRORS IN POSITION RESULTING FROM ALTITUDE INACCURACIES

It is here assumed that altitude is derived from an altimeter and is used with the signal arrival times from three satellites to determine the user's horizontal position and system time.

Equation (G-1) becomes for this case:

$$(x_j - x_A)(\Delta x_A) + (y_j - y_A)(\Delta y_A) + (z_j - z_A)(\Delta h) = c^2(t_j - t_o)\Delta t_o.$$

or $a_{11}\Delta x_A + a_{12}\Delta y_A - \Delta w = -\cos\theta_1 \Delta h$

$$a_{21}\Delta x_A + a_{22}\Delta y_A - \Delta w = -\cos\theta_2 \Delta h$$

$$a_{31}\Delta x_A + a_{32}\Delta y_A - \Delta w = -\cos\theta_3 \Delta h$$

$$\begin{bmatrix} & A & \\ & & \\ & & \end{bmatrix} \begin{bmatrix} \Delta x_A \\ \Delta y_A \\ \Delta w \end{bmatrix} = -\Delta h \begin{bmatrix} \cos\theta_1 \\ \cos\theta_2 \\ \cos\theta_3 \end{bmatrix}$$

$$\begin{bmatrix} \Delta x_A \\ \Delta y_A \\ \Delta w \end{bmatrix} = -\Delta h \begin{bmatrix} & & \\ & A^{-1} & \\ & & \end{bmatrix} \begin{bmatrix} \cos\theta_1 \\ \cos\theta_2 \\ \cos\theta_3 \end{bmatrix}$$

where $\Delta w = -c\Delta t_o$

Δh is the altimeter error

$$\Delta x_A^2 = \Delta h^2 \; [\overline{a_{11}}^2 \cos\theta_1^2 + \overline{a_{12}}^2 \cos\theta_2^2 + \overline{a_{13}}^2 \cos\theta_3^2 + \tag{I-1}$$

$$2\overline{a_{11}}\,\overline{a_{12}}\cos\theta_1\cos\theta_2 + 2\overline{a_{11}}\,\overline{a_{13}}\cos\theta_1\cos\theta_3 + 2\overline{a_{12}}\,\overline{a_{13}}\cos\theta_2\cos\theta_3].$$

Averaging over all configurations of the constellations, the terms involving $\cos\theta_i \cos\theta_j$ average out to zero. The HDOP for a 2-D configuration averaged over all possible 2-D configurations is: (from Equation (H-5))

$$\overline{\text{HDOP}^2_{2D}}^{\text{All Configurations}} = \overline{\overline{a_{11}}^2 + \overline{a_{12}}^2 + \overline{a_{13}}^2 + \overline{a_{21}}^2 + \overline{a_{22}}^2 + \overline{a_{23}}^2}^{\text{All Configurations}} .$$

Compare this with the average of equation (I-1):

$$\overline{x_A^2 + y_A^2}^{\text{All Configurations}} = \Delta h^2 [\overline{\overline{a_{11}}^2 \cos\theta_1^2 + \overline{a_{12}}^2 \cos\theta_2^2 + \overline{a_{13}}^2 \cos\theta_3^2 +}^{\text{All Configurations}}$$

$$\overline{\overline{a_{21}}^2 \cos\theta_1^2 + \overline{a_{22}}^2 \cos\theta_2^2 + \overline{a_{23}}^2 \cos\theta_3^2}$$

$$= \Delta h^2 Q^2$$

where $Q^2 < \text{HDOP}^2_{2D}$

From which we conclude:

$$\Delta s < \Delta h \; [\overline{(\text{HDOP}^2_{2D})}]^{1/2} .$$

From Figure 5-4 we see that

$$[\overline{\text{HDOP}^2_{2D}}^{\text{All Configurations}}]^{1/2} \approx 1.5$$

so that $\overline{\Delta s} < 1.5\Delta h$.

Example:

Consider the configuration of Appendix H.

The equations of page I-1 become:

$\Delta x_A - \Delta w = 0$

$\Delta y_a - \Delta w = 0$

$-\Delta w = -\Delta h.$

From which we obtain:

$\Delta w = \Delta y_A = \Delta x_A = \Delta h$

$\Delta x_A{}^2 + \Delta y_A{}^2 = 2\Delta h^2$

$\Delta s = \sqrt{2}$ (rms altimeter error).

The HDOP for this configuration is $\sqrt{2}$ (see Appendix H).

APPENDIX J. DIFFERENTIAL GPS ERROR ANALYSIS

The differential technique achieves its high accuracy in position estimate by reducing bias errors common to both reference site and user in the measurement. The following discussion demonstrates in some detail how the errors enter into a measurement and to what degree they establish the overall system performance.

Noise error evaluation is based on two position fixes using two separate and independent receivers, one at the aircraft and one at the ground reference site. Figure J-1 shows the geometry under discussion. The positions of the user, reference site and its satellite are denoted in 4-dimensional space by vectors $\underline{x}$, $\underline{x}'$ and $\underline{s}_i$ respectively, where the x_4 dimension represents the clock offset.

The first three elements of these "position" vectors correspond to a physical position in an earth-centered, earth-fixed coordinate system while the fourth element corresponds to the respective clock phases or times. The magnitude of the vector difference $\underline{S}$ -$\underline{X}$ is called the pseudorange and represents the distance between the ith satellite and the ground-based reference or user receiver, minus the time offset of the receiver clock:

$$r_i = \left[(\underline{s}_i - \underline{x})^T(\underline{s}_i - \underline{x})\right]^{\frac{1}{2}} - x_4 .$$

The unit vector between a ground based receiver and a satellite is

$$\underline{u}_i = \frac{(\underline{s}_i - \underline{x})}{|\underline{s}_i - \underline{x}|} .$$

In the presence of pseudorange errors we have the user-equivalent range error (UERE),

$$\rho_i = \frac{(\underline{s}_i - \underline{x})^T}{|\underline{s}_i - \underline{x}|} \delta(\underline{s}_i - \underline{x}) - \delta x_4$$

where the user estimated position is given by

$$\hat{\underline{x}} \triangleq (\hat{x}_1, \hat{x}_2, \hat{x}_3, \hat{x}_4).$$

The difference between true position and the estimated position is the "geometric" or navigation error

$$\underline{e}_G \triangleq \underline{x} - \hat{\underline{x}} .$$

The UERE or pseudorange measurement error can be defined similarly:

$$\underline{e}_u \triangleq (e_1, e_2, e_3, e_4)^T.$$

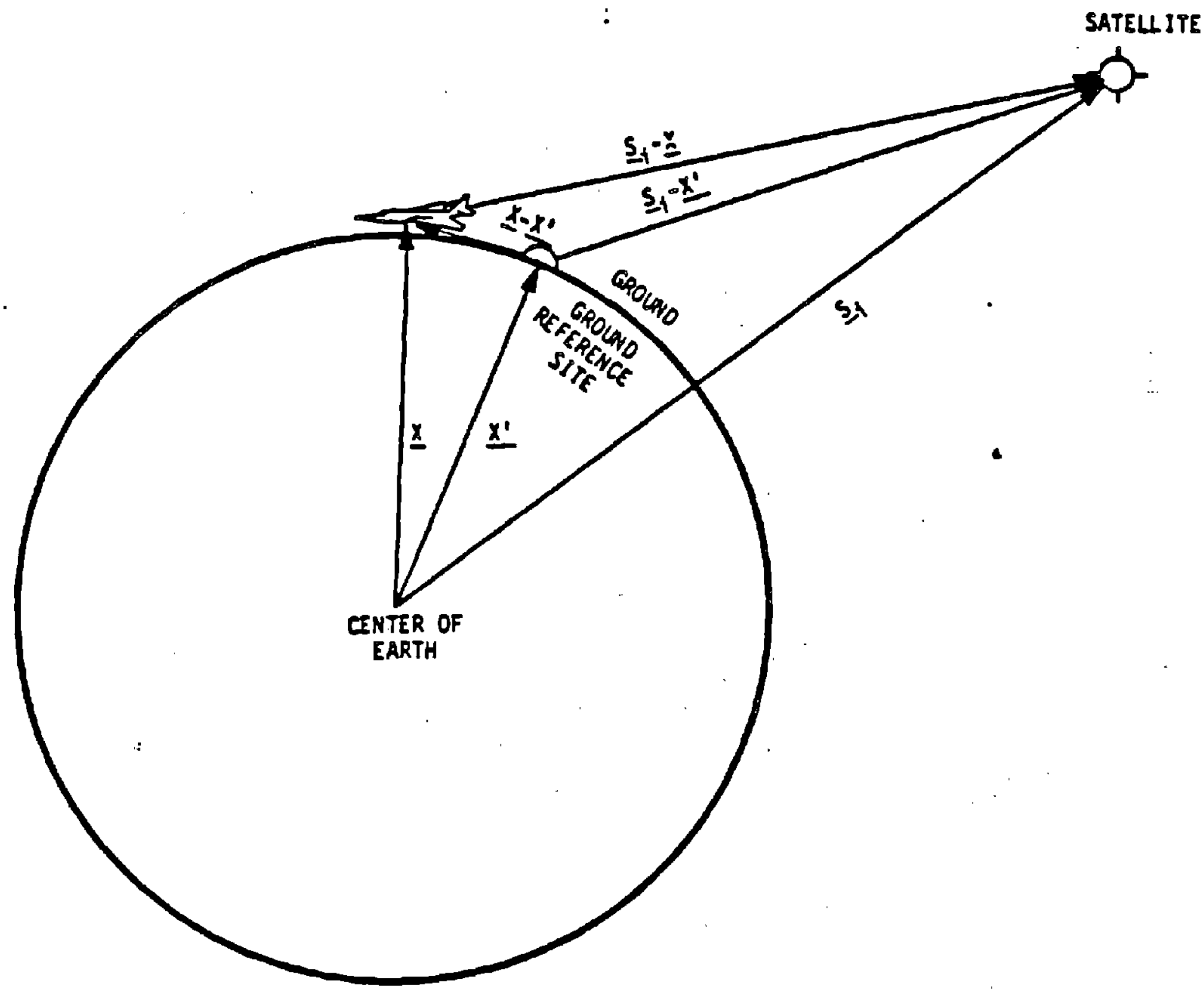


FIGURE J-1. DIFFERENTIAL GPS GEOMETRY

The transformation matrix, which depends only on user-satellite geometry, relates both errors as follows:

$$\underline{e}_G = G^{-1}\underline{e}_u .$$

The covariance of it is

$$Cov(\underline{e}_G) = G^{-1} Cov\, \underline{e}_u \, (G^T)^{-1}.$$

For the evaluation of the noise components we will use the method developed in reference 8. The ranging errors which are common to all measurements or correlated between satellites, will be lumped together with user's clock bias. The positional error is now worked out for three cases.

Case 1: Conventional Solution: - Single user, no correlation between pseudorange measurements (General).

In the first approximation, we ignore the correlated components of pseudorange errors, $\underline{e}_u$, if we are interested in the user position error only. Therefore, in the conventional approach

$$Cov(\underline{e}_u) = \sigma_u^2 I_u$$

$$Cov(\underline{e}_G) = \sigma_u^2 (G^T G)^{-1}.$$

The mean-square navigation or "geometry" error is

$$\sigma_G^2 = TRACE\,[Cov\,\underline{e}_G] = \sigma_u^2 (GDOP)^2.$$

Case 2: Correlation Exist Between Pseudorange Errors (Translator)

The following development demonstrates how the correlation enters into computed position and clock bias measurements. By separating errors into a correlated and uncorrelated component we define the following relationship:

$$e_i \triangleq n_i + c_i$$

where

n_i = Uncorrelated component between satellites

c_i = Correlated component between satellites.

It is assumed that n_i and c_i are independent and ergodic.

This condition leads us to the assumption that for a short time, the measurements are highly correlated and similar processes affect each pseudorange measurement.

Under these assumptions the pseudorange measurement error covariance is

$$Cov(\underline{e}_u) = Cov(\underline{n}) + Cov(\underline{c}) = \sigma_n^2 I + \sigma_c^2 R$$

where R is a correlation matrix, described below.

Similarly, the position error is

$$Cov(\underline{e}_G) = G^{-1} Cov(\underline{e}_u)(G^T)^{-1} = \sigma_n^2 (G^T G)^{-1} + \sigma_c^2 G^{-1} R (G^T)^{-1}$$

$$\sigma_G^2 = \sigma_n^2 (GDOP)^2 + \sigma_c^2 TRACE_{14} [G^{-1} R G^T]^{-1}.$$

In order to avoid detailed knowledge of G, this equation is simplified by simplifying the structure of R and computing the bounds.

Letting R be represented by a matrix:

$$R = \begin{bmatrix} 1 & r & r & r \\ r & 1 & r & r \\ r & r & 1 & r \\ r & r & r & 1 \end{bmatrix} = \begin{bmatrix} r & r & r & r \\ r & r & r & r \\ r & r & r & r \\ r & r & r & r \end{bmatrix} + \begin{bmatrix} 1-r & 0 & 0 & 0 \\ 0 & 1-r & 0 & 0 \\ 0 & 0 & 1-r & 0 \\ 0 & 0 & 0 & 1-r \end{bmatrix} = R_1 + R_2$$

Where

$$G^{-1} R_1 (G^T)^{-1} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & r \end{bmatrix}$$

and

$$G^{-1} R_2 (G^T)^{-1} = (1-r) G^{-1} I (G^T)^{-1} = (1-r)(G^T G)^{-1}.$$

Substituting derived values in the original equation we obtain:

$$\sigma_G^2 = [\sigma_u^2 + (1-r)\sigma_c^2](GDOP)^2 + r\sigma_c^2$$

and

$$\sigma_P^2 = [\sigma_u^2 + (1-r)\sigma_c^2][PDOP]^2$$

$$\sigma_H^2 = [\sigma_u^2 + (1-r)\sigma_c^2][HDOP]^2$$

$$\sigma_V^2 = [\sigma_u^2 + (1-r)\sigma_c^2][VDOP]^2$$

$$\sigma_T^2 = [\sigma_u^2 + (1-r)\sigma_c^2][TDOP]^2 + r\sigma_c^2.$$

From the above given equation, we may conclude

$r = 0$ means measurements (UERE) are uncorrelated.

$\sigma_u^2 + (1+r)\sigma_c^2$ becomes $\sigma_u^2 + \sigma_c^2 = \sigma_u^2$.

Since

$\sigma_c = 0$, when $r = 0$, $\sigma_u^2 = \sigma_u^2$

as in case 1, and

for r=1:

$$\sigma_T^2 = [\sigma_n^2 + (1-r)\sigma_c^2][TDOP]^2 + r\,\sigma_c^2.$$

Similarly $\sigma_n = 0$, when $r = 1$

and $\sigma_T^2 = [0 + 0][TDOP]^2 + \sigma_c^2 = \sigma_c^2.$

The correlation error of the measurement then becomes absorbed in X_4.

Case 3: Measurements at two positions. (Centralized GPS)

The user is assumed to be close to the reference site, and the same set of satellites are being used.

Errors for each user:

$$\underline{e}_G \triangleq \underline{x} - \hat{\underline{x}} = G^{-1}\underline{e}_u$$

$$\underline{e}'_G \triangleq \underline{x}' - \hat{\underline{x}}' = G'^{-1}\underline{e}'_u.$$

The relative error in measurement is given by

$$\underline{\varepsilon} \triangleq \underline{e}_G - \underline{e}'_G = G^{-1}\underline{e}_u - G'^{-1}\underline{e}_u$$

$$Cov(\underline{\varepsilon}) = E(\underline{\varepsilon}\,\underline{\varepsilon}^T).$$

We assume that

$$Cov(\underline{\varepsilon}) \simeq 2G^{-1}Cov(\underline{e}_u)(G^T)^{-1} - G^{-1}[E(\underline{e}_u\underline{e}'^T_u) + E(\underline{e}'_u\underline{e}^T_u)](G^T)^{-1}$$

$$\approx 2G^{-1}Cov(\underline{e}_u)(G^T)^{-1} - G^{-1}W(G^T)^{-1}$$

where

$$\frac{W}{2} \triangleq E(\underline{e}_u \underline{e}_u'^T) = E(\underline{e}_u' \underline{e}_u^T).$$

Positioning the UERE's into correlated and uncorrelated components as before:

$$e_i \triangleq n_i + c_i$$
$$e_i' \triangleq n_i' + c_i' , \qquad i = 1, 2, 3, 4$$

where $n_i (n_i')$ is the component which is uncorrelated between satellites and users and $c_i (c_i')$ is the component that is correlated between satellites and between users. The components n_i (n_i') and c_i (c_i') are assumed to satisfy stationary and ergodic properties. Moreover, we assume that n_i, n_j, c_k, c_l, (i, j, k, l = 1, 2, 3, 4) are all mutually independent except for the pairing c_k, c_l, (k, l = 1, 2, 3, 4).

We now consider the special case for which

$$E\{\underline{c}\underline{c}^T\} = E\{\underline{c}'\underline{c}'^T\} = \sigma_c^2 \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad |r| \leq 1$$

and

$$W = 2\sigma_c^2 \begin{bmatrix} u & v & v & v \\ v & u & v & v \\ v & v & u & v \\ v & v & v & u \end{bmatrix}, \quad \begin{matrix} |u| \leq 1 \\ |v| \leq 1 . \end{matrix}$$

This implies that:

1) Pseudoranges made to the same satellite by different users have correlation "u".

2) Pseudoranges made to different satellites by different users have correlation "v".

For this special case, the covariance of the differential navigation error can be written as

$$Cov(\underline{\varepsilon}) = 2[\sigma_n^2 + (1-r)\sigma_c^2 - (u-v)\sigma_c^2](G^TG)^{-1}$$
$$+ 2\sigma_c^2 G^{-1}[R_1 - V](G^T)^{-1}$$

where R_j is as defined earlier and V is a matrix with elements of v_{ij} =v for all i, j. Denoting differential navigation errors with the subscript D, we find

$$\sigma_{GD}^2 = 2[\sigma_n^2 + (1-r-u+v)\sigma_c^2][GDOP]^2 + 2\sigma_c^2(r-v)$$

$$\sigma_{PD}^2 = 2[\sigma_n^2 + (1-r-u+v)\sigma_c^2][PDOP]^2$$

$$\sigma_{HD}^2 = 2[\sigma_n^2 + (1-r-u+v)\sigma_c^2][HDOP]^2$$

$$\sigma_{VD}^2 = 2[\sigma_n^2 + (1-r-u+v)\sigma_c^2][VDOP]^2$$

$$\sigma_{TD}^2 = 2[\sigma_n^2 + (1-r-u+v)\sigma_c^2][TDOP]^2 + 2\sigma_c^2(r-v)$$

The following error equations illustrate the differences between the Centralized and Translator GPS techniques:

Centralized GPS:

$$\boxed{\sigma_{GD}^2 = 2[\sigma_n^2 + (1-r-u+v)\sigma_c^2][GDOP]^2 + 2\sigma_c^2[r-v]}$$

Translator GPS:

$$\boxed{\sigma_G^2 = [\sigma_n^2 + (1-r)\sigma_c^2][GDOP]^2 + r\sigma_c^2}$$

where r = the correlation between different space vehicle pseudorange errors for a specific user

v = different space vehicle, different users

u = same space vehicle, different users.

For users close to the ground site, $r \approx v$ and $u \approx 1$. Using the approximation $r \approx v$ allows simplification of the above equations to

$$\sigma_{GD}^2 = 2[\sigma_n^2 + (1-u)\sigma_c^2][GDOP]^2$$

$$\sigma_{PD}^2 = 2[\sigma_n^2 + (1-u)\sigma_c^2][PDOP]^2$$

$$\sigma_{HD}^2 = 2[\sigma_n^2 + (1-u)\sigma_c^2][HDOP]^2$$

$$\sigma_{VD}^2 = 2[\sigma_n^2 + (1-u)\sigma_c^2][VDOP]^2$$

$$\sigma_{TD}^2 = 2[\sigma_n^2 + (1-u)\sigma_c^2][TDOP]^2.$$

We note that the factor $(1-u)$, which multiplies the variance of the correlated component, σ_c^2, becomes small as $u \rightarrow 1$. Hence, for closely spaced users, we expect to see the effects due to the correlated error components become insignificant, and the various relative navigation variances depend the factor $2\sigma_n^2$ weighted by the appropriate DOP. The factor of two is due to the differencing of independent measurements, each having variance σ_n^2. Note that in absolute measurement cases, the factor of two is missing since the error has been defined in and above to be the difference between <u>two</u> pseudoranges.

APPENDIX K. SOURCES OF ERROR IN DIFFERENTIAL OPERATION

K.1 MEASUREMENT ERROR COMPONENTS - Estimated positions are based on precise measurement of the propagation time for satellite signals to reach earth-bound receivers. This is accomplished by measuring the signal time-of-arrival (TOA). A difference between TOA and the knowledge of the time when signal was sent provides an information on the pseudorange between a satellite and a receiving site. This measurement, however, includes also atmospheric path delays, clock offsets, and correlator error. A component breakdown of these errors forming the pseudorange measurement is as follows:

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

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 sent with navigation message

δ_R - receiver noise error

δ_{SA} - Selective Availability

The following error subdivision was used in Section 8.

A. BIAS ERRORS

- o Ionospheric - TEC changes with distance.
- o Ionospheric - TEC changes with elevation angle.
- o Ephemeris - Error in satellite position.
- o Differential Station Uncertainty - error in measurement.
- o Tropospheric - Refractive index fluctuations.
- o Tropospheric - Refractive index variations with elevation angle.

B. NOISE ERRORS

- o Receiver Noise - error in pseudorange measurements.
- o Tropospheric Noise - fluctuation in the atmosphere.

A discussion of these errors is addressed in Section K.4.

K.2 RECEIVER CHARACTERISTICS - A distinction between ground-based, marine and airborne receivers is based on the tracker design, specifically on the IF, carrier loop and delay loop bandwidth requirements. The above restrictions determine receiver acquisition time, noise level, data update rate requirements. The following parameters were selected for performance prediction.

RECEIVER BANDWIDTH, B

	B_{IF}, Hz	B_{carr}, Hz	B_{code}, Hz
Reference Site	300	10	0.5
Marine	300	10	0.3
Airborne	500	10	5.0

All navigation message signals are fed to a low-noise preamplifier. Typical preamplifier values used are:

Noise Figure: 4.5 db (3.0 db advertised by Hewlett-Packard)
Gain: 30 db
Antenna Temperature: 130°K

Received signal budget estimates are:

Received Signal (C/A Code)	-160 dbW-Hz
Line Loss	-1 db
Effective Carrier Signal	-161 dbW-Hz
Thermal Noise	-228.6 dbW-Hz
Equivalent Antenna Temperature	+28.7 db
Multiple Access Noise	+1.0 db
Noise Spectral Density	-198.9 dbW/Hz
Carrier Signal, C	-161 dbW
Signal Power to Noise Spectral Density	37.9 db-Hz

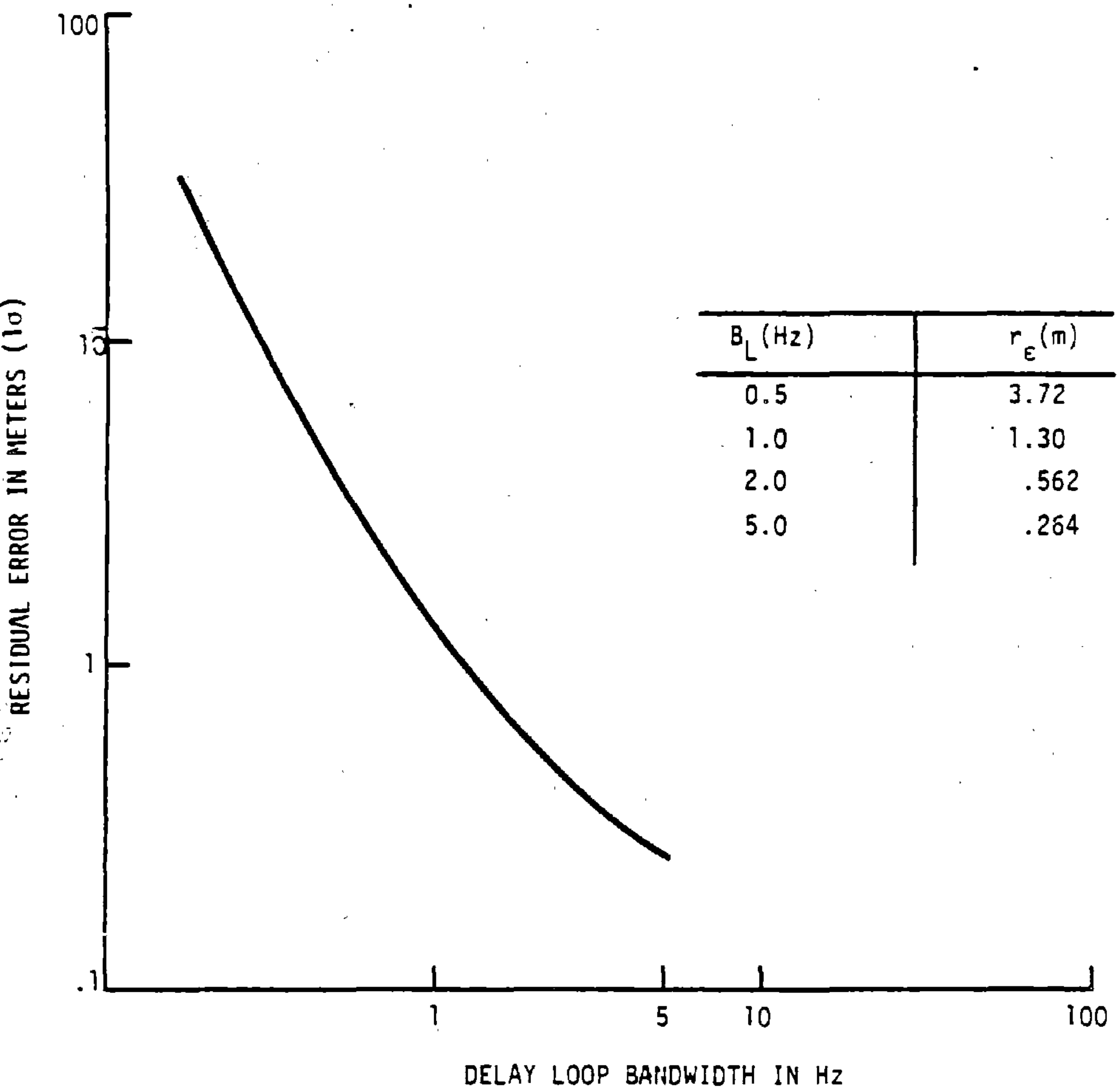
Receiver design is based on the capability of acquiring all satellites in view. More constraints are imposed on the differential station receiver than on other users to have full data collection continuously. Users, on the other hand, can make their optimum selection at will. From analysis, it was determined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

T_L - loop time: 1.52 seconds/satellite
T_G - guard 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:

$$E_a = 0.5 \times 1/2g\ T_u^2$$

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



B_L (Hz)	r_ϵ (m)
0.5	3.72
1.0	1.30
2.0	.562
5.0	.264

FIGURE K-1. ACCELERATION ERRORS

K.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, quantization and instrumentation errors, and are classified as being random and uncorrelated errors between measurements. The bias errors are caused by acceleration. The uncorrelated range errors are as follows:

$$R = ({}^{2}_{NOISE} + {}^{2}_{QUANTIZATION} + {}^{2}_{INSTRUMENTATION})^{1/2}$$

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 code loop.

Mathematical expressions for various noise sources are as follows:

A. 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

Code Loop Phase Jitter

$$\sigma_D^2 = (2\pi)^2\left[\frac{B_D}{\left(\frac{C}{N_0}\right)_D}\left(1 + \frac{2B_{IF}}{\left(\frac{C}{N_0}\right)_D}\right)\right]$$

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

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

$_D = 2 \times .022$ radians

where

$$\left(\frac{C}{N_0}\right)_D = \frac{C}{N_0} - 4.8 \text{ db} = 33.1 \text{ db.}$$

Carrier-Loop Phase Jitter:

$$\sigma_c^2 = \frac{B_c}{\left(\frac{C}{N_o}\right)_c}\left(1 + \frac{B_{LP}}{\left(\frac{C}{N_o}\right)_c}\right) = \frac{10}{4570.9}\left(1 + \frac{500}{4570.9}\right) = 2.427 \times 10^{-3}.$$

$$\sigma_c = .04926 \text{ radians}$$

where

$$\left(\frac{C}{N_o}\right)_c = \frac{C}{N_o} - 1.3 = 36.6 \text{ db}$$

$$B_{LP} = 500 \text{ Hz}.$$

The total rms noise caused by phase jitter in both tracking loops, assuming cross-correlation between loops, is negligible:

$$\sigma_N = \frac{\Delta}{2\pi}\left[\sigma_D^2 + \left(\frac{\sigma_c}{N}\right)^2 + 2\frac{\sigma_c}{N}\sigma_D\,\alpha_{12}(0)\right]^{\frac{1}{2}}$$

$$= \frac{293.2}{2\pi}\left[(2\pi)^2 \cdot 484.8 \times 10^{-6} + \frac{2.427 \times 10^{-3}}{(1540)^2} + 0\right]^{\frac{1}{2}}$$

σ_N = 6.45 meters.

B. Fine Quantization Error.

$$\sigma_Q = \frac{\Delta}{Q\sqrt{12}}, \quad Q = 64$$

$$= 1.32 \text{ METERS}$$

$$\sigma_Q = 0.08266 \text{ METERS}, \quad Q = 1024$$

C. Instrumentation Error

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

Total Range Error:

$$\sigma_R = (6.45^2 + .083^2 + .19^2), \ Q = 1024 \text{ was used}$$

$$= 6.45 \text{ meters}$$

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

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

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

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

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

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:

$$\sigma_{N(\dot{R})} = \frac{\lambda}{2 \times 2\pi}\left[\frac{2 \times 10}{4570.9}\left(1 + \frac{500}{2 \times 4570.9}\right)\right]^{\frac{1}{2}}$$

$\sigma_{N(\dot{R})} =$ .0103 m/sec

where

$\mathcal{T} =$ .2 seconds.

Quantization Error for Fine Range Rate Quantization:

$$\sigma_{Q(\dot{R})} = \frac{\lambda}{2\pi T N \sqrt{12}} = \frac{.19}{2 \times 1540 \times \sqrt{12} \times .2} = .000089 \text{ m/sec}.$$

Range Rate Bias Due to Acceleration:

$$\Delta\dot{R} = \frac{\lambda}{2\pi}\frac{\Delta\phi}{T} = \frac{1.845}{B_c^2}\frac{a}{\lambda}\frac{\lambda}{2\pi}\frac{1}{T}$$

$$= \frac{1.845 \times 4.9 \times 1}{1006.28 \times .2} = .07198 \text{ m/sec}$$

Total Range Rate error:

$$\sigma^2_{\dot{R}_T} = \sigma^2_{N(\dot{R})} + \sigma^2_{Q(\dot{R})}$$

$$\sigma^2_{\dot{R}_T} = .0103^2 + .000089^2$$

$$\sigma_{\dot{R}_T} = 0.103 \text{ m/sec}$$

K.3 EXTERNAL ERROR SOURCES - In the total receiver error budget, there are eight major error sources identified primarily as caused by the propagation delays or by the satellite position and time errors. The following sections will describe these errors and will identify major characteristics.

A. Ionospheric: TEC Changes with Distance

The TEC varies with horizontal position. Several factors contribute to these variations: ionospheric irregularities, diurnal variations, solar flares and geometric factors. Figure K-2 presents a typical electron content variation above a fixed position during a 24-hour observation period. For the sample analysis, a nominal value of 70 nanoseconds was used (1 nanosecond delay is equivalent to 10^{16} electrons per square meter). This value is also a function of altitude and geometry expressed in terms of an obliquity factor. The total effective electron content changes with the elevation angle of a satellite being observed. This effect is shown in Figure K-3. The mathematical expression used for computing the obliquity factor Q is:

$$Q = \frac{1}{\sin E'} = \csc E' = \frac{R + H}{\left[(R+H)^2 - R^2\cos^2 E\right]^{\frac{1}{2}}}$$

H = 350 km - ALTITUDE OF THE IONOSPHERE

R = 6378 km - EARTH RADIUS

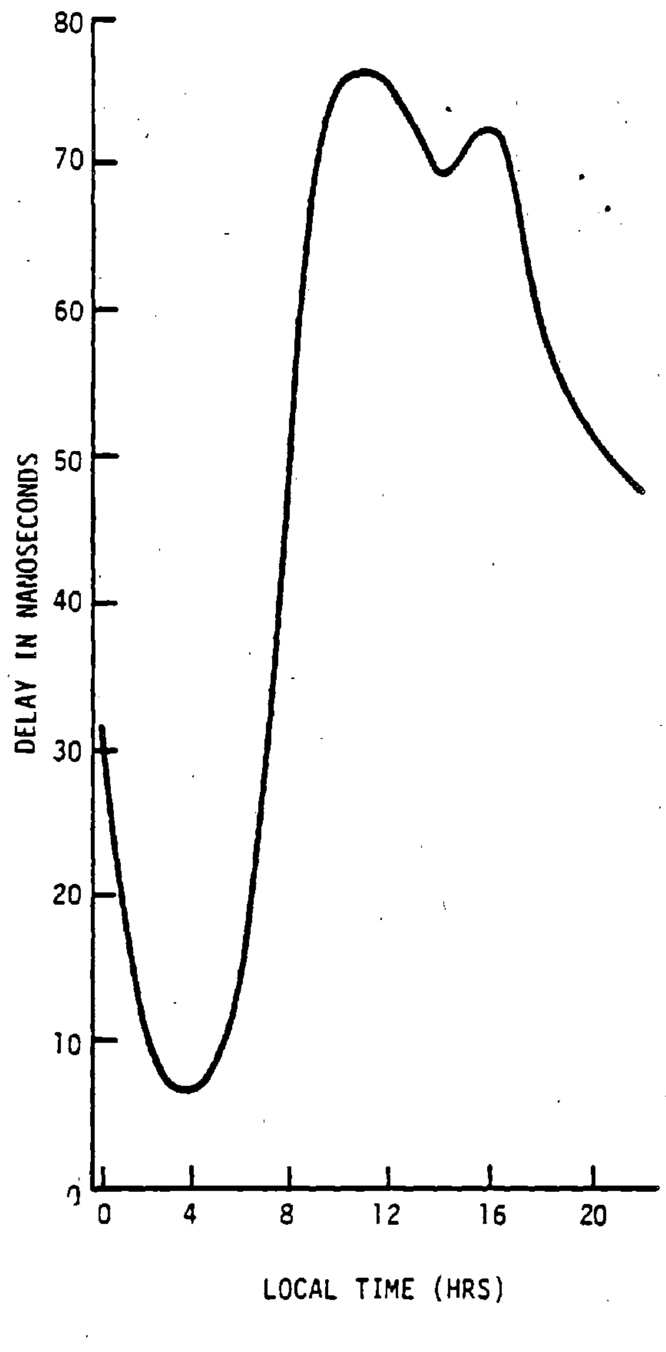


FIGURE K-2. IONOSPHERIC VARIATIONS WITH TIME

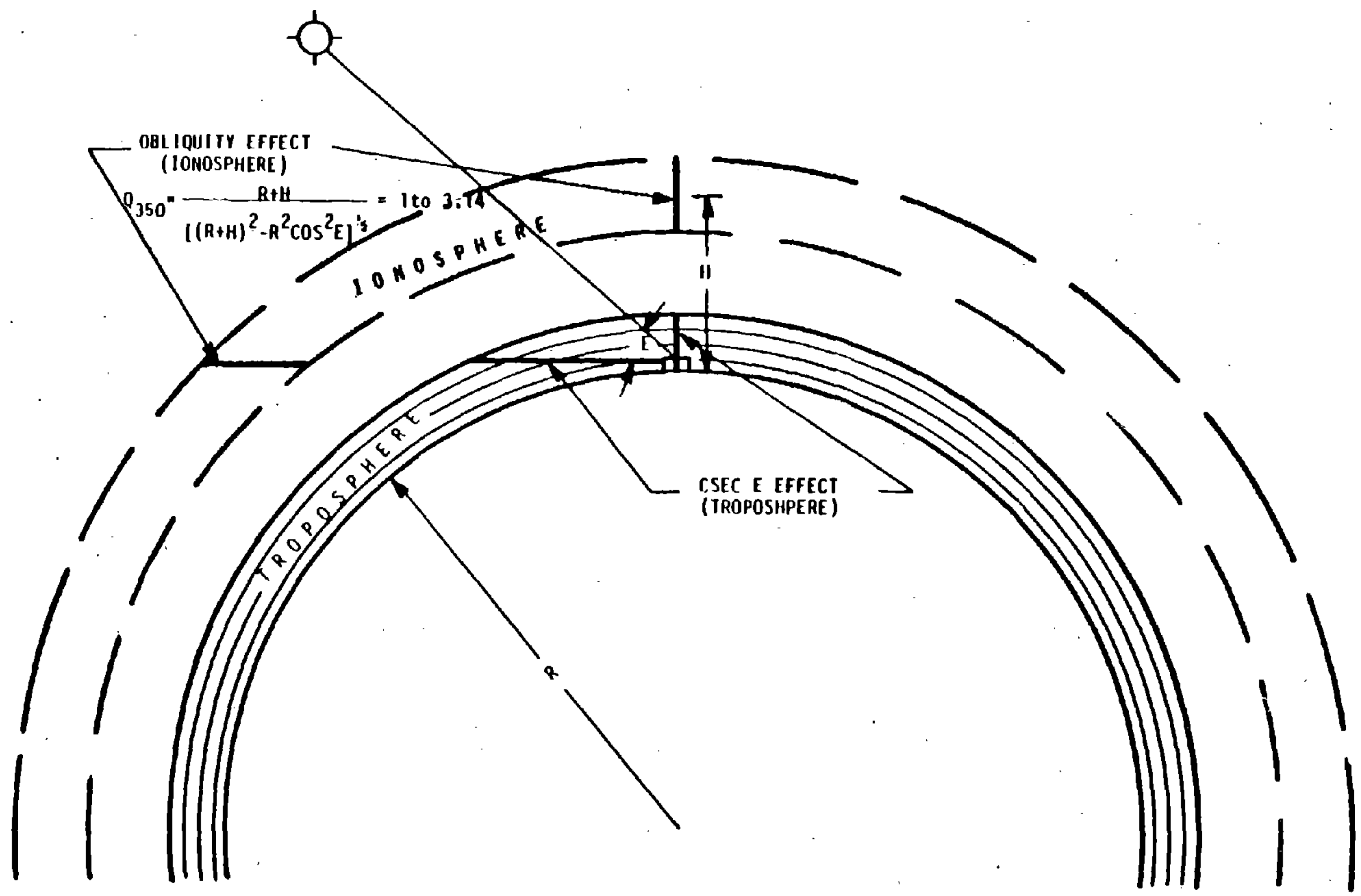


FIGURE K-3. ATMOSPHERIC DELAY GEOMETRY

Ionospheric models are useful in reducing this error. Ionospheric irregularities, which can cause delay difference of 0.1 - 0.4 meters, cannot be modelled out.

B. Ionosphere: TEC Changes with Elevation Angle, Δ E.

A displacement of the user receiver from the differential station along the baseline changes the observation angle to a satellite by amount of Δ E, where,

$$\Delta E_{50KM} = 57.8^\circ \cdot \frac{\delta}{R} = \frac{50}{6378} \times 57.8 = .4492 \text{ DEGREES}$$

where

δ = distance between user and reference receivers.

A change in Δ E results in a corresponding change in path length as shown in Figure K-4. This curve is extrapolated from the original ionospheric values for the 100 km separation equivalent of 0.9° and evaluated for the whole range of possible satellite position angles. The maximum value of this curve is at the maximum gradient, shown in the same figure for comparison. This error can be essentially eliminated by modelling by the receiver, using satellite-derived corrections applied at both the user and station locations.

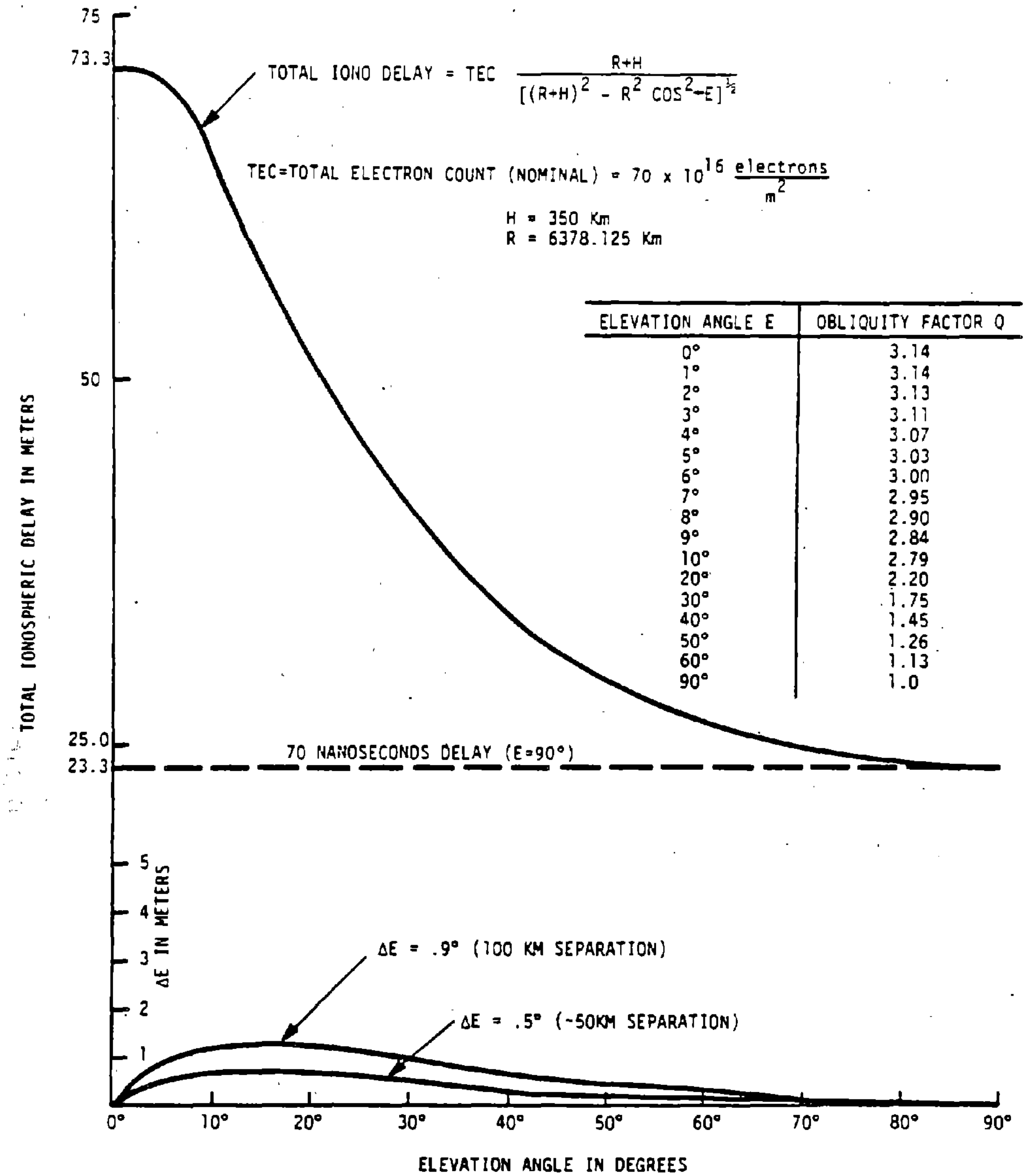
C. Ionosphere: TEC Changes with Time

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 nsec/sec. 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 K-1.

TABLE K-1. 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 .342 m/min

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.



ELEVATION ANGLE E	OBLIQUITY FACTOR Q
0°	3.14
1°	3.14
2°	3.13
3°	3.11
4°	3.07
5°	3.03
6°	3.00
7°	2.95
8°	2.90
9°	2.84
10°	2.79
20°	2.20
30°	1.75
40°	1.45
50°	1.26
60°	1.13
90°	1.0

FIGURE K-4. IONOSPHERIC VARIATIONS WITH ELEVATION ANGLE

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 is shown in Figure K-5. 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. This error cannot be removed by subtraction; thus a user has to absorb this error as a bias in his measurement. The magnitude of this error is shown in Table K-2. 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 K-6.

G. Receiver Noise in Pseudorange Measurement

A computation of the receiver noise component is derived in Section K.2. The resultant value is a function of the satellite evaluation angle. Factors related to the receiver noise characteristics are input signal-to-noise ratio, tracking filter bandwidth, and receiving antenna pattern effects.

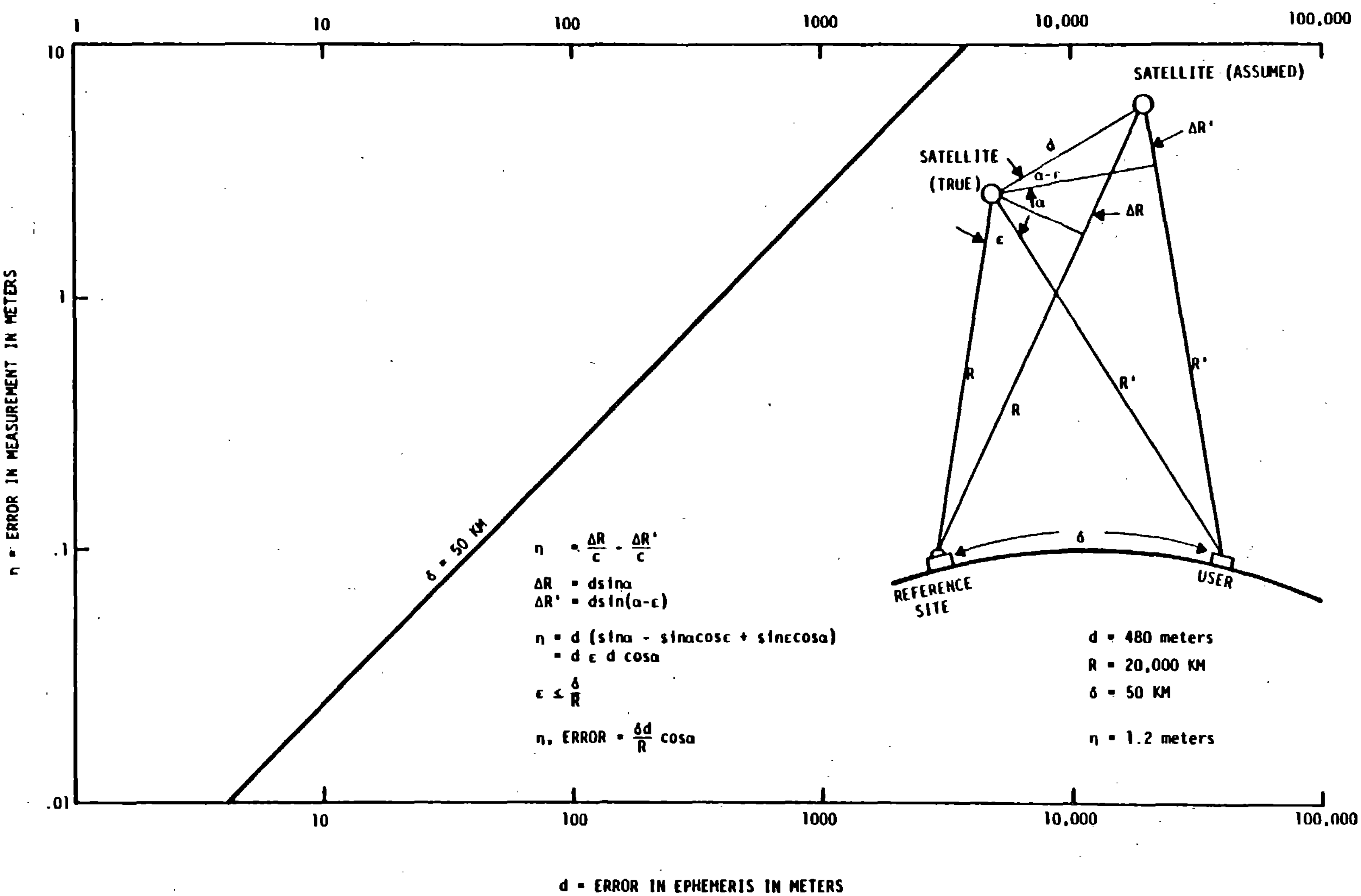


FIGURE K-5. EPHEMERIS ERRORS

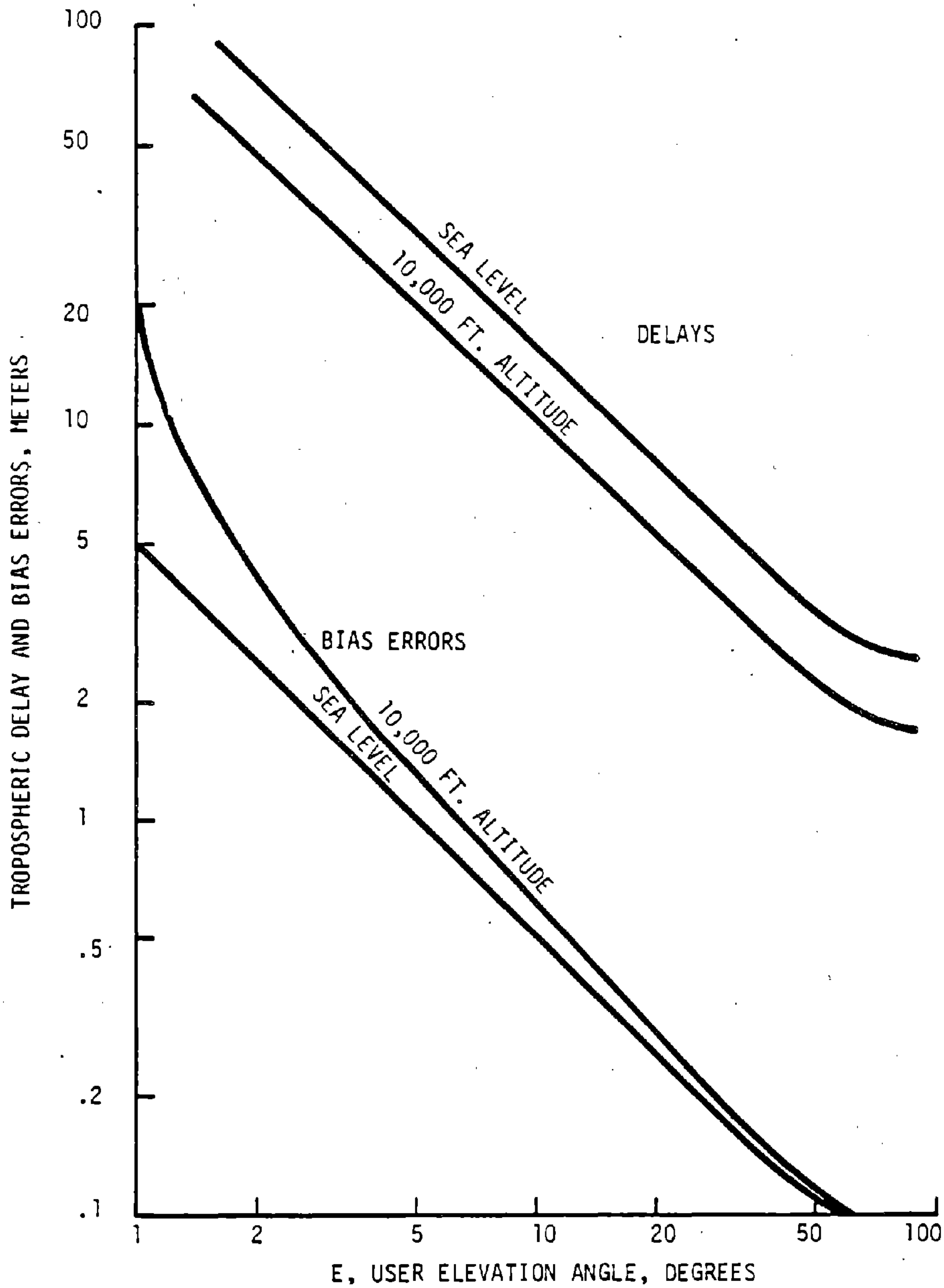


FIGURE K-6. TROPOSPHERIC DELAYS AND BIAS ERROR AT DIFFERENT ALTITUDES

TABLE K-2. DIFFERENTIAL STATION RECEIVER CHARACTERISTICS

Receiver Noise	1.6 meters
Multipath Noise	1.0 meters
Total error	1.9 meters

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