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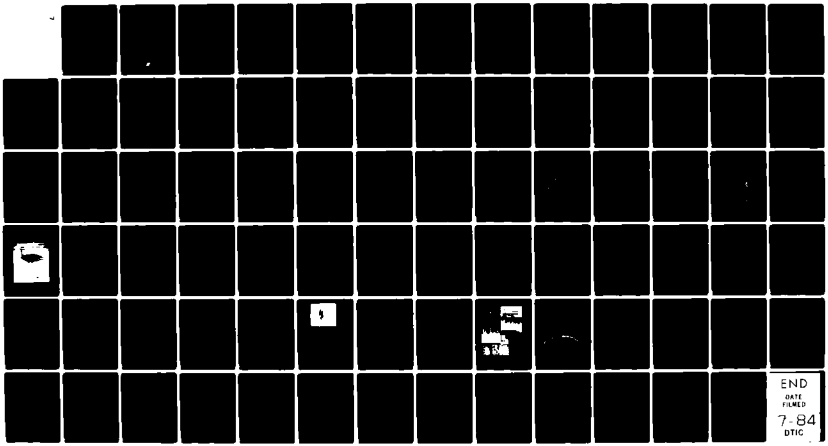

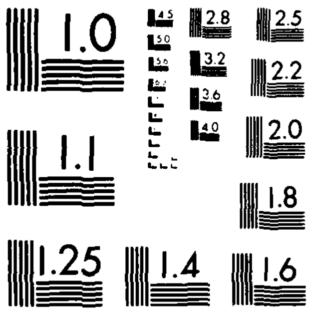

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CG-D-08-84
DOT-TSC-CG-83-5

Differential NAVSTAR GPS Design Concept for Harbor/Harbor Entrance Marine Navigation

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Cambridge MA 02142

May 1984
Final Report

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16. Abstract

This report presents a design concept for a high-precision system for harbor/harbor entrance navigation. The concept is based on differential operation of NAVSTAR GPS, whereby local corrections to the satellite signals are broadcast to mariners in a harbor area. The system is expected to provide continuous navigation service with a predictable (absolute) accuracy of 8-12 meters (2drms). The design is configured around a hypothetical system to cover New York Harbor. The report addresses the hardware configuration and costs of installing and maintaining the system. Also provided are guidelines for verifying the performance of the system.

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PREFACE

The work described in this report was performed under Project Agreement CG-445 for the U.S. Coast Guard, Office of Research and Development, Systems Technology Division, Navigation Systems Technology Branch. The sponsor of the project is LCDR John Quill who directed the work study efforts.

The work was performed by the Transportation System Center's Navigation Systems Division, part of the Center for Navigation. This Technical Report presents a comprehensive study of the differential operation and application of the NAVSTAR GPS concepts and how the civil maritime requirements can be met with future technology. The report presents a differential NAVSTAR GPS system for harbor navigation specifically designed for New York Harbor.

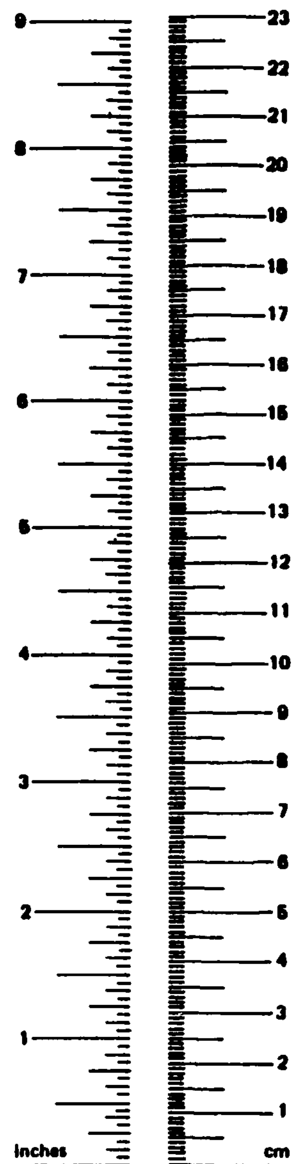
The authors wish to thank LCDR John Quill, of the Office of Research and Development, U.S. Coast Guard, for his encouragement and guidance and William D. Wood, Chief, Safety and Communications Division, TSC, for the technical review of this report and for valuable suggestions to improve it. The assistance of the Coast Guard staff of the 3rd Coast Guard District, Governor's Island, New York, NY, is gratefully acknowledged for providing technical details and charts on the VTS and the New York Harbor, in particular the help of CWO Frank Groves and Technical Adviser Peter J. Culicetto, Electronics Engineering Division, and CWO Robert Hunt, Operation Aids to Navigation Division. Also appreciated are the contributions and advice of LTJG James C. Preisig and John Kraemer. Special thanks go to Mark Manozzi, whose tireless efforts and expertise on the word processor made it possible to complete this document in a timely fashion.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

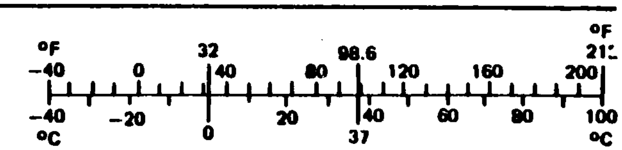
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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 BACKGROUND

The NAVSTAR Global Positioning System (GPS) is a satellite system which will provide global continuous navigation and position location service when it becomes operational. The NAVSTAR GPS program has been in existence for a decade now (see Figure 1-1). The system development is managed by the Joint Program Office (JPO) of the Air Force Systems Command Space Division in Los Angeles, CA. The management team consists primarily of Department of Defense (DOD) staff, but Department of Transportation (DOT) and NATO liaisons are stationed there as well.

Figure 1-2 shows the planned NAVSTAR constellation, consisting of 18 satellites in 6 planes, plus 3 spares, which will be active. In case of a satellite fault, one spare would be moved to a location which provides the best Position Dilution of Precision (PDOP) measure. Table 1-1 shows the program plan for the deployment of the satellites. They are being deployed such as to provide global 2-dimensional service by mid 1987 and global 3-dimensional service by the end of 1988. It is expected that most marine receivers will be designed to take advantage of the 2-dimensional service.

The system is designed to provide two levels of system accuracy: Precise Positioning Service (PPS) which will only be available to military users and Standard Positioning Service (SPS) which will be available to civil users. SPS makes use only of the coarse/acquisition (C/A) code, while PPS also employs the precise P-code, which is encrypted and transmitted simultaneously. The DOT is evaluating SPS to determine whether the NAVSTAR GPS can eventually replace existing systems such as the VOR/DME air navigation system, LORAN-C, and OMEGA. The U.S. Coast Guard (DOT) is responsible for examining the SPS performance and determining its applicability to Ocean, Coastal, Harbor/Harbor Entrance, and Inland Waterway phases of navigation.

When the NAVSTAR GPS becomes operational the marine community will have access to a worldwide navigation service with a precision currently available

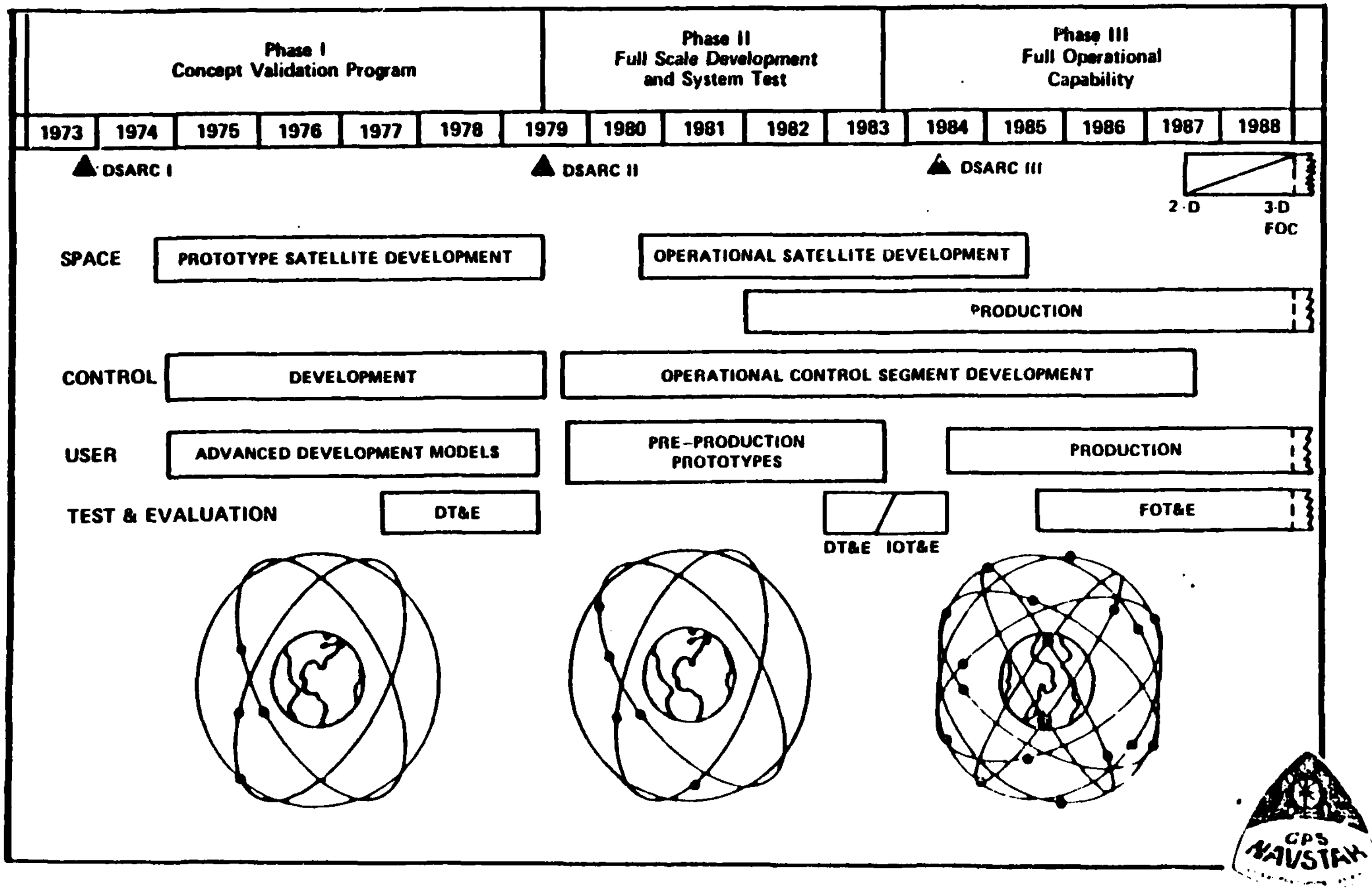


FIGURE I-1. GPS PROGRAM SCHED'

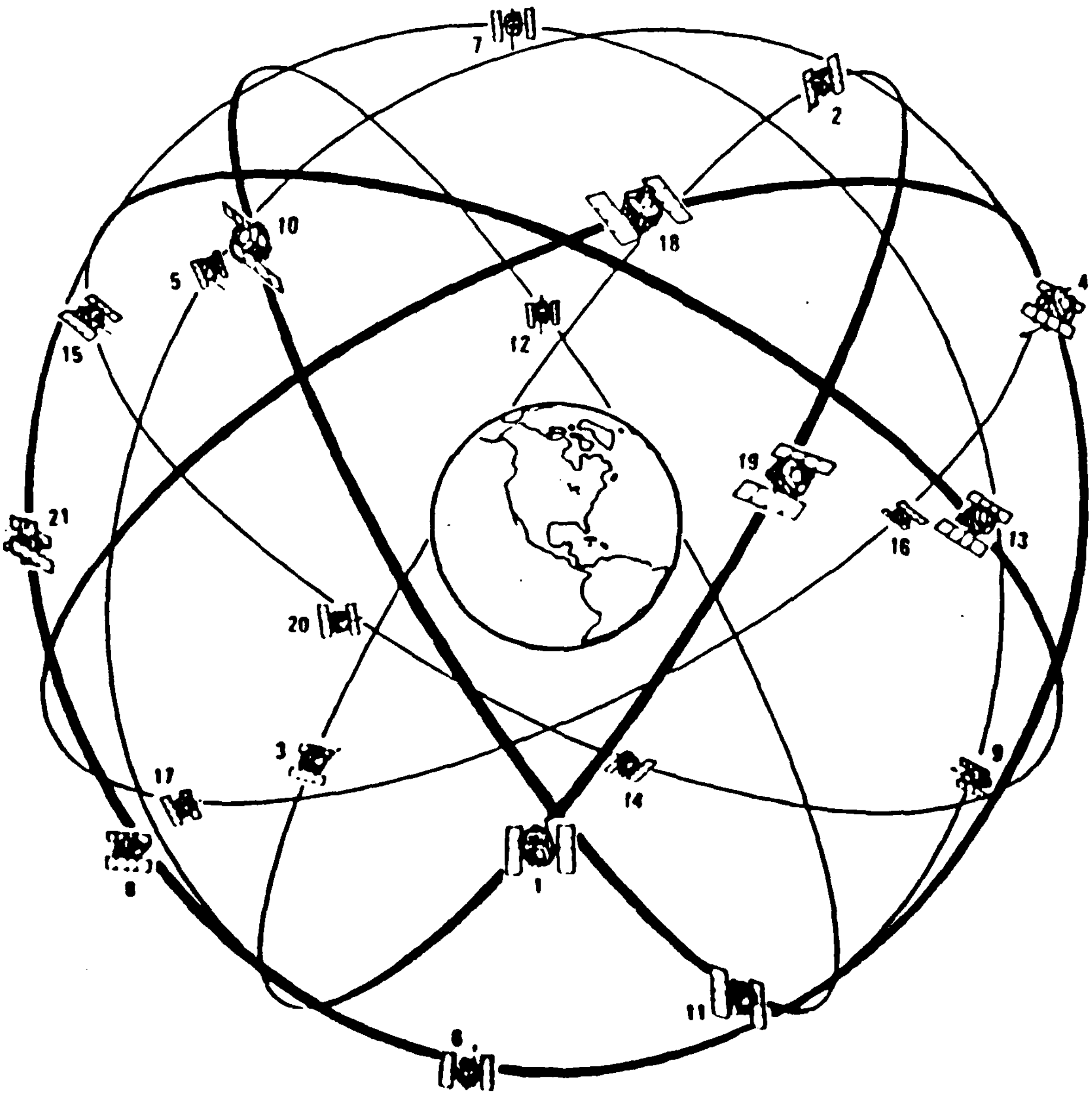


FIGURE 1-2. THE NAVSTAR OPERATIONAL CONSTELLATION
18 SATELLITES PLUS 3 ACTIVE SPARES

TABLE 1-1. NAVSTAR GPS IMPLEMENTATION SCHEDULE
(Excerpt from - DOD NAVSTAR GPS SYMP., 21 April 1983)

SATELLITE BLOCK NO.	NO.	ORBIT	STATUS AVAILABLE DATES	REMARKS
I	1-5	63°	Presently available	In addition, 3 spares to support 5-satellite coverage
	6-18	55°	Beginning late June '86 one satellite via shuttle followed by others at 2-month intervals	Initial Block I satellites rephased into 55° inclination orbits
II	19-21	55°		3 spares

only in limited areas. Navigation tests performed using the Phase I NAVSTAR satellites presently in orbit have indicated C/A accur--ies of 20-50 meters (2drms), these being significantly better than design goals. Such accuracies would meet the ocean and coastal phase marine requirements of the Federal Radionavigation Plan[1] and approach the stringent Harbor/Harbor Entrance requirements.

However, the success of the C/A signals poses a national security problem. As a result the JPO is planning to control the accuracy of the C/A signals under a program called Selective Availability. The current plan is to intentionally degrade the C/A's signal to provide 100 meter (2drms) SPS accuracy when the system becomes operational.

At 100-meter accuracy, the SPS is adequate for all ocean and coastal navigation needs, and for most other positioning requirements. It is not adequate for the tight navigation requirements for many Harbor/Harbor Entrance applications. However, examination of the nature of the errors in the NAVSTAR system reveals that most of them are varying slowly enough that differential operation can greatly improve accuracy over a local area. Accuracies of 8-12 meters (2drms) appear possible for navigation applications, and better than 5-meter accuracy for stationary receiver applications such as surveying and charting.

Differential operation consists of placing a high-quality receiver at a surveyed-in location and determining the position errors. By broadcasting the errors to nearby users, they can apply these corrections and obtain increased accuracy. This report deals with the implementation considerations of differential operation in a harbor area.

1.2 SCOPE

This report addresses the issues of receiver design, processor design, communication technique, signal format, implementation and cost of a differential station to be installed in a harbor area. In order to ensure that the solutions proposed here adequately address the problems of a real-world environment, a specific harbor was chosen for the site of the differential station. New York harbor was chosen because its islands and terrain make it representative of a number of areas around the country.

Section 2 describes some of the applications where differential operation of NAVSTAR GPS would provide service not currently available.

Section 3 provides some technical considerations involved in the design and implementation of a differential station. Design tradeoffs are worked out for a number of alternative techniques. The degradation of accuracy with distance from the station is discussed.

Section 4 describes the design concept proposed for the differential station. Criteria for the location and siting of the equipment are discussed. Finally, performance estimates are given for users of the service.

Section 5 provides estimates of the cost of the station and communication equipment, including the development cost of a differential receiver/processor. The purchase costs are based on current equipment prices, while installation and maintenance costs are obtained by comparison with similar Coast Guard installations.

Section 6 provides some guidelines for testing the performance of a differential station.

2. REQUIREMENTS FOR DIFFERENTIAL OPERATION

2.1 HARBOR/HARBOR ENTRANCE REQUIREMENTS

In the Ocean and Coastal phases of navigation, the 100-meter (2drms) accuracy projected for the Standard Positioning Service is more than adequate to meet the requirement of the Federal Radionavigation Plan (FRP). In the Harbor/Harbor Entrance phase, constricted areas and channels make it necessary to be concerned with restricted clearances especially in two-way traffic. The master of a vessel in restricted waters must navigate with precision to avoid grounding in shallow water and to avoid collisions with other vessels. Unable to turn around and severely limited in the ability to stop to resolve a navigational problem while negotiating the straight channel segments and turns dictated by the configuration of the channel, he may find it necessary to hold the total navigational error within limits measured in tens of feet.

The pilot needs highly accurate cross-track information almost continuously to navigate safely. Along-track information is also important in order to determine the timing of turns. Even the 8-meter (2drms) accuracy may require an improvement.

The HHE requirement cited in the FRP[1] is for 8-20 meters (2drms) (Table 2-1). The numbers are derived from consideration of both ship widths and channel widths.

2.2 OTHER APPLICATIONS OF DIFFERENTIAL GPS

While the U.S. Coast Guard is primarily concerned with the safety of marine operations, there are other applications of the highly accurate position location capability of NAVSTAR GPS. In particular, the time required to set a buoy could conceivably be reduced significantly by differential GPS. Buoy positioning checks could also be performed in less time. Charting and harbor surveys could employ differential GPS. It is possible that the existence of GPS could lead to widespread

TABLE 2-1. CURRENT MARITIME USER REQUIREMENTS & BENEFITS - HARBOR AND HARBOR ENTRANCE PHASES

Requirements	Measures of Minimum Performance Criteria to Meet Requirements									
	Accuracy (2 drms)									
	Predictable	Repeatable	Relative	Coverage	Availability	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity
Safety of Navigation – Large Ships & Tows	25-65 Ft (8-20 M) (1)	–	–	U.S. Harbor & Harbor Approaches	99.7% Minimum	(2)	6-10 Seconds	Two	Unlimited	Resolvable with 93.9% Confidence (Minimum)
Safety of Navigation – Smaller Ships	(1)	(1)		U.S. Harbors, & Harbor Approaches	99.7%	(2)	(1)	Two	Unlimited	Resolvable with 99.9% Confidence (Minimum)

Benefits	Measures of Minimum Performance Critieria to Achieve Benefits									
Fishing Recreational, and Other Small Vessels	(1)	(1)	–	U.S. Harbor, & Harbor Approaches	99.7%	(2)	(1)	Two	Unlimited	Resolvable with 99.9% Confidence

(1) Requirement under study; varies from one harbor to another
(2) Dependent on Mission time

use of a uniform datum, at least in the United States. This means that the navigation charts based on the North American 1927 Datum could be converted to the World Geodetic System - 1972 Datum (WGS-72).

When a stationary receiver is used with differential GPS, even greater accuracy can be achieved, because the accuracy is largely limited by receiver noise. With stationary receivers, more smoothing can be used to reduce these noise effects, and it is expected that better than 5-meter (2drms) accuracy can be achieved. Indeed, if the station transmits special messages to appropriately equipped users, better than 1-meter relative accuracy is believed to be achievable.

3. DIFFERENTIAL GPS CONCEPTS

3.1 COMPARISON OF CONVENTIAL AND DIFFERENTIAL GPS

In the conventional use of NAVSTAR GPS, the navigation receiver processes the signals from 3 or 4 or more satellites and computes the user position. A civil user receiver, using the C/A code, can expect to achieve positional accuracies between 40 and 100 meters (2drms), depending on the Selective Availability level. The error without Selective Availability is a slowly varying quantity comprised of unmodelled tropospheric and ionospheric errors, ephemeris, and satellite clock errors. The noise component of the error contributes typically 3 meters to a user's receiver error.

Since the error contributed by Selective Availability varies relatively slowly, most of the bias error not due to receiver noise could be eliminated by a local correction. That is, by placing a high-quality monitor receiver at a surveyed-in reference point, the bias errors could be estimated and corrections broadcast to users in the service area, (see Figure 3-1). This technique can improve user accuracy to better than 10 meters (2drms).

Two questions immediately come to mind about these corrections: (1) Over how wide an area are these corrections valid, and (2) how long are they valid? A number of studies[2,3] have demonstrated that the local corrections due to spatial decorrelation alone are valid to better than 5 meters (RSS) over a range of 200 miles or more, which is more than adequate to serve most harbor and waterway areas. The corrected position estimates begin to wander after a few tens of seconds, primarily due to Selective Availability. An earlier study[4] on this project concluded that for the 500-meter C/A code accuracy level, corrections transmitted every half-minute, would enable navigational accuracies of better than 15 meters (2drms).

The form of the corrections is an important consideration. At first glance, it appears that the transmission of latitude and longitude (Lat/Lon) corrections would be appropriate. If stationary receivers are placed relatively close to the reference station, thus using the same constellation, it makes little difference whether

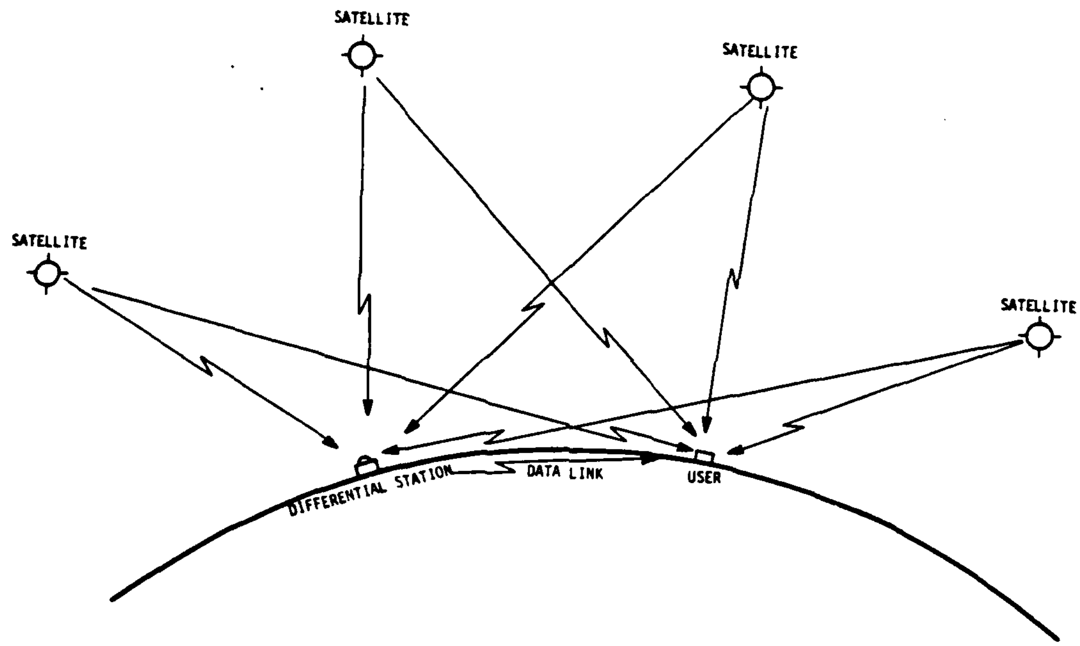


FIGURE 3-1. DIFFERENTIAL GPS GEOMETRY

Lat/Lon or pseudorange corrections are used, since the differences will be small. However, for a general differential system, such a procedure technique inadequate for the following reasons:

1. Receiver design variations would result in different satellites being used to compute position than those used by the differential station. Unless exactly the same set is employed by user and reference station, large errors would result.

2. Different ionospheric or tropospheric models might be employed by user and reference station. This is not a large error source.

3. Received corrections would not eliminate errors due to different inputs to navigational filters being employed by user and reference station.

As a result of these considerations, it is necessary for the differential station to calculate differences between measured and computed pseudoranges for each visible satellite, and to transmit these to the user population. The users will then make the corrections on the appropriate satellite pseudoranges before they are fed into their navigation processors.

The differential reference station not required in a conventional mode must provide corrections on all satellites visible to users being served by the station. Furthermore, the reference station must process satellites lower in elevation angle by a few degrees than the minimum mask angle likely to be used by the user population.

3.2 DIFFERENTIAL GPS 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 techniques are the cancellation of link-bias errors and a priori knowledge of the reference site position location.

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 on-board signal from two different paths: directly and via the user's on-board data link. Correction information is then returned to the user by an independent narrowband data link. This technique accommodates surveillance of the users position.

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

The baseline technique will be discussed in greater detail as a viable candidate for implementing differential GPS operations. The centralized technique exhibits navigation performance similar to the baseline and provides a surveillance function. However, it is saturable and adds complexity to the design. The translator technique requires too much bandwidth and offers too little performance increment to justify its implementation.

Under the baseline differential technique, the following are available:

1. The Lat/Lon corrections are applied directly to improve the user's derived position. Allocation of a new data link frequency is required. The line-of-sight or over-horizon transmission may be implemented.

2. The pseudorange corrections are applied to correct user's pseudorange measurements on each satellite prior to processing. Also, a separate frequency allocation is required for line-of-sight or over-horizon data transmission. A variation of this technique is the 'pseudolite', which transmits data at the GPS L1 frequency so that it looks to the receiver

like a satellite C/A code. This eliminates the need for a separate communications channel and provides an additional line of position. This method is discussed further in Section 4.4.1.

An important element of the differential system is the communication technique used to broadcast the corrections. Not only must the differential station be able to provide corrections to all of the satellite pseudoranges employed by a user, but the user must be able to receive the corrections by a data link. Thus if a line-of-sight broadcast is used, some users may find the signals blocked by terrain or structures. Therefore, if VHF frequencies, which have line-of-sight transmission properties, are used, it may be necessary to employ multiple transmitters to cover a harbor/harbor entrance area. An alternative is to use the radiobeacons to transmit the corrections. At these frequencies signals can be received over the horizon. The higher power transmitters are reaching out over 150 miles. Both these options are explored in this report.

3.3 DIFFERENTIAL SIGNAL FORMAT

The proposed data format to be used for the communication of corrections to nearby users is taken from a recent workshop at the Transportation Systems Center. The workshop recommended a format patterned after the NAVSTAR GPS data format[5]. Subframes consisting of 300 bits are employed, each headed by a preamble and time indication, similar to the GPS Telemetry Word (TLM) and Handover Word (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 3-2 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 (see Table 3-1).

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.

Message	Subframe			
TYPE 1 MESSAGE	SUBFRAME 1	PREAMBLE, STATION ID & HEALTH	Z-COUNT, SUBFRAME ID	PSEUDORANGE, RANGE RATE CORRECTIONS, AND SATELLITE ID's 6 SATELLITES, 40 BITS EACH
	SUBFRAME 2	SIMILAR		
TYPE 2 MESSAGE	SUBFRAME 1	PREAMBLE ETC.	Z-COUNT ETC.	DELTA CORRECTIONS, AOD's, AND SATELLITE ID'S 6 SATELLITES, 40 BITS EACH
	SUBFRAME 2	SIMILAR		
TYPE 3 MESSAGE		PREAMBLE ETC.	Z-COUNT ETC.	STATION LOCATION, ECEF COORD'S (X, Y, Z)
TYPE 4 MESSAGE	SUBFRAME 1	PREAMBLE, ETC.	Z-COUNT ETC.	WHOLE & FRACTIONAL DOPPLER COUNTS, AND SATELLITE ID'S 8 SATELLITES, 30 BITS EACH
	SUBFRAME 2	SIMILAR, IF REQUIRED		

SUBFRAME LENGTH - 6 SECONDS

FIGURE 3-2. PROPOSED DIFFERENTIAL GPS MESSAGES

TABLE 3-1. DIFFERENTIAL GPS DAT'.

MESSAGE TYPE	PARAMETER	NUMBER OF BITS	SCALE FACTOR & UNITS	RANGE
ALL (First word)	Preamble Station ID Station Health Parity/Spare	8 12 2 6/2	(Same as GPS) 1 - -	 0-4093 4 states -
ALL (Second word)	Z-Count Subframe type Spare Parity/Spare	17 3 2 6/2	6 seconds - - -	1-100, 794 s. 0-7 - -
TYPE 1 (corrections) Each Satellite 6 SV/Subframe	Pseudorange Correction Range-rate correction Satellite ID FrameSatellite Health Parity/Spare	16 8 5 2 6/3	0.1 meters 0.004 m/sec 1 - -	± 3276.8 m. ± .512 m/s 0-31 4 states -
TYPE 2 (Auxiliary corrections) Each Satellite 6 S/V Subframe	Delta Correction Age of Data Satellite ID Satellite Health Parity	16 8 5 2 6/3	0.1 meters See ICD-GPS-200 1 - -	± 3276.8 m. 0-31 4 states -
TYPE 3 (Station Location)	ECEF X-Coordinate ECEF Y-Coordinate ECEF Z-Coordinate Parity Spares	32 32 32 48 96	0.1 meter 0.1 meter 0.1 meter - -	$\pm 2.15 \times 10^7$ m. $\pm 2.15 \times 10^7$ m. $\pm 2.15 \times 10^7$ m. - -
TYPE 4 (Surveying) Each Satellite 8 Satellite Subframe	Delta Doppler Count Fractional Doppler Phase Satellite ID Satellite Health Parity	8 8 5 3 6	1 1/256 wavelength 1 - -	0-255 1-32 8 states - -

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 (Figure 3-2) contains the correction data for up to six satellites per subframe. If more than six satellites are in view, alternate subframes will divide the satellite corrections. Each subframe contains the pseudorange and pseudorange rate corrections, identity and health indications. The pseudorange corrections have a resolution of 0.1 meter, and the pseudorange rate corrections have a resolution of 0.004 meter per second.

The Type 2 message is similar to the Type 1 Message. However, instead of pseudorange and range-rate corrections, Age of Data of Ephemeris (AODE) and "delta corrections" are broadcast. A delta correction for a satellite is defined as the difference between pseudorange corrections utilizing old and new satellite ephemeris and satellite clock data. The AODE word enables a receiver to determine whether it is using the same satellite ephemeris data as the reference station. 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.

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 one to 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 defined at a later date. The carrier frequency of the data link can be at a frequency that might be available or convenient to a particular user group, provided that it can accept a 50-bps data rate as is assumed in this report.

3.4 GPS RECEIVER CHARACTERISTICS

3.4.1 C/A Code Signal Reception

A unique C/A code is assigned to each GPS satellite. Up to 32 Gold Codes are available as GPS satellite codes. The C/A code satellite signals are transmitted on the L_1 1575.42 MHz frequency. The signal is encoded at a chip rate of 1.023 MHz using biphase PSK modulation. Then, the 50 bps data is modulated in the PN (Gold) Codes.

The received signal level from a satellite, at 5 degrees elevation angle, provides a C/N_0 (carrier-power-to-noise spectral density) of 41.1 dB-Hz. This represents a S/N (signal to noise power ratio) of about -21.9 dB in the 2 MHz bandwidth. Because each satellite transmits at the same frequency, its signal spectra overlap with some variable separation due to their relative doppler shifts. Reception from a selected satellite is attained by generating a duplicate Gold Code in the receiver and by performing an autocorrelation with the incoming signal. This is achieved by altering the time delay of an internally generated code until the code bits line up.

At the same time the local oscillator signal frequency is adjusted to place the IF signal within the receiver's IF band pass filter. The filter bandwidth is typically 300 Hz to assure 50-bit data reception, but it could be as little as 100 Hz. This raises the received signal-to-noise level from -21.9 dB in 2-MHz bandwidth to +21.1 dB in 100-Hz bandwidth.

3.4.2 Receiver Functions

The GPS receiver performs two basic measurements, pseudorange and its rate of change. Both measurements are performed in the receiver using code and carrier loops respectively. A block diagram of a reference station differential receiver is shown in Figure 3-3.

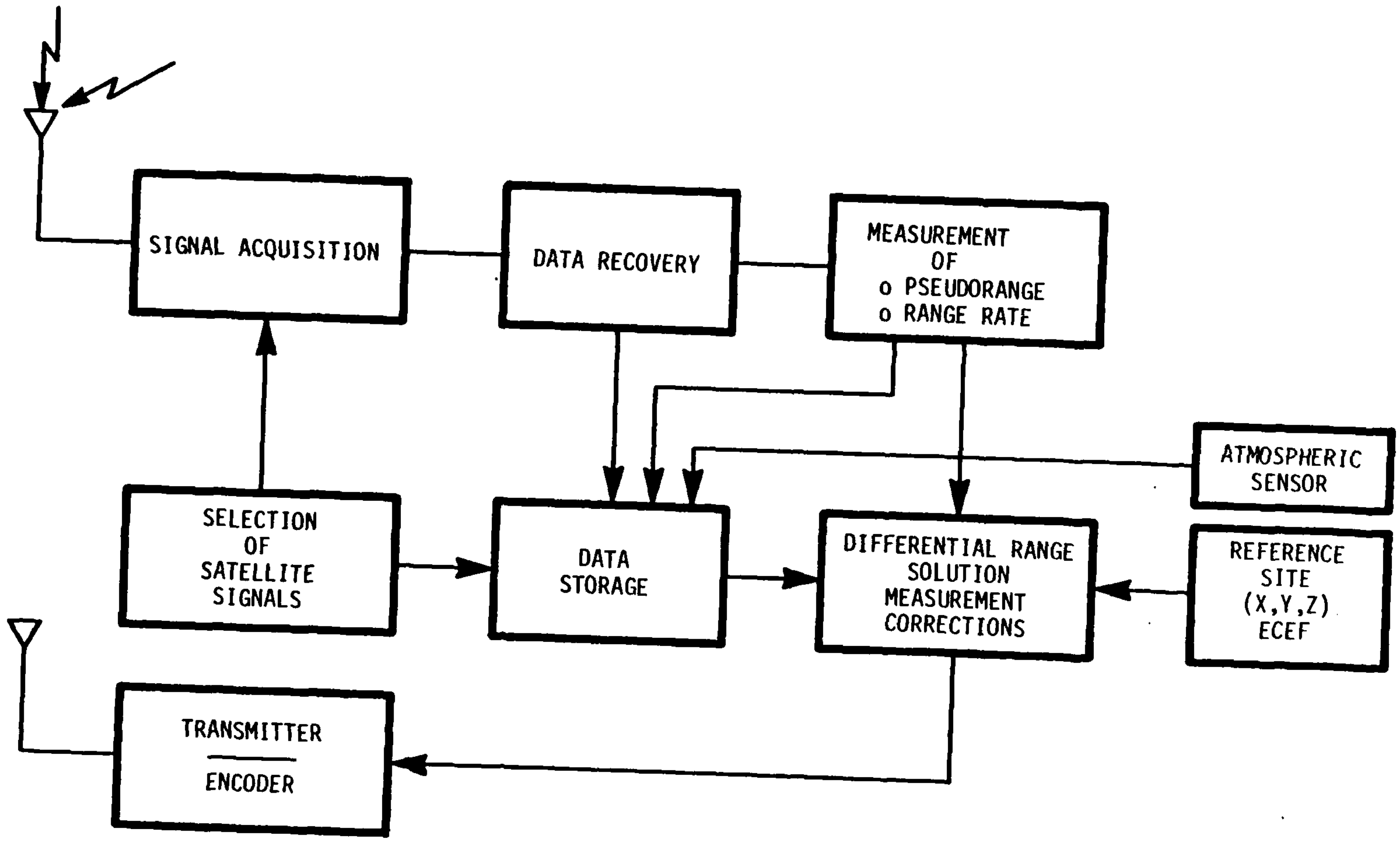


FIGURE 3-3. DIFFERENTIAL REFERENCE STATION BLOCK DIAGRAM

The delay lock loop aligns the internally generated code in synchronism with the satellite signal. The time difference is then the raw pseudorange measurement. Lock acquisition is the process of acquiring lock in the code and carrier loops. A wider carrier loop bandwidth helps to acquire frequency lock much quicker but at the same time reduces C/N_0 ratio. The receiver operates by internally generating code and continuously shifting as pseudoranges change in time. Similarly, the frequency of the local oscillator is shifted with the change in doppler as the satellites and receiver move. There is, of course, no motion for a reference station receiver. A lock condition occurs only when both loops are "locked". When the user oscillator frequency and satellite frequency are matched and both codes are aligned, the navigation data contained in the GPS message can be read.

3.4.3 Receiver Configurations

There are three basic configurations that could be used in the design of the reference station receiver. They are illustrated in Figure 3-4.

1. Parallel channel operation, whereby each channel is dedicated to a different satellite.

2. Sequential operation, whereby the channel(s) are time multiplexed between satellites. Such a receiver might use one channel only, or have several channels that share satellites. Another variation is the dual-channel design that uses one channel for navigation and the other for data.

3. Multiplex operation, whereby a single channel is rapidly time multiplexed between the satellites in view. It differs from sequential operation because the multiplexing period is small compared to the response time of the tracking loops. As a result it behaves more like a parallel receiver.

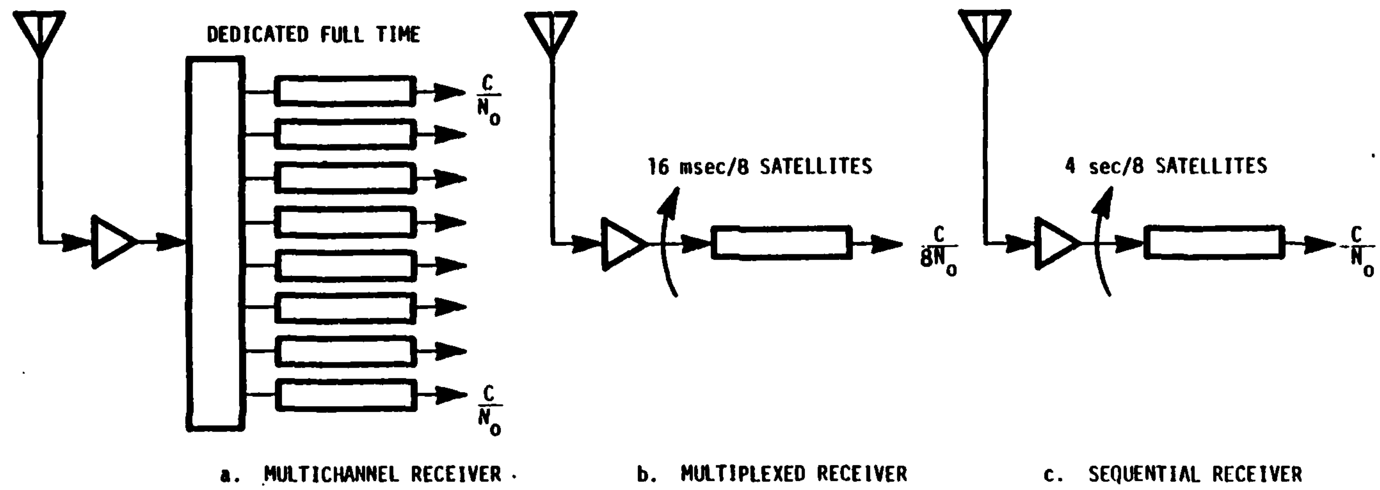


FIGURE 3-4. RECEIVER CONFIGURATION

The best performance is obtained from parallel channel operation, because it has the highest effective energy-to-noise factors of the three configurations[6]. It is also the most expensive because of the duplication of hardware. Parallel operation is used in the NAVSTAR GPS high-performance military receivers. Examples are the Phase I X-set, which uses 4 channels, and the Phase III high-dynamics sets, which use 5 channels. None of these track all satellites in view. Rather, a best-set-of-four satellite selection strategy is used. The differential station receiver is required to monitor all satellites in view, which means up to eight satellites. In addition, the pseudosatellite technique would require an additional channel dedicated to reception of error messages on a continuous basis.

Stanford Telecommunications, Inc. has built a dual-channel receiver for the FAA for experimental purposes[7]. Single channel operation has been used in a number of GPS receiver designs, including the military man-pack and low-dynamics receivers. However, single or dual channel sequential operation is not satisfactory for differential station use. One major reason is that the carrier phase and doppler count can not be maintained between dwells and the accuracy of the pseudorange corrections during dynamic tracking would be marginal. This means that there would not be enough time to obtain pseudorange rate corrections with sufficient accuracy to meet all potential users needs.

An example of a multiplexed receiver is the "Texas Instruments 4100." The rapid sampling of the satellite signals gets around the slow update problems associated with the single or dual channel sequential receivers. However, the loss of integration time for the detection of the signal reduces the signal power to noise spectral density ratio, thereby reducing the accuracy of the corrections.

While there are no current examples of such an operation, a four-channel receiver could be designed so that each channel tracked one or two satellites by multiplexing. The reduction in performance from a dedicated eight-channel receiver would be significant.

Since a differential station receiver/processor would represent a very low-volume, custom design, it is likely that the total cost of purchase would be relatively independent of the technique employed. For this reason, it would be preferable to get the best accuracy possible by prescribing the parallel channel configuration.

3.4.4 Receiver Parameters

In order to achieve high accuracies for the differential corrections, the ideal station receiver should take full advantage of the fact that it is stationary. Receiver code loop bandwidth should be as narrow as possible, as should carrier loop bandwidth. Since the satellites are in rapid motion, the code loop tracking circuit is a second order type which enables it to follow the almost linearly changing delay without a lag bias. The carrier loop tracks a signal whose frequency is changing very slowly. The change is dominated by the Selective Availability "waveform", and to a lesser degree by the rate of change of the motion of the satellite relative to the station.

4. NEW YORK HARBOR NAVSTAR DIFFERENTIAL GPS STATION DESIGN

4.1 GENERAL DESIGN CONSIDERATIONS

In order to realistically address the implementation issues of installing a differential NAVSTAR GPS system for harbor navigation, it was decided to select a harbor that would be representative of a number of harbor areas where differential GPS operation might eventually be implemented. New York harbor was chosen because its terrain and coastline geography offer a typical signal coverage problem for a designer. In addition, the availability of Coast Guard facilities is also believed to be typical.

The requirements are defined for the selection of a site for the harbor differential station. It should be within a 100-kilometer range coverage of the vessels desiring differential navigation service. It is not necessary for the station to be visible to the user population. However, it is necessary that the station be located in an area where satellites can be seen down to low elevation angles, preferably down to three degrees above the horizon in all directions. Marine receivers are expected to employ mask angles of ten degrees, which means they would ignore satellites below that angle. However, some receivers may use mask angles of as little as five degrees. The ground station has to process satellites somewhat below that angle.

The U.S. Coast Guard has a LORAN-C monitoring site at Sandy Hook, south of Governor's Island. It is quite flat, and most of the azimuth angles overlook the ocean. Some blockage could occur from the VHF tower, but it is not expected to be serious. The site is manned 24 hours a day, so that routine maintenance can be performed with existing staff. Therefore, the Sandy Hook LORAN-C Monitor site is recommended as a site for the differential station and antenna.

A broadcast station site and the technique employed to broadcast the differential corrections to the vessels in the harbor area must be selected. It is generally agreed that one of the most promising techniques is to make use of the existing radiobeacon facilities and modulate the carrier of selected station transmitters. This technique is technically tractable, makes use of existing equipment, and the frequency is low enough that the signal is less bothered by blockage than line-of-sight frequencies such as VHF would be.

Two candidate radiobeacon sites are the Ambrose Light Station and East Rockaway facilities. However, each has its limitations, as discussed below.

A VHF or microwave link will be required to relay the corrections to the radiobeacon transmitter from the differential station at Sandy Hook, 7-10 miles away. It depends whether in present use the CG VHF or microwave link is also available for GPS data transmission.

The preferred design of a differential station will incorporate several channels in parallel operation, and employ sophisticated processing techniques to achieve the highest in accuracy. The receivers will employ very narrow code loop and carrier loop bandwidths, and coherent detection techniques. Full advantage will be taken of the carrier-phase, lock-loop Doppler measuring capability to reduce the effects of receiver noise. "Prompt" code correlation will be used for the reception of data.

The navigation processor will estimate the location of the satellites from their ephemerides at the point in time that the receiver channels are sampled. The true range will then be calculated, using the known position of the differential station antenna. The pseudorange to each satellite is obtained from a measurement after the satellite clock error has been corrected. One design option remains, i.e., whether position solution should be estimated and the user's clock bias determined. If the user clock error correction is applied at the differential site, then the pseudorange correction for each satellite is obtained by subtracting the true range.

While it is not necessary for the ground station to actually compute its own estimated position in order to compute the differential corrections, it will do so in order to determine system quality. In addition, each pseudorange correction will be examined for reasonableness before it is transmitted. The differential message allows for health status of the satellites and station to reflect the quality of the measurements. Station health is repeated every six seconds with new data. Satellite health update will vary from 6 to 30 seconds with new data every hour. Ionosphere and almanac update every 12.5 minutes.

The differential station will also examine the inputs from a nearby monitor to check the quality of the correction messages transmitted to the users on a regular basis.

4.2 DIFFERENTIAL STATION SYSTEM LAYOUT

4.2.1 New York Harbor Site Characteristics

The New York Harbor area is distinguished by a high traffic density of both local and deep-draft vessels. A map of the area is shown in Figure 4-1. It incorporates three navigation phases: river, harbor and coastal. Major traffic movements in the harbor area are shown in Figure 4-2.[8] A Vessel Traffic Service station has been recently installed, which incorporates surveillance by radar and VHF communications.

4.2.2 Site Selection for Differential Station and Transmitter

In the selection process for a differential site location in the NY Harbor coverage area, the following criteria were used:

- Availability of a facility to transmit pseudorange error messages.
- Location of the GPS equipment to achieve optimum service coverage.
- Convenient access for installation and maintenance.
- Location on current Coast Guard property.
- Availability of prime power and equipment shelter.
- Availability of Coast Guard staff either on or near site.
- The transmission of the correction messages is premised on the use of the marine non-directional beacon band.

Based on this decision, four possibilitiles for a differential site emerged:

1. Differential station and transmitter at Sandy Hook.
2. Differential station and the transmitter at Ambrose Light Station.

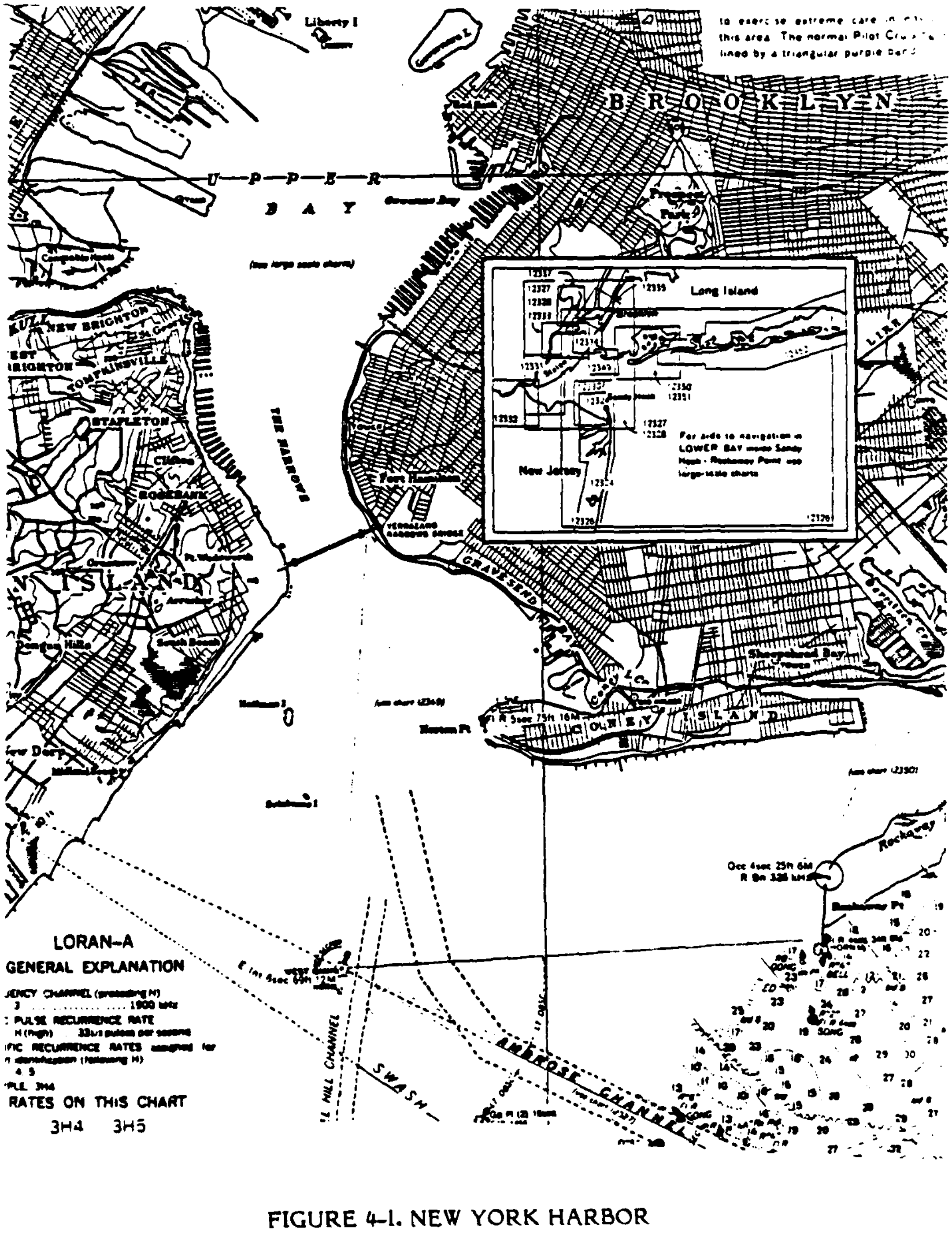


FIGURE 4-1. NEW YORK HARBOR

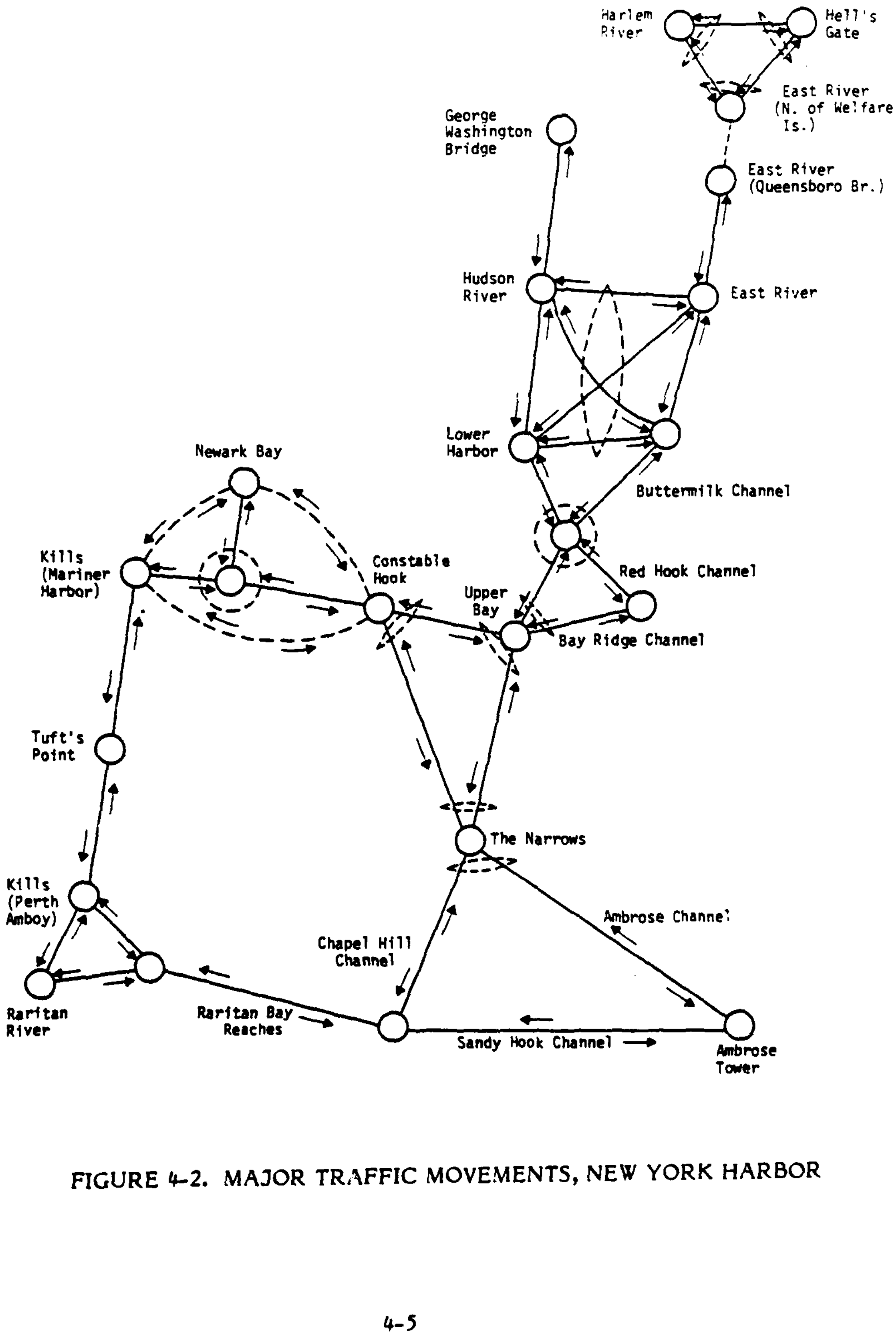


FIGURE 4-2. MAJOR TRAFFIC MOVEMENTS, NEW YORK HARBOR

3. Differential station and transmitter at East Rockaway.

4. Split site: differential station at Sandy Hook, transmitter at Ambrose Light Station.

These locations are shown in Figure 4-3. The locations and ranges of the radiobeacon transmitters in the area are shown in Figure 4-4, along with the coverage provided by a 30-mile range transmitter at Ambrose Light Station. The ranges specified here are for direction-finding applications, which require typically 50 microvolts per meter, however in use as a data link only 8 microvolts are required. Therefore the useful range of the beacon signal for data transmission is approximately three times the DF range.

A. Sandy Hook Differential Station and Transmitter - The Coast Guard has a VHF station and LORAN-C monitoring facilities at Sandy Hook, manned full time by Coast Guard personnel. It has complete prime power facilities, VHF and telephone communication lines, VTS surveillance radar, and shelters. The site is accessible by land. The support for the installation of a differential station is readily available. However, placement of a transmitter here would require a new beacon station. The Coast Guard has no immediate plans for such a site under its present beacon improvement program. Of the 37 new beacons proposed in the Federal Radionavigation Plan, none is located at or near Sandy Hook. The assignment of a new frequency for such a transmitter could prove difficult, given the density of radiobeacons in the area.

B. Ambrose Light Station Differential Station and Transmitter - This is a remote site, located on an offshore platform (see Figure 4-5). The site has difficult access for field tests. It would be an undesirable location during the early applications of differential operation, because special attention, troubleshooting and field servicing would be required. It would be appropriate for the transmission of the corrections, since there is a high-power radiobeacon transmitter installed on the light station, as well as a low-power calibration transmitter. The high-power transmitter is one of a chain of long-range beacons which operate in a time-shared, sequential fashion. This would not be compatible with the differential application, which must be continuous. However, the calibration beacon is a good candidate for the differential correction transmission. Its frequency is at the upper end of the marine radiobeacon band,

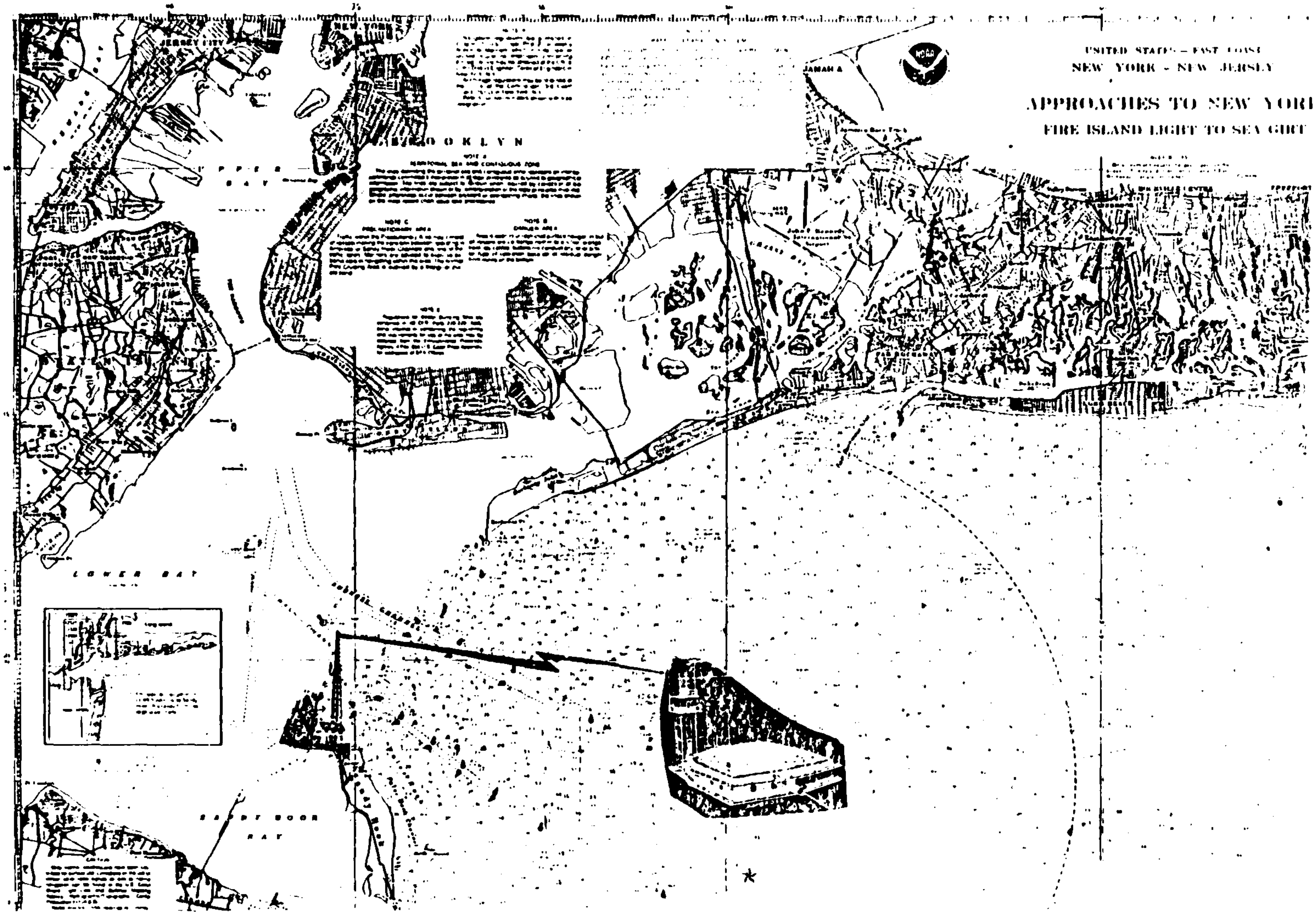


FIGURE 4-3. MAP OF THE APPROACHES TO NEW YORK

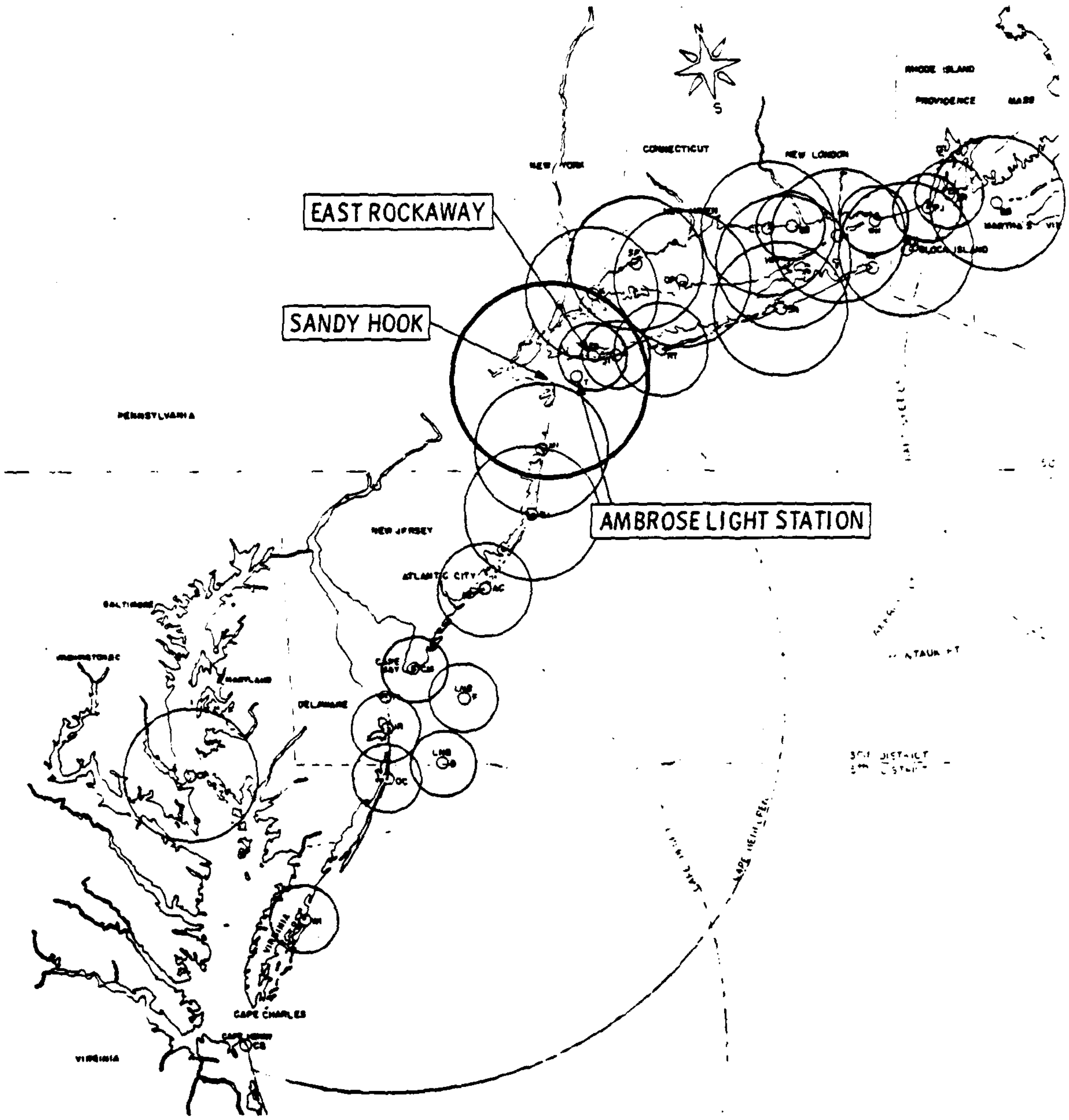


FIGURE 4-4. RADIOBEACON LOCATIONS AND COVERAGE AREAS

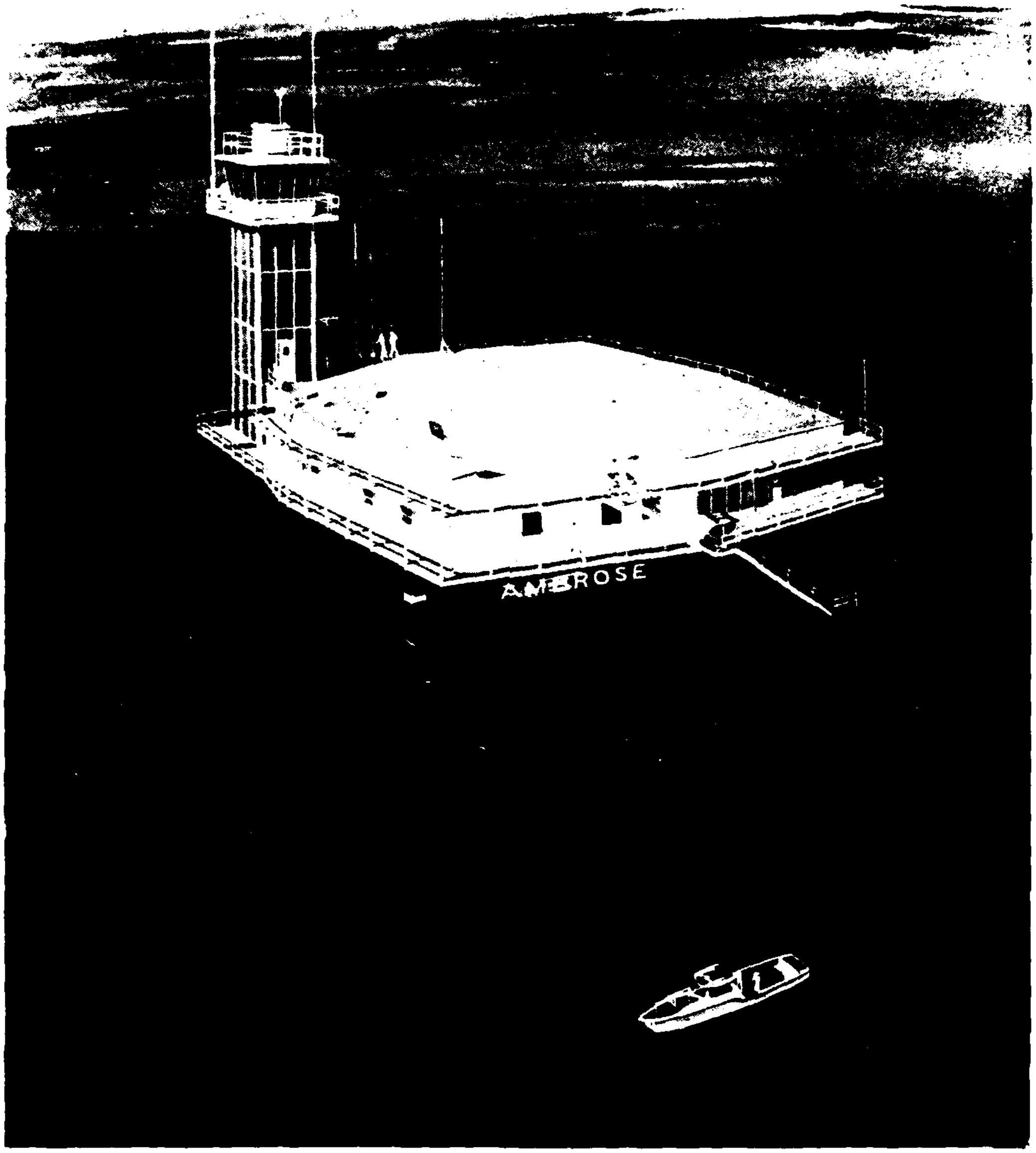


FIGURE 4-5. AMBROSE LIGHT STATION

at 326 kHz. The nearest locations of adjacent frequency transmitters are at Point Judith, RI (325 kHz) and Wachapreague Inlet, VA (324 kHz). The calibration signal is turned on only on request from mariners within 5 miles who wish to calibrate their on-board direction-finding equipment. Thus it is currently used only intermittently. In order to adapt this for use with differential operation of GPS, it would be necessary to substitute a higher power transmitter to obtain a 30-mile range. In addition, it would be necessary to obtain authorization to modulate the beacon transmitter with the GPS message and to conduct 24-hour operations.

C. East Rockaway Differential Station and Transmitter - A radiobeacon facility currently exists at East Rockaway, transmitting at 302 kHz. It is also the site of a group station which supervises the Ambrose Light Station operations. It is fully equipped with prime power, shelter and communications facilities. Assuming the site is relatively free from obstructions, it could support a differential station. Since the data link range is larger than the DF range, the current transmitter could be modulated to provide service out to 30 miles.

D. Split Site: in this configuration, the differential receiver station would be located at Sandy Hook, and the transmitter at the Ambrose Light Station. UHF and microwave communication links are available for relaying the corrections from Sandy Hook to Ambrose for transmission to users. The Differential GPS transmitter would operate in the Ambrose calibration frequency band. The implications of transmission from Ambrose are the same as those described in B.

Based on the advantages and disadvantages as discussed above, the split site alternative appears to be the one which could be installed with the least modification of the existing Coast Guard facilities. The design is thus premised on the assumption of a split-site configuration.

4.3 DIFFERENTIAL STATION DESIGN

4.3.1 Station Design Consideration

The differential ground station consists of a receiving antenna with preamplifier and receiver complex. The functional block diagram is shown in Figure 4-6. The receiver complex includes an RF front end, baseband receiver, processor, high-quality clock, and data link interface. The receiver complex is housed in a shelter, but is designed to operate in a turn-key fashion. The data link interface is connected to a microwave link which relays the differential corrections to the radiobeacon communications link.

The receiver architecture has the following features:

1. Eight parallel channels, each assigned to a separate satellite.

2. Satellites are tracked as soon as their signal can be detected. The quality of the corrections is monitored. When the signal is stable enough and the corrections are determined to be valid, the corrections are then broadcast for that satellite. Typically this is expected to occur at elevation angles below 5 degrees.

3. Narrow bandwidths are employed for carrier and code loops to take advantage of the stationary receiver.

4. Coherent processing techniques are used to achieve the best noise performance.

5. Phase-lock loop tracking is used on the carrier to enable sophisticated processing techniques to be employed.

The processor will employ Doppler processing in order to obtain the highest possible accuracy in the estimate of pseudorange rate variations. Some further smoothing of the pseudorange estimates may be performed by the processor. The corrections sent to the data link will follow the format described in Section 3.2.1.

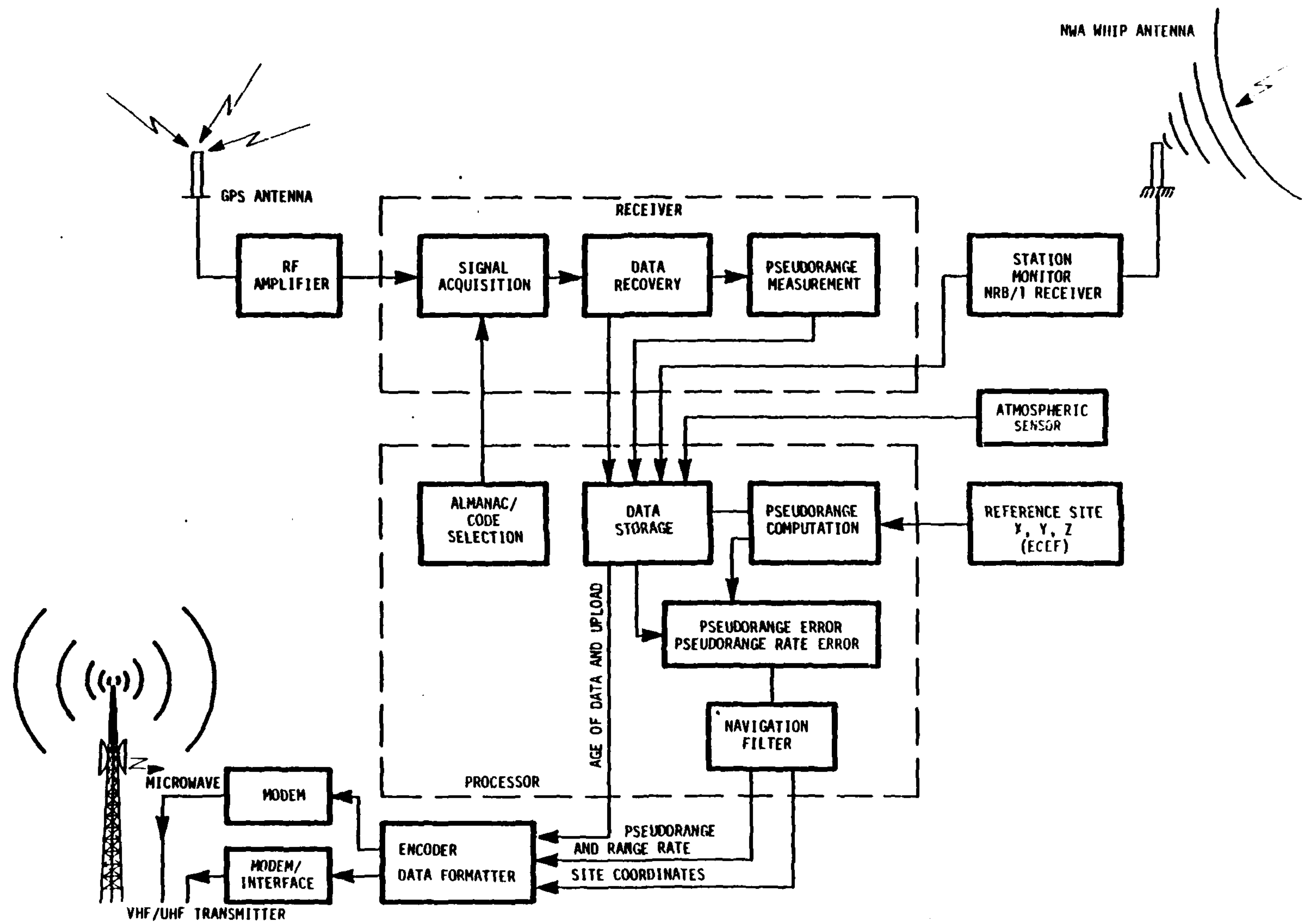


FIGURE 4-6. DIFFERENTIAL GPS FUNCTIONAL BLOCK DIAGRAM

More detail is given in the next few sections on the design criteria used to specify the components of the differential station.

4.3.2 GPS Antenna

Satellite signals are received with an antenna of nominally hemispherical coverage mounted on a tower 30 to 50 feet high. The height is determined by the requirement to see satellites in all directions down close to the horizon. Thus, it must see over buildings and trees, although the effects of the VHF tower are not expected to be significant.

The GPS receiving antenna elevation pattern should meet the requirements shown in Figure 4-7. The pattern rolloff of about 0.5 dB per degree near the horizon should not be difficult to achieve. It is required in order to reduce antenna nulls caused by ground reflections.

4.3.3 Differential Station Receiver

An eight-channel receiver simultaneously tracking up to seven satellites plus a data link channel is recommended for the differential station. There are several reasons for this. First, it is necessary for all the satellites in view to be tracked, because a number of receiver architectures could be employed by users. Figure 4-8 shows the relative amount of time that different numbers of satellites are visible to the users. User could use three, four, or all satellites in view to determine position. Second, accurate corrections of pseudorange and pseudorange rate require that the satellite timing measurements be taken simultaneously. Third, the improved performance of continuous tracking over time-shared tracking makes parallel channel operation highly desirable.

An alternative for near-term implementation would be to use two TI 4100 receivers, under the control of a channel manager module[9]. The channel management software would assign the eight channels to appropriate satellities, and override the current channel assignment algorithm. The accuracy would be reduced somewhat from parallel-channel operation, as it is related to the actual time spent in each channel.

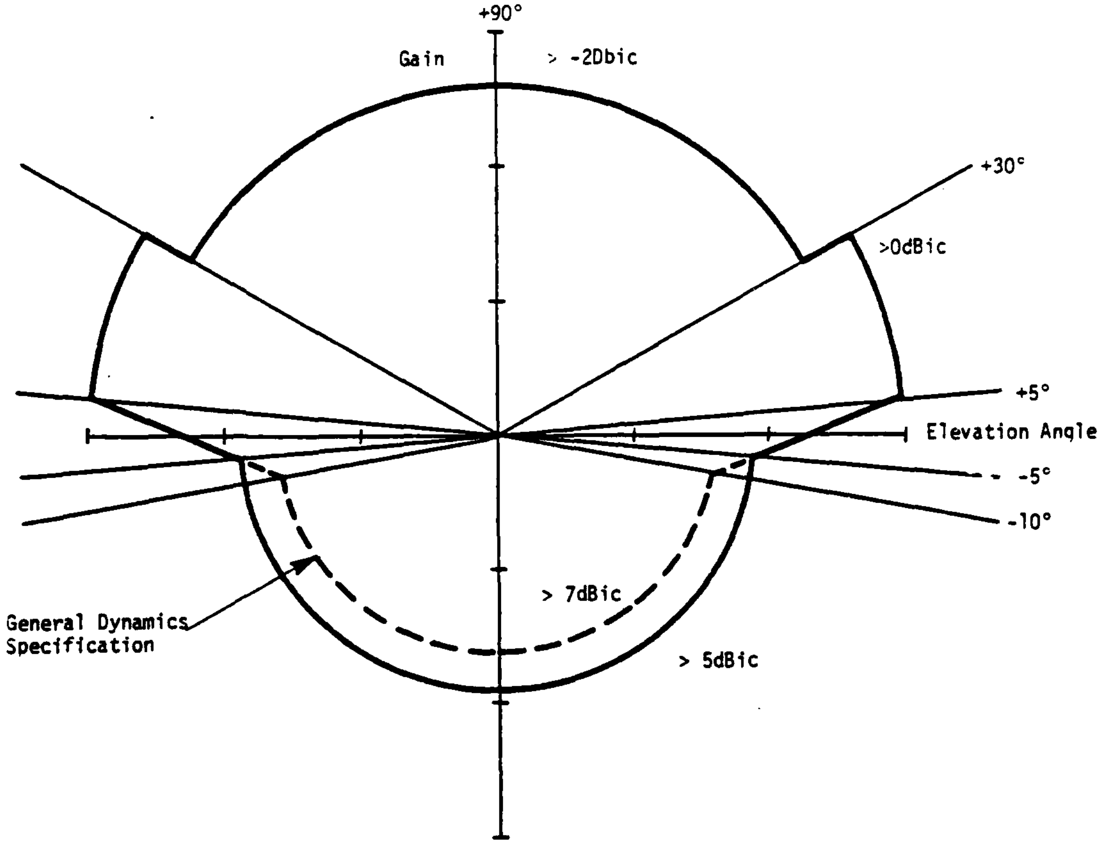


FIGURE 4-7. ANTENNA GAIN VS. ELEVATION ANGLE REQUIREMENT

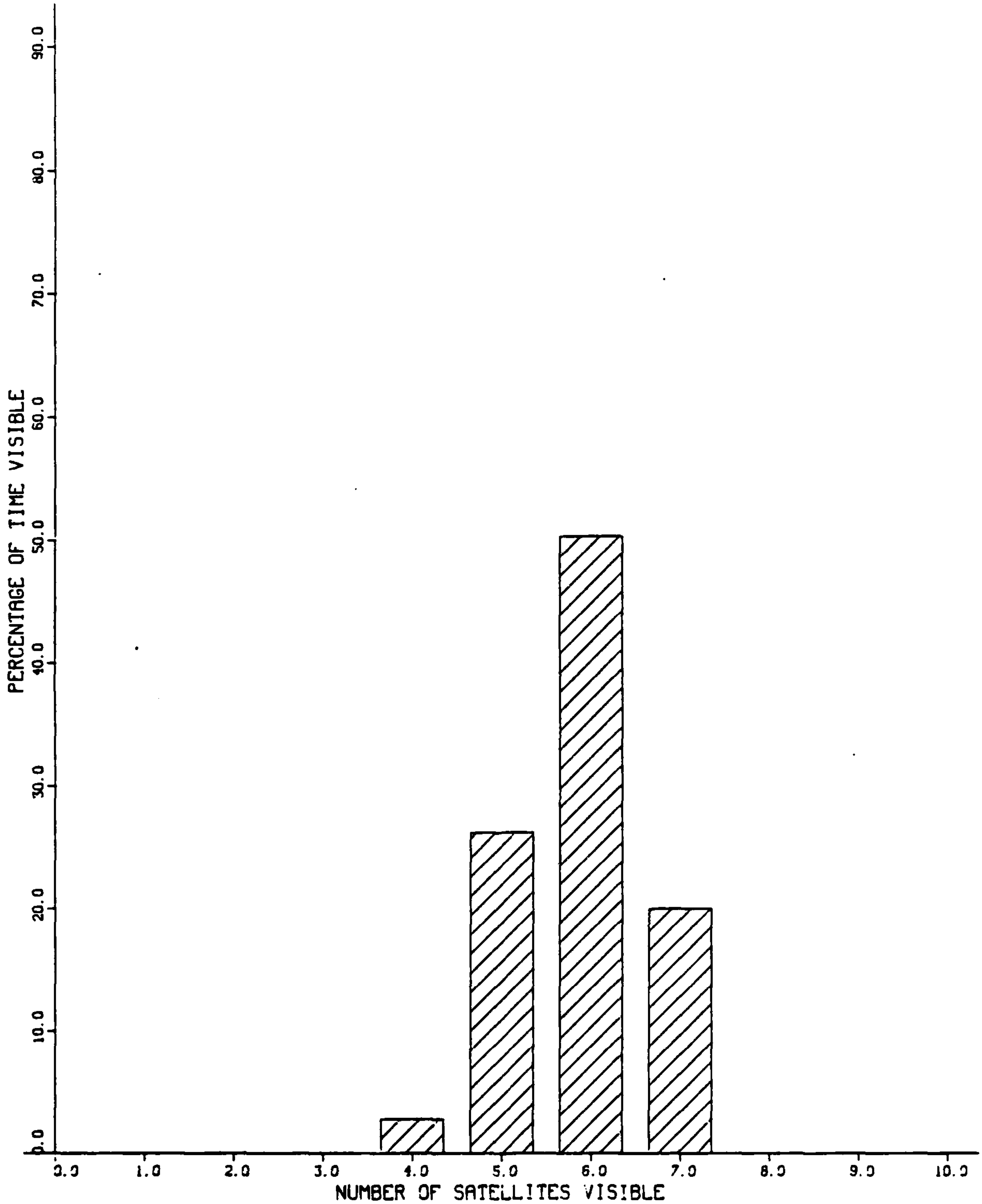


FIGURE 4-8. SATELLITE VISIBILITY HISTOGRAM, 10 DEGREE MASK ANGLE, SANDY HOOK
(Constellation of 18 Satellites Plus 3 Active Spares)

A case could be made for four-channel operation, wherein each channel could share two satellites or track one, depending on how many are visible. Using this scheme each subframe of the Type 1 message would indicate the corrections of up to four satellites, all with the same time reference. However, at least some receiver manufacturers are claiming that future receiver costs will be relatively unaffected by the number of channels employed[10].

All satellites are tracked as soon as their signals can be detected. When the signal is stable enough, the measurements can be used for obtaining corrections. This is expected to occur at elevations below five degrees. Most marine receivers are expected to use mask angles of about 10 degrees, but some may use as little as 5 degrees. Using the approach described here, it is unlikely that any user would see satellites not visible to the reference station. Therefore it is safe to assume that once the optimum constellation is selected by the user, pseudorange correction data will also be available.

The fact that the reference station is not moving makes it possible for narrow code and carrier loop bandwidths to be employed. The ultimate limits on filter bandwidth are set primarily by the variations in the satellite pseudorange rate caused by the Selective Availability, which is imposed to foil delta pseudorange measurements. Of lesser significance are the effects of satellite motion, i.e., the changes in Doppler. Computations indicate that a reasonable code loop bandwidth is 0.1 Hz and a carrier loop bandwidth of 1 Hz for a parallel channel receiver. Figure 4-9 shows a simplified receiver functional diagram with its code and carrier loops. The differential receiver block diagram is shown in Figure 4-10. It shows that all 8 channels are referenced to a single oscillator source.

Coherent detection buys some noise rejection capability. If the tau-dither tracking is used, then the data detection circuit could use "prompt" correlation, thus avoiding a 3 dB loss suffered in the tau-dither early/late single channel switching design. Tight phase lock loop control should be employed in the carrier loop circuit. This enables accurate pseudorange rate measurements to be obtained for the correction message. The pseudorange rate measurement is accomplished by counting Doppler

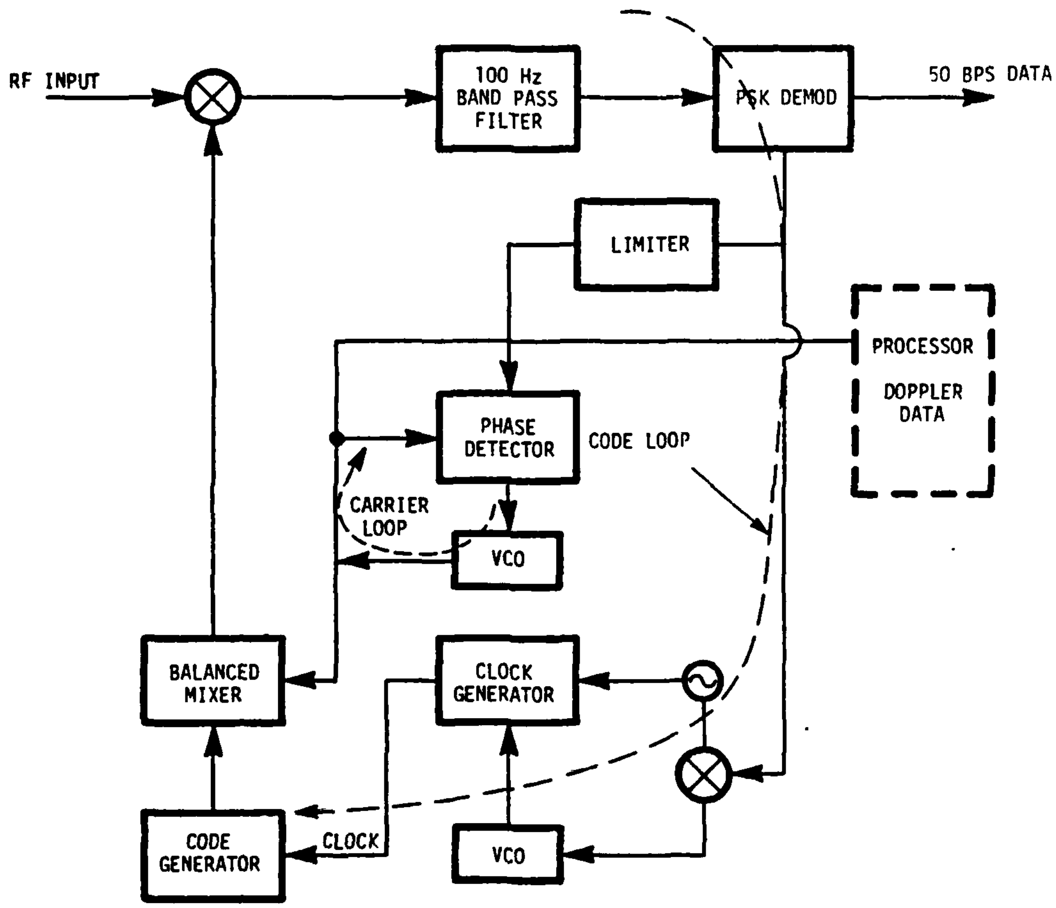


FIGURE 4-9. RECEIVER FUNCTIONAL BLOCK DIAGRAM

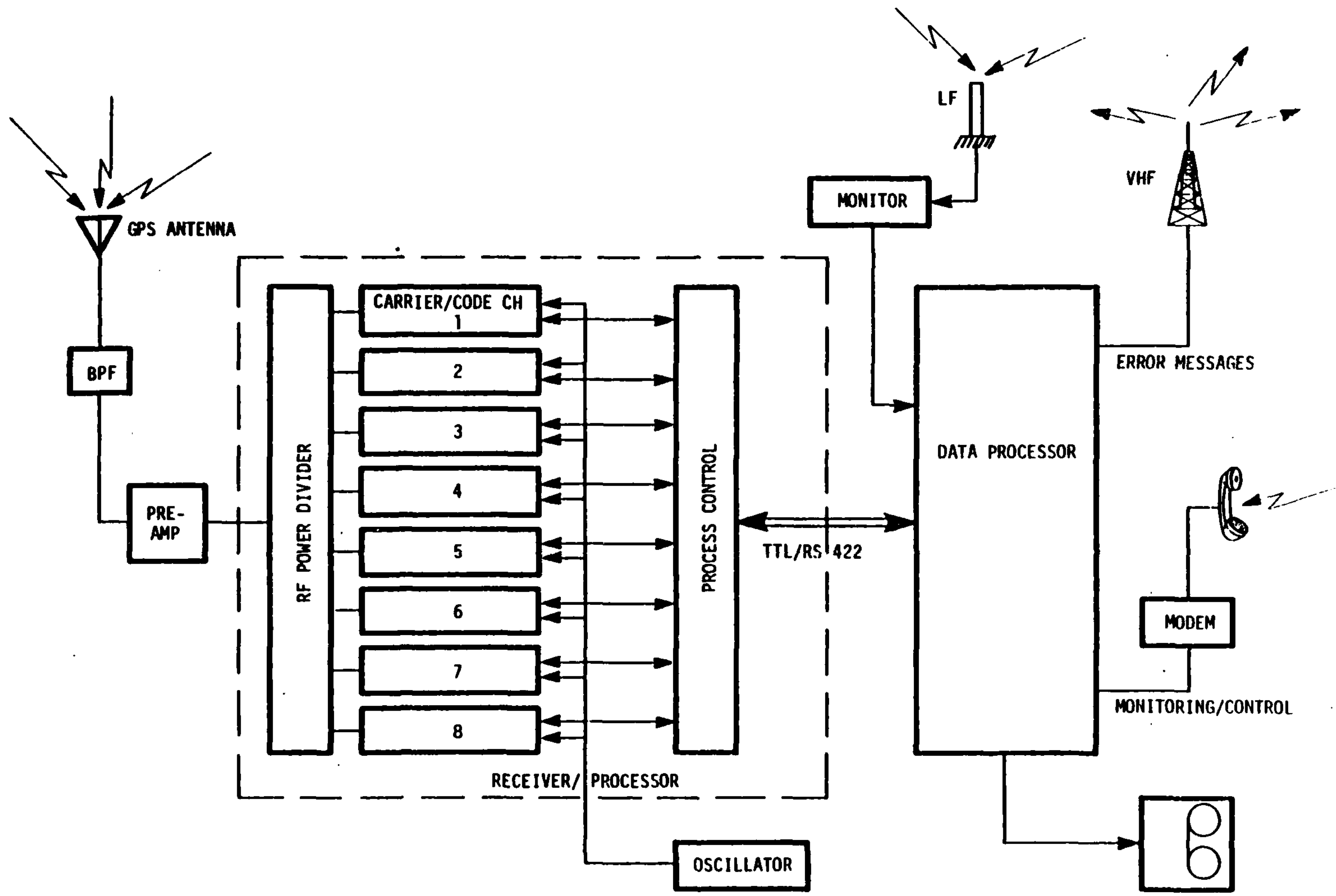


FIGURE 4-10. DIFFERENTIAL GPS RECEIVER BLOCK DIAGRAM

cycles over a period of time. The period of time must be long enough to smooth out noise-induced errors, but short enough that the rate corrections are sufficiently up to date. These considerations suggest a period of about 0.5 seconds. The quantization of the correlator must be chosen small enough that it does not limit the ultimate accuracy of the receiver. A quantization of 4 bits is adequate; it corresponds to 0.57 meters resolution.

Pseudorange code samples can be passed along to the processor as often as independent samples can be obtained, which means that the sample rate should be at least once every 2.5 seconds.

4.3.4 Differential Station Clock

The clock drift should be such that the timing error should be less than about a nanosecond over an update period which is about 12 seconds. This calls for frequency stability of a few parts in 10 billion. If the clock is not slaved to GPS time it should employ a rubidium standard to insure that the long-term drift stays within bounds. The pseudorange errors should not be excessively large, as they must be represented by 16 bits of correction data. The station can in any case use GPS to correct long-term drifts since the corrections can have a constant offset with no effect on the user accuracy.

4.3.5 Differential Station Processor

Following the recommendation of the recent workshop held at the Transportation Systems Center, the processor computes pseudorange corrections employing the satellite ephemerides and satellite clock offsets derived from the satellite data, but does not use ionospheric or tropospheric models. All users of differential service must likewise use the ephemerides and satellite clock offsets. If a user employs no models of the atmosphere at all, the differential corrections obtained near the station will be highly accurate. Only when the user gets farther than 50-100 nautical miles away do these corrections become less accurate, i.e., begin to "decorrelate". Since the user position and station position are reasonably well known, the user can recover some of the accuracy lost due to spatial decorrelation by applying atmospheric models based on user and station positions. This is discussed further in Section 4.5.

In order to compute the pseudorange corrections, there is no need to actually compute the position of the station. However, a Kalman filter should nevertheless be employed to determine the best estimate of station clock error. Smoothing should also be employed on the pseudorange estimates. This gets subtracted from all the pseudorange corrections in a particular subframe. The steps of the process of computing the pseudorange corrections are the following:

1. Obtain the satellite coordinates at the selected reference time from the satellite ephemeris data, and subtract the station coordinates. Compute the true range for each satellite in the subframe.

2. Sample the smoothed satellite raw range measurements and subtract the satellite clock offsets. By so doing, the proper pseudorange measurement is obtained.

3. Obtain the station clock error estimate from the Kalman filter and subtract it from each satellite pseudorange.

4. Subtract the difference between the adjusted pseudorange measurements and the true ranges to get the pseudorange corrections.

5. Check the values obtained with previous values and check the size of the corrections to determine the quality of the corrections. If there is a problem, the appropriate health bits should be set in the correction message.

6. Obtain the position estimate of the station from the Kalman filter and check to see if the error is within bounds. If there is a problem, the station health message should indicate its severity.

7. Check the health status bits in the satellite message and enter appropriate status in the station health message.

Once these have been performed, the pseudorange corrections are ready for transmission to the data link.

The pseudorange rate data are obtained from the carrier loop Doppler counts as indicated above. It may be desirable for some smoothing to take place for these measurements as well. They are essentially independent of the atmosphere and the satellite data, so no corrections appear to be necessary.

In addition to formatting the correction subframes for transmission, the processor must also periodically prepare the Type 2 Messages with the "delta" corrections and the Type 3 Messages with the station ECEF coordinates. These should be sent about every 5 and 10 frames, respectively. It should also be pointed out that when 6 or less satellites are visible, the corrections can be sent every 6 seconds, rather than every 12.

Other duties of the processor include internal calibration and examination of the monitor outputs to assure that the station and communications link are operating properly.

4.4 DATA LINK

4.4.1 Data Link Alternatives

The task of communicating the corrections to the users poses a whole new set of problems. In addition to the problems of standardizing the format, obtaining a frequency allocation and adding complexity to the user's processor, there is the problem of providing link reliability for adequate coverage. There are two types of communications that could be employed:

1. Line-of-Sight (e.g., VHF, UHF, L-Band, microware), where the transmitter tower must be strategically located and tall enough to be visible to the users in the coverage area.

2. Ground-Wave. Low and medium frequency bands (e.g., radiobeacon), where the frequency is low enough to reach targets beyond the horizon.

There are precedents for using existing facilities to transmit this kind of data. A new set of beacon standards which provide for OMEGA differential corrections to be transmitted is being prepared for Europe. The U.S. Coast Guard is examining the technique in Puerto Rico. There is also a proposal in Europe to adopt standards for providing FM digital data transmission by audio subcarrier on either side of the 19-kHz pilot tone. The data links are expected to have an approximate data rate of 600 bps.

If LF or MF frequencies are employed for the broadcast of differential corrections, the signals propagate along the earth and diffract well around buildings, structures, and terrain. As a result there are few holes in the coverage, especially on water.

If higher frequencies have to be used, such as VHF or microwave, blockage is more severe, diffraction is limited, and there could be numerous holes in the coverage areas where the signal fades out and becomes unusable. In such a situation, it may be possible to deploy several transmitters for the broadcast of differential corrections. In order to avoid interference or garbling to a user receiving approximately equal signal levels from two transmitters, the broadcasts could be time-multiplexed. This would be possible if the data rate were increased by the number of transmitters, and if each broadcast one correction data set at one time.

The pseudosatellite technique has gained considerable attention and its feasibility is being carefully evaluated by industry and government. This technique incorporates a data link within the GPS frequency environment. It has the capability of "looking like" another satellite to a user's receiver and provides range-to-station information as well as the correction data.

The pseudosatellite technique is based on the use of GPS L_1 frequency for the transmission of ground-derived pseudorange correction messages to nearby users. The pseudosatellite techniques have the following desirable features:

1. No receiver hardware modifications or additions are required for the user equipment and no external data link is required. Thus it is attractive from a user cost standpoint.

2. The ground reference site transmitter is made to "look like" a satellite. The frequency, modulation and coding are identical to satellite signals. Data formats are fully compatible, and a data rate of 50 bps is maintained.

3. It provides a high quality channel for the data link, because of Gold Code signal structure.

4. By tying the reference station to GPS time, the signals can be synchronized with the NAVSTAR transmissions, thus allowing users to measure their ranges to the reference station. The station signal can then be used to improve the user's position estimate.

While the pseudosatellite concept is attractive, it has some disadvantages as well:

1. It is limited to line-of-sight coverage.

2. It could cause interference to nearby non-differential users.

3. It could cause interference to differential users as well.

The problem of pseudosatellite interference manifests itself in two related ways: 1) It raises the noise level; and 2) It can ultimately cause false lock. The fact that there is usually a frequency separation between the reference station carrier and any satellite signal carrier does not eliminate the problem. Cross-correlation components result which appear as noise to the user receiver. Close to the station the signal level can be high enough that the correlator output can rise above the threshold and declare a locked condition irrespective of the satellite delay. While this could be reduced somewhat by careful tailoring of the ground transmitting antenna, i.e., by moving antennas to different locations, or by time multiplexing error message transmissions, even then the problem may still be difficult to circumvent. Up to now, no form of pseudosatellite technique has been accepted.

4.4.2 Data Link Recommendation

The recommended data link technique for broadcasting differential GPS corrections is to modulate the Marine Radiobeacon transmitters. The reasons are the following:

1. Radiobeacons are located near the harbors and areas where differential GPS service is likely to be desired. The real estate is already purchased, and support facilities are already established.

2. Radiobeacons are primarily CW transmissions, except for the Morse Code identification. Modulating the transmitters is technically tractable, and can be done without causing interference to radiobeacon users or reducing radiobeacon performance[11,12,13].

3. Receivers, components, and antennas are quite inexpensive at these frequencies. They would be similar to AM radios in their appearance.

4. Radiobeacon signal propagation travels over the surface of the earth and diffracts around buildings and structures. Coast Guard technical personnel at Governor's Island are not aware of any "holes" or areas of poor coverage associated with the radiobeacons near New York.

4.4.3 Radiobeacon Transmitter

The range at which signals can be received from an LF transmitter of a given power depends on the conductivity of the earth along the propagation path. The best performance is obtained over the ocean, which is a good conductor at these frequencies. Ground conductivity may be less by a factor of 1000. As a result, stations near the ocean require less power to achieve a given range.

The power required to achieve a field strength of 50 microvolts per meter is shown in Figure 4-11. Interestingly enough, the field strength requirement which defines the range of the station varies with latitude. North of 40 degrees the power level requirement is 50 microvolts/meter. From 30 to 40 degrees the requirement is 75, and from the equator to 30 degrees it is 100 microvolts/meter. Sandy Hook is located right at the 40 degree latitude dividing line.

Radiobeacon transmitters are of solid state design with three power level options designated as follows:

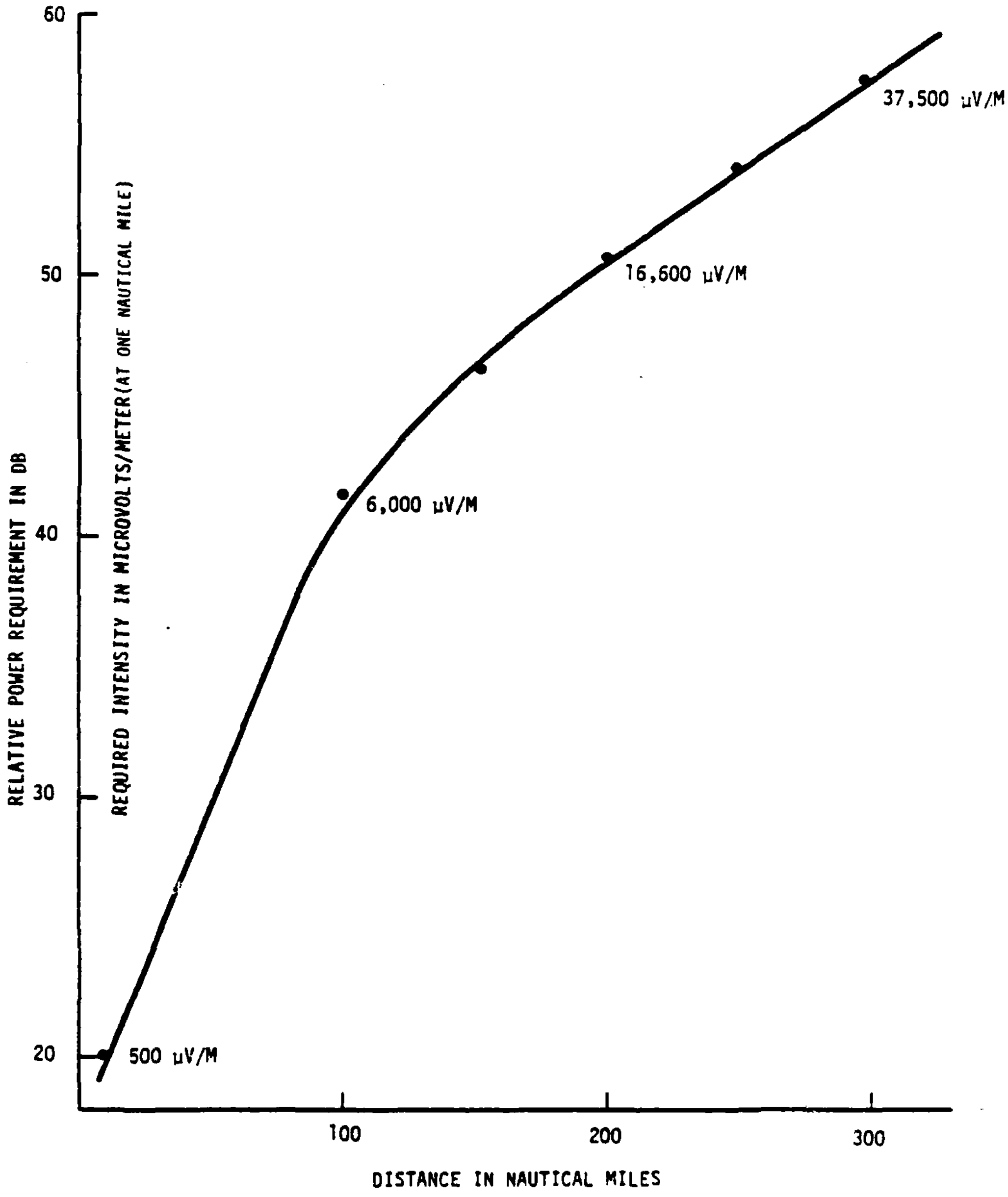


FIGURE 4-11. RELATIVE RADIOBEACON POWER REQUIREMENTS VS. PATH DISTANCE

CDWQ - NX250 DB 62.5 watts
CDWQ - NX1000 DB 250 watts
CDWQ - NX4000 DB 1000 watts

Typical Radiobeacon antenna heights range from 35 to 125 feet in comparison with the signal wavelength which averages 1000 meters (3280 feet). These antennas are very sensitive to atmospheric presence of salt spray, or wind induced tilt - and require automatic tuning.

The transmitted beacon Signal characteristics are:

Data Element Length - 0.125 sec.
Dash Element Length - 0.375 sec.
Interval between Elements - 0.125 sec.
Interval between Characters - 0.375 sec.
Interval between characteristics - 0.625 sec.

However, there are still a number of problems that must be addressed:

1. Differential operation requires continuous correction data at 50 bits per second or more. The Ambrose primary signal at 286 kHz is sequenced; it transmits for 1 minute, and is turned off for 5 minutes. Continuous operation would require a major change in Coast Guard beacon policy. The range which covers the New York Harbor area and beyond, is 150 nautical miles, so no change in equipment would be required.

2. There is a second frequency used by the Ambrose beacon. It is at 326 kHz, and is used for Direction Finding (DF) equipment calibration. It is turned on only at the request of a mariner between 8:00 A.M. and 6:00 P.M. daily. Its current range is only 5 nautical miles. If Coast Guard approval could be obtained, this facility could be used for differential corrections. It would require using a more powerful transmitter with 100 watts, to provide the 30-nautical mile coverage that would be required to cover the New York Harbor area.

Assuming these obstacles can be overcome, the radiobeacon transmitters can be modified to incorporate the differential correction data.

The constraints imposed on the selection of the modulation technique are primarily those of bandwidth limitations. Beacon frequencies are spaced at 1 kHz, but stations employing frequencies closer than 3 kHz are located far enough away from each other that no user would be able to hear both at the same time. The subcarrier used for the Morse Code identification is located 1020 Hz above the carrier.

It appears that a data link transmitting 50 bits per second could be achieved. The proposed technique is to phase modulate the carrier with the data. Most of the spectral energy would be within 100 Hz of the carrier. This is expected to be transparent to users, who typically have receivers with much wider bandwidths.

A totally solid-state Non-Directional Beacon Transmitter, Type ND500D (NAUTEL), operating with dual frequencies and adjustable power from 50 to 125 watts will be required for transmission of pseudorange error messages up to 30 nautical miles range. A modification to transmit 50 bps data appears to be a minor change and is not be expected to exceed 20% of original transmitter cost. A modified transmitter block diagram is shown in Figure 4-12. A phase modulated data message will be superimposed on the carrier and transmitted in time coincidence with the regular Morse Code keyed subcarrier as shown in Figure 4-13.

According to recent field measurements of differential OMEGA corrections using Radiobeacon transmitters[14], the signal strength required for reliable data reception is about 8 microvolts per meter. For direction-finding use, 50 microvolts per meter is typically required. As a result the differential correction range is about 2.5-3 times the DF range for the same transmitter. This greatly expands the coverage area of the corrections over what had been anticipated.

4.4.4 Radiobeacon Antenna

A typical antenna efficiency at these frequencies ranges from 8-10 percent and usually requires frequent antenna tuning and a flat area with good ground surface conductivity. The existing antenna at the Ambrose site is located on a platform above

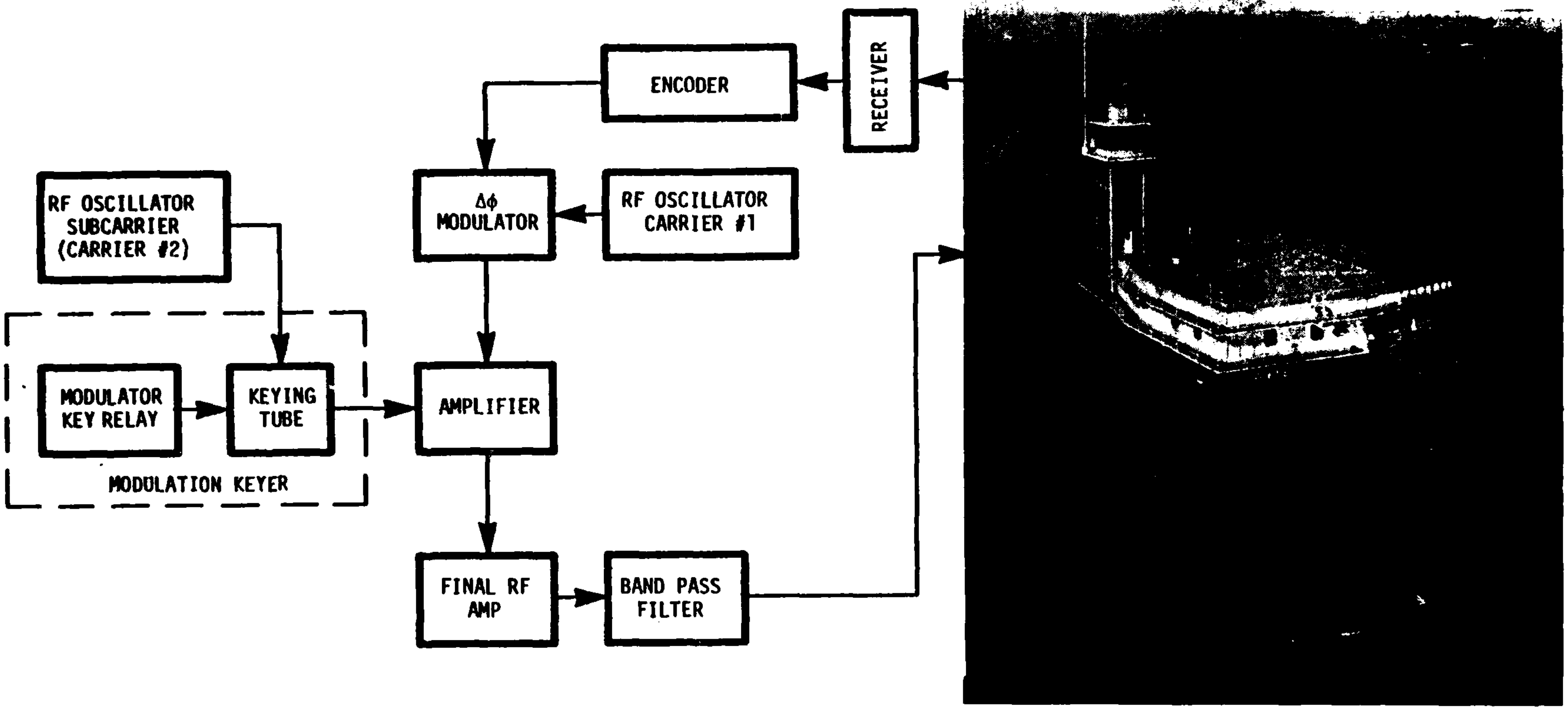


FIGURE 4-12. NON-DIRECTIONAL BEACON TRANSMITTER BLOCK DIAGRAM

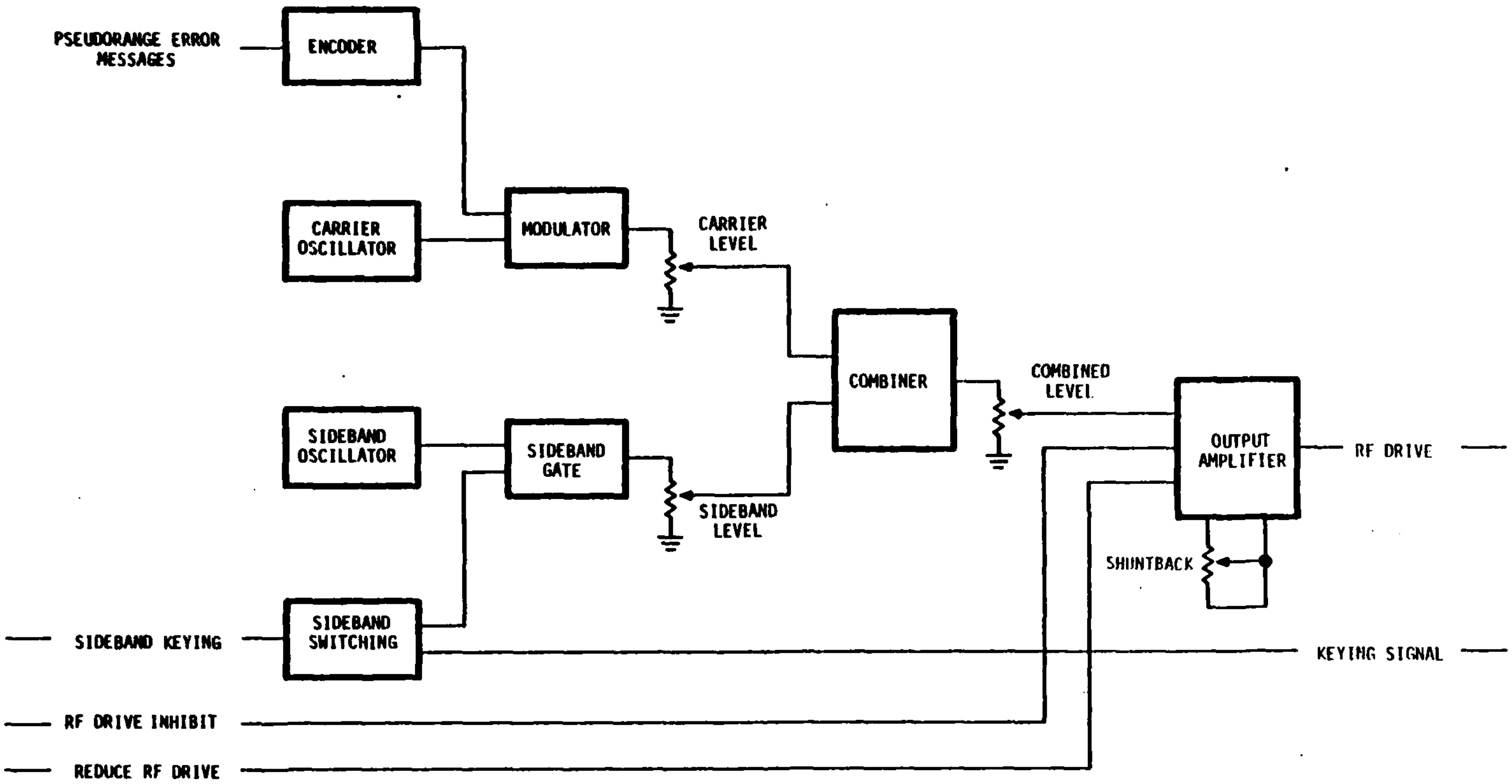


FIGURE 4-13. NON-DIRECTIONAL BEACON SCHEMATIC

the ocean, an ideal "ground". Therefore, it is assumed that no additional modifications will be required, except for the increased transmitted radiated power level required. A typical beacon antenna is shown in Figure 4-14.

4.5 PERFORMANCE ESTIMATES

4.5.1 Reduction of Accuracy Due to Spatial Decorrelation

The ionospheric and tropospheric effects on the time delays of the satellite signals is shown in Figure 4-15. As the user travels farther away from the differential station, the accuracy of the corrections will be reduced. This phenomenon is called "spatial decorrelation".

Several factors contribute to this error:

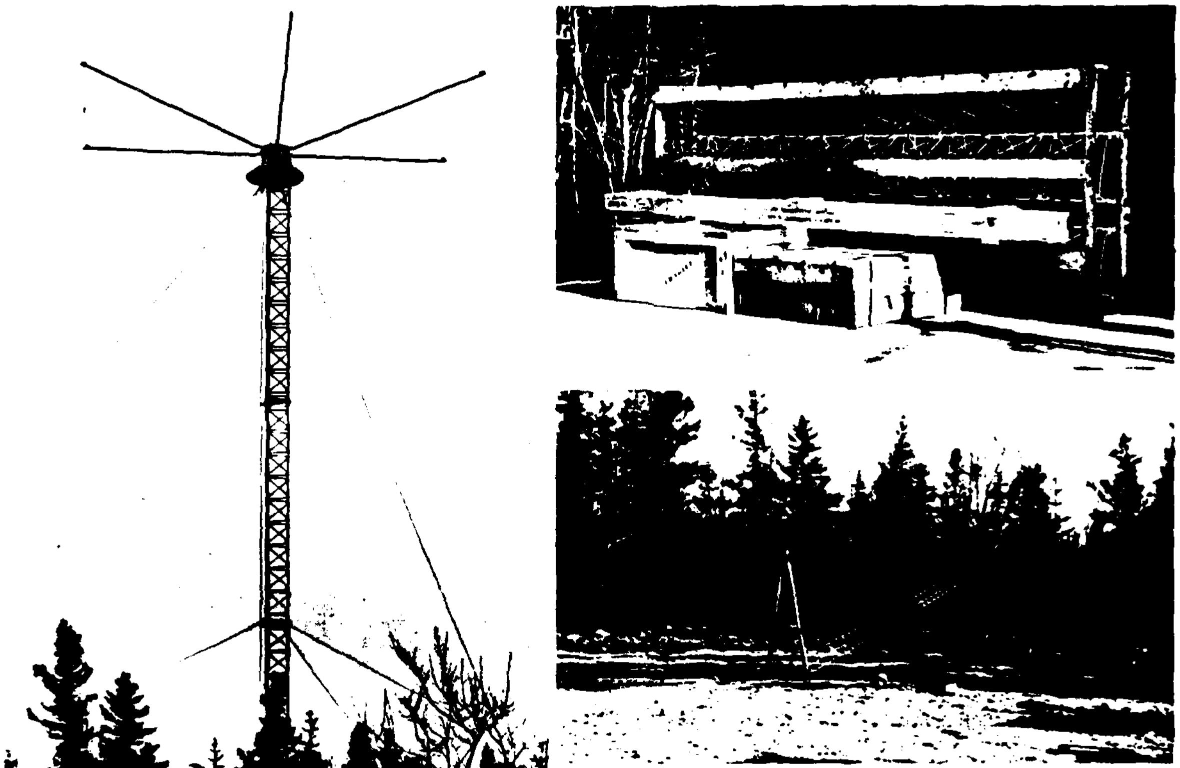
1. Ionospheric Irregularities - The ionosphere exhibits local irregularities in the electron densities, which result in small, unpredictable delays.

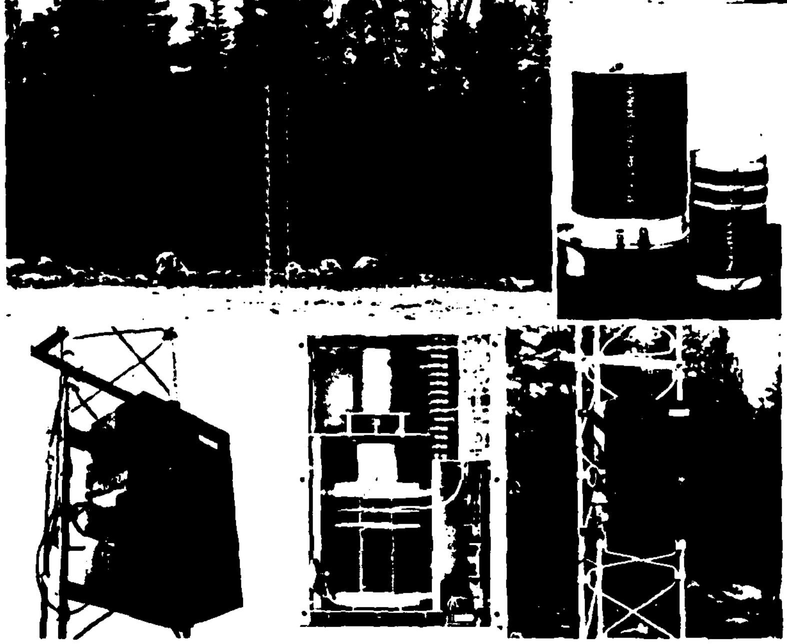
2. Unmodelled Diurnal Ionospheric Delays - The large-scale features of the ionosphere are not perfectly represented by the models. Even after applying the models to the satellite-to-receiver paths to both the user and differential locations, a residual error remains.

3. Unmodelled Tropospheric Delays - While the tropospheric delay is quite stable, there are local variations of temperature and humidity which cannot be modeled.

4. Uncompensated Ephemeris Error - An error in the assumed position of the satellite can result in an error for widely separated user and reference station receivers. An error of 50 meters in satellite position is assumed as a worst case.

The resulting positional errors depend as well on the user receiver noise and the GDOP environment. The 2 drms positional accuracy is equal to twice the product of the pseudrange error standard deviation and the horizontal DOP, or HDOP. Previous work





APPLICATION

PA 40 A
PA 60 A

These series of antennas are designed to provide a complete antenna-tuning-matching package to interface directly at a 50 ohm (coaxial) impedance with low/medium powered transmitters in the LF and MF bands.
They are particularly suitable for improving efficiency of locator radiobeacon installations normally fitted with a whip, where low profile and high efficiency are important. Also applicable for any radiobeacon where omnidirectional signals are required at low to medium power levels, for regular or emergency MF broadcasting, and for other LF/MF communication installations up to 1500 Khz.

FIGURE 4-14. POLESTAR ANTENNA SYSTEMS

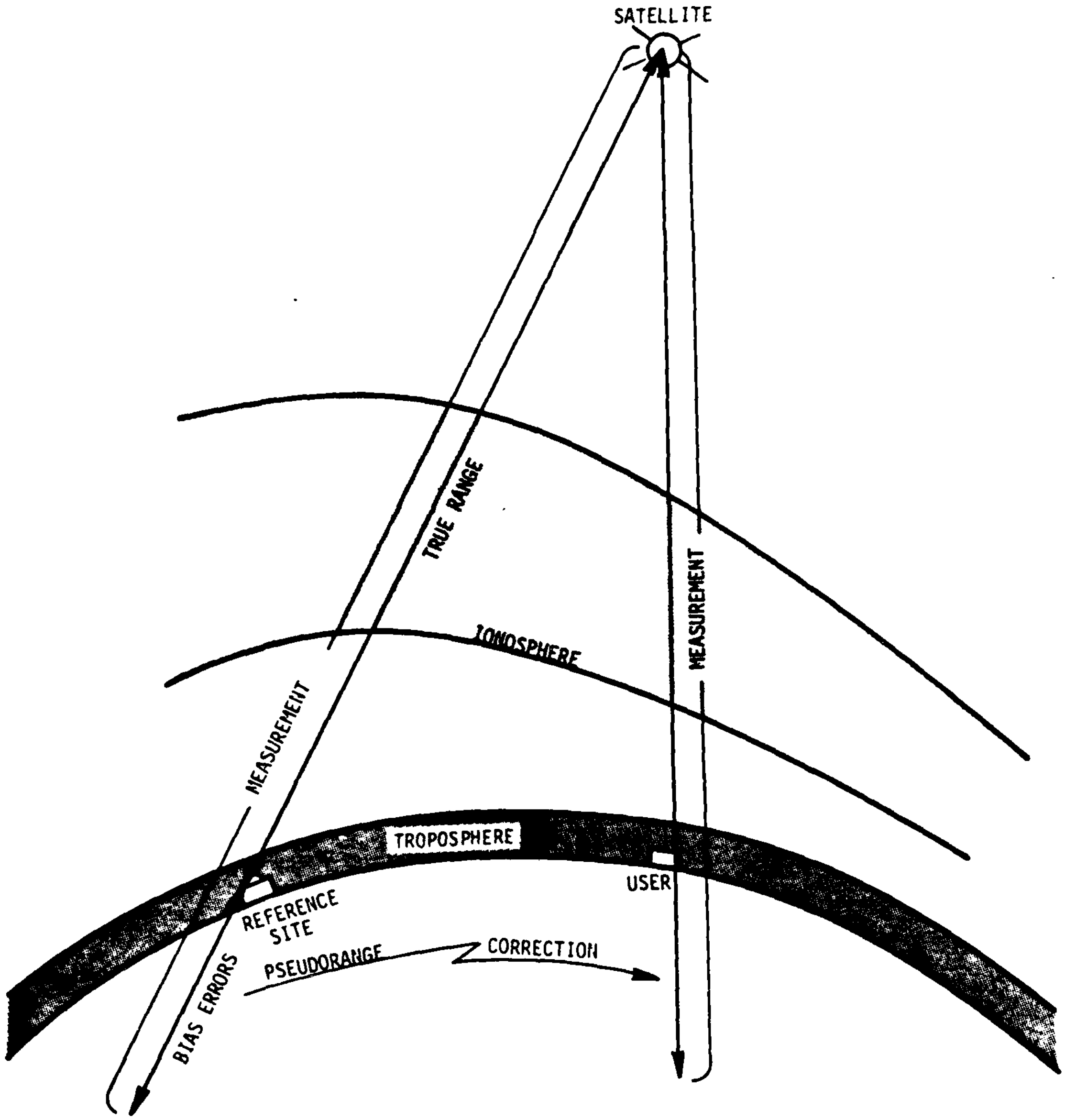


FIGURE 4-15. BASELINE DIFFERENTIAL GPS

has shown[4] that the HDOP has a median value of 1.3. For example, the 2 drms positional accuracy corresponding to a 5-meter 1-sigma pseudorange error would be 13 meters. The 2 drms accuracy figure corresponds to a probability level of about 97%.

4.5.2 The 2 drms Position Error Estimate Near the Differential Site

Performance estimates must make use of some reasonable assumptions about the user receiver quality. For the purposes of this report, it will be assumed that a sequential receiver will be employed which uses the best set of three satellites along with altitude aiding. Noncoherent tracking circuits are assumed, and no particularly sophisticated Doppler processing would be expected. However, a Kalman filter would be employed. The characteristics of a typical receiver are shown in Table 4-1.

Since the New York Harbor area is within 30 nautical miles of the differential station, spatial decorrelation has a negligible effect. The type of atmospheric models employed by the users' receiverd is therefore not significant.

Table 4-2 shows the computation of the reference station's contribution to pseudorange error. Due to the sophisticated processing, multiple channel operation and narrow code loop bandwidth, the one-sigma error is less than a meter. The error in pseudorange passed on to the users appears as a bias error, although statistically it is a stationary process with zero mean value.

Table 4-3 shows the accuracy in pseudorange expected by a marine user who has applied the differential corrections. It can be seen that the total error of 3.2 meters is dominated by receiver noise. In order to translate this into positional error, it is necessary to use the horizontal dilution of precision (HDOP) for marine receivers. The median HDOP for 18-satellite plus 3 spares constellation described here, employing a 10-degree mask angle, is 1.3. Therefore, the 2drms horizontal position error is estimated to be 1.3x2x3.2 = 8.3 meters, or approximated 9 meters. A sample of computations is shown below:

Receiver noise	2.60 meters
User receiver uncertainty	0.43 meters
Temporal error	0.26 meters

TABLE 4-1. RECEIVER PARAMETERS - MARINE

PARAMETER	VALUE	
	NAV. CH	DATA CH.
CLOCK		
Clock Stability	1 X 10^{-8}(1-3 Sec)	1 X 10^{-8}
CODE LOOP		
Type	Tau-Dither	
Order	2nd	
Bandwidth	0.30 Hz	
Damping Factor	0.707	
Delay Prepositioning	Yes	
Doppler Prepositioning	No	
Satellite Dwell Time	0.68 sec.	
Dither Timestep	0.01 sec.	
Dither Code Shift	± 0.5 CHIP	
IF Noise Filter Bandwidth	~300 Hz	
CARRIER LOOP		
Type	AFC	AFC/Costas
Order	1st	1st/2nd
Bandwidth	10 Hz	10 Hz/10 Hz
Damping Factor	N.A.	N.A.
Doppler Preposition	Yes	Yes/Yes
Satellite Dwell Time	0.68 sec.	0.68 sec.
IF Noise Filter Bandwidth	300 Hz	300 Hz/300 Hz
NAVIGATION FILTER		
Type	Kalman	
States	6	
Observables	Pseudorange	
SATELLITES TRACKED		
Satellites Tracked	3 (minimum)	
Satellite Mask Angle	~ 5°	

TABLE 4-2. COMPUTATION OF THE REFERENCE SITE RECEIVER NOISE

$$\frac{\sigma_1^2}{\Delta^2} = \frac{K_1 B_L}{\frac{C}{N_o}} + \frac{K_2 \; B_{IF} B_L}{\left(\frac{C}{N_o}\right)^2}$$

$K_1 = \frac{1}{2}$

K_2 = 0 FOR COHERENT DETECTION

B_L = 0.1 Hz

B_{IF} = 4000 Hz

$\frac{C}{N_o}$ = 41.1 dB-Hz

Δ = 293.2 METERS (C/A CODE)

$\sigma^2 = 293.2^2 \times \frac{0.1}{2 \times 12{,}882}$

σ = .58 METERS (1-SIGMA)

TABLE 4-3. DIFFERENTIAL NAVSTAR GPS PSEUDORANGE ERRORS (METERS)

PARAMETERS	REFERENCE SITE B_{IF}=4000Hz, B_L=0.1 Hz		MARINE USERS B_{IF}=300Hz, B_L=0.3Hz	
	BIAS	NOISE	BIAS	NOISE
RECEIVER NOISE		0.58		2.6
UNCERTAINTY IN MEASUREMENT			0.43	
CLOCK GROUP DELAY				0.9
MECHANIZATION		0.57		1.0
MULTIPATH		1.0		1.2
SPATIAL/TEMPORAL ERRORS			0.57	
TOTAL ERROR COMPONENTS		1.3	0.71	3.16
TOTAL ERROR				3.24
POST FILTER ERROR		0.43		

Clock group delay	0.90
Mechanization	1.00 meters
Multipath	1.2 meters
Range Error (UERE)	3.2 meters (1-sigma)
Position Error	8.3 meters (2 drms)

A position error of 9 meters (2drms) represents a high accuracy navigation service, one which meets the requirement for navigation in most Harbor/Harbor Entrance areas. Users with more sophisticated receivers can improve the performance somewhat, but it is questionable whether it is needed. Certainly this performance is more than adequate for the traffic lanes and constricted waterways in New York Harbor.

4.5.3 The 2 drms Position Error Estimate with Spatial Decorrelation

The noise components contributing to the spatial decorrelation are ionospheric irregularities unmodeled diurnal delays, unmodeled tropospheric delays and ephemeris errors.

Table 4-4 shows the estimated errors in pseudorange due to spatial decorrelation for a low-lying satellite.[2] A linear behavior with user-station separation is assumed. The numbers are considered to be worst case numbers, representative of mid-day variations in the atmosphere. Figure 4-16 shows the spatial decorrelation with separation.

A well-designed user receiver will typically exhibit about a 3.2-meter error (1-sigma) in pseudorange. Figure 4-17 shows the composite positional error as a function of user-station separation.

To illustrate the significance of these figures, suppose a differential station were located at Sandy Hook. The accuracy of the user's differential receiver would be about 17 meters (2drms) in Boston, MA and Norfolk, VA. However, in the New York Harbor area there would be very little spatial decorrelation, and about 9 meters (2drms) accuracy could be achieved. These data may be compared with the measured data taken at long separation distances as reported by Dr. Ernest Fickas, SRI Interactional.[15]

TABLE 4-4. SPATIAL AND TEMPORAL DECORRELATION

	Spatial Decorrelation Meters/kM	Temporal Decorrelation Meters/Sec
IONOSPHERIC IRREGULARITIES	0.0061	0.0049
DIURNAL IONO DELAYS	0.0043	0.0018
FLAIR		0.0024
TROPOSPHERIC DELAYS	0.004	
EPHEMERIS ERROR (SA)	0.005	
TOTAL	0.0098	0.0057

ASSUMTIONS:

- o NOMINAL IONOSPHERIC DELAY AT ZENITH 10 METERS
- o DATA UPDATE INTERVAL 12 SEC.
- o SELECTIVE AVAILABILITY 100 METERS (2drms)

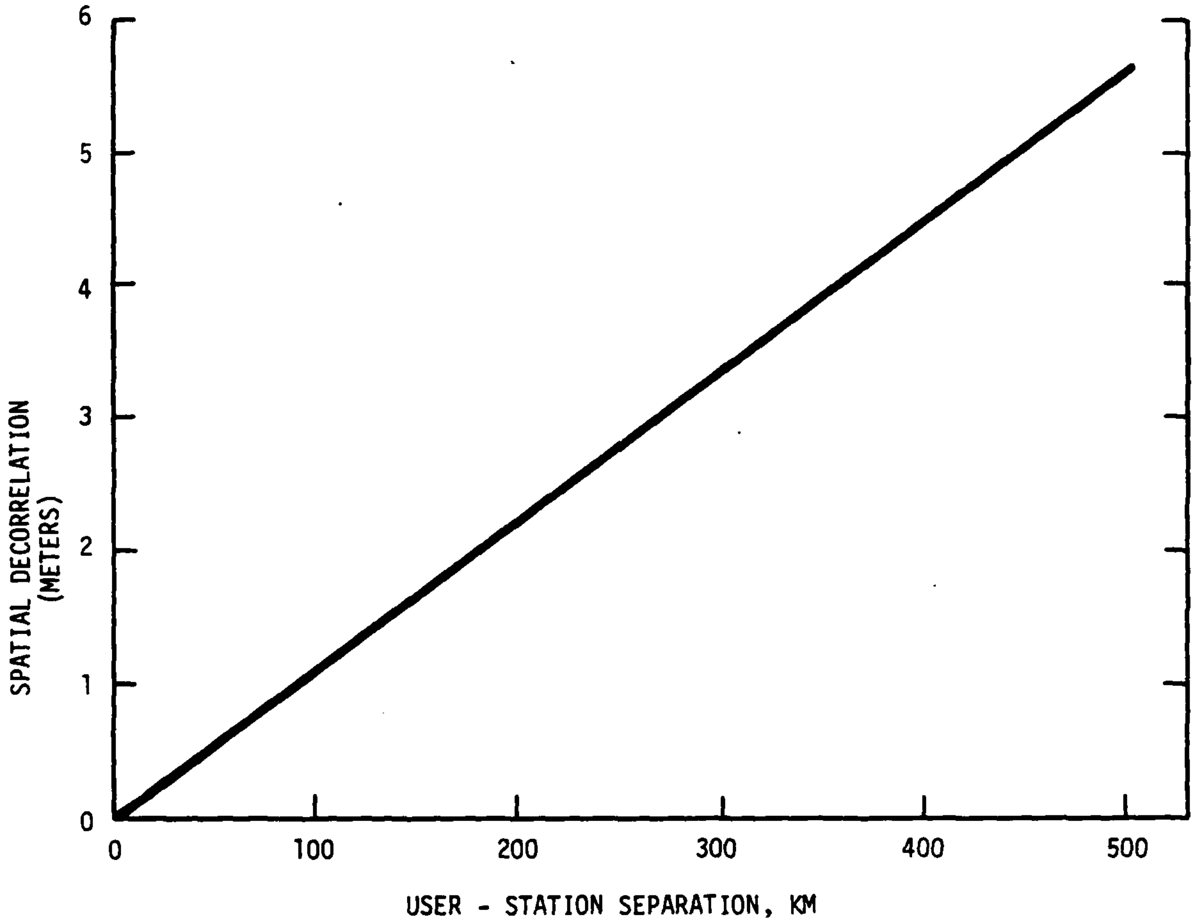
PSEUDORANGE ERROR COMMPONENT AT 50 kM SEPARATION:	
o SPATIAL ERROR	0.49 METERS
o TEMPORAL ERROR	0.068 METERS
o DELTA-IONO BIAS	0.13 METERS
o SELECTIVE AVAILABILITY (Acc. COMPONENT - $\frac{1}{2} gt^2$)	0.26 METERS
TOTAL ERROR COMPONENT	0.57 METERS

TOTAL PSEUDORANGE ERROR AT 50 kM SEPARATION:

PSEUDORANGE ERROR (UERE) = $[3.2^2 + 0.57^2]^{1/2}$ = 3.24 METERS (1-SIGMA)

TOTAL POSITION ERROR AT 50 kM SEPARATION

POSITION ERROR = 2 HDOP. UERE = 2x1.3x3.24 = 8.3 METERS (2dmrs)



SEPARATION DISTANCE	0 KM	500 KM
Spatial Decorrelation Error	0	4.9 meters
Δ-IONO BIAS	0	2.8
TOTAL ERROR	0	5.65 meters

FIGURE 4-16. SPATIAL DECORRELATION WITH SEPARATION (IN METERS)

SEPARATION DISTANCE	0 KM	250 KM	500 KM
Receiver Noise	3.6 METERS	2.6 METERS	2.6 METERS
User Receiver Uncertainty	0.43	0.43	0.43
Clock Group Delay	0.9	0.9	0.9
Mechanization	1.0	1.0	1.0
Multipath	1.2	1.2	1.2
Temporal Error	.26	.26	.26
Spatial Error (0.0098xD)	-	2.45	4.9
Δ-IONO Bias	-	1.50	2.8
RANGE ERROR (UERE)	3.2 METERS	4.3 METERS	6.5 METERS
POSITION ERROR (2drms)	8.3 METERS	11.2 METERS	16.9 METERS

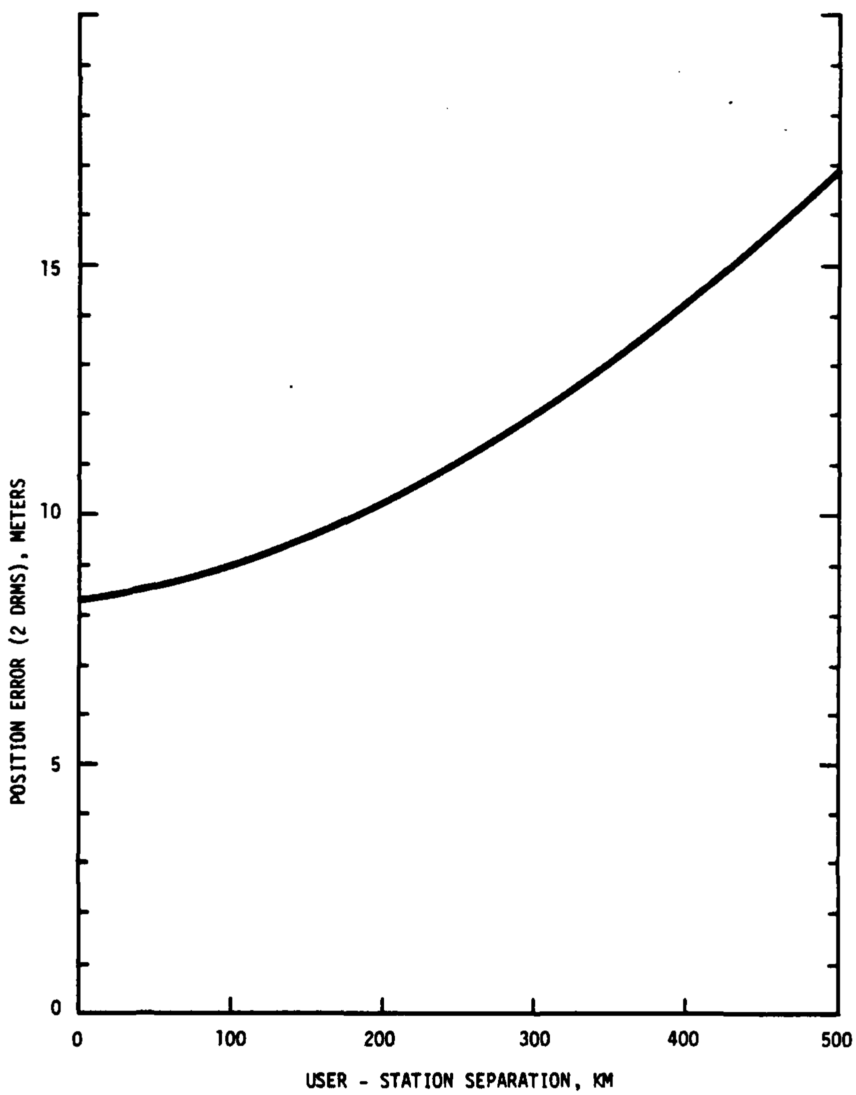


FIGURE 4-17. POSITION ERROR VARIATION WITH SEPARATION (IN METERS)

5. STATION COSTS

5.1 SUMMARY

A budgetary cost estimate summary is provided for an operational Differential GPS system located at the SANDY HOOK/AMBROSE site combination. The estimate includes the system development costs as shown in Table 5-1. The subsequent units will not have the development costs shown here.

TABLE 5-1. DIFFERENTIAL GPS INSTALLATION SITE
COST SUMMARY
(In 1983 Dollars)

	Sub Unit	Total
1. Initial Equipment Costs		
Development	$710K	
Operational Unit	$252K	$962K
2. Installation Costs		$ 20K
Total		$982K

Projected operating system costs are compared with a typical VHF-FM Shore-Based Direction Finding Triangulation System[15] in Table 5-2. This cost comparison is selected because of the similarity in the electronic equipment for implementing both systems.

TABLE 5-2. COST SUMMARY FOR
DIFFERENTIAL GPS AND VHF-FM (CHESAPEAKE BAY)
(In 1983 Dollars)

	Diff GPS	VHF-FM DF
Initial Acquisition and Installation Costs	$272K	$193K
Maintenance	$ 14K	$ 15K
Total	$286K	$208K

In deriving these estimates, the following breakdown was used:

A. Initial Equipment Costs

- o System Development
- o Operational Unit Costs
- o System Modification Costs

B. Installation Costs

- o Cost absorbed in original unit price
- o Contract

C. Annual Costs

- o Maintenance
- o Leasing

5.2. INITIAL EQUIPMENT COSTS

Development costs for the 8-channel, coherent, C/A code receiver hardware and software constitute the major expense item in the site installation. The estimate is based on the enhancement of the present design techniques, whereby two 4-channel receivers are combined to provide 8-channel information.

Itemized Differential GPS Receiver Development Costs are as follows:

Add RF/IF Amplifier	$ 20K
Add IF Power Splitter	20
Digital Receiver Mods	20
Differential Receiver Design and Software	350
Channel Management	100
Monitor Input	30
Communications Interface	20
Integration	50
Checkout	100
TOTAL	$710K

An estimate of operational unit costs is shown in Table 5-3.

System Modification includes designing and building an adapter for the differential message transfer from UHF to HF communications channels. Estimated cost for the adapter is $2K including installation and checkout.

TABLE 5-3. DIFFERENTIAL GPS SITE INSTALLATION COST BREAKDOWN IN 1982 DOLLARS

DIFFERENTIAL GPS SITE INSTALLATION AT SANDY HOOK	QTY	EQUIPMENT NEEDED FOR INSTALLATION (DOLLARS)
DIFFERENTIAL GPS RECEIVER	2	$200K
GPS ANTENNA AND CABLES	1	1
UHF COMMUNICATIONS LINK	1	15
NRB/1 MONITORING RECEIVER	2	4
NWA WIP ANTENNA	2	1
NARS8/9/10 MF TELEGRAPH REMOTE CONTROL	1	4
TOTAL		$225K
DATA LINK INSTALLATION AT AMBROSE		
ND500D TRANSMITTER -125W	1	$ 13K
MODIFICATION		3
PA35D ANTENNA	1	6
NX200TAU -ANTENNA TUNING UNIT	1	3
ACCESSORIES		1
UHF/LF ADAPTER		2
TOTAL		$ 28K

5.3 INSTALLATION COSTS

The cost of installation and checkout of the equipment at the sites is expected to be about $20K.

5.4 ANNUAL COSTS

Annual costs include equipment leasing and maintenance. The projected breakdown of the annual costs are:

o	Maintenance of Differential GPS Equipment	$ 10K
o	Maintenance of UHF Link	1
o	Telephone Leasing	4
	Total	$15K

6. TEST PLAN GUIDELINES

6.1 GENERAL

This section addresses the methods of verifying the performance of a differential system once it has been installed. There are three fundamental measures of performance that must be established by the provider of the service: coverage, accuracy, and reliability. The means by which these measures are established are determined by the features peculiar to the system and the anticipated use of the system. Here the primary anticipated use of the differential system is for navigation in harbor/harbor entrance areas and inland waterways. However, other uses may be developed such as buoy positioning, charting, and land and harbor surveying. The performance tests should anticipate these secondary applications if possible.

6.1.1 Coverage

Coverage is primarily determined by the limitations of the communications link. VHF communications involve line-of-sight propagation, which means that blockage by bridges, buildings, ships and other structures can cause attenuation or dropout of the signals. Radiobeacon signals diffract around such objects, but reflections from structures and the water can cause fading. Therefore the tests need to establish that sufficient link margin exists in the crucial areas such as narrow channels. They also need to establish the limits of coverage and identify areas where significant fading or blockage exists.

Coverage may also be reduced by blockage, whereby low-lying satellites are not visible to the user because of intervening bridges, buildings or other structures. The seriousness of this problem will vary throughout the day, depending on the number and position of the satellites. One way of handling this problem is to first identify areas in the zone of coverage where structures extend above 10 degrees elevation over significant sectors of the horizon. Then a stationary receiver with recorder can be placed there for a day or two and the data analyzed to identify periods during which insufficient satellites or large errors exists. A better technique may be to estimate the local horizons (i.e., minimum elevation angle vs. direction) and perform an analysis using the known positions of the satellites from their orbits. The latter method has the advantage that the analysis can be performed before the NAVSTAR GPS becomes operational.

6.1.2 Accuracy

Establishing system accuracy is a complex task. First of all, there is the matter of definition of accuracy: 2drms and Circular Error Probable (CEP) measures are the most popular for defining horizontal position errors. The 2drms measure describes a positional error at "at least" the 95% level. Studies at TSC indicate that for the NAVSTAR GPS eventual constellation it will be at about the 97% level, i.e., a 2drms error of 10 meters would imply that 97% of the position fixes would be within 10 meters. The CEP describes a positional error at the 50% level. For the NAVSTAR GPS the 2drms error is larger than the CEP error by a factor of 2.5.

There are also three different types of accuracy: absolute, repeatable, and relative. Absolute accuracy refers to the accuracy relative to a chart. Repeatable accuracy refers to the differences observed at a fixed point over a period of time. Relative accuracy refers to the differences observed by two nearby receivers at the same time. Except for the practical difficulties in defining a grid, NAVSTAR GPS repeatable and absolute accuracies are the same.

Accuracy measurements are also complicated by the fact that stationary receivers can smooth out noise errors over long periods of time and thus achieve much more precision and accuracy than receivers on board a moving vessel. As a consequence, the use of static receivers to establish the differential GPS performance level would be unduly optimistic, especially if the navigation filters were tuned on a premise of zero velocity. The fact that the accuracy of a position estimate is dependent on the parameters used in a navigation filter further complicates the attempts to define a "system" accuracy, since the accuracy becomes somewhat dependent on the receiver design and the choice of user receiver parameters employed for tests. Recording pseudorange data in addition to positional data will enable a post-processing analysis to compare a number of processor parameters.

It is anticipated that NAVSTAR GPS will not be affected by weather and seasonal variation to the same degree as LORAN-C. The frequency of GPS is such that it will propagate through the atmosphere without any effect on the signals. However, the received signals will be affected by reflections from the earth's surface (multipath, antenna nulls) and structures (blockage), including the superstructure of the vessel itself. There should be a few tests, which could involve stationary receivers, that are run for long periods of time to verify that seasonal and weather effects on the differential GPS are minimal.

6.1.3 Reliability

Reliability is difficult to measure or even to define until years of experience have been obtained with a system. The first differential stations will no doubt experience numerous and lengthy outages at first, until maintenance procedures have been defined and "infant mortality" problems have settled out.

As a consequence, only predicted system reliability values are available until experience has been gained with some differential equipment. Scheduled equipment maintenance should be included in the equipment specifications, along with a requirement for self-monitoring and self-calibration.

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