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

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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.

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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

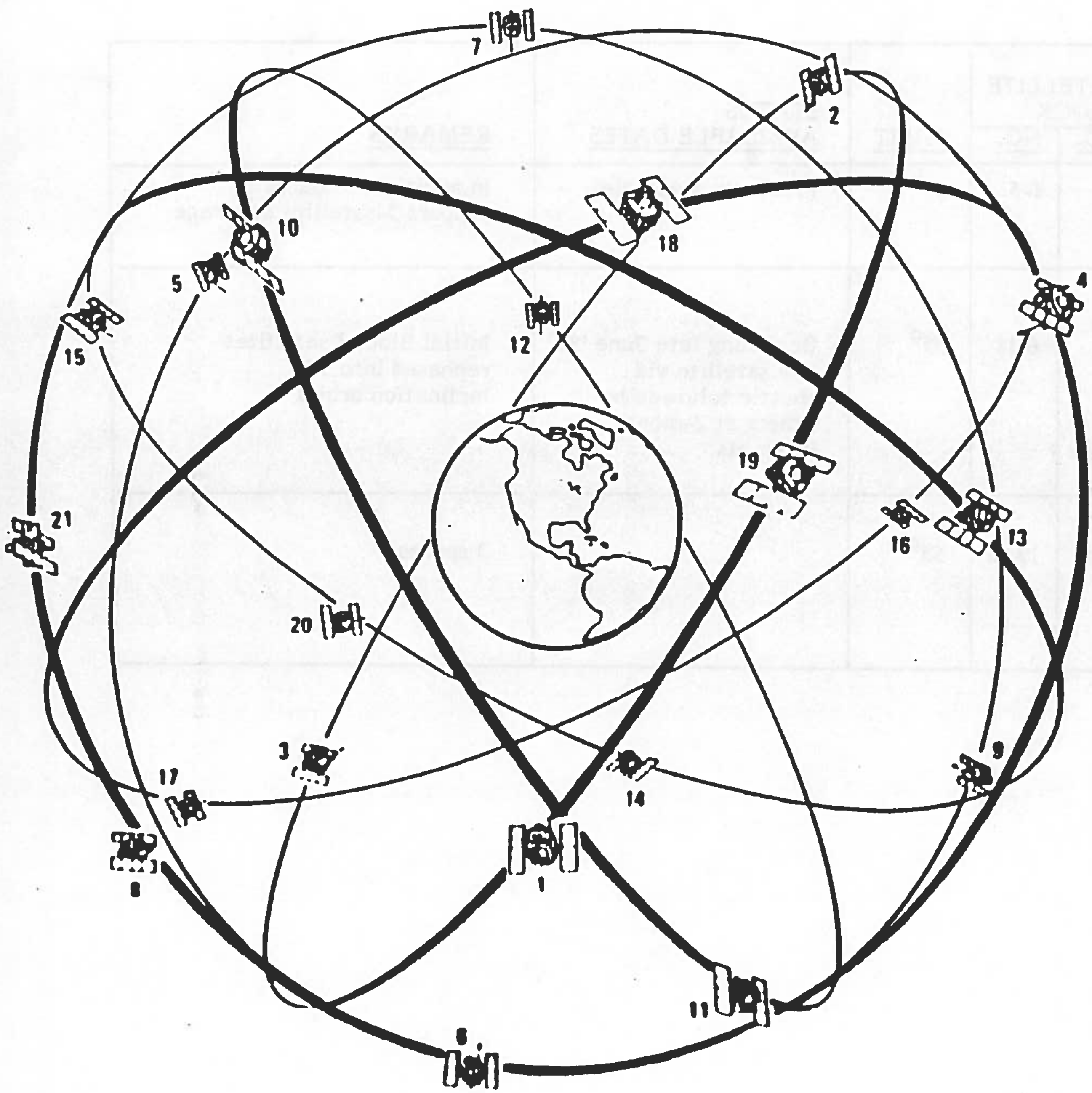


FIGURE 1-2. THE NAVSTAR OPERATIONAL CONSTELLATION
18 SATELLITES PLUS 3 ACTIVE SPARES

only in limited areas. Navigation tests performed using the Phase I NAVSTAR satellites presently in orbit have indicated C/A accuracies 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.

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 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

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.

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.

TABLE 3-1. DIFFERENTIAL GPS DATA

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

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_o (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.

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_o 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.

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.

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.

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:

- o Availability of a facility to transmit pseudorange error messages.
- o Location of the GPS equipment to achieve optimum service coverage.
- o Convenient access for installation and maintenance.
- o Location on current Coast Guard property.
- o Availability of prime power and equipment shelter.
- o Availability of Coast Guard staff either on or near site.
- o 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.

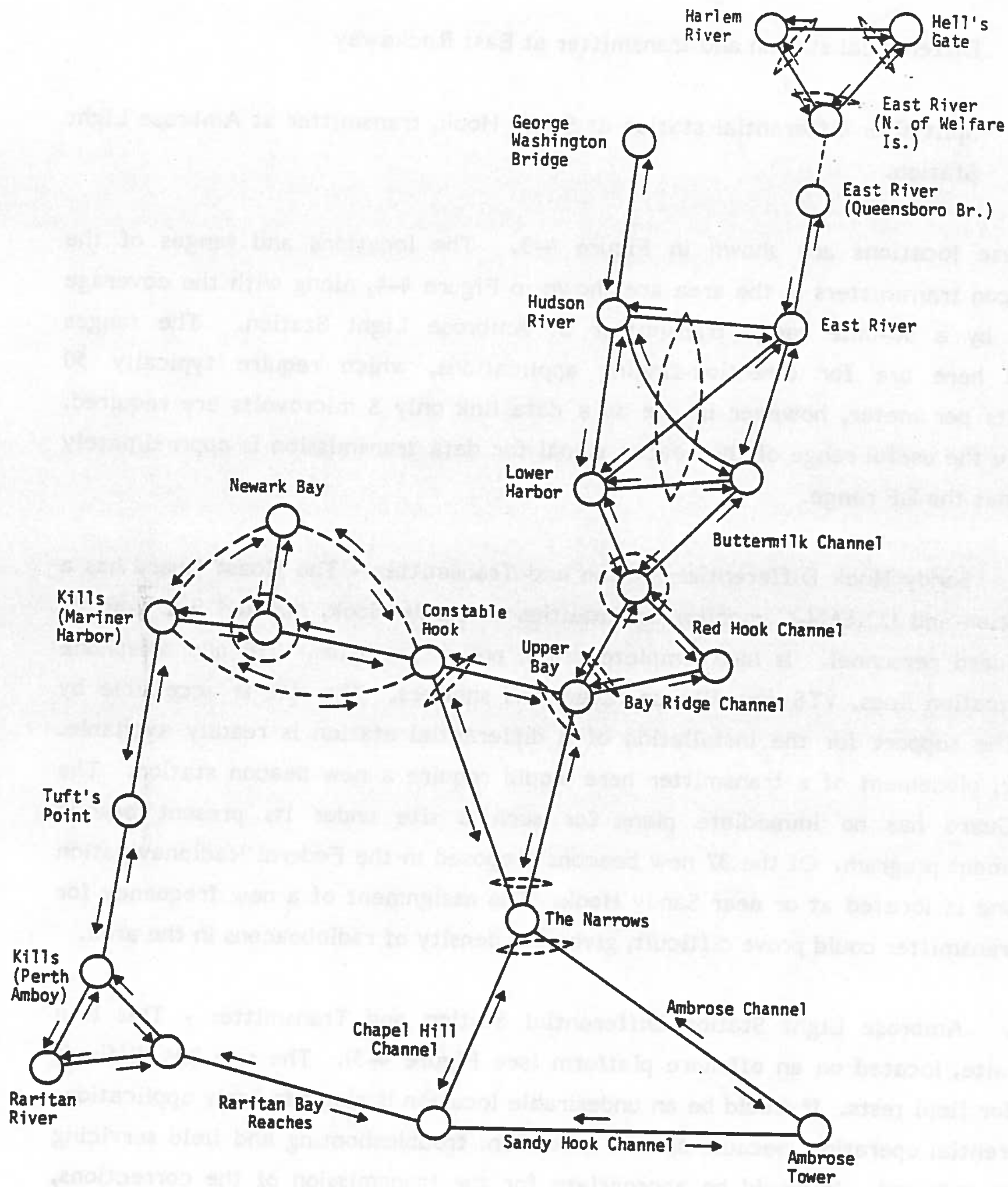


FIGURE 4-2. MAJOR TRAFFIC MOVEMENTS, NEW YORK HARBOR

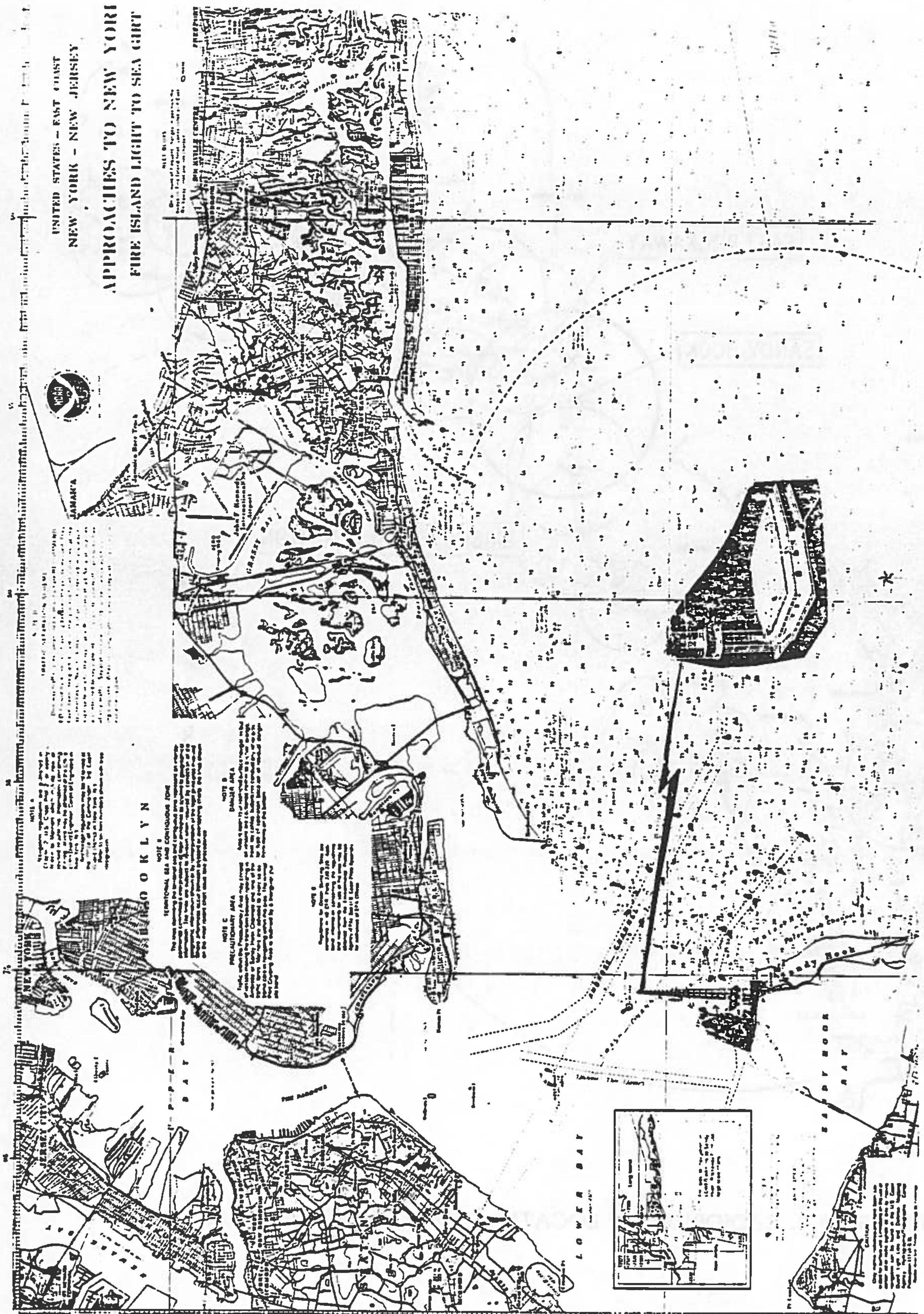


FIGURE 4-3. MAP OF THE APPROACHES TO NEW YORK

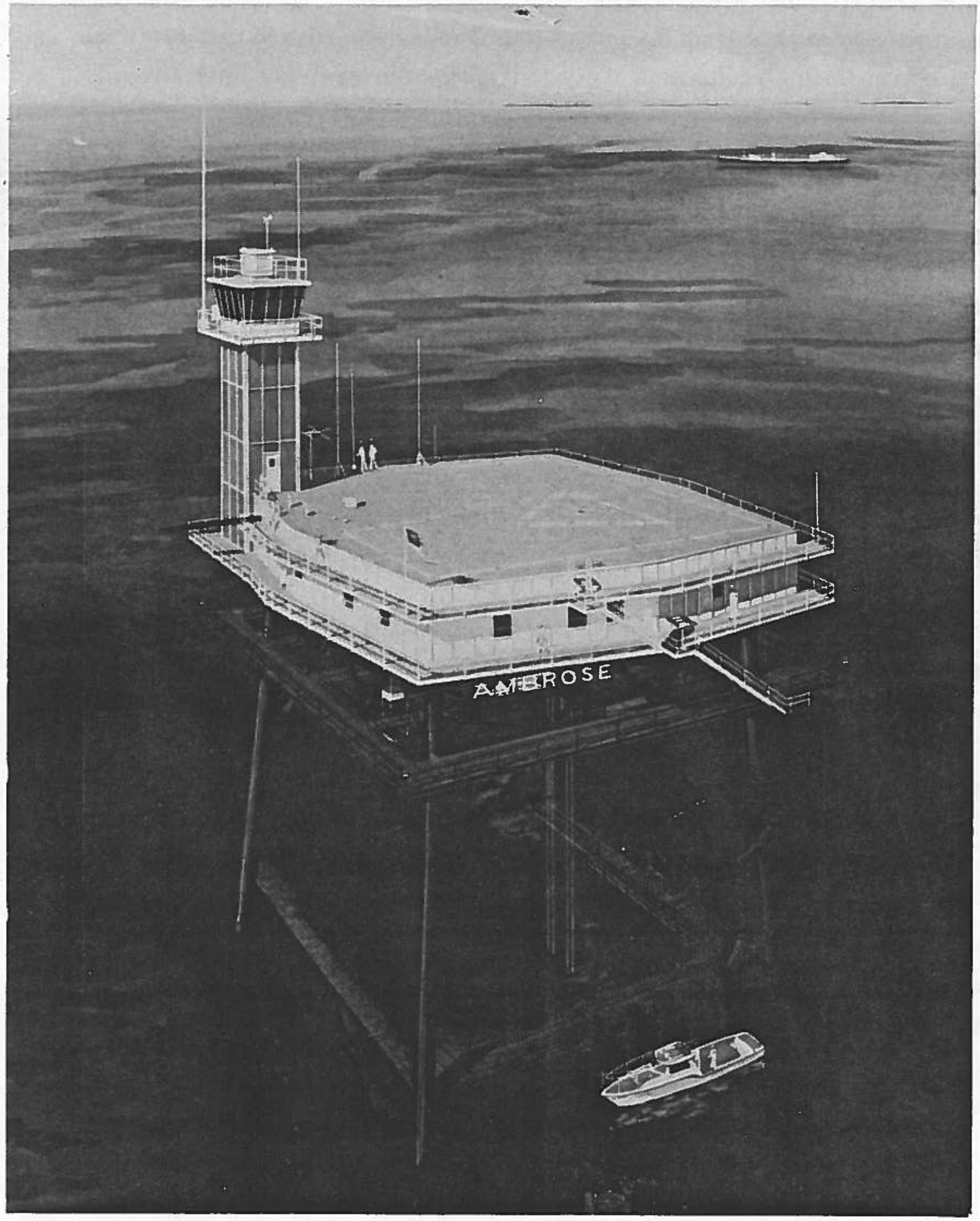


FIGURE 4-5. AMBROSE LIGHT STATION

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.

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.

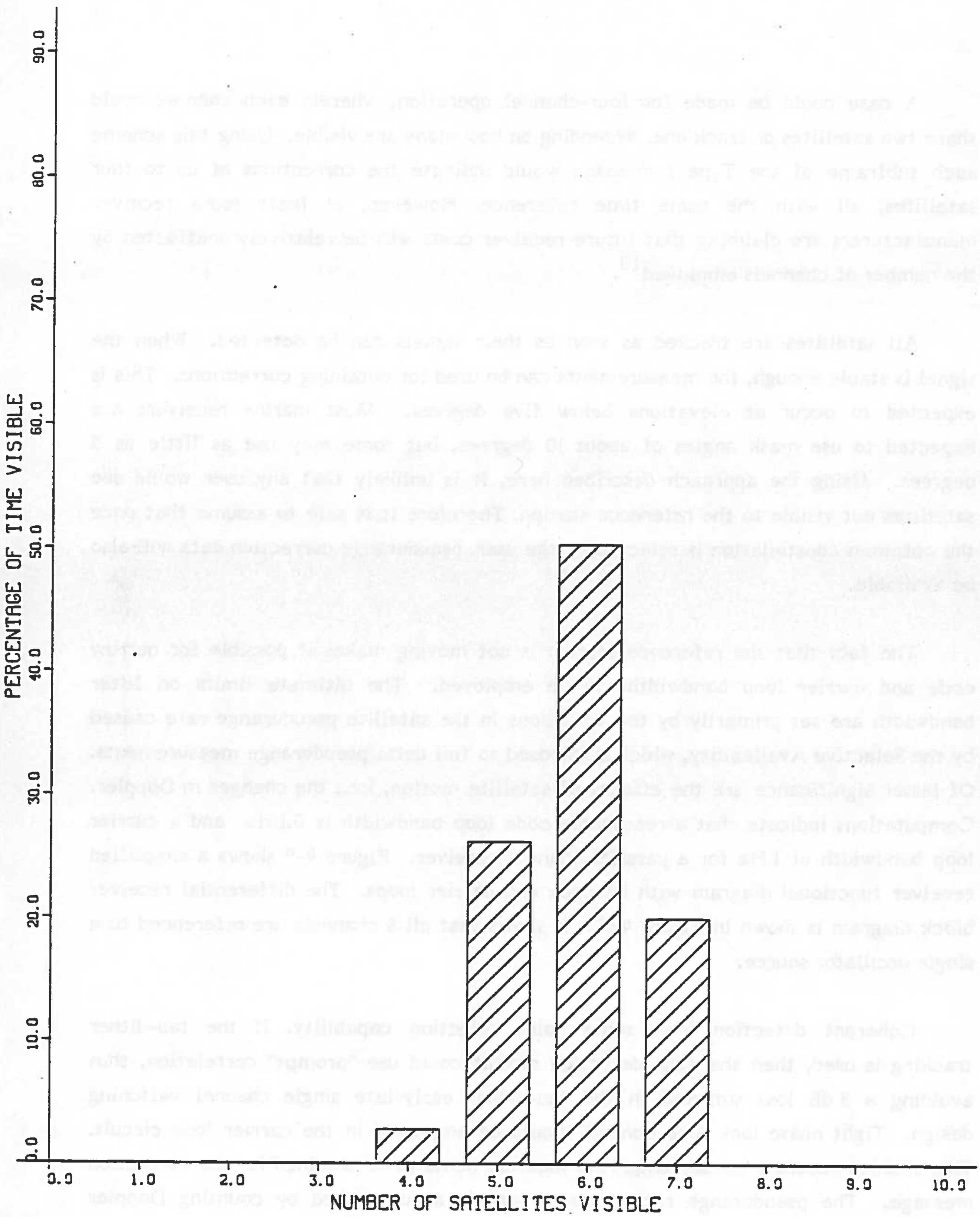


FIGURE 4-8. SATELLITE VISIBILITY HISTOGRAM, 10 DEGREE MASK ANGLE, SANDY HOOK
(Constellation of 18 Satellites Plus 3 Active Spares)

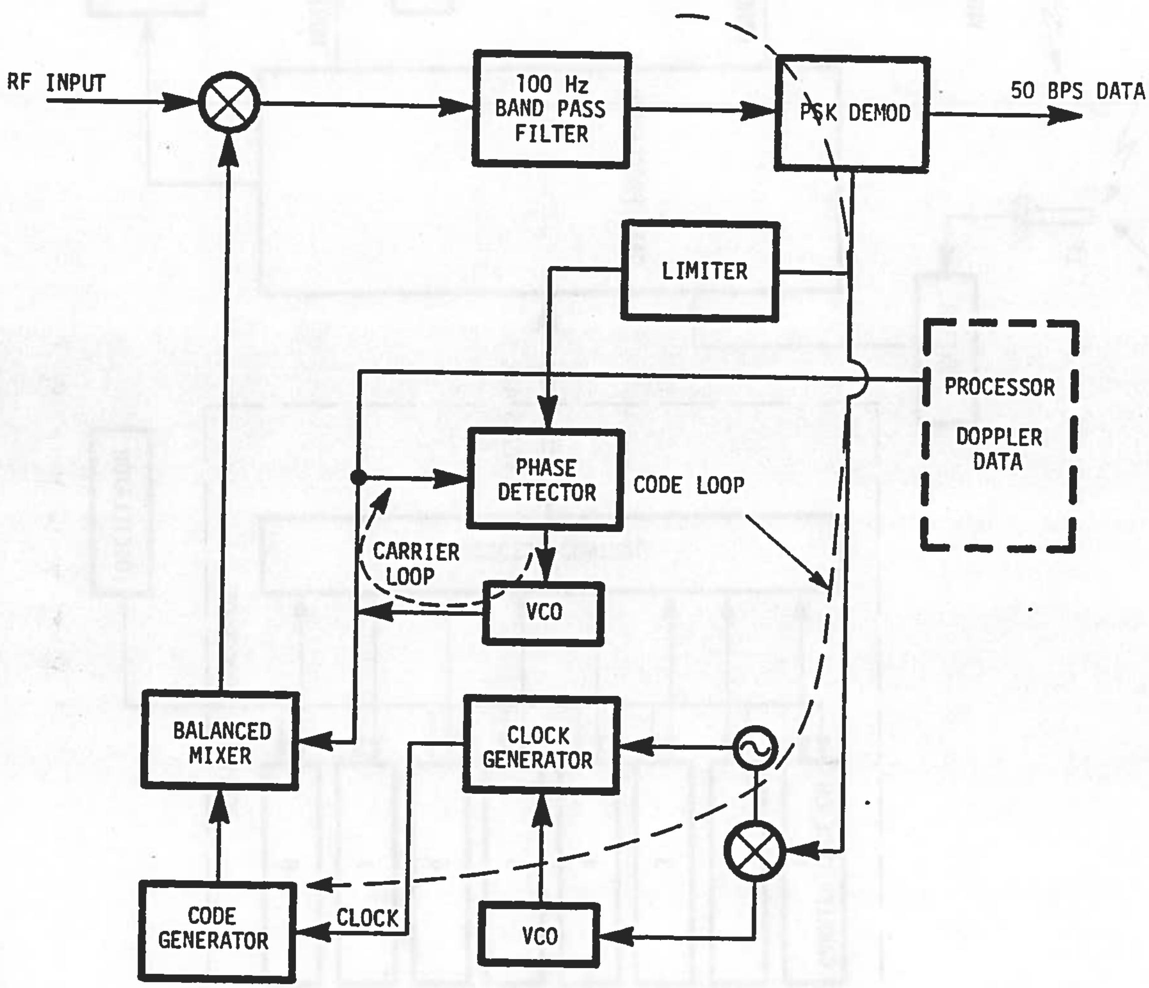


FIGURE 4-9. RECEIVER FUNCTIONAL BLOCK DIAGRAM

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.

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

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:

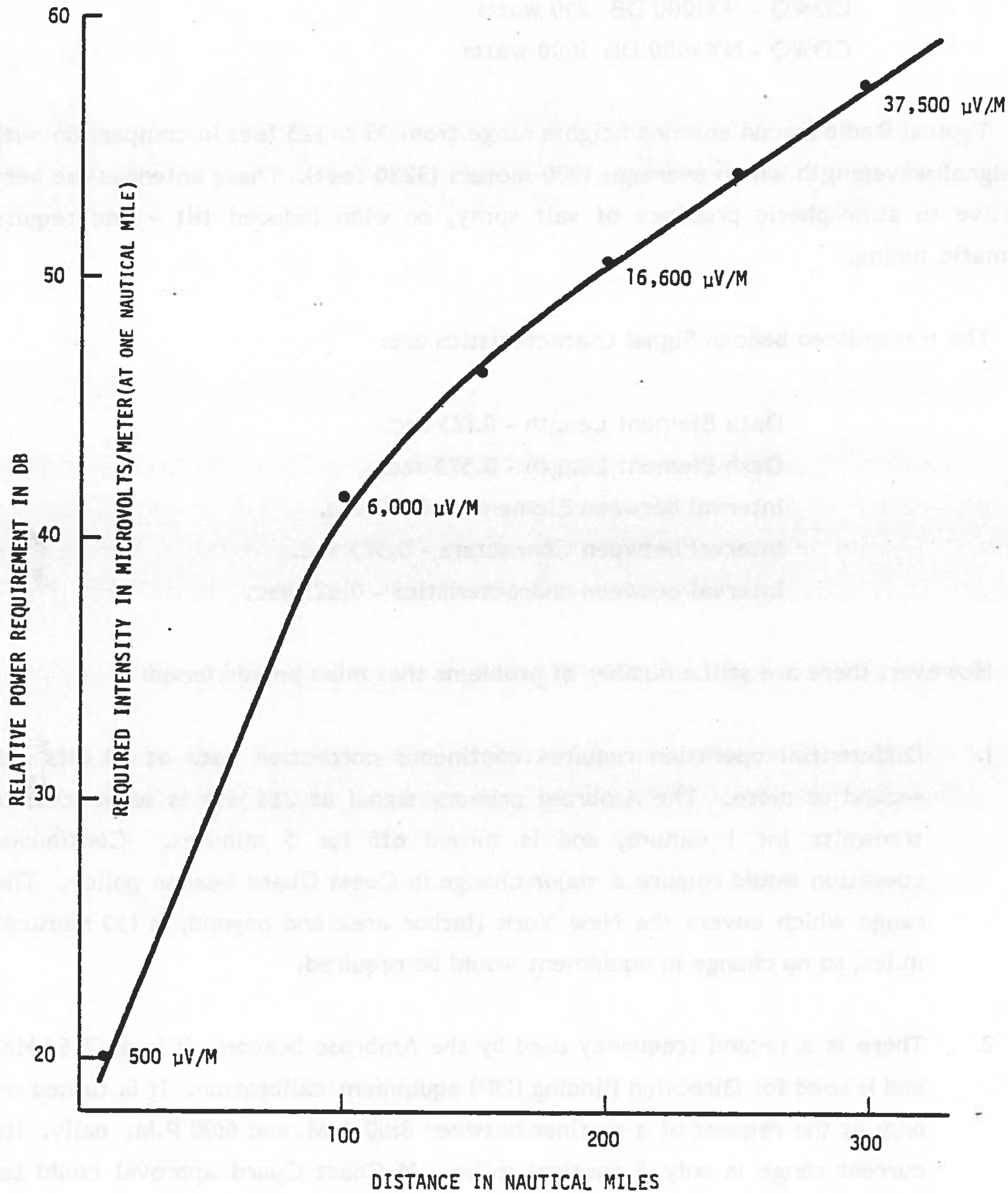


FIGURE 4-11. RELATIVE RADIOBEACON POWER REQUIREMENTS VS. PATH DISTANCE

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

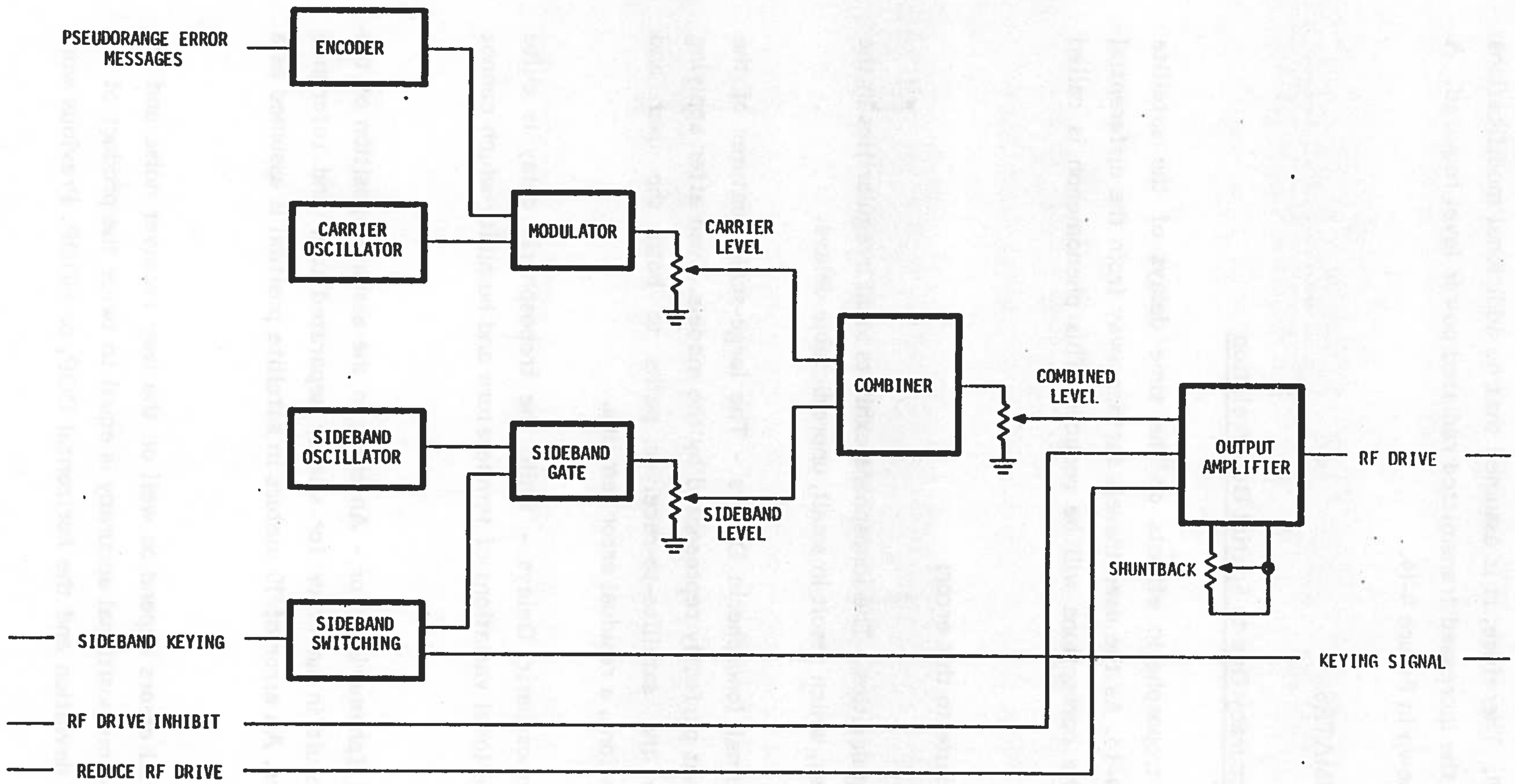
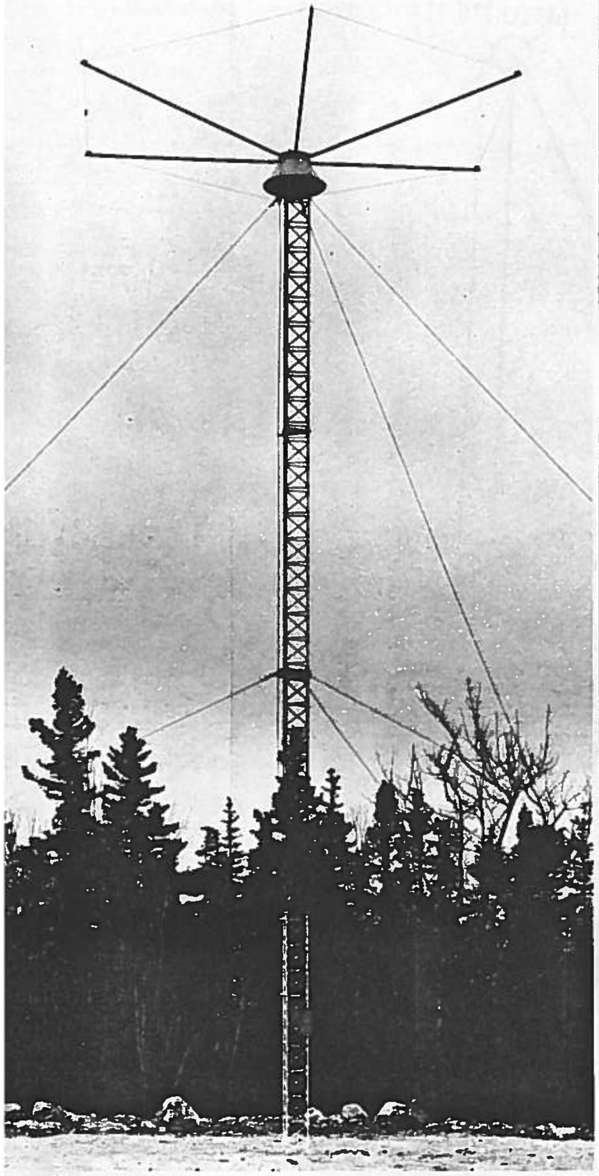
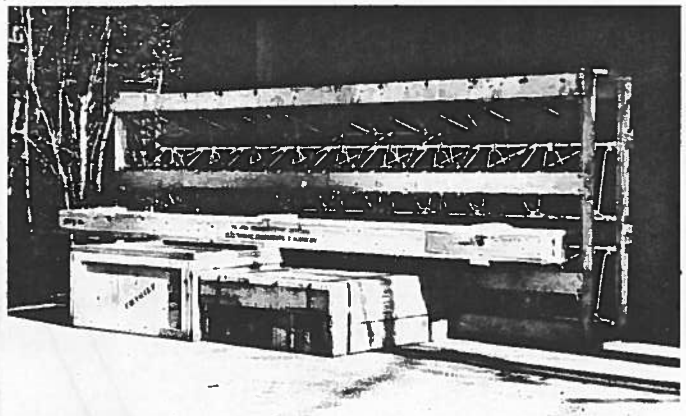
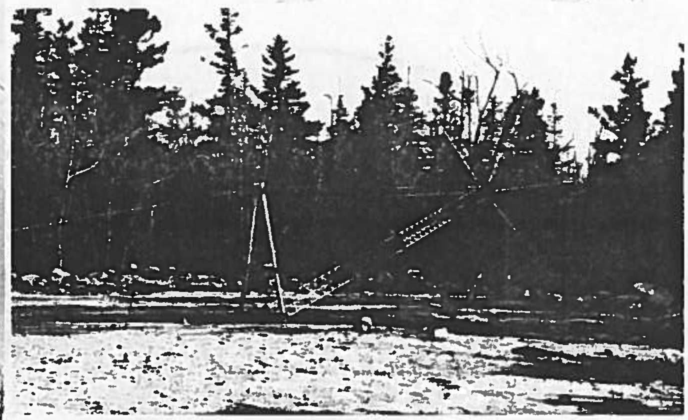
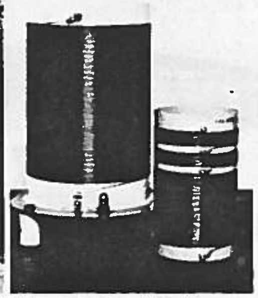


FIGURE 4-13. NON-DIRECTIONAL BEACON SCHEMATIC







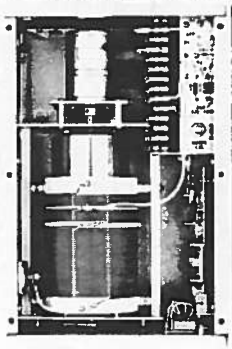


APPLICATION

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.



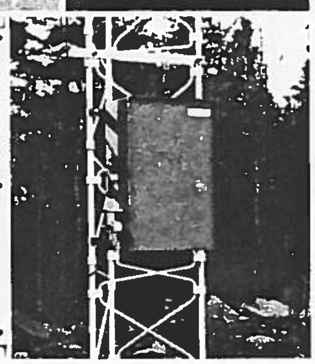


FIGURE 4-14. POLESTAR ANTENNA SYSTEMS

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 4-2. 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

$\Delta = 293.2$ METERS (C/A CODE)

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

$\sigma = .58$ METERS (1-SIGMA)

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.

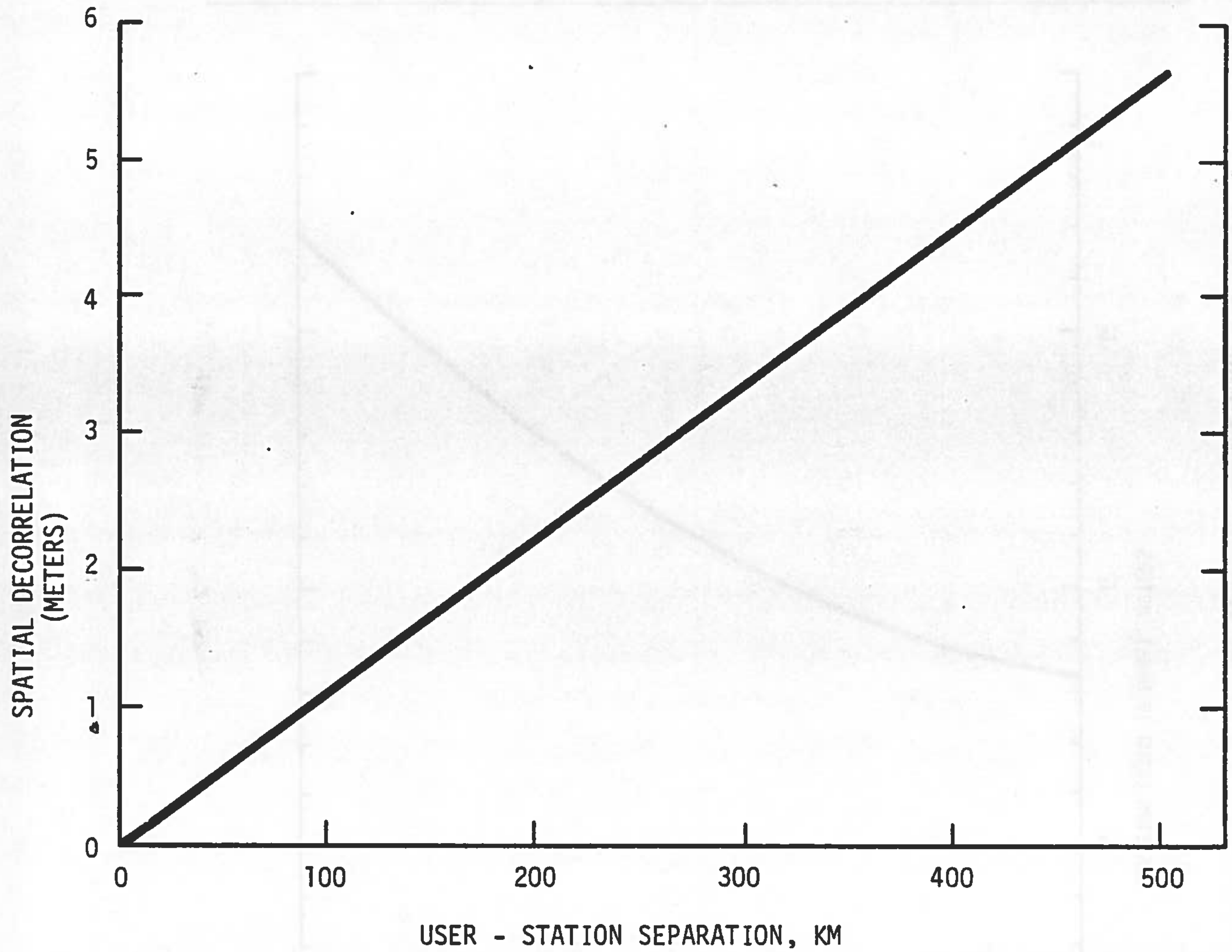
4.5.3 The 2 drms Position Error Estimate with Spatial Decorrelation

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]



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)

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

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

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

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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