ABSTRACT

Background information is given explaining the need to broadcast differential Global Positioning System (DGPS) corrections to mariners. Results from a DGPS experiment carried out by the United States Coast Guard (USCG) over the last 3 years are then discussed. In this experiment, differential corrections were modulated onto the signal from an existing maritime radio beacon. The experiment proved that DGPS could provide the additional accuracy required for harbor and harbor approach navigation. As a result of this experiment the USCG is now implementing a program to provide DGPS coverage to U.S. harbors and harbor approaches. The majority of this paper deals with how this program will be implemented and the improvements to GPS accuracy and integrity that it will provide to mariners.

INTRODUCTION

The United States Department of Defense (DOD) is deploying a worldwide radionavigation system based on satellite technology. The system is known as the Global Positioning System (GPS). DOD plans to declare the system operational in 1993. Until declared operational for use by the general public, there is no guarantee that GPS signals will be continuously available.

GPS provides two positioning services - in other words, there are two levels of accuracy provided by the system. First is the Precise Positioning Service (PPS); it will provide U.S. and allied military, and authorized civil users an accuracy of 16 meters spherical error probable (SEP). The second, the Standard Positioning Service (SPS), will be available to all users at an accuracy of 100 meters 2 drms (95% confidence) or better. For national security reasons, the accuracy of GPS can be controlled by DOD using the system capabilities of Selective Availability (SA) and Anti-spoofing (AS). Selective Availability is the mechanism used by DOD to degrade the SPS accuracy by introducing errors in the satellite clock and navigation message. Anti-spoofing is the process whereby the GPS P-code is converted to a secret "Y-code". Therefore, users would need cryptographic equipment and "keys" to access the P-code on the navigation signals of GPS. This equipment will not generally be available to the civil user. DOD policy states that in time of national emergency under the direction of the National Command Authority, SPS could be degraded to levels beyond 100 meters.

The Federal Radionavigation Plan (FRP) requires an accuracy of 8-20 meters 2 drms, with a 99.7% availability, for harbor and harbor approach (HHA) navigation. The FRP defines integrity as the ability of a system to provide timely warnings to users when the system is not usable. For harbor and harbor approach (HHA) navigation, the FRP requires an accuracy of 10 meters 2 drms with 95% confidence (95% confidence). The second, the Standard Positioning Service (SPS), will be available to all users at an accuracy of 100 meters 2 drms, (95% confidence) or better. For national security reasons, the accuracy of GPS can be controlled by DOD using the system capabilities of Selective Availability (SA) and Anti-spoofing (AS). Selective Availability is the mechanism used by DOD to degrade the SPS accuracy by introducing errors in the satellite clock and navigation message. Anti-spoofing is the process whereby the GPS P-code is converted to a secret "Y-code". Therefore, users would need cryptographic equipment and "keys" to access the P-code on the navigation signals of GPS. This equipment will not generally be available to the civil user. DOD policy states that in time of national emergency under the direction of the National Command Authority, SPS could be degraded to levels beyond 100 meters.

To obtain better accuracy and integrity from GPS a number of research efforts have been undertaken to improve the civil capability of the system. Many of these efforts focus on the broadcast of real-time local corrections and are collectively grouped under the concept of Differential GPS (DGPS). The research indicates that DGPS will provide the integrity and performance characteristics that are not available from GPS.

The United States Coast Guard (USCG) Research & Development Center has been conducting DGPS research since 1985. The feasibility of providing DGPS for marine navigation with an absolute accuracy of 10 Meters 2 drms was demonstrated in 1987. In 1988 the Montauk Point, NY radio beacon was temporarily converted to provide a DGPS test broadcast. Given the success of these 1989 tests, and the desire to more thoroughly evaluate DGPS in operational environments, a prototype DGPS service was established on August 15, 1990.

The success of the DGPS research and prototype service has since led the Coast Guard to begin implementing a DGPS navigation service. The Coast Guard's DGPS implementation goal is not to circumvent the national security aspects of GPS but to improve the accuracy and integrity of GPS for the Coast Guard, other government agencies, and civil users. The DGPS implementation project will fulfill the Federal Radionav-
igitation Plan (FRP) requirement for 8-20 meter navigational accuracy in HHA areas. The objective of this project is to design, procure and install a system of DGPS Reference Stations, Broadcast Sites, Monitor Sites and Control Stations. The Broadcast Sites will be marine radiobeacon transmitters and should utilize existing sites. New Broadcast Sites may be established to cover gaps to meet the operational requirements. [3] The implementation plans call for providing a DGPS navigation service by 1996.

DGPS RESEARCH HISTORY

In the early 1980's, the Department of Transportation (DOT) began studying the potential civil use of GPS. DOT quickly realized that many potential applications would require higher levels of accuracy and integrity than SPS would be able to provide. The Volpe National Transportation Systems Center (VTSC) and the U. S. Coast Guard R&D Center continued to study the problem. VTSC obtained recorded GPS broadcast data from DOD, with Selective Availability (SA) included, to be compared with the proposed civil signal. The Coast Guard in its traditional role as provider of radionavigation systems for the mariner began investigating the possibility of improving the GPS signal to meet the FRP requirements and to meet other CG mission needs for high accuracy position determination. Since the Coast Guard has conducted research and tested differential techniques on other radionavigation and positioning systems like Loran C and Omega, differential GPS was a natural progression of technology application.

Along with DGPS research, the Coast Guard R&D Center conducted a study in 1988 to validate the Federal Radionavigation Plan requirement for 8-20 meter, 2 drms accuracy for harbor and harbor approach navigation for vessels over 30,000 dead weight tons. [4] The R&D Center study concluded that the 8-20 meter requirement was appropriate for large vessels in restricted waterways. The study also concluded that radio aids to navigation with this level of accuracy would enhance traditional visual and radar navigation if implemented and used properly and would also enhance navigation under restricted visual conditions down to 0.25 nautical miles (nm). The study finally noted that "additional understanding needs to be gained, particularly on the proper design and utilization of RA devices for negotiating turns under 0.0 nm visibility conditions, before concluding that an RA system with 8-20 meter (2 drms) accuracy can be used safely as an all weather navigation system." Research is continuing in this area. One possible solution is to use DGPS as the position sensor for more sophisticated navigation displays. The Coast Guard is evaluating this concept in conjunction with Electronic Chart Display Information Systems (ECDIS) research.

The International Association of Lighthouse Authorities (IALA) and the International Maritime Organization (IMO) have also kept track of GPS trends and potential. They recognize the potential improvement to navigation safety offered by using a world wide navigation system. IALA and IMO also recognize the need for better integrity and accuracy than GPS/SPS can provide. These international organizations have endorsed DGPS and the use of Medium Frequency (MF) marine radiobeacons as the correction broadcast medium.

USCG DGPS TECHNOLOGY OVERVIEW

Differential Concept

Conceptually, DGPS is fairly simple. A reference is established at a known geodetic location. The GPS position is computed and compared to the known geodetic position. "Differential corrections" are computed based on knowledge of the geodetic position and transmitted to users over a separate communications link. The corrections can be either "position differential" or "pseudorange differential". For position differential, the correction is an offset vector transmitted to the user in XYZ coordinates. The major problem with this approach is that the corrections are extremely sensitive to which satellites are used to determine the position solution. If the user is not using exactly the same set of satellites, the position solution could end up being worse than uncorrected GPS.

Pseudorange differential involves computing corrections to the range to each satellite. The reference station computes the correct range based on broadcast ephemeris data and knowledge of the precise geodetic location, and rate of change of the range to each satellite in view. The correction and correction rate-of-change information is broadcast to the user. Since the satellite range is determined within the user's receiver, these corrections allow the user's equipment to correct satellite data for a better position solution. The correction rate allows the user to project solutions until the next set of corrections is received from the DGPS service.

Knowing the reference location also allows the service provider to detect when the satellites are sending erroneous data. When the reference station detects satellite data that is so erroneous that the satellite should not be used, a message can be transmitted to the user. This additional information gives a better indication of system integrity thus improving confidence in the system.

Why Radiobeacons For The Broadcast?

Any radio frequency transmission medium which can be modulated to achieve a 50 bit-per-second data transfer rate is suitable to broadcast differential corrections. The bit rate for DGPS corrections is driven by the characteristics of Selective Availability (SA). A minimum 50 bit-per-second rate is needed to attain reliable accuracy (better than 10 meters) using the Radio Technical Commission for Maritime Services (RTCM) Special Committee (SC) 104 Version 2 data format. [5,6]

The task of communicating differential GPS (DGPS) corrections to a large number of users in all harbor and harbor approach areas of the United States and Puerto Rico poses several problems. Format standardization, frequency allocation and complexity of user equipment are technical issues which must be considered along with cost-effectiveness, ease of implementation, and time constraints. In view of these considerations, several alternatives for broadcasting differential corrections were considered. The technical, economic, and time constraints of various alternatives, including Loran, satellite, VHF/UHF, HF, and LF/MF (radiobeacons) were considered. At the conclusion of the analysis, radiobeacons were selected. Some of the advantage-
es of radiobeacons are outlined here:

- The radiobeacon broadcast range and the DGPS accuracy range are compatible.
- Radiobeacon broadcast equipment is reliable, commercially available, and relatively inexpensive.
- International radio regulations provide for the broadcast of differential correction information on radiobeacons. No further regulatory changes are necessary.
- IALA has stated that "maritime radiobeacons are the most suitable means of transmitting corrections in a coastal area."
- Commercial receiver manufacturers are developing DGPS user equipment with an internal radiobeacon MSK receiver.
- Coast Guard owned and operated radiobeacons already exist and will be operational for the foreseeable future.

**USCG DGPS System Components**

The Coast Guard is developing DGPS using pseudorange corrections broadcast over the existing network of marine radiobeacons. The corrections will be broadcast using the RTCM SC104 Version 2 data format. The SC104 format is very similar to the GPS navigation message and uses the GPS parity algorithm. The most significant difference is that SC104 uses variable length messages instead of a fixed length message. The Coast Guard approach is flexible and robust providing signals that will be usable by marine, land and air users. The approach also supports 3D solutions and can be modified to satisfy other users' requirements as they are identified.

The Coast Guard DGPS system consists of several components as shown in Figure 1. These components are listed below with a brief description of the function performed.

- Satellite - Provides GPS navigation signal and message. DGPS cannot exist without the GPS signal.
- Reference Station - Measures errors contained in received GPS signals and generates corrections. Consists of an all-in-view GPS receiver and a microcomputer for processing the information. Performs first level integrity check. Colocation with the broadcast transmitter is not required.
- Transmitter - Real time differential corrections are put in the RTCM SC104 format and broadcast by Minimum Shift Key (MSK) modulation of the radiobeacon signal. Data formatting may also be done in the reference station.
- Broadcast standard - A document describing the broadcast signal structure and data format. Essential for developing and using the user equipment.
- User equipment - A GPS receiver capable of using differential corrections provided from the MSK receiver.

This type of architecture can be called a hybrid autonomous design. Reference stations do not necessarily need to be co-located with broadcast sites as in the purely autonomous design, but they are one-to-one correspondences between broadcast sites and reference stations. All components will have redundant backup capability. This architecture uses proven, state-of-the-art technology, is highly flexible, and will readily support expansion and improvements. It is also easily adapted to wide-area DGPS (WADGPS), when this technology matures. DGPS Reference Station equipment is rapidly becoming so inexpensive that it may be cost-effective to house them at all broadcast sites. This way, landline communications outages will not affect availability of service. This proposed architecture is highly

![Figure 1 - USCG DGPS System Components](image-url)
robust, and should be capable of supporting geodetic and aviation requirements as well as maritime requirements. In order to ensure that we can reliably meet HHA radionavigation requirements, the following initial "design criteria" have been proposed:

- HDOP of > 2.3 is considered a service outage.
- User equipment (UE) shall contribute a limited amount (to be defined) to the horizontal position error
- The range of applicability for DGPS corrections is 300 nm from the reference station.
- The usable range of an MSK beacon is equal to the advertised range for homing purposes.

Table 1 provides an estimate of the availability, maturity and cost of the required DGPS system elements. The table also includes some "optional" system elements. These elements are required for an HHA radionavigation service. The majority of the elements are already available. Those elements that are not 100% mature are undergoing design changes and are evolving to the maturity required for implementation.

### Table 1 - Status of System Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Required/ Optional</th>
<th>Availability/ Source</th>
<th>Level of Maturity/ Date Available</th>
<th>Typical Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAVSTAR SAT BOST</td>
<td>Required</td>
<td>Available/ DOD</td>
<td>60% / present</td>
<td></td>
</tr>
<tr>
<td>ECLECTIC MONUMENT</td>
<td>Required</td>
<td>Available/ NOAA</td>
<td>100% / present</td>
<td>5K</td>
</tr>
<tr>
<td>DGPS REFERENCE STA</td>
<td>Required</td>
<td>Available/ Comm1</td>
<td>80% / present</td>
<td>18 - 40K</td>
</tr>
<tr>
<td>COMMUNICATIONS WITH BROADCAST SITE</td>
<td>Optional</td>
<td>Available/ Comm1</td>
<td>95% / present</td>
<td>Telephone Line</td>
</tr>
<tr>
<td>DGPS BROADCAST FACILITY</td>
<td>Required</td>
<td>Available/ USCG</td>
<td>90% / present</td>
<td>5 - 10K</td>
</tr>
<tr>
<td>DGPS SERVICE STANDARD</td>
<td>Required</td>
<td>In Development/ USCG</td>
<td>70% / 12/91</td>
<td></td>
</tr>
<tr>
<td>BROADCAST MONITOR</td>
<td>Optional</td>
<td>In Development/ USCG</td>
<td>40% / 12/92</td>
<td></td>
</tr>
<tr>
<td>USK BROADCAST RECEIVER</td>
<td>Required</td>
<td>Available/ Comm1</td>
<td>90% / present</td>
<td>5 - 6K</td>
</tr>
<tr>
<td>DGPS RECEIVER</td>
<td>Required</td>
<td>Available/ Comm1</td>
<td>90% / present</td>
<td>4 - 18K</td>
</tr>
</tbody>
</table>

The controlled testing and evaluation has been extremely beneficial in evaluating DGPS equipment, signals and service. Operational testing was so successful that the prototype service is still operating in support of CG operational units. DGPS is now being used during day-to-day operations to position floating aids to navigation in southern New England.

The real proof of the operational effectiveness of DGPS for Aids to Navigation (ATON) work came in the wake of Hurricane Bob in August, 1991. Waterways were closed in New England because of the extensive damage to the Coast Guard's floating aids system. The DGPS service was also disrupted due to power outages and lost communications between the reference station in Groton, CT and the broadcast site in Montauk Point, NY. The reference station was moved to Montauk Point and placed back in service. User equipment was delivered to additional USCG operational units. DGPS was used...
The radiobeacon at Montauk Point was being reconfigured and used for ADF testing throughout the month of June.

The waterway was reopened in just over 4 days. Using traditional methods for checking and repositioning aids the job would have taken over a month.

**DGPS NETWORK EXPANSION**

The R&D prototype at Montauk Point provided excellent local information. Engineering prototypes are required and planned to provide further data on the adequacy of the service in other environments. The engineering prototypes will be used to gain insight into the environmental effects expected throughout the entire coverage area. The following is a list of planned engineering prototypes and the benefits to be derived from each installation:

- September, 1991, Whitefish Point, MI; ATON positioning and propagation data over fresh water with high atmospheric noise.
- October 1991, Aransas Pass, TX; NOAA charting activities and propagation in the Gulf of Mexico, higher conductivity and higher atmospheric noise.
- Early 1992, Galveston, TX; same as Aransas
- First half of 1992, Three stations will be added to provide experimental DGPS coverage from Northern Maine to Cape Hatteras; data communications network testing.

**OPERATIONAL REQUIREMENTS**

The primary goal of the Coast Guard DGPS Navigation System is to fulfill the FRP requirements for HHA navigation. DGPS provides the technology to meet this requirement. This capability is expected to enhance maritime safety in keeping with the National Transportation Policy by providing a precise, all-weather radio-navigation service to supplement existing radar and visual navigation techniques. It will also provide a highly accurate position sensor for future electronic chart displays. The DGPS implementation project will also establish an infrastructure for follow-on operations and maintenance for the DGPS system over its 25 year life cycle.

The requirements of other Coast Guard Operations Programs and other government agencies will be met as secondary goals. Table 3 gives some examples of the other requirements that can be met by meeting the HHA requirements. The proposed coverage of the system is shown in Figure 2.

**DGPS STANDARDS**

**Broadcast**

A draft DGPS MF/MSK broadcast standards document is being prepared by the U. S. Coast Guard for circulation among industry experts during the first half of 1992. This document will describe the MF/MSK signal-in-space, including all details concerning the interface between the service provider and the user. Manufacturers should be able to obtain all the information they require concerning reception of the broadcast. Industry comments will be used to refine the document.

**Receiver**

There is also a need for DGPS receiver standards. The Coast Guard recognizes this need and will work closely with industry and the standards organizations. It is important to formalize and possibly expand the existing recommendations in RTCM SC 104. The Coast Guard has adopted these recommendations and will continue to work on required improvements and international acceptance. Minimum receiver performance standards will also be developed.
Field testing at experimental engineering prototype stations, along with contractor design support, is expected to provide the information necessary to develop procurement specifications for the DGPS system components. Procurement of system components will begin in 1993, with field installations targeted to start in the summer of 1994, ultimately ending by the end of 1995. The complete DGPS system is expected to be working by January 1996. Figure 3 shows the projected implementation time line for the Coast Guard DGPS service.

DGPS policy has not yet been prescribed by the Secretaries of Defense and Transportation. However, DGPS policy is expected to be consistent with that of other existing Federally-provided radionavigation systems.

DGPS is planned to be available in the clear (unencrypted), free of charge, to all users capable of receiving the signals. As stated earlier, it is important to note that the service is not intended to circumvent the U.S. policy for Selective Availability. On the contrary, the U.S. Coast Guard works closely, on a daily basis, with its counterparts in the Department of Defense in draft-
CONTINUING R&D EFFORTS

The Advanced GPS Project at the R&D Center will continue efforts in laying the groundwork for a DGPS service and in improving the service capability. Work in the following areas is currently planned:

DGPS Reference Station: Use the USCG developed reference station to test new reference station concepts, spatially separated reference station networks, and as a baseline for comparison of commercial reference stations. Over the past year there have been significant improvements in the accuracy of commercial reference stations. Although they provide state-of-the-art accuracy, commercial reference station receivers continue to lack operational control and maintenance features desired for a true navigation service.

DGPS Broadcast Facility: A two-card radiobeacon MSK “modulator” circuit board set designed to plug into the “Standard” (STD) computer bus has been built. The frequency generated can be any multiple of 100 Hz in the 285-325 kHz radiobeacon band. The boards and software were developed by the R&D Center staff. This prototype design hardware will be improved to increase reliability.

Broadcast Monitor: The Coast Guard has begun work on an automatic broadcast monitoring system. This development will continue into 1992.

MSK Radiobeacon Broadcast Receivers: Three contracts for developing MSK receivers are in different stages of progress. One contract has resulted in a prototype receiver using digital signal processing technology that performs better than the older MSK receivers being used on the project.

DGPS User Equipment: Ashtech L-XII and M-XII, Magnavox 4200D and Trimble 4000DL DGPS receivers are being tested and used in field evaluations. Coast Guard would like to expand testing to other commercial equipment as it becomes available. To date, none of the tested receivers has fully implemented the RTCM SC-104 Version 2.0 recommendations.

SUMMARY

Based on tests and regular operation of the prototype DGPS broadcast service from Montauk Point, New York, from August 1990 through August 1991, we have found:

- GPS does not provide the accuracy and integrity required for HHA radionavigation.
- Marine radiobeacons are an acceptable method for the Coast Guard to provide a public DGPS broadcast service.
- DGPS should be considered for any immediate Coast Guard radio positioning applications. The performance of the prototype service is comparable to the various precise radio positioning systems now in use by the U.S. Coast Guard. The cost of DGPS will be far less than existing precise systems. The expanded range of operation (200 miles) is a tremendous advantage over existing systems.

- DGPS is much easier to install, maintain, operate and is more reliable than any microwave positioning system ever used by the R&D Center.
- USC DGPS reference stations should be located in the NAD-83 coordinate system.

These test results and the high level of public interest in obtaining a high accuracy navigation system have prompted the Coast Guard to aggressively pursue implementation of a nationwide DGPS service. There is still a lot of work to be done to implement the service and continued research is required to improve the service. The USCG will continue to investigate and develop methods and technologies that increase the accuracy range covered by a single DGPS reference station while maintaining the required level of accuracy, allow the combination of measurements by several DGPS reference stations to develop wide area corrections, and provide broadcast coverage over a wider area than is possible using a single radiobeacon. As the accuracy range of the corrections increases, a broadcast method with extended range may be desirable. However, at the present time there is a good correlation between the range of the high power radiobeacon broadcast and the accuracy range of the DGPS correction. Radiobeacons are very cost-effective and their use will allow the USCG to deploy a working DGPS service by 1996 with an accepted technology.

REFERENCES


