USCG DIFFERENTIAL GPS NAVIGATION SERVICE

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ABSTRACT

The United States Coast Guard provides a Differential Global Positioning System (DGPS) service for the Harbor and Harbor Approach (HHA) phase of marine navigation. DGPS technology is the first to economically offer geodetic accuracy meeting the Federal planning requirement of sub10 meters for harbor and harbor approach navigation. The DGPS service coverage area includes the coastal United States, Great Lakes, Puerto Rico, and most of Alaska and Hawaii. This DGPS service is available to the public navigator as an all-weather navigation sensor to supplement traditional visual, radar, and depth sounding techniques.

The design process for the United States Coast Guard's DGPS service began with efforts to define system operational requirements. The goal of these requirements was to ensure the same level of user integrity provided by present Coast Guard electronic navigation aids (Loran-C and Omega). Refinement of operational requirements by risk analysis of specific harbor navigation scenarios was then conducted. The final system architecture evolved to meet the defined requirements under traditional restraints of current technology, present and future economics, and the flexibility to adapt to future requirements.

The operational doctrine to define DGPS service parameters and the service management infrastructure has been developed. The DGPS operations phase has begun. This paper provides a brief history on the evolution of DGPS and describes the operation of the DGPS service including technical information and broadcast site specifications.

BACKGROUND

The U.S. Coast Guard is mandated by Federal law (14 USC 81) to implement, maintain, and operate electronic navigation aids that meet maritime needs of the U.S. armed forces and/or U.S. commerce. The U.S. Coast Guard's expertise in enhancing maritime safety through the utilization of radio (electronic) navigation services dates to 1921 with the first operational radiobeacons. In the last two decades, the U.S. Department of Defense (DOD) has led technology from terrestrial to space-based radionavigation systems, first with TRANSIT, and then the prototype NAVSTAR Global Positioning System (GPS).

In 1987, the U.S. Coast Guard Research and Development Center in Groton, Connecticut, began conducting research and testing of differential techniques to enhance GPS accuracy. Simply stated, the differential technique involves installing navigation equipment at a precisely known location. The equipment receives the GPS signal and compares the position solution from the received signal to its known location. The result of this comparison is then generated in the form of a correction message and sent to local users via radiobeacon broadcast. The received correction is applied by the user's GPS equipment to reduce the system position error, thereby improving the user's absolute accuracy. This effort was coordinated through the Special Committee (SC) 104 created by the Radio Technical Commission for Maritime Services (RTCM).

The differential effort was driven by the search for a system with the capability to meet the accuracy requirement for Harbor/Harbor Approach navigation as had been defined in the Federal Radionavigation Plan (FRP). The FRP identifies that accuracy on the order of less than 10 meters (2drms)[1] is required for the HHA phase of navigation [FRP 94]. The FRP also states requirements for the Coastal and Ocean phases for maritime navigation which have respectively been satisfied with Loran-C and Omega services.

In 1989, the U.S. Coast Guard modified the existing marine radiobeacon located at Montauk Point, New York to broadcast differential corrections in the RTCM SC-104 format. The Montauk Point field tests demonstrated that Minimum Shift Keying (MSK)[2] modulation of an existing radiobeacon signal was effective in transmission of RTCM SC-104 format corrections. The MSK modulation technique could be utilized with no adverse effect on the automatic direction finding receivers of traditional marine radiobeacon users. Important to both the U.S. Coast Guard and the public,

[1] 2drms means twice the distance of the root mean square error. In practice, any position fix obtained using the given system has a 95% probability of having a radial error equal to or less than the 2drms value expressed.

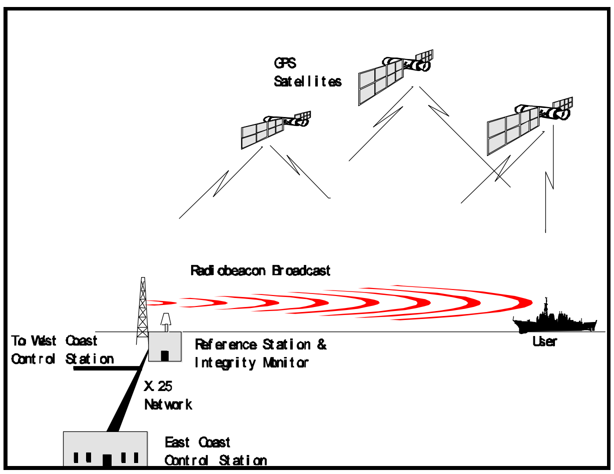
[2] Minimum Shift Keying is a special form of frequency modulation. MSK involves utilizing the smallest possible frequency shift of the carrier frequency to relay digital information. A shift up in frequency from the carrier relays a digital “1" and down a “0". The actual shift in frequency is 1/4th the data transmission rate.

MSK technology is economical to implement at existing radiobeacons and within user receivers. By January 1990, the RTCM published the SC-104 format version 2.0 document. With a formal U.S. industry differential GPS correction standard and the initial radiobeacon broadcast success, Montauk Point began the first continuous public U.S. DGPS broadcast on August 15, 1990. This transmission marks the beginning of the U.S. Coast Guard transition from DGPS research and development towards implementation of a U.S. maritime differential GPS service.

DGPS ARCHITECTURE

The DGPS service architecture is shown in figure 1. The functional elements of the U.S. Coast Guard DGPS Navigation Service include:

Figure 1



- Reference Station - Precisely located GPS receiving equipment which calculates satellite range corrections based on a comparison of the satellite navigation message to its known location.

- Integrity Monitor - Precisely located GPS receiver and MSK radiobeacon receiver which applies differential corrections. The corrected position is compared to its known location to determine if the correction broadcast from the Reference Station is in tolerance.

- Broadcast Site - A marine radiobeacon transmitting correction data in the 285 to 325 kHz band.

- Control Station - Site for human centralized control of the DGPS service elements. DGPS performance data processing and archiving is accomplished here. The East Coast Control Station is located at the USCG Navigation Center in Alexandria, Virginia. The West Coast Control Station is located at the Navigation Center Detachment in Petaluma, California. Both sites are manned 24 hours per day.

- Communication Network - An X.25 packet-switched service providing connectivity between broadcast sites and control stations.

- DGPS User Equipment - Consists of two interfaced receivers with a display; a radiobeacon receiver for MSK demodulation and a GPS receiver capable of applying differential corrections.

TECHNICAL CHARACTERISTICS

GPS correction data based on NAD-83 coordinates is provided for both real-time and post processing applications. Real-time correction data is broadcast to the user via radiobeacon only for satellites at an elevation angle of 7.5 degrees or higher through use of the type 9-3 message in the RTCM SC-104 format. The official GPS coverage provided is based on elevation angles of ten degrees or higher. Satellites at elevation angles lower than 7.5 degrees are adversely affected by spatial decorrelation, multipath, and minimal processing time between acquisition and actual use. Corrections for a maximum of nine satellites will be broadcast. If more than nine satellites are above 7.5 degree elevation angle, a situation which occurs less than one percent of the time, then corrections are broadcast for the nine satellites with the highest elevation angles [USCG Broadcast Standard].

The latency of this information is determined by the baud rate at which it is transmitted. There are 210 bits in a type 9-3 message (three satellites corrected) including the message header. Therefore, at 100 baud the latency is 2.1 seconds. Naturally, this time is cut in half when transmitting at 200 baud. In reality, latencies on the order of 2-5 seconds are realized depending on the number of satellites in use. Other factors contributing to latency include partial decoding techniques, parity checking, and the receiver's internal processing.

GPS satellite data consisting of CA code, P1 and P2 Range, and L1 and L2 Carrier Phase information is collected every 30 seconds by the National Geodetic Survey (NGS) from both Reference Stations at each broadcast site. NGS processes the data and makes it available to the public for post processing applications. A benefit to this arrangement is that NGS provides monument stability for each DGPS site by continually checking and updating geodetically surveyed antenna positions and reporting their findings to the Coast Guard. The output interval of 30 seconds for this data is set by the Control Station watchstander. Because the X.25 network is used for control, monitoring, and remote data access, limits must be set on the amount of data, not the type of data, shared. Otherwise, remote user access could interfere with and delay control station alarms. Only authorized users are allowed access to the DGPS X.25 network.

Each DGPS broadcast site houses dual Ashtech Z-12/R Reference Stations to provide redundancy. Geodetic GPS antennas are used with built in low noise amplifiers to provide the necessary RF signal gain (35 dB) for the receiver to work properly with an antenna cable up to 30 meters long [Ashtech].

Each DGPS broadcast site houses dual Trimble 4000IM MSK Integrity Monitors to provide redundancy. The Integrity Monitor MSK antenna is a near field passive loop antenna. The GPS antenna includes an omni-directional L1 GPS receiving antenna [Trimble].

SYSTEM PERFORMANCE [Broadcast Standard]

-Accuracy- The position accuracy of the USCG DGPS Service is within 10 meters (2drms) in all specified coverage areas. A reasonable approximation for determining the achievable accuracy at a given point is to take the typical error at a short baseline from the reference station (approximately 0.5 meters), add an additional meter of error for each 150 kilometers of separation from the reference station broadcast site, and add an additional 1.5 meters for the user equipment. Some high-end user sets are achieving pseudorange measurement accuracies of less than 30 centimeters in the absence or the abatement of multipath. Hence, the user with high-end equipment who is within 300 kilometers from a given broadcast can achieve accuracy better than 3 meters (2drms).

The continuous velocity accuracy of the system (i.e. the vessel's speed over ground) is better than 0.1 knots rms in VTS areas which utilize Dependent Surveillance.[3]

-Availability- This is defined as the percentage of time in a one month period during which a DGPS Broadcast site transmits healthy pseudorange corrections at its specified output level. The DGPS Navigation Service was designed for, and is operated to, maintain a broadcast availability level which exceeds 99.7%, assuming a complete and healthy satellite constellation is in place (i.e. HDOP<2.3). Any DGPS area of coverage that falls within a Vessel Traffic Service region which utilizes 'dependent surveillance' for vessel tracking will maintain a signal availability in the coverage area of 99.9%. A signal availability will be higher than a broadcast availability if a coverage area receives more than one broadcast.

-Integrity- System integrity is built upon the foundation of the monitor stations. The Integrity Monitors will ensure the correction broadcast and signal strengths are in tolerance. Users are alarmed within 10 seconds if an out-of-tolerance condition exists. The user equipment suite plays a significant role in assuring that the integrity of the system is preserved. It should be capable of automatically selecting the appropriate radiobeacon. A satisfactory broadcast is one which is classified as healthy, is presently monitored, and the pseudorange time out limit of 30 seconds for at least four satellites has not been reached. The user need not be within the advertised range of the broadcast for it to be satisfactory.

-Reliability- This is the probability that the service, if useable at the beginning of a mission segment (maneuver), will remain available over the course of the maneuver. Reliability is the frequency with which failures occur and is measured in the number of outages per million hours of operation as shown in Table 1.

MANEUVER CATEGORY	RELIABILITY (Outages/Mhr)
<140 sec	2000
140 to 280 sec	1000
280 to 560 sec	500

Table 1

-Coverage- The USCG DGPS Navigation Service is designed to provide coverage at the specified levels for all "Harbor and Harbor Approach Areas" and other "Critical Waterways" for which the U.S. Coast Guard provides aids to navigation. Due to the omni-directional nature of the broadcasts, and that a high power radiobeacon may cover more than one harbor, coverage often extends into additional areas. As a result, complete coverage of the coast line of the continental United States is provided out to 50 nautical miles. Coverage is also provided for the Great Lakes, most of Hawaii, Alaska, and Puerto Rico.

SITE MAP

Of the 51 sites shown transmitting corrections (Figure 2), all but four (Millers Ferry, Sallisaw, Rock Island, and Alma) are presently controlled and monitored by the Control Station. Site specific information is provided in Table 2.

[3] Dependent Surveillance is any technology which depends on active participation between the mariner and the Vessel Traffic Service to control the flow of traffic.

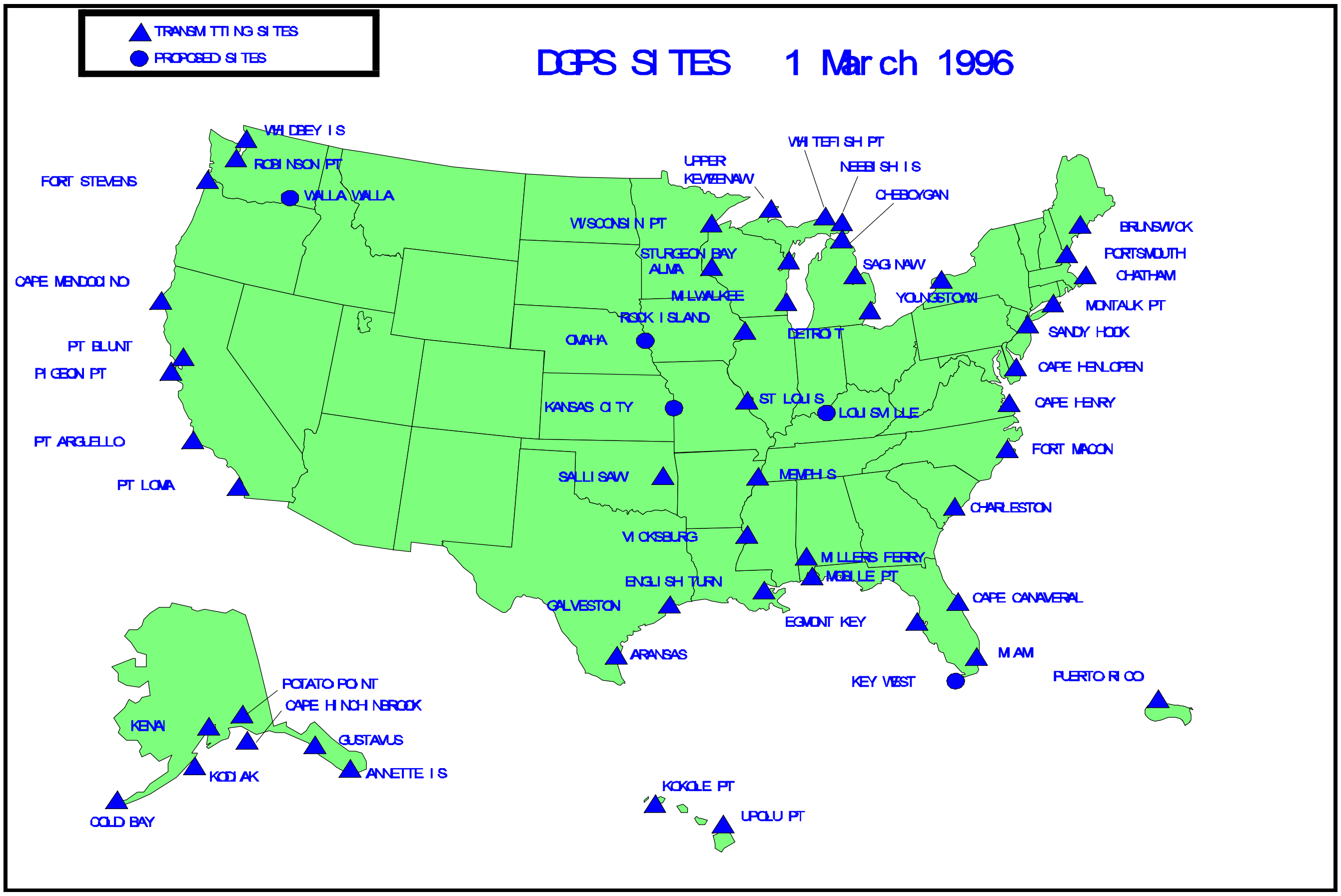


Figure 2

PRESENT STATUS AND FUTURE PLANS

On November 1, 1995, the Coast Guard DGPS system began operation under a 'Preoperational phase'. This phase was used to operationally test and evaluate system performance. As a result, much was learned and many improvements to the DGPS service will be made over the next few years.

On January 30, 1996, DGPS entered a 'Initial Operational Capability' (IOC) phase in which the service is available for positioning and navigation. During IOC, enhancements to Control Station software and hardware will be accomplished, radiobeacon antennas will be upgraded to meet mission goals, transmitters will be replaced with new state-of-the-art equipment which operate with battery backup, and the DGPS service will undergo validation. All the while, coverage will be provided throughout North America with high time availability. Upon completion of IOC, the DGPS service will be declared 'Full Operational Capability' (FOC) meeting all availability, accuracy, integrity, and reliability performance requirements.

Discussions are ongoing with other Federal agencies for additional sites west of the Mississippi to provide coverage for navigable portions of the Missouri and Arkansas Rivers. The Walla Walla site is established in support of the Federal Railroad Administration's "Positive Train Control" study. Present needs and plans do not call for utilization of signals from GLONASS or a geostationary system such as WAAS.

SUMMARY

The primary mission of the DGPS service is to provide sub-10 meter accuracy for the harbor/harbor approach phase of marine navigation. This is the most important issue we face as DGPS service providers. However, other users have found innovative ways to utilize DGPS services and where feasible, the Coast Guard DGPS network has expanded to meet their needs. NOAA is locating GPS receiving equipment at some of our Broadcast sites to predict GPS signal delays caused by the neutral atmosphere. The Coast Guard encourages sharing its resources with other agencies, academia, and the scientific community as the overall cost is reduced and everyone benefits from the valuable lessons learned

The U.S. Coast Guard will continue to fully cooperate on international fronts with the International Association of Lighthouse Authority (IALA) and the International Maritime Organization (IMO) to achieve global DGPS commonality. Nationally, the U.S. Coast Guard is consulting with other agencies to adapt the DGPS service to meet their needs. Agencies active in DGPS include the National Geodetic Survey (NGS) for inland surveying, the National Oceanic and Atmospheric Administration (NOAA) and the National Fish and Wildlife Association for hydrographic surveying, the Army Corps of Engineers (ACE) for dredging and coastal construction, the Department of Interior for natural resource mapping, the Federal Highway and Federal Railroad Administrations to name just a few.

REFERENCES

Federal Radionavigation Plan 1994, U.S. Department of Defense, DOD-4650.5 and U.S. Department of Transportation, DOT-VNTSC-RSPA-95-1, National Technical Information Service, Springfield, VA, May 1995.

Broadcast Standard For The USCG DGPS Navigation Service, COMDTINST M16577.1, April 1993, Commandant (G-OPN), U.S. Coast Guard Headquarters, Washington, DC.

Ashtech Z-12-R Differential GPS Reference Station Technical Reference Manual, 2nd Draft, 1 November 1994.

Trimble Technical Reference Manual CDRL #A008, Final Version October 24, 1995.

Table 2

United States Coast Guard DGPS Site Information 01 Feb 1996
Atlantic and Gulf Coasts

Broadcast Site	Frequency (kHz)	Trans Rate (BPS)	Latitude (N)	Longitude (W)	Range (NM)	Radiobeacon ID
NAS Brunswick, ME	316	100	43 53.70	69 56.28	115	800
Portsmouth Harbor, NH	288	100	43 04.26	70 42.59	100	801
Chatham, MA	325	200	41 40.27	69 57.00	95	802
Montauk Point, NY	293	100	41 04.03	71 51.63	130	803
Sandy Hook, NJ	286	200	40 28.29	74 00.71	100	804
Cape Henlopen, DE	298	200	38 46.61	75 05.26	180	805
Cape Henry, VA	289	100	36 55.58	76 00.45	130	806
Fort Macon, NC	294	100	34 41.84	76 40.99	130	807
Charleston, SC	298	100	32 45.45	79 50.57	150	808
Cape Canaveral, FL	289	100	28 27.60	80 32.60	200	809
Miami, FL	322	100	25 43.97	80 09.61	75	810
Key West, FL	286	100	TBD	TBD	110	811
Egmont Key, FL	312	200	27 36.03	82 45.65	210	812
Puerto Rico	295	100	18 27.77	67 04.01	125	817
Mobile Point, AL	300	100	30 13.65	88 01.45	170	813
English Turn, LA	293	200	29 52.74	89 56.50	170	814
Galveston, TX	296	100	29 19.79	94 44.21	180	815
Aransas Pass, TX	304	100	27 50.30	97 03.53	180	816

Great Lakes Region

Broadcast Site	Frequency (kHz)	Trans Rate (BPS)	Latitude (N)	Longitude (W)	Range (SM*)	Radiobeacon ID
Wisconsin Point, WI	296	100	46 42.60	92 01.40	40	830
Upper Keweenaw, WI	298	100	47 13.70	88 37.50	130	831
Sturgeon Bay, WI	322	100	44 47.70	87 18.80	110	832
Milwaukee, WI	297	100	43 01.60	87 53.31	140	833
Whitefish Point, MI	318	100	46 46.28	84 57.48	80	834
Neebish Island, MI	309	200	46 19.28	84 09.04	60	835
Cheboygan, MI	292	200	45 39.21	84 27.94	110	836
Saginaw Bay, MI	301	100	43 37.72	83 50.27	85	837
Detroit, MI	319	200	42 17.84	83 05.72	100	838
Youngstown, NY	322	100	43 13.87	78 58.20	150	839

Table 2 (cont.)

Inland River Region

Broadcast Site	Frequency (kHz)	Trans Rate (BPS)	Latitude (N)	Longitude (W)	Range (SM*)	Radiobeacon ID
Vicksburg, MS	313	200	32 19.88	90 55.19	115	860
Memphis, TN	310	200	35 27.94	90 12.34	115	861
St Louis, MO	322	200	38 36.67	89 45.50	115	862
Rock Island, IA	311	200	42 00.50	90 14.00	150	863
Alma, MN	317	200	44 18.25	91 54.23	150	864
Millers Ferry, AL	320	200	32 05.40	87 23.73	150	865
Sallisaw, OK	299	200	35 22.00	94 49.00	100	866
Kansas City, MO	305	200	39 07.07	95 24.88	100	867
Louisville, KY	TBD					

* Great Lakes and Western Rivers DGPS sites indicate radiobeacon ranges in statute miles, all others are in nautical miles.

West Coast Region

Broadcast Site	Frequency (kHz)	Trans Rate (BPS)	Latitude (N)	Longitude (W)	Range NM	Radiobeacon ID
Cold Bay, AK	289	100	55 11.41	162 31.90	180	898
Kodiak, AK	313	100	57 37.13	152 11.35	180	897
Kenai, AK	310	100	60 40.10	151 21.00	170	896
Potato Point, AK	298	100	61 03.00	146 42.00	100	895
Cape Hinchinbrook, AK	292	100	60 14.30	146 38.80	120	894
Gustavus, AK	288	100	58 25.50	135 41.80	170	892
Annette Island, AK	323	100	55 04.33	131 36.50	170	889
Whidbey Island, WA	302	100	48 18.76	122 41.77	90	888
Robinson Point, WA	323	200	47 23.25	122 22.49	60	887
Walla Walla, WA	TBD					
Fort Stevens, OR	287	100	46 12.29	123 57.36	180	886
Cape Mendocino, CA	292	100	40 26.40	124 24.40	180	885
Point Blunt, CA	310	200	37 51.18	122 25.14	60	884
Pigeon Point, CA	287	100	37 11.22	122 23.40	180	883
Point Arguello, CA	321	100	34 34.70	120 38.60	180	882
Point Loma, CA	302	100	32 39.92	117 14.58	180	881
Kokole Point, HI	300	200	21 59.00	159 45.50	300	880
Upolu Point, HI	285	100	20 14.80	155 53.20	170	879