Differential Global Positioning System Navigation Using High-Frequency Ground Wave Transmissions

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Since 1992, the Strategic Systems Department of the Applied Physics Laboratory has been investigating the use of high-frequency (HF) ground wave transmissions in the upper HF band for sea-based communications. This effort has examined the optimization of shipboard antennas for two-way communications with ground stations. This article describes early tests using differential Global Positioning System navigation for investigating the accuracy of determining a ship's position from a base station using HF ground wave transmissions.

(Keywords: Differential GPS, HF signal transmissions, Kalman filtering, Navigation.)

INTRODUCTION

In late 1990, the U.S. Coast Guard undertook a comprehensive data link study to determine which RF broadcast systems could be used to support differential Global Positioning System (DGPS) correction transmissions over the continental United States (CONUS) and to determine which radio systems were appropriate for a given operating area. The broadcast constraints for the system design had to meet accuracies of ±3 m at data rates of 100 bits/s with data latencies of less than 4 s. The frequencies finally selected were in the LF (285–325 kHz) and MF (405–415 kHz) bands; existing Marine radio beacons were used since they could broadcast beyond line of sight (LOS) and propagated via ground wave signals. The entire radio spectrum from LORAN-C (long-range navigation) to HF, including FM subcarrier and cellular radio, was addressed for reliably providing differential corrections to the transmitting stations using plain old telephone system (POTS) modems and sending the broadcast messages to coastal users within 100 km of CONUS. The HF system proposed for the data link was a DGPS sky wave mode of propagation that was not compatible with the GPS receivers available in early 1993. More importantly, incorporating the reference and remote stations into the system was costly. Although the system could provide broadcasts beyond LOS, it was affected by poor performance due to propagation variations in spite of a predicted 700-km sky wave mode range.

The purpose of APL's early high-frequency ground wave (HFGW) experiments at sea was to improve two-way voice and data communications between submerged submarines and surface ships; previous experience with HFGW on land can be found in Ref. 1 and will be discussed in an upcoming article in the *Technical Digest* by Vetter et al. The experiments provided an opportunity to investigate differential GPS broadcasts transmitted over an upper HF band to surface ships. The higher accuracy onboard the ship was necessary to assess antenna patterns from a submarine-deployed cable when more precise real-time navigational ship resources were unavailable. Previous theoretical and empirical measurements in this area supported the use of ground wave for communications in the HF and VHF regimes.[2,3] The advantages of using HFGW rather than the other options were that it provided a non-LOS mode of propagation with over-the-horizon capabilities, allowed the use of reasonably sized resonant antennas, and was based on extensive APL test experience in Europe with ranges over land to 100 km.

Using HFGW to send differential corrections reliably over sea was an attempt to show that its capabilities could meet the accuracy levels desired with currently achievable HFGW baud rates and system latency effects. A series of DGPS tests of opportunity were undertaken from March 1993 through May 1994 to evaluate the capability and show the use of HFGW for real-time differential navigation in a low dynamic environment. DGPS methods have been shown to significantly reduce the effects of selective availability (SA), ionospheric errors, and ephemeris errors on the positional solution. Post-test analysis of the GPS data collected in the early test phase showed that a shipboard C/A-code receiver could achieve accuracy levels of 2–5 m in position.

This article presents the results of using DGPS navigation techniques to improve the accuracy of a C/A-code GPS receiver for tracking ships using radio signals transmitted via a ground wave technique in the HF radio band. An inexpensive, commercial off-the-shelf (COTS) C/A-code GPS receiver (Trimble SVeeSix) was placed onboard the USNS *Range Sentinel* (T-AGM 22), which acted as the surface ship for a series of tests, and at the APL office at Cape Canaveral, Florida. A precision code (P-code) GPS receiver was also used onboard the ship to collect positional data and was used as a scoring reference. The GPS receiver at the APL Cape Canaveral office was used to calculate pseudo-range and delta-range differential corrections. The differential corrections were applied to the pseudo-range and delta-range measurements collected onboard the surface ship, and a Kalman filter was used to process the ranging measurements and calculate a state vector solution for post-flight evaluation. A COTS software package (LabWindows) was also used to generate real-time differential corrections.

DGPS THEORY AND PROCESSING SCHEME

Differential navigation using satellites has been practiced since the mid-1960s using translocation and Transit satellites.[4] With this method, a precisely located fixed site receives data from a satellite at a known location in space from which calculations or corrections are made and sent to a remote site. This early work was done using a reference station on the APL campus and a remote ground site 75 km away. Earlier than this, differential navigation was also used with the Omega and LORAN ground-based navigation systems. With the advent of GPS, the use of precision navigation anywhere on the Earth's surface became a reality. However, because GPS is still considered a military system and because of the effects of SA imposed on the precision code L1 broadcast signals, the best accuracy obtainable is currently limited to about ±100 m using the GPS standard positioning service (SPS) receivers. Differential techniques achieve accuracies comparable with those obtained with the best receivers nearly anywhere on Earth within a reasonable distance of a reference site.

Two techniques are commonly used for deriving a DGPS solution from coarse-acquisition code (C/A-code) GPS data. The first and simplest uses latitudinal and longitudinal corrections. For this method, a receiver at a known location (reference) calculates a position from a given number of satellites. The remote receiver is configured to use the same satellites and compute a position. The differences in latitude and longitude between the reference location and the position computed by the receiver at the reference location are applied to the position computed by the remote receiver. The greater the distance between the reference location and the remote receiver, the less similar the satellite geometries are relative to the two receivers, and the less accurate the differential corrections will be.

The second and more accurate DGPS method is to determine corrections to the range and range rate measured for each satellite. The remote user is independent in the selection of satellites to compute position, provided that corrections for all satellites in view can be generated from reference receiver data. A reasonable limit in the separation between the reference and remote receivers with this method is on the order of 1000 km. Also, additional processing of the remote receiver data is required to compensate for the error from user clock bias.

For this evaluation, the range-correction method was used to compute the DGPS solutions. Corrections to the range rate measured for each satellite were computed for the reference receiver data and then applied to the remote receiver data. Common-mode clock biases for range and range rate were removed, and the measurements were input to an 8-state Kalman filter to output state vector position and velocity estimates. Figure 1 illustrates the DGPS concept and shows flowcharts of the data processing for both the real-time and non-real-time modes. The real-time differential corrections used the COTS LabWindows package integrated into the HFGW system.

GPS REFERENCE RECEIVER COMPARISONS

To evaluate receivers for DGPS at-sea testing, three types of receivers (Table 1) were used to collect data at the APL Cape Canaveral facility during a period when GPS was being used for experiments by the Air

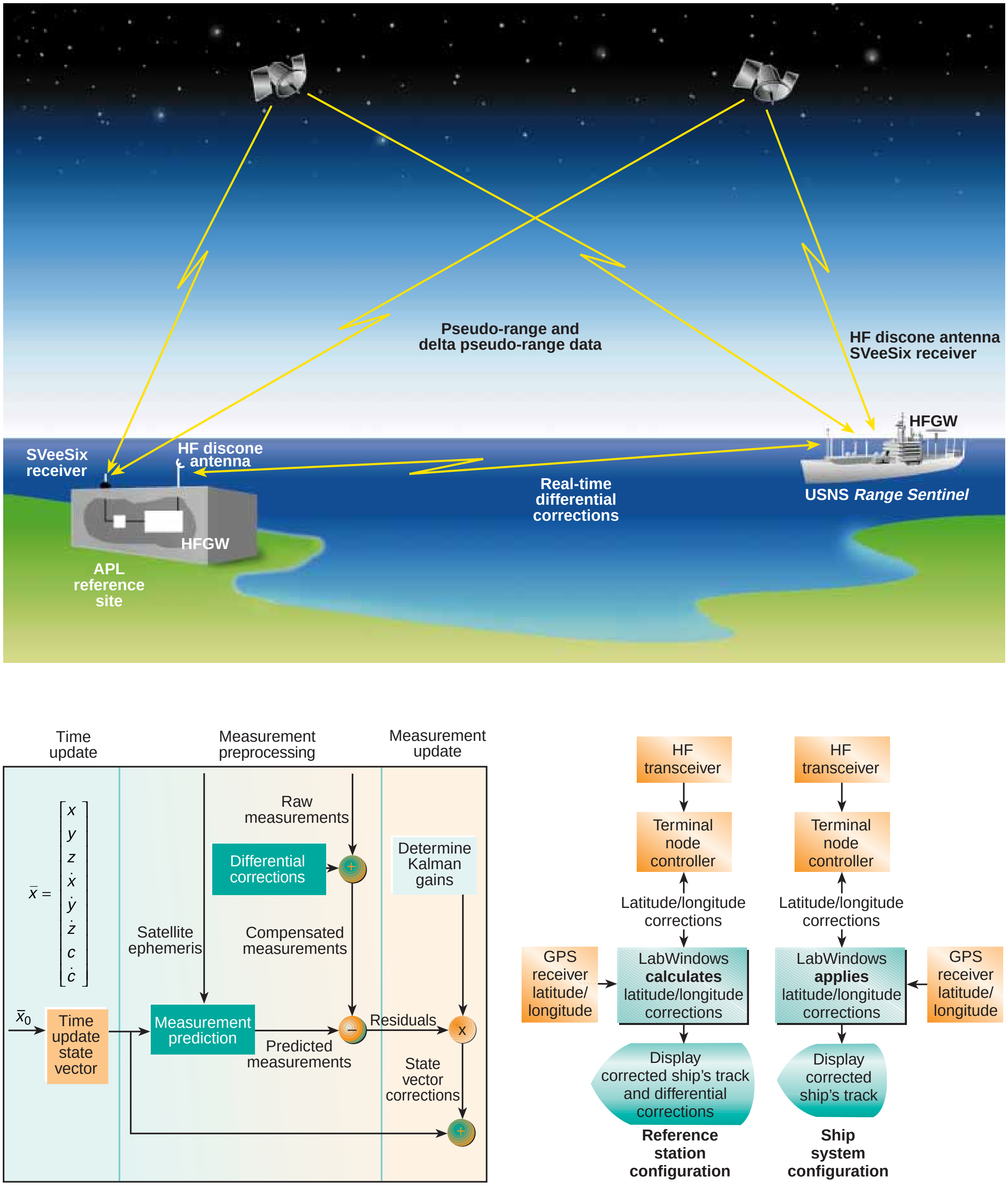


Figure 1. DGPS navigation concept (top) and flowcharts of the data processing for the non-real-time mode (bottom left) and real-time mode (bottom right). The state vector is composed of inertial Earth-centered frame of position and velocity components and user clock bias (c) and clock rate ($\dot{c}$).

Force and the encrypted SA corrections were turned off. The collected data provided a reference point to calibrate the three receivers. The receivers ranged from two COTS low-cost receivers that can handle the unencrypted GPS signals (Trimble and Rockwell) to a high-cost SPS receiver (Ashtech) used for high-precision geodetic studies. All of the data were collected at a 1-Hz rate and saved to a hard disk for later evaluation along with the navigation solutions output from the receiver. Since SA was turned off during the

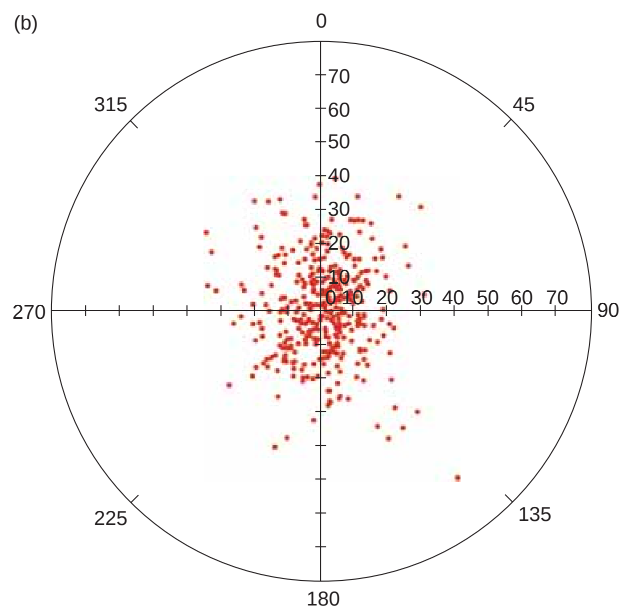
Table 1. GPS SPS unkeyed receiver characteristics.

GPS receiver	Technical description	Data types provided
Trimble (SVeeSix)	6–8 channel tracker code and carrier phase	Measurements and position
Rockwell PLGR	4–5 channel tracker code only	Position only
Ashtech (P-12)	All-in-view 12 channel tracker code and carrier phase	Measurements and position

entire data collection period, the navigation solutions should be comparable to those provided by the P-code precise positioning service (PPS) receivers. Figures 2a, 2b, and 2c show the navigation solutions obtained with the Trimble, Ashtech, and Rockwell receivers, respectively, using C/A-code measurements only, whereas Fig. 3 shows the average radial error compared with the surveyed position. The results indicate that the inexpensive COTS-based Trimble SVeeSix model provided results closely comparable to both the Rockwell portable lightweight GPS receiver (PLGR) model and the more expensive geodetic-quality Ashtech model. In addition, the SVeeSix model was the best candidate for the DGPS at-sea tests because it could be made easily configurable for real-time data collection and implementation into the differential correction process used by the HFGW system.

HFGW/DGPS HF RADIO SYSTEM

The HFGW and DGPS radio system used for all the tests included components borrowed from the HFGW base system and COTS components to solve the DGPS problem. Figure 4a and 4b illustrate the basic configuration applicable at the reference site and the ship, respectively. The DGPS tests focused on both non-real-time and real-time GPS tracking, as well as



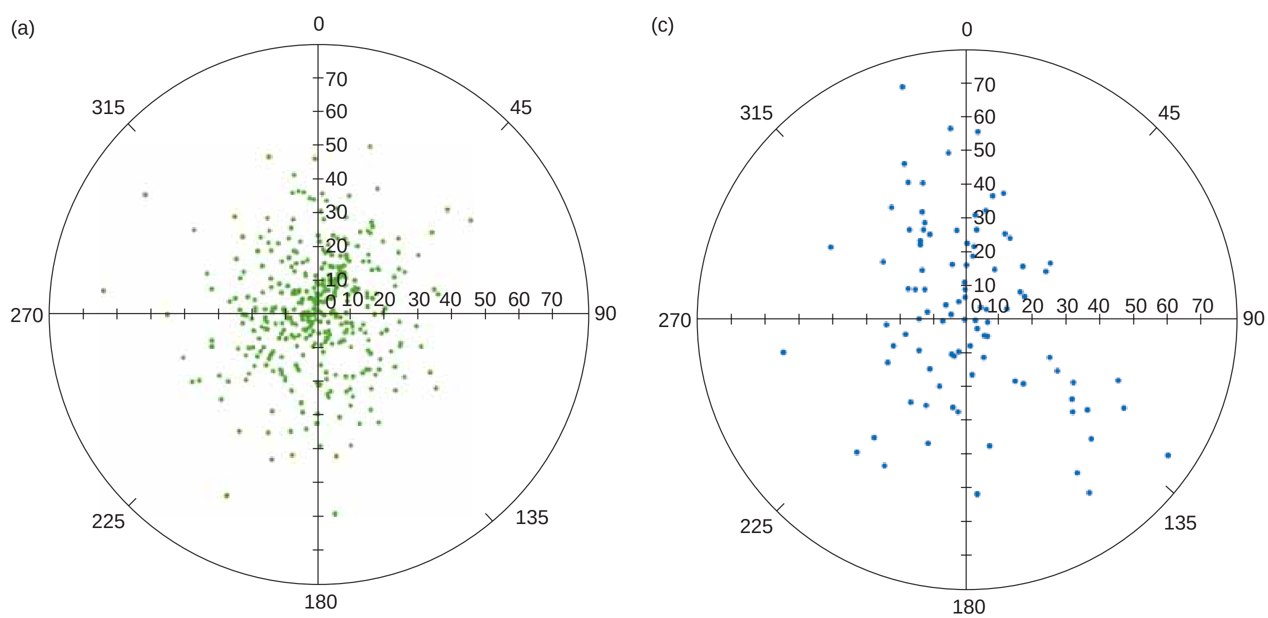


Figure 2. Navigation solutions (in meters) for three GPS receivers obtained using C/A-code measurements only. Selective availability was turned off. (a) Trimble, (b) Ashtech, and (c) Rockwell.

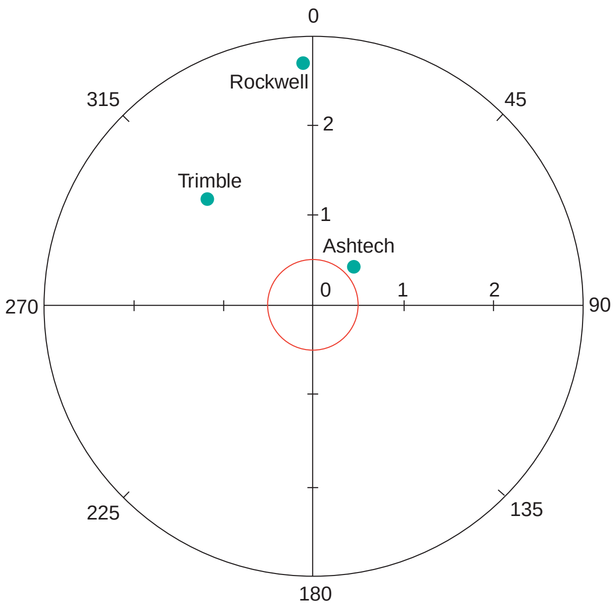


Figure 3. Average radial navigation error (in meters) compared with the surveyed position for DGPS receiver test. Selective availability was turned off.

binary data file transfers conducted dockside and during the short- and long-range test evolutions. One advantage of using upper HF for ground wave differential corrections instead of LF or MF is the size of the antennas, which scale inversely with wavelength. Typical HF antennas used by HFGW are less than 6 m in height compared with the larger sized antennas used by the Coast Guard's Marine radio beacon service. The antenna used on the ship consisted of a variety of vertical element discone and center-fed dipoles tuned and frequency selectable to the 20–30 MHz band.[5] All antennas were precisely located relative to the center of gravity of the ship and used in lever-arm GPS receiver compensations for post-processing evaluations and real-time differential correction processing. The reference site used previously surveyed GPS locations accurate to ±1 m in horizontal accuracy.

The GPS receiver at the base station was used to compute real-time differential GPS corrections. These differential corrections were then transmitted to the ship using HFGW signals. The corrected ship's position, course, and speed were also transmitted back to the reference station using HFGW signals. This digital-data link also allowed the passing of messages and binary data files between the ship and the reference site. The configurations were easily modified to provide real-time differential solutions by adding a data link between the two sites through the HFGW terminal node controller and radio transceiver system.

DOCKSIDE AND AT-SEA TEST DESCRIPTIONS

A series of tests were designed to relay real-time differential corrections over the HFGW signals from a reference station located near Cape Canaveral to a ship at sea. Table 2 describes the various tests and test configurations. For all occasions, GPS data were continuously collected both at the reference site and at the shipboard receiver antenna location. Except for the real-time modes of operation, all the data were post-processed using DGPS techniques to remove correlated systematic errors (i.e., the SA effects). The GPS reference P-code receiver used for scoring of accuracy performance and its antenna were previously surveyed to a precise location. For all tests, the base station included a discone reference antenna, a special 5/8-wave whip antenna used as a backup to the discone antenna for HF transmissions, and the SVeeSix standard GPS patch antenna.

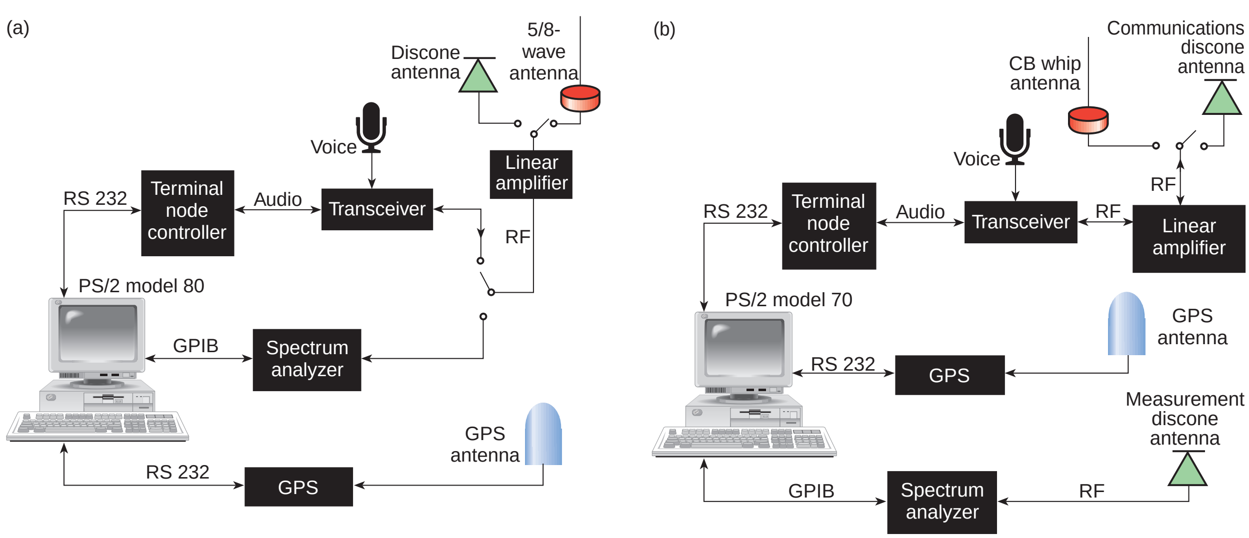


Figure 4. HFGW communications and DGPS test configuration: (a) reference site and (b) ship.

Table 2. DGPS HFGW test description.

Case number	Test description	Date	Range (km)	HFGW shipboard test configuration
1	Dockside DGPS test	Jul 1993	2	Discone antenna on ship and base
2	Post-processing test	Jul 1993	200	Two HFGW discone antennas
			400	Single CB whip antenna
3	Post-processing test	Nov 1993	40	Single HFGW discone antenna
			80	Single whip antenna
4	Real-time DGPS test	Mar 1994	55	Four prototype birdcage antennas (20–25 MHz)
				Single discone antenna
				Single whip antenna
5	Real-time DGPS test	May 1994	110	Two prototype HFGW birdcage antennas
				Single discone antenna
				Single whip antenna

The track of the ship consisted of a typical 3-day testing period where the differential GPS data were collected and evaluated at various distances from the base station reference antenna (Fig. 5). The ship was at a range of 40 km from the reference station for the first test case and had a course of approximately 50° and a speed of approximately 15 knots. For the second test case, the ship was approximately 75 km from the reference station on a course of approximately 35° and a speed of less than 3 knots. The ship's heading data were not recorded for this test, which may have led to larger differences between the DGPS positional solution and the P-code GPS receiver positional solution because of uncorrected antenna lever-arm effects. The third test was conducted at a range of 110 km from the reference station and provided an opportunity for more extensive applications testing with measurement of bit error recovery and transmission of data files over this distance using HFGW signals.

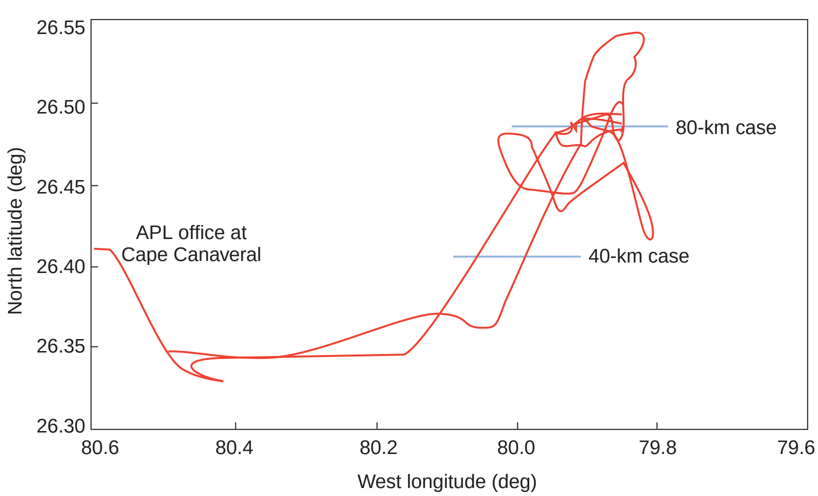


Figure 5. Ship's track for short-range DGPS at-sea test.

STATIC DGPS DOCKSIDE TEST RESULTS

Range-corrected positional fixes were calculated from the Trimble receiver data collected for approximately 120 min on the USNS *Range Sentinel* while the ship was dockside at Port Canaveral on 16 July 1993. Although this duration was inadequate for a full evaluation, it provided an independent verification for demonstrating system operation. Base station SVeeSix receiver data were used as the reference in the DGPS solution. The SVeeSix typically uses at least four satellites to calculate a navigation fix. However, only three satellites were available for DGPS corrections since the reference receiver was not tracking all the satellites in view. The DGPS positions were compared with positional data from a keyed P-code GPS receiver. Figure 6 shows the differences over the 120-min span (case 1) between a dual-frequency corrected P-code GPS receiver and both the DGPS and the uncorrected Trimble data. The DGPS-computed positional accuracy improved significantly, on average, from 50 to 16 m over the uncorrected positional accuracy. This improvement is a function of certain aspects of this test and

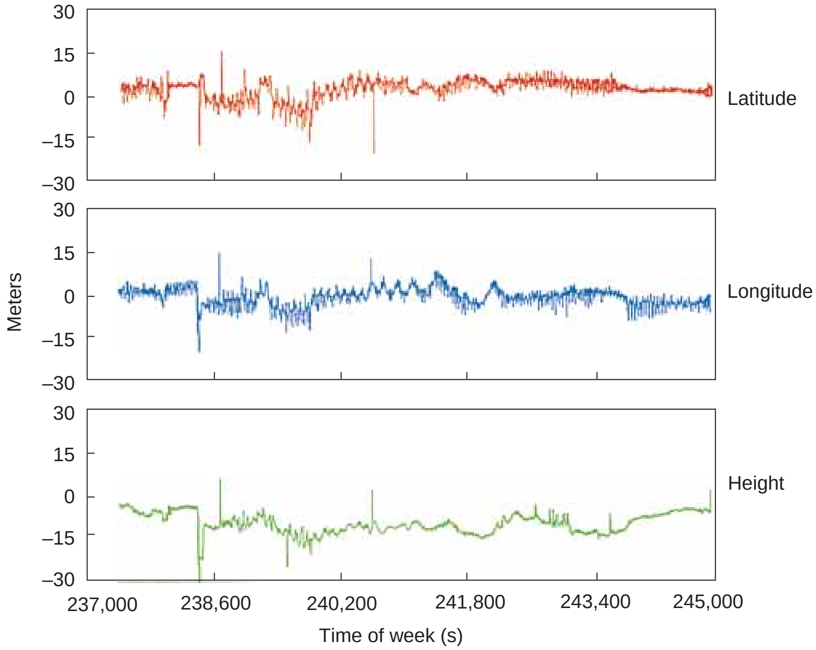


Figure 6. Positional differences over a 120-min span between a dual-frequency corrected P-code GPS receiver and both the DGPS and the uncorrected Trimble data. The DGPS-computed positional accuracy improved significantly, on average, from 50 to 16 m over the uncorrected positional accuracy.

will vary as these factors are varied. However, the accuracy improvement from uncorrected to DGPS data would probably be greater if data from more satellites had been recorded at the reference station.

DYNAMIC DGPS AT-SEA TESTING

Short-Range Test Results

The statistics for the real-time Trimble and the DGPS corrected positions were differenced with the dual-frequency P-code GPS receiver data. The DGPS solution indicated a 1-s difference of 2.84 and 3.34 m for the 40- and 80-km test cases, respectively. These values indicate that the accuracy of the DGPS solution was comparable with the accuracy of the onboard dual-frequency P-code receiver. The real-time Trimble differences show a slow oscillation that is the result of SA. Latitudinal and longitudinal differences derived from solutions formed from the DGPS corrected pseudo-range measurements and the range derived from the P-code receiver positional solution are shown in Fig. 7. The offset in location between the P-code receiver antenna and the Trimble GPS antenna was corrected by using the ship's course to approximate the ship's heading.

For the 40-km test case (case 3, not shown), five GPS satellites were used in the Kalman filter solution, and one of these was used for link differences with the other satellites. The link-difference mode of calculation eliminates common mode errors in the solution by selecting one satellite to be the reference. The measurement differences indicated a bias of approximately 40 m for all the ranging channels. This common mode bias was removed from the state vector solution by the Kalman filter.

For the 80-km test case (case 3), five satellites were used in the Kalman filter solution, with one of these used for link differences with the other satellites; delta-range measurements were used from one satellite because of a possible multipath problem in the range data. The satellite ranging data are shown in Fig. 7a, with Fig. 7b showing the SVeeSix and DGPS positional differences. The measurement differences indicated a very small common mode bias among the ranging channels. The positional differences for the 55-km test case (case 4, not shown) showed similar results.

Long-Range Test Results

Positional fixes from Trimble SVeeSix C/A-code GPS receivers installed at the reference site and on the ship were obtained using the DGPS range correction technique. The ship was at sea in support of HFGW testing. GPS data were collected from 17 to 20 July 1993. Both the real-time fixes and the range DGPS solutions were compared with an onboard dual-frequency GPS receiver (P-code receiver) at ranges of 200 and 400 km, respectively (case 2). The positional differences were similar to the 40- and 80-km short-range test cases and are not shown here but are tabulated separately in the next section. The positional differences in the DGPS solution were substantially less than the real-time SVeeSix C/A-code receiver for the 200-km case. However, for the 400-km case, the differences between the DGPS solution and the P-code GPS data were larger than expected on the basis of Kalman filter residuals and covariances.

DIFFERENTIAL GPS TEST PERFORMANCE

The results of all DGPS test comparisons are summarized in Table 3, which shows the average horizontal navigational differences compared with the reference used to make the evaluations as well as the differential correction technique used.

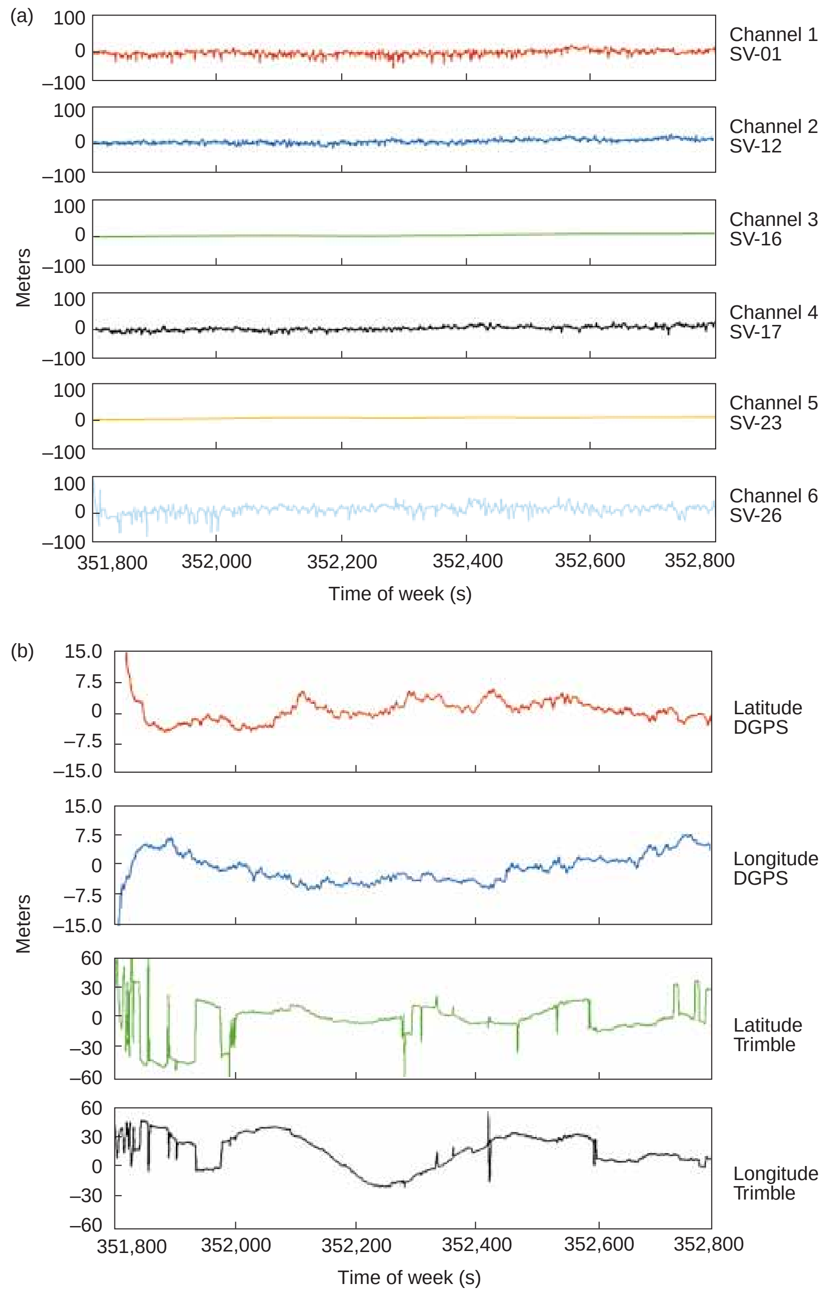


Figure 7. Pseudo-range differences (a) and latitudinal and longitudinal differences (b) for the 80-km test case. The DGPS differences were derived from solutions formed from the DGPS corrected pseudo-range measurements and the range derived from the P-code receiver positional solution.

Figure 8 presents the results of the real-time corrected differential and uncorrected GPS data compared with a COTS Rockwell PLGR PPS receiver being operated in the authorized P-code mode. These comparisons indicate that the differentially corrected Trimble C/A-code receiver positions were generally within 10 m of the Rockwell PPS positions. The mean differences were −4 m in latitude, 0 m in longitude, and 4 m in magnitude with standard deviations of 12, 9, and 15 m, respectively. Only 5 h of Rockwell PPS data were available for comparison because of data collection problems experienced with the Rockwell receiver. The excursions in the differential latitudinal and longitudinal differences were caused by the reference receiver at the base station not tracking the same constellation of satellites as the GPS receiver located onboard the ship. The time delay of the differential corrections as received at the ship is also shown. This time delay was calculated by differencing the GPS receiver time as transmitted from the reference site with the GPS receiver time at the ship location. The delay indicated that the average age of the differential corrections was approximately 12 s. Figure 9 shows the actual differential corrections calculated and sent for the 110-km test case (case 5). The oscillations in the data corrections represent the effects of uncompensated SA. The corrections were transmitted from the reference site every 15 s.

DGPS APPLICATION TESTS

The last at-sea test period in May 1994 to 110 km provided an opportunity to test other applications with the baseline software used during the two previous at-sea tests. For this test, it was essential to have good voice communications for conducting the experiments, and these were provided via the HFGW mode of communication. Transfers of digital GPS data between the ship and the reference site were started shortly after making initial voice contact and throughout the day. Transfers of compressed shipboard status reports were accomplished at ranges of 40 and 80 km from the reference station. The binary data file that was transmitted consisted of a typical status report in WordPerfect file format. This WordPerfect file contained graphics characters and binary tabular information and was compressed approximately 50% by using a standard utility program. The transfer times of these compressed reports at 1200 baud were less than 2 min. Throughout the day, digital text messages containing status information about the test were routinely passed

Table 3. DGPS dockside and at-sea test performance results (1σ uncertainties apply to values in parentheses).

Test type and date	DGPS method used	Real-time Trimble latitude (m)	Real-time Trimble longitude (m)	Real-time Trimble radial (m)	DGPS latitude difference (m)	DGPS longitude difference (m)	DGPS radial (m)
Dockside test	CV	37(7)	33(12)	50(12)	7(5)	−19(9)	20(10)
Long-distance post-processed							
200 km	KF	20(11)	−24(11)	32(16)	−3(3)	3(1)	4(3)
400 km	KF	22(23)	−7(7)	23(24)	16(2)	−7(2)	18(3)
Short-distance post-processed							
40 km	KF	4(13)	10(31)	11(34)	1(2)	−3(2)	1(3)
80 km	KF	6(19)	5(17)	8(26)	1(2)	3(2)	1(3)
Short-distance real-time DGPS							
110 km	CV	10(4)[a]	6(7)[a]	12(10)[a]	1(4)	1(6)	1(9)

[a]Approximate estimates.

NOTE: CV = common-view method, KF = Kalman filter solution method.

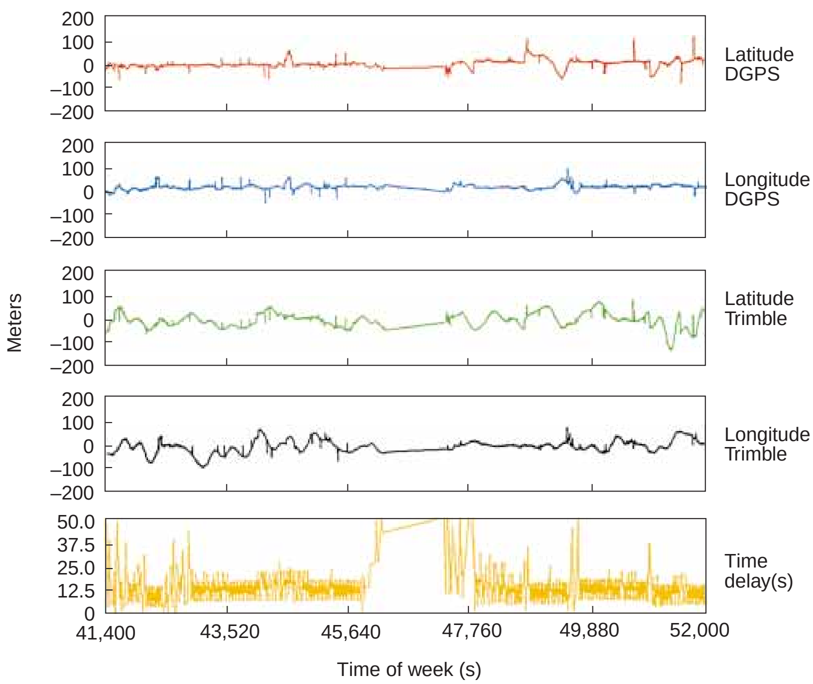


Figure 8. Real-time corrected differential and uncorrected GPS data compared with a COTS Rockwell PLGR PPS receiver being operated in the authorized P-code mode. These comparisons indicate that the differentially corrected Trimble C/A-code receiver positions were generally within 10 m of the Rockwell PPS positions.

between the reference site and the USNS *Range Sentinel*. The noise background at the reference site office increased during the middle of the day, which affected the reliability of receiving the digital communications at the reference station. This problem was mitigated by increasing the transmitted power at the ship from 100 to 1000 W. Figure 10 is a histogram of the number of digital GPS packets sent versus the time of receipt of the packets. This result shows that approximately 79% of the digital packets were received within 15 s of being sent, with less than 7% of the packets requiring a second attempt before acknowledgment was received at the base site. Because the terminal node controllers were used in the connection mode (continual digital transmission until the receipt of data was acknowledged) for this test, the packet receipt times measured were not a true indicator of latency effects that would have been obtained had the terminal node controllers been in the beacon mode. Thus, effects such as ship maneuvering and antenna switching are embedded in the high connect times measured that would not have been the case for beacon mode operation. In spite of this, it was felt that the digital transmissions sent at the low baud rates of 100 bits per second using HFGW would have been

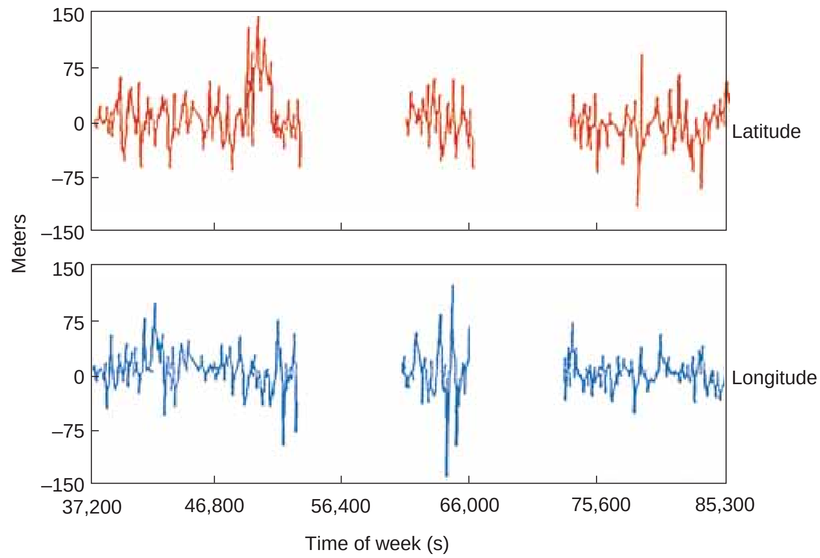


Figure 9. Real-time differential corrections for the DGPS 110-km test case. The oscillations in the data corrections represent the effects of uncompensated selective availability. The corrections were transmitted from the reference site every 15 s.

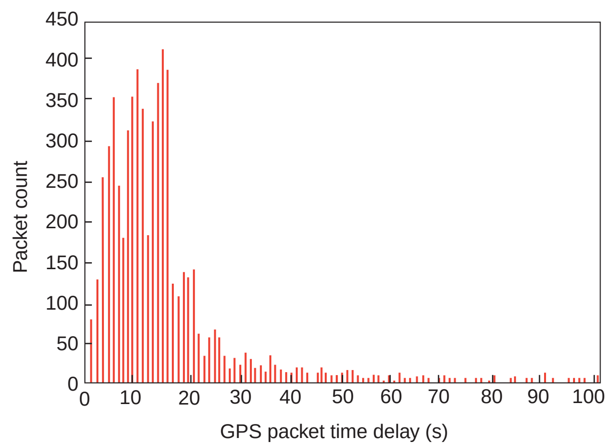


Figure 10. Histogram of the number of digital GPS packets sent versus the time of receipt of the packets. Approximately 79% of the packets were received within 15 s of being sent, with less than 7% requiring a second attempt before acknowledgment was received at the base site.

comparable to that required for a design system had the optimal connection mode been chosen.

SUMMARY

The results of testing onboard the USNS *Range Sentinel* ship during three different at-sea tests showed that HFGW can be used to provide differential GPS corrections in real time at distances beyond LOS from a shore-based reference station. Differential GPS techniques can substantially improve the positional solution of a GPS SPS receiver operating in a marine environment. The test results showed that a C/A-code receiver can give positional solutions as accurate as a P-code GPS receiver over distances up to 80 km and speeds up to 15 knots.

Future improvements to this HFGW capability include enhancing the accuracy of the differential GPS positional solutions by forcing the GPS receivers to track satellites on the basis of a combination of geometric dilution of precision calculations and receiver signal-to-noise (S/N) levels rather than solely on S/N levels, as was the case with the Trimble SVeeSix receiver used for these tests. Further testing was also thought necessary to determine the maximum effective range for using HFGW for transmitting differential GPS corrections. Additional testing would have been beneficial to determine the maximum bit-error rates and evaluate the ability of the HFGW system to support a 2400-baud data rate. Currently, the terminal node controller supports only a 1200-baud data rate. These enhancements and tests would have been able to provide a digital report for transmission to the base station and for transmission of facsimile, slow-scan TV, and digitized video images between the base station and the ship.

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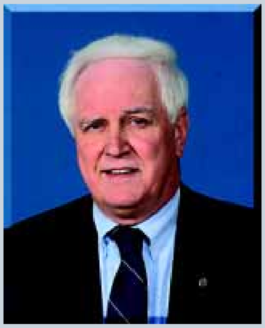

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