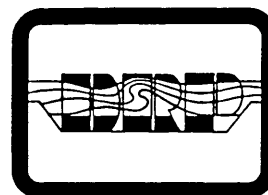# *Dredging Research*
Technical Notes

Real-Time Testing and Demonstration of the U.S. Army Corps of Engineers' Real-Time On-The-Fly Positioning System

Purpose

This technical note describes the U.S. Army Corps of Engineers' Real-Time On-the-Fly (OTF) positioning system and summarizes the results of testing and demonstrations conducted to date.

Background

The Corps of Engineers has been developing a GPS (global positioning system) carrier phase-based positioning system for hydrographic surveying and dredging since 1988. This system provides real-time three-dimensional (3-D) positions with horizontal and vertical accuracies better than 1 dm over ranges up to 20 km from a single reference station without static initialization. The project has passed from concept development through feasibility studies, system analysis, resolution of carrier ambiguities on-the-fly, to final system integration.

Real-time testing of the system began in March 1993, and public demonstrations began in October 1993. Testing of the system has been performed under varying conditions to evaluate the limits of OTF ambiguity resolution for precisely positioning moving platforms. Tests have shown that this system is capable of 1 to 3 cm in all three dimensions.

Additional Information

This technical note was written by Ms. Sally L. Frodge, U.S. Army Topographic Engineering Center; Dr. Benjamin W. Remondi, National Geodetic Survey; and Dr. Dariusz Lapucha, John E. Chance and Associates, Inc. For further information, contact Ms. Frodge, (703) 355-2816, or the manager of the Dredging Research Program, Mr. E. Clark McNair, (601) 634-2070.

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Introduction

The Corps of Engineers is responsible for keeping the waterways of the United States navigable. Recognizing the need for and potential benefit of a more accurate positioning system for its hydrographic surveying and dredging mission, the Corps embarked on an ambitious research program to develop a prototype positioning system based on GPS carrier signals. This prototype system is designed to deliver, in real time, 3-D positions with subdecimeter accuracies, for ranges up to 20 km using a single reference station.

Development of the OTF prototype system was initiated in 1988 by the U.S. Army Topographic Engineering Center, funded by the Corps' Dredging Research Program.

The need for such a system by the Corps initially arose out of its ongoing dredging mission. Several millions of dollars are spent each year by the Corps in maintaining the waterways of the United States. The Corps conducts "condition surveys" on a routine basis to identify channel obstructions. If dredging is required to clear the channel obstruction, the Corps often contracts this work. If the work is contracted, a typical scenario is for the Corps to perform a hydrographic survey before the work is done to identify to the contractor the specific material to be removed.

After the work is completed, the Corps performs a "contract payment survey." The current horizontal accuracy standard used for a contract payment survey is 3 m 1DRMS (1 deviation root mean square), although there has been discussion to tighten this requirement to 3 m 2DRMS. (This increased requirement represents accuracy of within 3 m of the desired location 95.5 percent of the time (2DRMS), versus 68.3 percent (1DRMS)). The majority of the positioning systems used today by the Corps are range-range or range-azimuth systems. Most of these systems require daily calibration or initialization at a site local to the job. In addition, occupation of other previously surveyed shore stations is necessary for each day of the survey.

Survey and dredging operations must also be referenced to a vertical datum. Tidal, river, or lake gages are used to establish readings upon which a vertical datum such as mean lower low water is established. The surveyor must determine the differences in elevations from the established datum using such methods as a zoning model, limiting the accuracy typically to 0.2 m. Final payment is made to the contractor when the contractor and the Corps agree that the identified material was removed and reach a consensus on the volume of removed material.

The prototype system developed by the Corps provides subdecimeter accuracies in three dimensions in real time. Using a positioning system that is accepted as definitively accurate can decrease the dispute over costs which arise from disagreements on the actual amount of dredged material removed. Additional savings are realized on a per-job basis because of the fewer personnel and decreased number of shore stations. Only a single shore station is needed, and daily calibration is not necessary. It is anticipated that implementation of this system throughout the Corps will save the government and its taxpayers millions of dollars.

System Development Phases

Development of the system has progressed in three primary phases, as documented in previous papers (DeLoach and Remondi 1991; Remondi 1991; Burgess and Frodge 1992; Remondi 1992a,b; DeLoach, Frodge, and Remondi 1993). The project has gone through a full development cycle from conceptual level to the development of a working prototype. Feasibility studies, system analysis, extensive testing strategies, and considerable research with regard to the resolution of carrier ambiguities "on-the-fly" were some of the major program activities.

Development and testing of the prototype system has been completed, and demonstrations have been ongoing since August 1993. The project is in its seventh year of the planned 7-year effort. The goal of this last year of this specific effort has been to demonstrate the OTF capability to the Corps districts, further refine the OTF software, and fully determine the operational environments under which the system is most effective.

To date, the OTF system has been demonstrated, undergone testing, and has been used as a production-level engineering system. The results and findings of these applications are discussed later in this paper.

Description of the OTF System

The real-time OTF prototype delivers high-precision kinematic positioning accurate to less than 5 cm at the antenna phase center, while simultaneously providing a separate output for meter-level differential GPS (DGPS) for navigation purposes. A block diagram of the system is shown in Figure 1. The system performs on-the-fly carrier phase ambiguity resolution.

As a design constraint, the OTF system was developed using only equipment that could be purchased off the shelf. The OTF software is the heart of the system and was the focus of much of the development effort. The software was designed to require minimum operator attention and has several built-in quality control procedures to ensure that the high performance and reliability of the system is maintained.
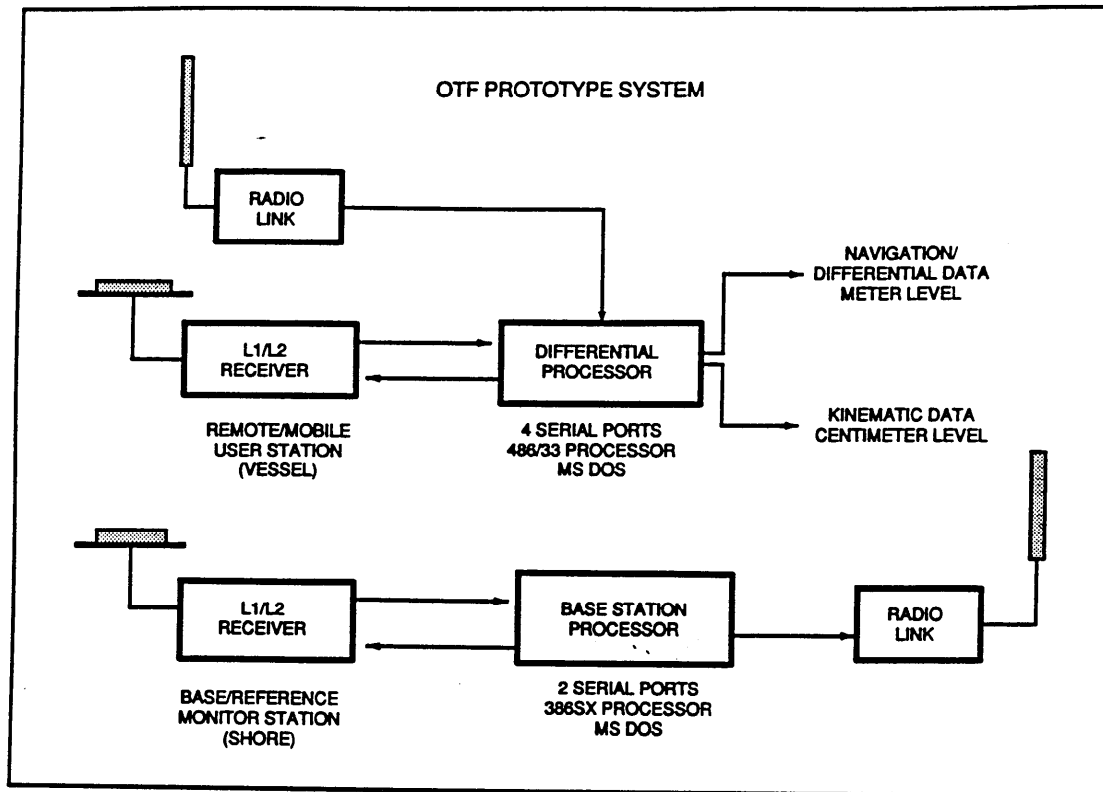
Figure 1. Block diagram of OTF prototype system

The system consists of setups at the reference and remote stations and a data link, as shown schematically in Figure 1. Dual-frequency (L1/L2) GPS receivers are required at both the reference (monitor) and remote (user) stations. Shipping the raw data from the reference station allows a single 386 SX personal computer (PC) to carry out the reference station functions. These functions include setting the GPS receiver to output the required data, translating those data to the desired format, and transferring the formatted data to the data link for transmission. Additionally, the station package is capable of recording data if the operator requests it.

Although the prototype has been developed and built using 486 computers and Trimble 4000 SSE receivers, it is hoped that, in the near future, other platforms and receiver types will be interfaced to use the OTF software.

The high-precision kinematic OTF (KOTF) mode positioning is available from the system once integer ambiguities are resolved by the software. As long as the system remains in the KOTF mode, real-time subdecimeter positioning in three dimensions is available at the mobile (user) site. To remain in this KOTF mode requires both reference station data and a maintenance of lock on at least four satellites. If that number drops to below four, the ambiguities will again be resolved after the system reacquires lock on a sufficient number of satellites. The software is "smart" software and will automatically detect the need to reinitialize. The software will also trigger reinitialization if quality factors based upon residuals fail to meet certain predefined limits. Note that the system is still capable of

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meter-level DGPS navigation even if loss of lock occurs, and will provide this function for a limited time even without data from the reference station.

The system uses L1/L2 carrier phase and carrier/acquisition (C/A) code ranges for ambiguity resolution, although L2 codeless code ranges and P code ranges can also be used. The system has been designed not to rely on the continuity of L2 carrier phase, since only the fractional phase part of the L2 carrier measurements is used. After ambiguities are resolved, only the L1 carrier ranges are required to maintain the high-precision KOTF positioning. However, ionospherically free dual-frequency kinematic GPS was also developed. Note that the Interface Control Document 200 (ICD 200) parameters are required by the system not only at startup of the software, but whenever the GPS satellite constellation changes or an ephemeris update occurs. Figure 2 depicts the general flow of required GPS data. The meter-level DGPS process uses primarily C/A code and L1 carrier ranges.
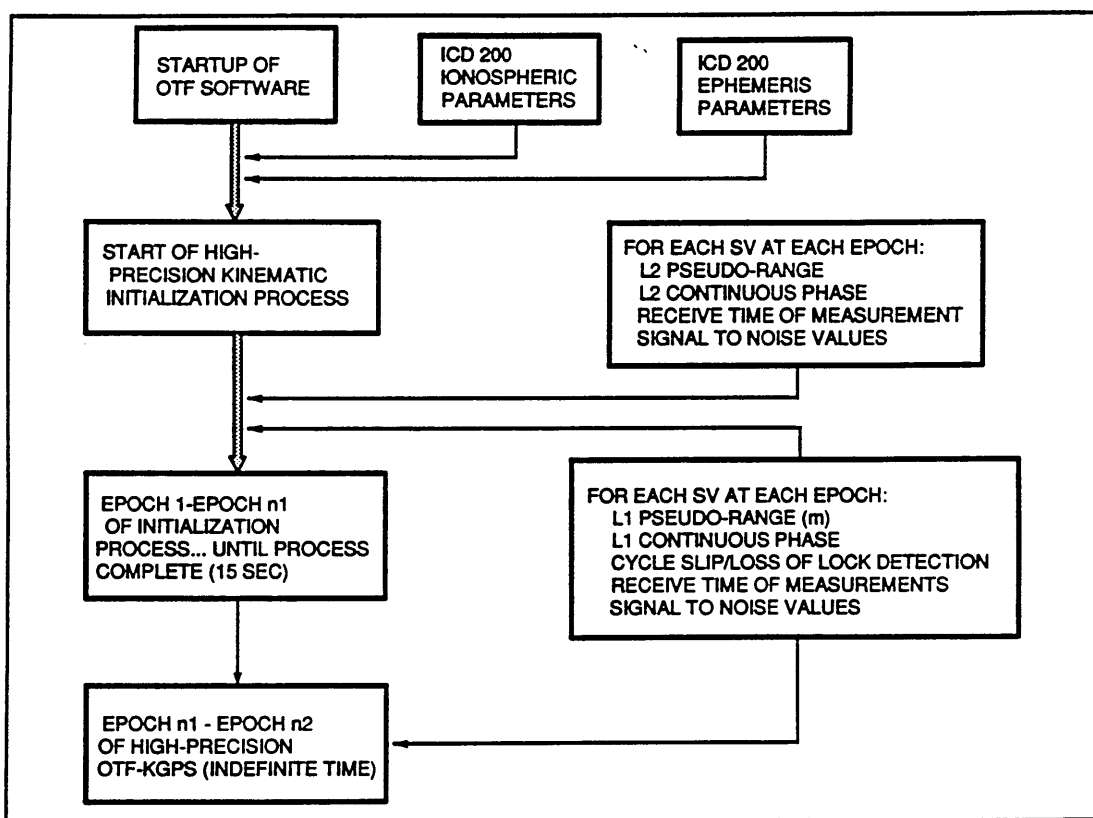
Figure 2. Schematic of information flow required by OTF system

The current prototype has been developed on the premise that all required raw GPS observations, that is, the GPS time tag, L1/L2 carrier phase, and L1 code, are transmitted from the reference station, and the actual computations necessary for KOTF and code DGPS take place at the remote/user station. The KOTF process requires time-matched reference and remote station data. In the code differential process, extrapolated reference station differential corrections are applied to the current remote

station observations, as is done in standard DGPS systems. The difference is, however, that these corrections with their rates are generated at the remote site from the raw data that were received from the reference station data.

The system can be interfaced with any other system requiring this level of accuracy in positioning, using an interface string (Figure 3). This string was designed to be as close as possible to the existing National Maritime Electronics Association GPS string formats. The system works in a robust and reliable manner out to the design goal range of 20 km in real time, although the range limit is greater. Future testing this year will determine more exactly what the range of the system is.

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General Information:
This output string format was developed for this project.  It is a string
similar to that used by the National Maritime Electronics Association (NMEA),
so that manufacturers can easily interface to it.  An example string is

    $RTGGK,HHMMSS.SS,MMDDYY,DDMM.MMMMMM,N,DDDMM.MMMMMM,W,Q,UU,DD.D,EHT.XXX,
        M*HH<CRLF>

where the fields are comma delineated and represent:

$RTGGK                      $RT is in place of the $GP NMEA designator for GPS
                            GGK is NMEA-like for lat, lon, and kinematic
HHMMSS.SS                   UTC TIME of POSITION FIX
                            (for example, 102933.00)
MMDDYY                      UTC DATE of FIX in month, day, year format
                            (for example, 052493)
DDMM.MMMMMM                 Latitude of FIX is degrees and decimal minutes to
                            six places (for example, 3013.123456)
N                           Latitude N or S
                            (for example, 3013.123456,N)
DDDMM.MMMMMM                Longitude of FIX in degrees and decimal minutes to
                            six places (for example, 09203.123456)
W                           Longitude E or W
                            (for example, 09203.123456,W)
Q                           GPS QUALITY INDICATOR (for example, 3)
                                0:  FIX not available or invalid (not used)
                                1:  Non-differential GPS FIX (not used)
                                2:  Differential FIX
                                3:  Kinematic FIX

UU                          Number of SATELLITES IN SOLUTION
                            (for example, 07)
DD.D                        DILUTION OF PRECISION (DOP) of FIX
                            (for example, 01.3)
EHT.XXX,M                   ANTENNA ELLIPSOIDAL HEIGHT (not MSL) in meters (M)
*HH                         CHECKSUM
                            (for example, *FB)
<CRLF>                      CARRIAGE RETURN-LINE FEED CHARACTERS

The length will change depending on the ellipsoid height value.  The maximum
length of an NMEA string is 80 characters.  Differences from NMEA GGA format:

    1.  Ellipsoidal height not antenna altitude (msl/geoid).
    2.  Geodial separation not output.
    3.  No age of correction or differential station number.
    4.  Date of fix output.
```
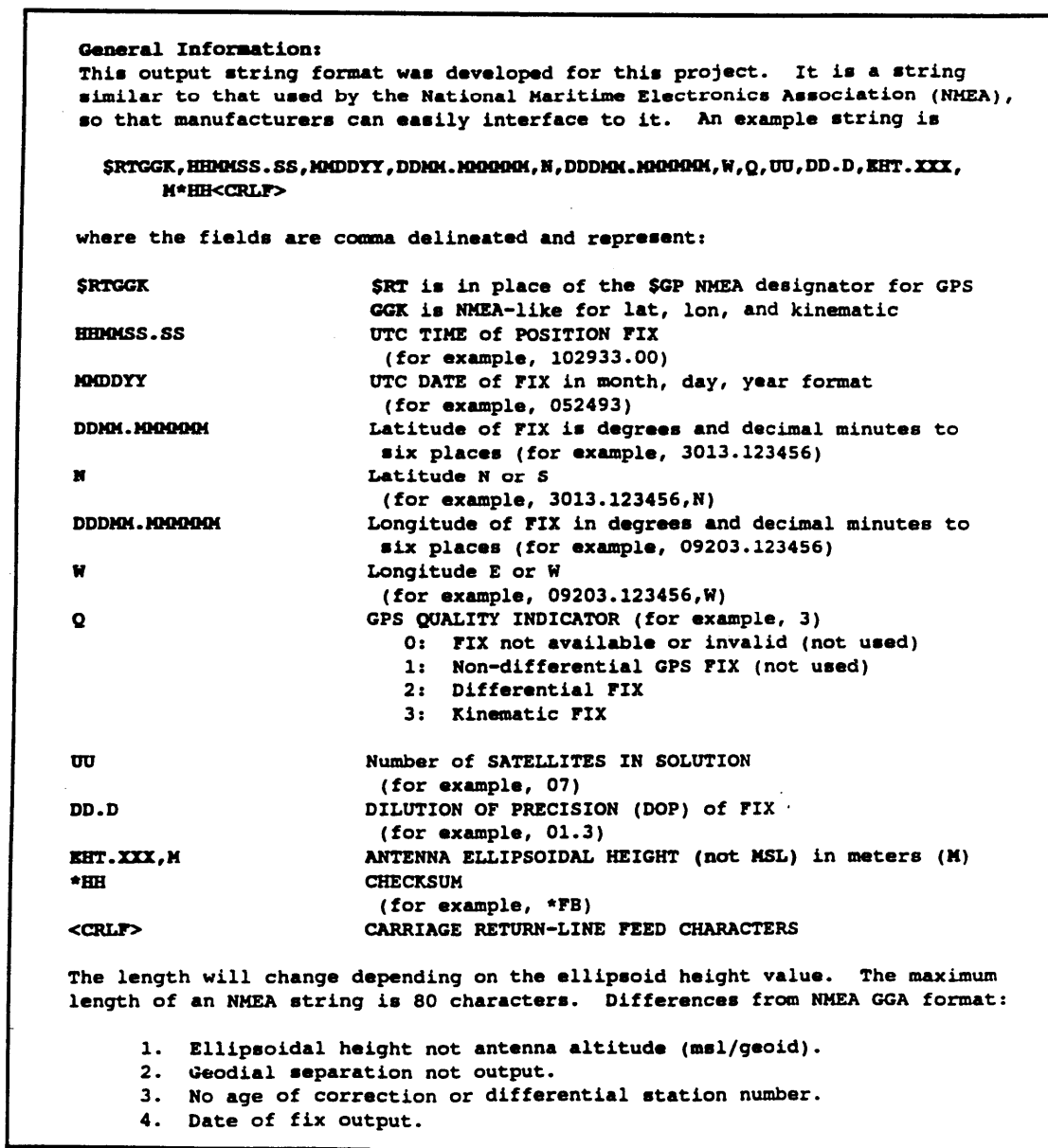
Figure 3. Interface string OTF output data format (kinematic and differential)

The system requires a data link capable of a minimum of 4,800 baud. The system has been tested using 9,600-baud Dataradio UHF (460 MHz) that can operate at line-of-sight distances up to 25 km, depending upon antenna height and power used. Tests have also been run using 1-W spread units. Spread spectrum sets have the advantage of not requiring a Federal Communication Commission license, but provide a more limited range of possibly 10 km (line-of-sight, rather ideal conditions). Within the tests run, the effective range obtained, without using any repeaters, was 8.1 to 8.5 km. VHF sets recently acquired have been used with the system testing and have provided a disappointing 8 to 9 km. Successful tests were run out to 18.6 km using the UHF sets. Further testing is planned.

The remote/user station uses a single 486 DX/33 PC. At the user station, the reference and remote station data are combined to accurately determine the remote station position. The remote station software, in its typical mode of operation, provides navigation and KOTF output at a 1-Hz rate. OTF ambiguity resolution computational time is usually ≤1 sec. When used operationally or demonstrated, the initialization time interval is set to 15 sec, although OTF initialization has been achieved in 1 sec (two epochs). This equates to instantaneous initialization. The system is reliable and easy to use.

Theoretical Basis for Kinematic On-the-Fly GPS

The development of the algorithms necessary for high-precision kinematic OTF GPS began in late 1989 and can be traced through a number of papers (Remondi 1991; Remondi 1992a,b). Initialization is performed in three steps. First, a meter-level first guess is acquired. Second, a search grid is established. Third, the grid "candidates" are evaluated to isolate the correct grid point. In fact, there are many variants, and the following approach is both representative and simple to describe.

Step 1: Meter-Level Positional Boundary

The initial estimate of receiver's position is from the code range measurements. This equation is

$$R_{bu}^{jk} = \rho_{bu}^{jk} + \varepsilon_R, \; j = j_1, \, j_2, \, ...j_n \tag{1}$$

where

R = code range measurement
j = other satellites needed to form the double difference
k = reference satellite
b = base or reference receiver
u = user receiver

ρ = range model (in meters)

ε_R = unmodeled part

It is assumed that there are at least three other satellites; however, most of the time there will be four to six other satellites (that is, $j = j_1, j_2...j_n$, where $n = 4, 5,$ or 6). Although this system of equations can be solved for the position of user receiver (that is, $\rho = \rho(x_u, y_u, z_u)$), better results are achieved by smoothing the code ranges with carrier range measurements. The carrier range equation is

$$\lambda \left[\varphi_{bu}^{jk} + N_{bu}^{jk} \right] = \rho_{bu}^{jk} + \varepsilon_\varphi \qquad (2)$$

where

λ = wavelength of carrier signal (meters per cycle)

φ = carrier phase measurement (cycles)

N = unknown carrier phase integer ambiguity (cycles)

ε_φ = unmodeled part of the carrier (meters)

The same range model ρ is in both equations. Since N is a constant bias, N will drop out of a time difference, leaving the following:

$$R_{bu}^{jk} (t_\varphi) = R_{bu}^{jk}(t_i) - \lambda \left[\varphi_{bu}^{jk} \lambda (t_i) - \varphi_{bu}^{jk} \lambda(t_\varphi) \right] + \varepsilon_{\varphi R} \qquad (3)$$

Simply put, code range measurements at any subsequent epoch, t_i, can be mapped to the reference time (epoch), t_φ. This provides a large number of different measurements of $R_{bu}^{jk} (t_\varphi)$ which can be averaged. Finally, placing these averaged ranges into the initial code range equations allows the x_u, y_u, z_u to be determined at the meter level. The search grid of Step 2 is defined about this initial positional estimate. The better the initial positional estimate is determined, the smaller the search volume can be. This equates to a faster overall initialization time since many otherwise attractive candidates will be eliminated because they fall outside the boundaries of the search volume. Stated another way, the smaller search volume leads to faster computational times since fewer candidates need to be considered.

Step 2: Forming the Search Grid

There are many ways to form the search grid. An efficient way, and one easy to explain, is based on the intersection of three double difference planes from a given set of four satellites. By selecting four satellites, each of which is not too low in elevation and which together provide a favorable Positional Dilution of Precision (PDOP), the real values of carrier phase ambiguities can be compared at the initial positional estimate and

rounded to closest integers. Placing these determined integers each into the carrier phase equations for that specific set of those four grid satellites provides a single grid point. Neighboring grid points can be computed by incrementing any one of the integer ambiguities by unity. Having found three orthogonal neighboring grid points, one can compute others within predefined neighboring volumes by vector addition.

Significant efficiencies can be achieved by performing this procedure for both L1 and L2, although in principle one can do it for just L1. The points of each grid are formed as the intersection of three double difference planes and thus the grids are actually a lattice of 3-D positions. There will be only a finite number of 3-D points that will appear in close enough proximity to each other to be considered intersection points of the L1 and L2 grids, identified through the process outlined above. These remaining grid candidates can be evaluated to determine which is truly the correct candidate. Typically, if there are 30,000 initial points on each of the L1 and L2 grids (for a total of 60,000 points), somewhere around 500 candidates will remain to be processed by the following step, described below.

Step 3: Evaluating the Candidates

The remaining candidates must now be evaluated. This is the final step of the KOTF initialization process. For a test grid candidate one uses the carrier phase equations to determine the integer ambiguities for all double differences. This permits a computation of the modeled range, ρ, and ultimately provides a residual. The correct grid candidate will have small residuals, whereas the others will not. Should multiple grid candidates have similar small residuals, lane resolution may not be possible.

The statistics calculated will indicate clearly if a correct candidate has been found, indicating that the correct solution for the integers has been resolved. If the resolution is uncertain at the reference time, t_φ, one can continue the process in subsequent epochs, t_i, until a single lane emerges as clearly the correct candidate.

Within the OTF software, the time interval for this process is user selectable. As mentioned, this time is currently set at 15 sec, although several of the tests over the summer were run using a 30-sec time interval. The data are first analyzed in a forward manner, from epoch t_φ forward in time toward epoch t_n. If the OTF system's software cannot resolve the integers, the software will automatically begin the initialization process again, processing the same data backward in time, beginning with epochs t_n and proceeding backward toward t_φ. The initial 15 sec is normally sufficient; however, even if additional time segments are required, initialization may not require the entire set of epochs back to t_φ (that is, initialization will take greater than 15 sec but less than 30 sec). The software will indicate if initialization was obtained on the forward or backward pass.

During the demonstrations, there were some rare cases where obstructions coupled with poorer GPS constellation PDOP and geometry relative between the satellites and the survey vessel caused initialization to require more than two passes. Note, however, that initialization still occurred in less than 1 min (within the fourth pass). Once the system is initialized, the display will change to reflect that, in addition to the DGPS data, the KOTF high-precision positional data are now available. The statistics for the resultant top five candidates are shown on the screen.

Results from the Real-time Testing

Real-time testing was broken into stages that progressed from static baseline tests, to land mobile tests, and finally to tests in an operational environment aboard a survey vessel. The static tests began in March 1993. These tests determined that the system performed well over the full variation of GPS visibility and conditions. Typically, positions were obtained 98 percent of the time (23.5 hr/day). The remaining 2 percent of the time, integers could not be established because of poor satellite constellations (containing several low-elevation satellites) or not enough satellites. Results from monitoring the system over the static baselines for months of 24-hr periods show that the system is **very** quiet. Typical values are standard deviations of 3 to 4 mm in latitude and longitude (maximum variance, 10 to 20 mm) and 10 mm in height (maximum variance, 50 mm).

The usual setup for any land mobile test or demonstration entailed setting up a truck or cart as the mobile remote user and then navigating the user system to positions previously established using static GPS methods. Several truck tests of this type have been run over ranges from the reference station to the mobile remote, varying from ≤1 to 19.5 km. Both the short- and long-range tests produced similar results for accuracy and repeatability. Horizontal positions checked within 1 to 2 cm, and the vertical positions were within 1 to 3 cm. This type of test involves some stationary occupations of the point; these times were kept to a minimum (almost always less than 1 min). The system was also closely observed while en route between stations, with driving speeds varying between 8 and 40 km/hr. Its performance was found to be very satisfactory. Figure 4 shows some typical results from a truck test run near the John E. Chance and Associates, Inc. (JECA) facilities in Louisiana.

The next step was to move the system onto a survey vessel. Initial tests were run in the vicinity of Norfolk, VA, in August 1993. For these tests, the OTF reference station was installed atop the Norfolk District office building, and the remote/user equipment was installed on the survey vessel (S.V.) *Adams*. These tests compared the real-time vertical positions obtained over time using the OTF system with tide gage readings to determine vertical accuracy relative to tidal movement of the vessel. Additionally, recordings were made using a spirit level as another independent check. For these tests, the *Adams* was tied to the dock for a full tidal swing of 8 hr. OTF positional data were logged on disk and also recorded
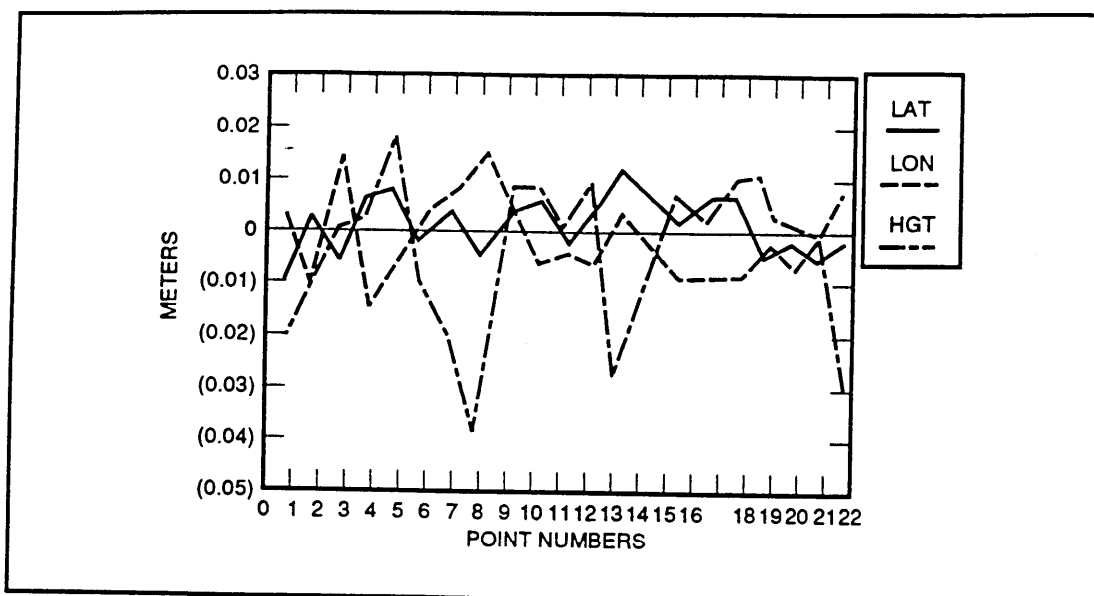
Figure 4. Kinematic land test results

with the tide gage data, measuring to a point on the *Adams*. The distance between the *Adams* and the reference station was 290 m for one test and 1,900 m for the other.

Table 1 summarizes the results from tests run to determine the vertical accuracy of the system. The comparison between the two sets was better over the longer baseline, perhaps a bit surprising. It is thought that this can be attributed to fewer problems arising from boat traffic during the longer baseline test.

Table 1 Results from Vertical Comparison Tests		
Compared	Standard Deviation (290 m)	Standard Deviation (1,900 m)
GPS vs. Level	1.9 cm (0.061 ft)	1.5 cm (0.049 ft)
GPS vs. Gage	1.4 cm (0.045 ft)	1.6 cm (0.051 ft)
Level vs. Gage	1.3 cm (0.042 ft)	0.9 cm (0.029 ft)

Figure 5 shows a detailed plot of the data from the longer baseline test. Field notes show that the passing boat traffic coincides with the larger variations that can be seen on the graph, for example at approximately
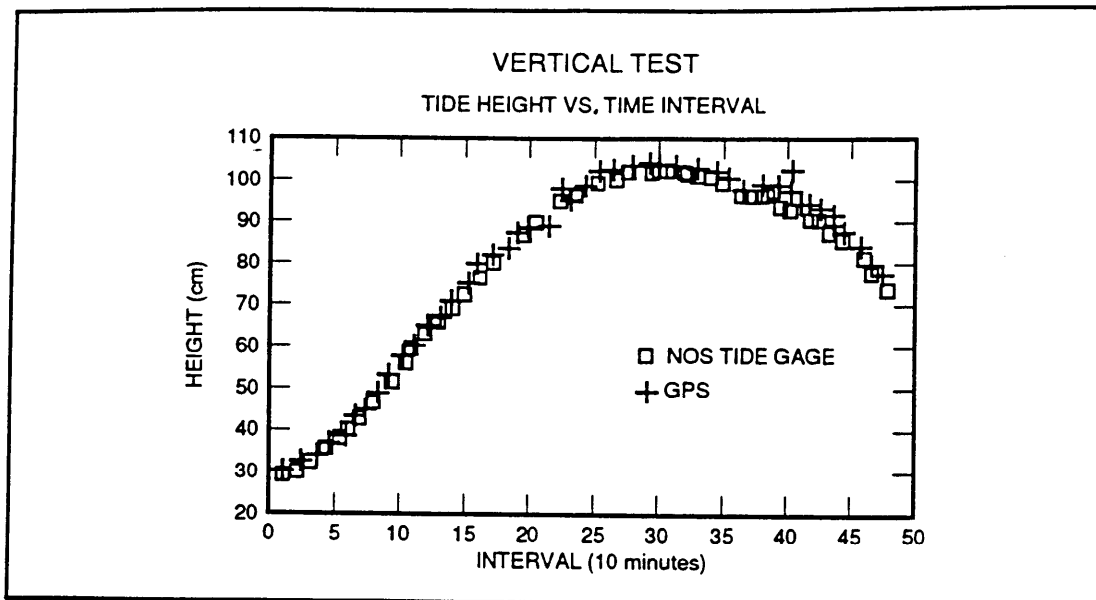
Figure 5. Vertical test results (□ represents NOS tide gage; + represents GPS)

220 min and 390 min. More detailed descriptions of the tests and results mentioned above are given in a previous paper (Frodge and others 1993).

One of the most important advantages of this system for many users is the increased accuracy in the vertical component. During a breakwater survey conducted by JECA in California, the data displayed in Figure 6 were collected. This is a comparison of data collected with a heave compensator at 10 Hz and the vertical data provided by the OTF system at 1 Hz. Because of the differences in rates, the OTF was extrapolated between the data points. The two sets of data compare remarkably well.
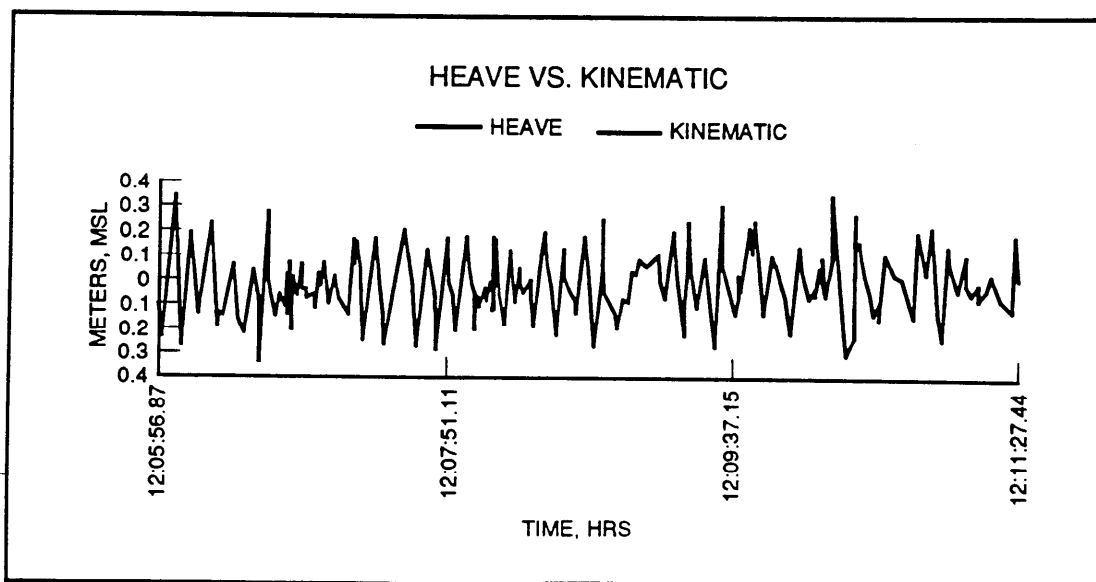

Figure 6. KOTF data compared to heave compensator data

Several tests/demonstrations of the OTF have occurred since September 1993. The first demonstration, in early October 1993, took place in Wilmington, NC—in the downtown area and just south of the city on the Cape Fear River. The site was selected to maximize performance of the range-range system that is normally used onboard the Wilmington District's S.V. *Gillette*. The *Gillette* ran several longitudinal and cross-sectional lines. Running these lines took the vessel underneath a bridge twice, once on the way to the survey area and again on the return trip.

The OTF system was used as positioning input to the HYDRO navigation system that was brought onboard the *Gillette* for the demonstration. The *Gillette* uses HYPACK as its normal system. The HYPACK system used a Del Norte range-range system as its input for positioning. Both systems were hooked into the same fathometer. This part of the demonstration was to show that the OTF system could be used as are comparable systems which the Corps districts already have in operation. Data were saved for later analysis, as well. This analysis focuses on the vertical performances.

The demonstration onboard the *Gillette* also showed how the OTF system performed in an operational environment, for example, automatically reinitializing after experiencing obstructions, such as the Wilmington bridge. As mentioned before, the system usually initialized within 15 sec, although there were occasions where multiple initialization time intervals were required. To demonstrate the specific capabilities of the OTF system, a cart test was run onshore. Changes, adding the forward and backward processing method described earlier, were made in the software between the Wilmington demonstration and the next demonstration (in Astoria, OR) to improve the initialization time.

The demonstration in Astoria took place in mid-November. The general format for the demonstration was the same as that in Wilmington. The OTF system was set up on the Portland District's S.V. *Hickson*. The demonstration site again was selected such that the vessel would have to transit underneath a bridge twice during each demonstration. The shore demonstration used a truck setup. No significant problems were experienced with the OTF system. The worst case experienced was that the OTF system lost lock and did not reinitialize until within the fourth pass. Note that this still took less than 1 min, since each pass is, at maximum, 15 sec. The typical case was that one 15-sec pass was required, and the system initialized in the forward manner on that first pass. There were, notably, several occasions where the *Hickson* passed under the bridge and the system maintained uninterrupted operation at both the meter and sub-decimeter levels. This situation did not occur in Wilmington, probably since the bridge at Wilmington was lower, and some improvements to the software between the Wilmington and Astoria demonstrations increased the robustness of the system.

Other tests that utilize the OTF system are planned or ongoing. The U.S. Army Topographic Engineering Center (TEC) is an experimenter with

the National Aeronautic and Space Administration's (NASA) Advanced Communications Technology Satellite (ACTS) (Austin and Frodge 1993). NASA set the ACTS into position during the recent space shuttle mission. For a 2-week period in December, a static DGPS baseline experiment was run using ACTS as the data link. The baseline length was approximately 320 km. The ACTS was used to provide a real-time data link over that baseline for static DGPS. Although significantly faster rates can be supported by ACTS, a 2-sec update rate was used for these experiments. Meter-level DGPS ran over the link with no apparent problems. The OTF system was not even expected to initialize; however, it did several times and held the KOTF solution for several periods of 0.5 hr or more. Detailed analysis of the data has not yet occurred to determine if these were indeed the correct integers, but even that initialization occurred is intriguing.

During December 1992, an extensive survey was conducted over long baselines stretching over several states using NovAtel cards (Cannon and others, in press). Some of the analysis of these data has focused on resolving the problems of the ionosphere over such long baselines. TEC is hoping to receive funding to double or triple the range of the OTF system to 40 to 60 km. The kind of results obtained from the analysis of the NovAtel survey and the ACTS experiment are some of the groundwork being done to prepare for that effort. It appears very likely that the range can be extended to at least that stated above. The significant limiting factor for use of the system would then be the data link.

The OTF system has been used on production-level jobs by JECA. In addition to the breakwater survey during which the data shown in Figure 6 were collected, the OTF system has also been used to position over 8,000 points in less than 3 weeks for a land survey project (Lapucha, Pottle, and Fellows, in press).

Additional tests were conducted to demonstrate the OTF system onboard a dredge in the open waters of the ocean, as well as in a busy harbor area. In a demonstration onboard the Corps dredge *Essayons*, the system was operated in ocean waters that provided 2- to 4.5-m swells. Also, since the *Essayons'* work is in the shipping lanes, vessel traffic was evident. In another test onboard the *Essayons*, while working in the Richmond Harbor area, the system encountered a realistic operational environment that determined the operational limits and constraints of the OTF system.

Future Testing

Plans are being made to place the system onboard a survey vessel working in a somewhat higher sea state, such as that provided by the mouth of the Columbia River.

Future plans also include using the OTF system as positioning for the autonomous land vehicle (ALV). The ALV has already been tested at

speeds up to 88.5 km/hr on the open interstate with no operator intervention, as evident in a graduate student's impressions recorded on video camera to verify that the vehicle operated without human assistance, that is, robotically. These types of systems can be used in a variety of applications. This type of work is moving toward systems necessary for the development of the Intelligent Vehicle Highway System, as well as for site cleanup of ordnance or in areas that are, for whatever reason, deemed unsafe for humans. Other work in the area of robotics is planned, as well as some potential work in the area of deformation monitoring of large engineering structures. Additionally, an ongoing project is working toward applying the OTF technology to real-time determination of tides. Plans are to collect data over a 6-week period during summer 1994 in the Bay of Fundy.

Conclusions

Centimeter-level accuracy in real time is a reality. The tests have demonstrated that this technology will have a great impact on both surveying and navigation. This particular system is robust, reliable, and easy to use and has surpassed its original design goal specifications. The tests have shown that real-time tide corrections using OTF are possible; this is very important for the dredging industry. Although this system is referred to as a "prototype" and will be further developed, it has far exceeded the original design specifications and can be used today as a reliable working system for applications that require real-time centimeter horizontal positioning, for example, breakwater surveys. It is also a valuable engineering tool for those operations for which postprocessed data will suffice. In reality, it has been demonstrated that real-time OTF is as easy to provide as DGPS within the current range limitations.

References

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