Proposal to Integrate NOAA's Navigation Services through the Application of Real-Time GPS to Position Ships

David B. Zilkoski and **Richard A. Yorczyk**
National Geodetic Survey
Barry Gallagher and **Lloyd C. Huff**
Coast Survey
Douglas M. Martin
Center for Operational Oceanographic Products and Services
National Ocean Service, NOAA
Silver Spring, Maryland 20910

Introduction

Through innovative application of Global Positioning System (GPS) technology and Geographic Information Systems (GIS), mariners have greater access to consistent and accurate positioning than ever before. The capability now exists for mariners to make better informed judgements regarding the operation of their vessels using improved knowledge about the vessel and its surroundings. With this expanded capability, ports and shippers will have the opportunity to safely maximize their capacity. By relating the experience of an ongoing, proof-of-concept project using GPS to accurately position a vessel in three dimensions and in real-time, this paper proposes that the National Oceanic and Atmospheric Administration's (NOAA's) navigational services may use GPS, remote sensing techniques, the National Spatial Reference System (NSRS), and the National Water Level Observation Network (NWLON) to provide the mariner with an integrated suite of decision-making tools. The goal of this proposal is to increase the capacity of American ports by providing them with the entire array of pertinent NOAA data products. These products will be provided to the mariner digitally, in real-time, and will be complete, accurate, consistent, and up-to-date.

The key to safe navigation is accurate positioning. To navigate safely mariners need to know not only where they are, but they simultaneously need to know the location of things around them. The information they need must be consistent, accurate, and up-to-date and also must be accessible in real-time. As part of its mission, NOAA provides tools, techniques, and data that are essential for safe passage through the nation's waterways. Spatial consistency is provided via the NOAA-managed NSRS and NWLON. Positional accuracy is derived from techniques and procedures developed by NOAA. Information describing the physical environment pertinent to marine navigation is acquired, processed, analyzed, and distributed by NOAA. Under the NOAA corporate structure, the National Ocean Service (NOS) has the primary responsibility for NOAA's navigation issues. NOS contains three major structural components with navigation concerns:

- **Office of Coast Survey (OCS)** - provides bathymetry, nautical charts, and docking charts http://chartmaker.ncd.noaa.gov/;

- **Center for Operational Oceanographic Products and Services (CO-OPS)** - provides tidal datum and water level information http://www.co-ops.nos.noaa.gov/; and

- **National Geodetic Survey (NGS)** - the office primarily responsible for managing NSRS - provides the shoreline and geodetic control, ensures spatial consistency by providing access to NSRS, and helps increase positional accuracy by developing and implementing best practices http://www.ngs.noaa.gov/.

Project Description

Typically, when a GPS receiver is used in a stand-alone, autonomous, real-time point positioning mode, with selective availability turned off, the accuracies of the resulting coordinates are on the order of about 10 meters. To achieve greater levels of accuracy a technique called relative positioning can be employed. Relative positioning is a GPS technique that reduces the errors in the position of the user's GPS receiver by using corrections (called correctors) to the received satellite signals which are computed at a nearby GPS reference station temporarily or permanently installed at a known location. Because the location (coordinates of the reference receiver) is already known, rather than computing its position, the receiver at the GPS reference station can compute corrections to the satellite signals. These corrections can be applied to the same satellite signals being received simultaneously by the user's receiver. The U.S. Coast Guard (USCG), by radio broadcast, provides mariners with corrections to GPS pseudo-range measurements from a network of relative positioning sites. When this technique is properly employed, real-time positional accuracies in the 1-10 meter range are regularly attained. For more informatio, see the USCG GPS Navigation Center web site:

http://www.navcen.uscg.mil/gps/

Since the early 1980s, NOAA has carried out geodetic control survey projects in the United States using GPS satellites. These surveys, as well as all completed phases of this project, have been performed using GPS receivers capable of making carrier-phase measurements. Analysis of GPS survey data has shown that GPS can be used to establish precise relative positions in a three-dimensional Earth-centered coordinate system.

NOAA coordinates a network of continuously operating reference stations (CORS) that produce data for post-processing both GPS carrier-phase and pseudo-range measurements in support of three-dimensional positioning activities throughout the United States and its territories. NOAA's

National CORS Network includes all of the USCG relative stations. By using CORS data, accessed from the World Wide Web, in a post-processing mode, GPS carrier-phase measurements can provide 1-3 centimeter (cm) accuracies in all three dimensions. For more information, see NOAA's CORS web site:

http://www.ngs.noaa.gov/CORS/

GPS is routinely used to depict the horizontal location of marine vessels on charts. With the availability of high-accuracy, relative GPS techniques results in real-time, there is a new opportunity to use GPS to accurately measure a marine vessel's dynamic draft (settlement and squat) and three-dimensional attitude (roll, pitch, and heading). By capitalizing on NOAA's Height Modernization efforts in exploiting GPS for accurate height measurement, it is now possible for NOAA to integrate three-dimensional GPS positioning into navigational products and services. NOAA has begun a project to transfer this technology to the Port Authority of Oakland, California. NOAA provides the technical personnel for demonstrating the application on large marine vessels operating in the Port of Oakland. The overall goal of this project is to provide the position of a vessel in real-time to within 10 cm (about 4 inches), including the vessel's keel relative to the bottom of the shipping channel.

This project for real-time, 10-cm, three-dimensional positioning of marine vessels using GPS consists of five activities (phases):

Phase 1 - Demonstration using GPS to determine accurate shipboard heights: demonstrate the feasibility of determining accurate GPS heights on large marine vessels by obtaining GPS data and using post-processing ("after the fact") techniques to determine an accurate relationship of vessel settlement and squat (dynamic draft) for under-keel clearance, as well as an independent measurement of vessel trim, roll, pitch, and heading;

Phase 2 - Real-time demonstration of GPS to determine accurate shipboard heights: repeat Phase 1 in real-time, using the GPS configuration based on the results of Phase 1;

Phase 3 - Acquisition of bathymetric data: acquire information necessary to describe the location and shape of the shipping channel, shoreline, and docking areas in a consistent coordinate system;

Phase 4 - Relation of real-time positioning of a ship to the channel bottom, shoreline, and docking areas; and

Phase 5 - Integration of real-time GPS positioning on ships with electronic charts.

Progress to Date

Phase 1 - Demonstration using GPS to determine accurate shipboard heights
In 1996, the Port of Oakland and NOAA hosted three meetings to discuss a real-time ship positioning project. The participants represented several interested groups. They included:

- Federal agencies (Waterways Experiment Station/U.S. Army Corps of Engineers, USCG, NOAA, and Geodetic Survey of Canada),
- port and harbor authorities,
- various commercial carriers and shippers,
- San Francisco Bar Pilots, San Francisco Marine Exchange,
- GPS and communication manufacturers, and
- private surveyors.

These meetings helped formulate a working understanding within NOAA of users' needs and for users to obtain a better understanding of what the new technology can do for them.

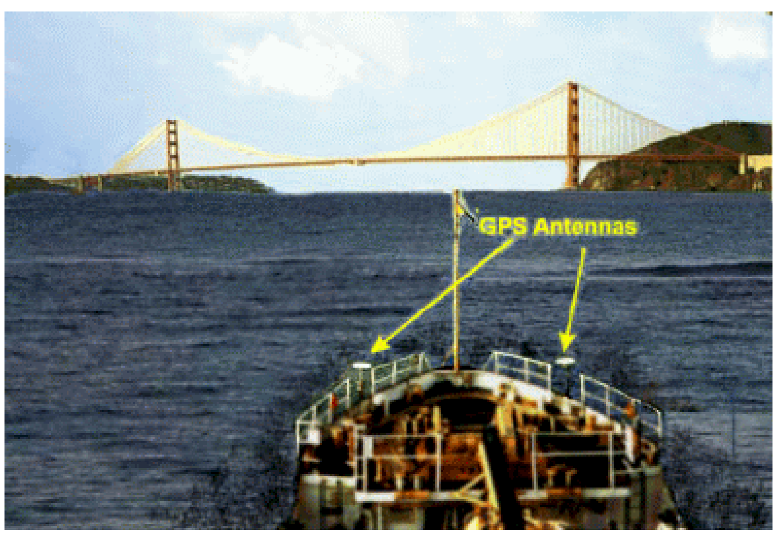

Figure 1 - GPS antennas on the bow of the *Buttonwood*, San Francisco Bay, California.

As part of the proof-of-concept project, in 1996, NOAA, Trimble Navigation Ltd., and USCG collaborated to perform GPS tests on the USCG buoy-tender ship *Buttonwood*. GPS data were used to compute the vessel's dynamic draft and three-dimensional attitude. During the test, five GPS receivers continuously collected data; one at a base station on the USCG pier on Yerba Buena Island and four on the *Buttonwood*-- two on the stern and two on the bow (see Figure 1).

NOAA processed the GPS data and computed the vessel's three-dimensional attitude and dynamic draft. The results indicated that the linear equivalent to the vessel's attitude and dynamic draft were accurate in all three dimensions to the 10-cm level using GPS. The GPS tests also demonstrated how the ship itself served as an effective tool to measure local water-level changes and actual water-level values wherever it traveled.

The primary issue complicating the use of GPS in providing accurate height information arises from relating the various vertical reference systems to one another:

- **Local Tidal Datums** - the arithmetic mean of specific phase of the tide observed over a specific, 19-year cycle.

- **Geoid** - the equipotential surface of the Earth's gravity field which best fits global Mean Sea Level (MSL). The geoid surface is characterized by geoid models which are derived from gravity measurements.

  Note: the geoid surface and Local MSL as measured at tidal stations do not necessarily coincide, due to sea-surface topography effects caused by currents, wind, salinity, and temperature.

- **Ellipsoid** - a smooth mathematical surface derived from rotating a best fit ellipse around the Earth's axis of rotation. The ellipsoid provides a convenient surface for computation of spatial coordinates on Earth.

and three types of heights related to these vertical reference systems:

- **Orthometric height -** the height above the geoid, i.e., popularly called the elevation above sea level. Traditionally, orthometric heights have been determined by classical line-of-sight leveling techniques, but may also be derived from the difference between a GPS-derived ellipsoid height and modeled geoid height at a given point.

- **Ellipsoid height -** the distance above the ellipsoid. It is easily derived from GPS measurements.

- **Geoid height** - the vertical separation between the geoid and the ellipsoid, derived from geoid models.

In 1996, NOAA carried out a GPS survey in San Francisco Bay to relate the local tidal information in terms of ellipsoid heights. (See Figures 2 and 3.) One of the objectives was to demonstrate how GPS-derived ellipsoid heights relative to Mean Lower Low Water (MLLW) can be used instead of classical line-of-sight surveying procedures for mapping, charting, and navigation applications.

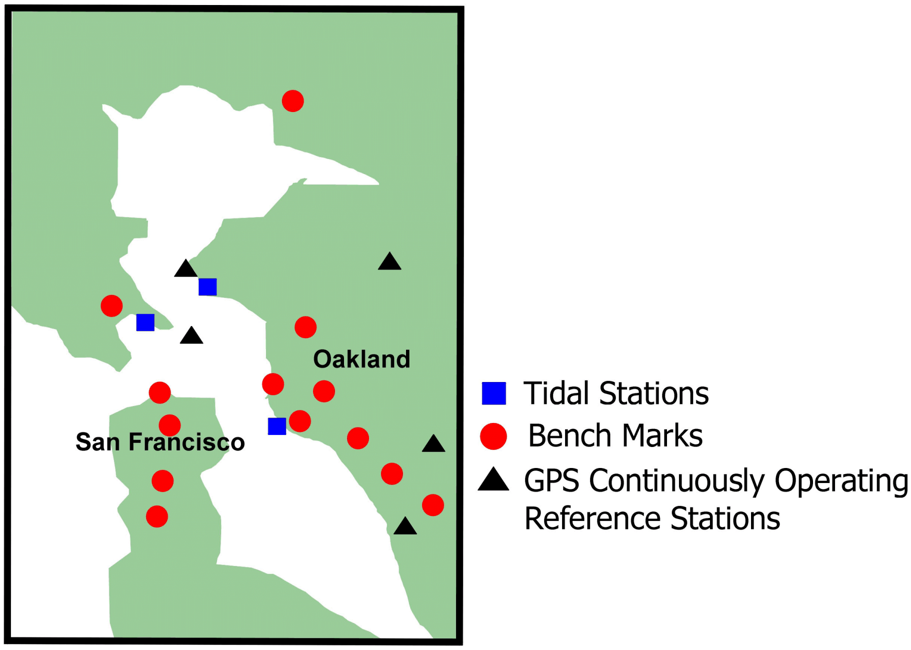

Figure 2 – Survey using GPS to derive ellipsoid heights at three tidal stations and 13 benchmarks.

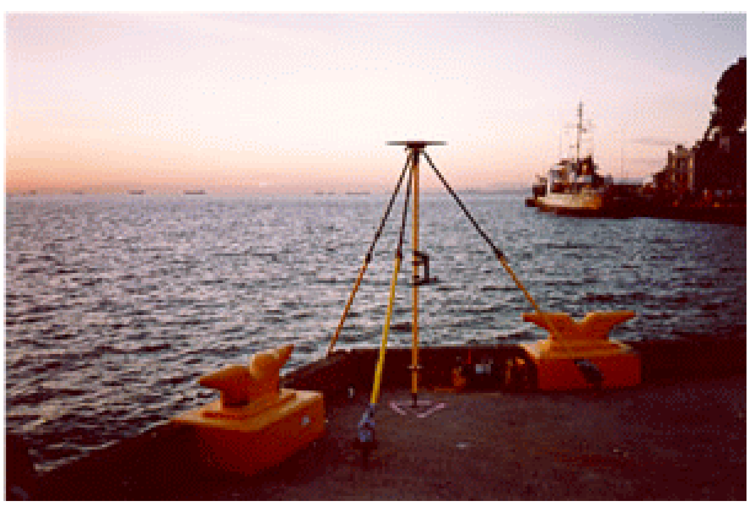

Figure 3 - Occupying tidal stations with GPS.

The chart datum (MLLW on most NOAA charts) is only approximated by a sparse set of tide station observations averaged over long periods of time, hence limiting the accuracies of charted depths. However, GPS can provide consistent depths and heights for a dense network relative to the ellipsoid. In this phase, using GPS results and tidal information, the relationships between ellipsoid heights of tidal bench marks and local sea level measurements, (e.g., mean low water and MLLW), were established at the Golden Gate, Alameda, and Richmond Physical Oceanographic Real-Time Systems (PORTS) sites (Zilkoski and D'Onofrio, 1996).

This technique provides ellipsoid heights for local water level values, placing water levels on a common, accurate, spatially referenced datum rather than approximated sea level heights. Because ellipsoid heights are easily derived from GPS measurements and the mathematical convenience of the ellipsoid for computation, the intent is to get all of the components in the ellipsoid height system. The ultimate goal is to map Oakland Harbor in the ellipsoid height system, including the bottom of the channel, and be able to use GPS on ships in an electronic chart display to transit the Bay and dock during zero visibility. The electronic chart display would generate a warning message to the mariner if the ship gets too close to the bottom of the channel or if the ship transits outside the navigational channel.

Automated navigation will happen. Implementation is only a matter of time. But, until tidal datums and bottom depths are referenced to the ellipsoid, GPS-ellipsoid heights need to be converted to heights relative to the geoid using the following equation: GPS-derived orthometric heights are mathematically equal to GPS-derived ellipsoid height minus the geoid height (the vertical separation between the geoid and ellipsoid).

An adequate knowledge of the difference between the geoid and ellipsoid surfaces was necessary for full implementation of the height modernization effort in San Francisco Bay.

When the resultant GPS-derived orthometric heights were compared to published leveling-derived orthometric heights, the difference between the two exhibited a downward tilting trend across the bay from Oakland to San Francisco.

Figure 4a indicates that there is a small tilt, less than 10 cm between the GPS-derived orthometric heights and published leveling-derived orthometric heights, from San Francisco to Oakland. This is due to remaining uncertainties in the ellipsoid heights, geoid heights, and orthometric heights. With the luxury of post-processing, this trend can be accounted for and alleviated. In the case of real-time vertical positioning relying on GPS, NOAA would provide correctors, in real-time, to remove this nearly 10-cm uncertainty which would otherwise have to be added to the error budget. Figure 4b depicts the differences after the trend was removed from the differences. Figure 4b indicates that the overall difference between the GPS-derived orthometric heights and leveling-derived orthometric heights is in the 2-cm range. This comparison also indicates another problem, a systematic slope near the Golden Gate Bridge (-2.3 cm). This may be an indication of local subsidence which would have the effect of physically lowering the bench mark. Future GPS surveys are planned to determine if this is true movement or remaining systematic errors in the height differences.

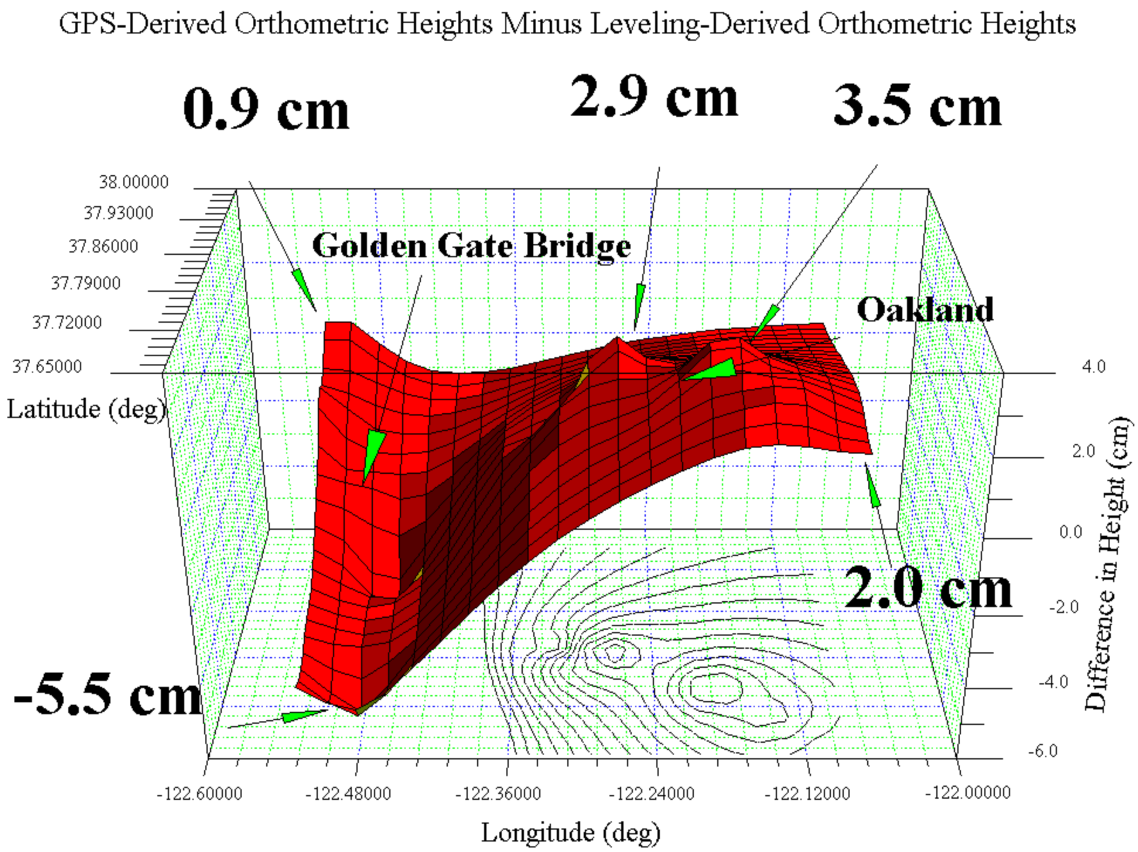

Figure 4a – Plot of differences between GPS-derived heights and classically-leveled heights in San Francisco Bay.

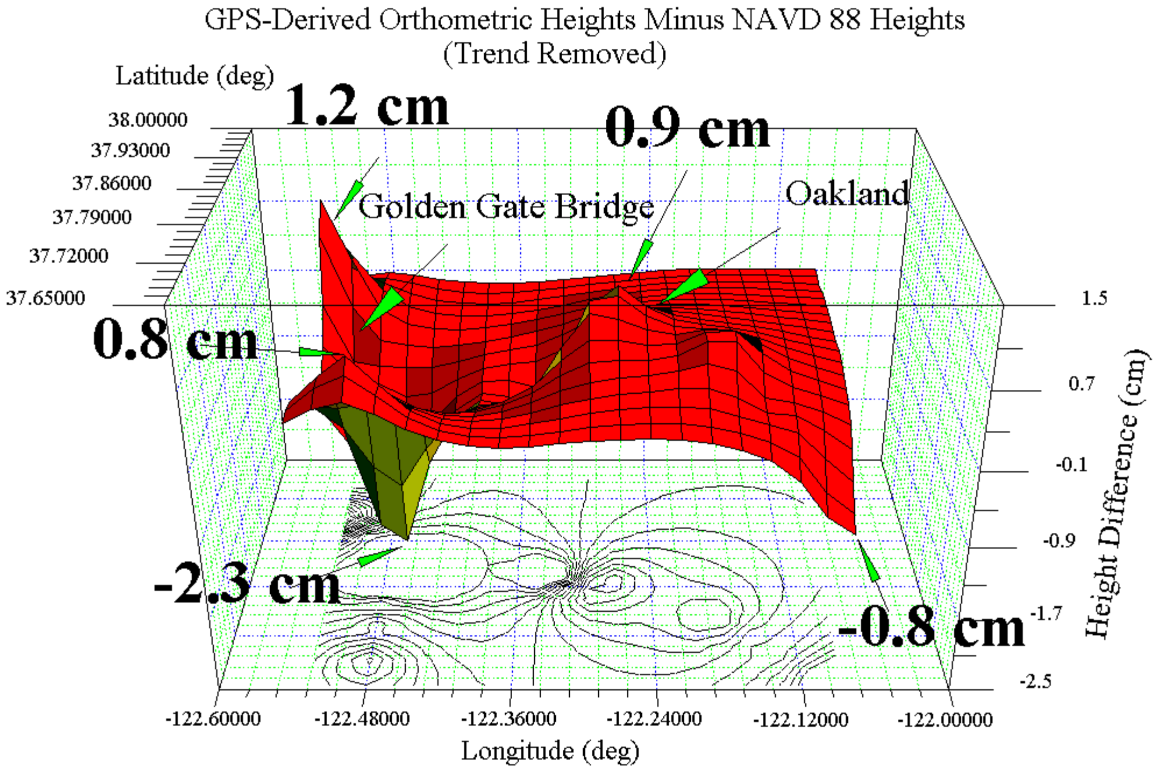

Figure 4b – Plot of differences between GPS-derived heights and classically-leveled heights in San Francisco Bay.

In deriving orthometric heights from GPS measurements and relating them to tidal datums and water levels, there are several factors contributing to uncertainty:

- Local tidal datums - from sparseness of tidal stations.
- Tidal datum and orthometric height reference - from impacts of crustal motion - uplift and subsidence of the Earth's surface impact accuracy of tidal stations and bench marks.
- Geoid model - from sparseness of near-shore gravity measurements and the effect of steep offshore slope of the ocean bottom found along the Pacific Coast.
- Orthometric height reference - from sparseness of bench marks which are necessarily only on land.
- GPS measurement biases - from multipath effects caused by reflected GPS signals arriving at the receiver and from ambiguities in the carrier phase measurements.

Improvements to the geoid model will help mitigate the problems with deriving orthometric heights from GPS measurements. The geoid model can be improved locally in some areas by collecting nearshore gravity data which can be efficiently acquired from low-flying, airborne gravity surveys.

Multipath effects are caused by GPS signals arriving at the receiver from multiple sources, not just directly from the GPS satellite, but also from reflection off nearby structures or reflective surfaces. These effects may be alleviated to some extent by better placement of the GPS antenna, but the greatest impact on multipath effects are likely to result from hoped for improvements to the GPS antenna design and through development of special filtering algorithms for use within GPS receivers.

In carrier phase measurement, the range from the satellite to the receiver is derived from computing the number of full wavelengths of each signal plus the fractional length of the last wavelength. Inherent in using carrier phase measurements is integer ambiguity, i.e., determination of the number of full wavelengths, because only the phase within a wavelength is directly measurable. Techniques now exist to help resolve these ambiguities, but they can benefit significantly if GPS modernization includes the addition of a third civil signal on GPS satellites.

The 1996 report by Zilkoski and D'Onofrio titled "The Geodetic Phase of NOS' San Francisco Bay Demonstration Project," which describes the project in detail, is available on the NGS web site at:

http://www.ngs.noaa.gov/initiatives/HeightMod/Geodetic/sfbay_geodetic.html

Phase 1 has been completed and documented in a report by Zilkoski et al. (1999). The full report can be downloaded from the NGS web site at:

http://www.ngs.noaa.gov/initiatives/HeightMod/Buttonwood/

Phase 2 - Real-time demonstration of GPS to determine accurate shipboard heights
During 1997, 1998, and 1999, NOAA installed several GPS receiver arrays on large marine vessels and oil tankers and collected accurate GPS-derived bathymetric data in selected sections of the shipping channel.

Shipping lines Maersk, Orient Overseas Container Line, and SeaRiver Maritime participated in this phase which included installing GPS receivers made by two different manufacturers on five container ships and one tanker. The GPS receivers and supporting equipment were installed in outside cases or in an inside arrangement that protected the equipment from shock, vibration, overheating, and spray. On the container ships, the GPS receivers used to measure height and attitude, computers, other electronics, batteries, and fan were mounted in self-contained, padded, ventilated metal cases (Figure 5). These equipment cases were specially designed and built by NOAA and each was attached to an alternate twin deck (ATD) platform, which allowed positioning on top of a cargo container anywhere on the ship. Two GPS receivers were also mounted in separate ice coolers modified to house a battery and the receiver, and were used for measuring height only.

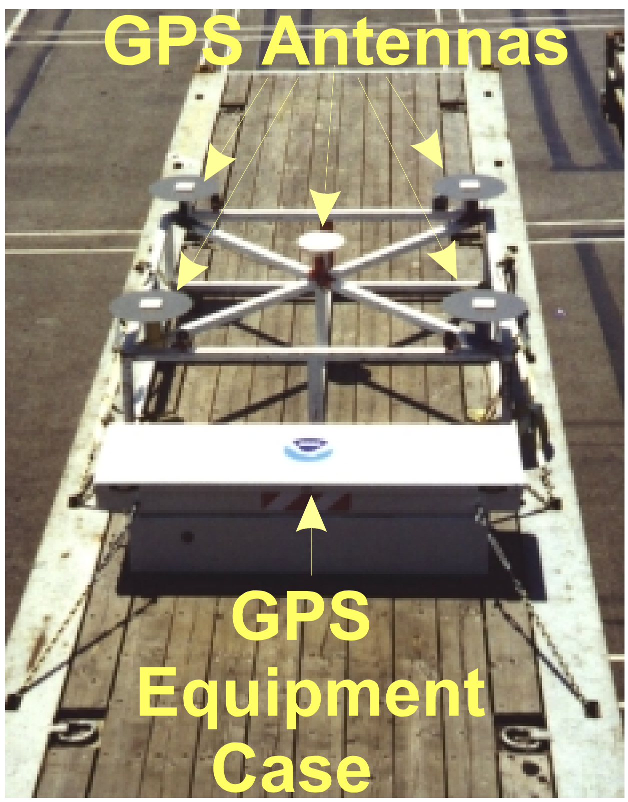

Figure 5 - Equipment used for GPS height and attitude measurement on an ATD.

Figure 6 - Container ship with ATD mounted on top container

GPS antennas were mounted at six locations on the container ship to measure heights. Two of the antennas were placed on the bridge wings, one port and one starboard, across from each other. The GPS antennas on the bridge only measured height. The GPS antennas on the ATDs measured heading, roll, pitch and height. This arrangement allowed for computing depth of keel from each of the five levels shown in Figure 7.

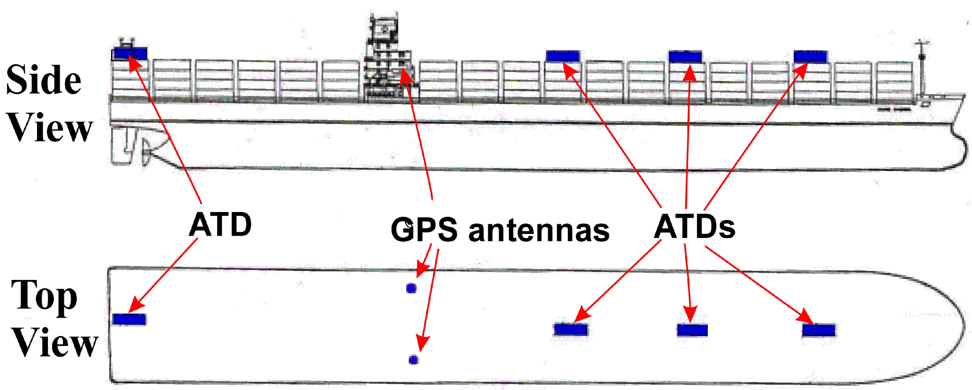

Figure 7 - Layout of GPS equipment on container ships

The typical, one-way, operating time between the ports of Oakland and Long Beach was approximately 37 hours. The 37-hour data cycle included: bringing all systems mounted on the ATD's up to operational mode; waiting for loading; loading; installing bridge GPS antennas; transit; off loading, removal of GPS antennas, and waiting for delivery of ATD's to the NOAA staging area. The GPS hardware operated flawlessly in both inside and outside applications. This field experience confirmed the hardware's ruggedness, as claimed by GPS receiver manufacturers. This 37-hour cycle was performed for five transits between these ports for a total of 185 hours on different container ships.

This demonstration of GPS on container ships, a tanker, and a NOAA launch has shown that the use of GPS to measure squat and settlement offers greater measurement accuracy and measurement opportunity when compared to previous technology. Aided by full-scale testing, the observations made in the field agreed with measurements obtained by older traditional equipment and techniques, which helps to confirm the validity of the technology used. The ability to measure vertical motion (hence dynamic draft) in the centimeter range, 24 hours a day, by GPS, provides the accurate determination of a variety of ship characteristics and data for better under-keel clearance management.

Knowledge of a vessel's dynamic draft (settlement and squat) is essential for the mariner to accurately determine the vessel's under-keel clearance. Settlement is a speed dependent, local depression in the water surface around the hull as the vessel moves through the water. The vessel finds itself in the trough of the artificial wave caused by the vessel's motion through the water. The water is locally not as deep and thus the bottom of the vessel is closer to the bottom than it would be if the ship were not moving. Squat is a speed dependent change in vessel trim (angle of the vessel's waterline with respect to the water surface) caused by motion of the vessel's hull through the water. In order to compensate for the possible impacts of dynamic draft, it is a common practice for large vessels to add about one meter to their predicted settlement and squat, to ensure a safe margin in their under-keel clearance.

Though not the intent of the project, the GPS receivers arrayed on the container ships were able to detect flexing of the vessels' hulls. When a ship is subjected to various unequal forces along its hull, it will often flex and twist in response to those stresses. Large vessels are subject to pronounced hogging and sagging (Rawson and Tupper, 1968), a phenomenon relating to a ship bending up in the middle (hogging) and bending up at both ends (sagging). Static loading, sea surface waves, and propulsion are the most significant causes of flexing. If the strain on the vessel is too great, it may endanger the ship's structural integrity. This application of GPS may in the future prove to be of assistance in warning mariners when the vessel's hull is in danger of deforming beyond its recommended constraints. Since the maximum draft occurred at midship bilge keels during turns and GPS receivers were mounted on each side of the ship, it was not required to measure twisting. In future experimentation, twist could be measured by installing fore and aft outriggers with GPS antennas along each side of the ship.

An in-depth description of the applications of GPS technology for measuring vessel settlement and squat can be found on:

http://chartmaker.ncd.noaa.gov/csdl/htp/sas.html

Phase 3 - Acquisition of bathymetric data:
NOAA has determined heights (both ellipsoid and orthometric) for marks in a dense network along a "pilot" area of the shoreline in San Francisco Bay. By using GPS data collected simultaneously during an aerial photogrammetry flight and at CORS sites in the area, NOAA has combined GPS-controlled, tide-coordinated photography, soft-copy (digital) photogrammetric techniques, and analytical photogrammetric techniques to generate the digital shoreline and docking charts in the pilot area. Figure 8 illustrates a digital output from the photogrammetric process.

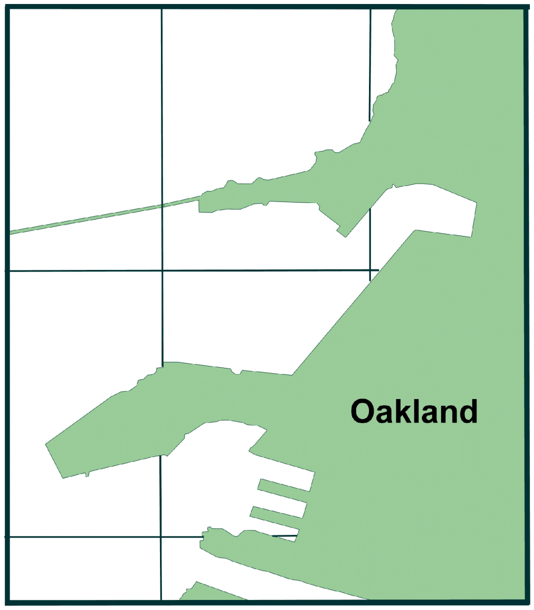

Figure 8 – Digital docking chart and shoreline of Oakland Harbor generated using photogrammetric techniques.

A seamless digital data base, which takes full advantage of both CORS and the modernized height system, will be created for the pilot area. Soft-copy photogrammetry technology will be used to experiment with the generation of digital terrain models which are otherwise too labor-intensive to efficiently implement (Tuell, et al. 1999).

Phase 4 -Relation of real-time positioning of a ship to the channel bottom, shoreline, and docking areas:
An electronic demonstration of the results of positioning a large container ship in the Port of Oakland has been developed and will soon be made available by NOAA.

Phases 2, 3, and 4 have been completed and are in different stages of documentation. Certain aspects of these phases have been reported in Parker (1998) and Parker and Huff (1998).

FUTURE PLANS

Having accomplished the first four phases, NOAA is now prepared to demonstrate the integration of the system (**Phase 5**) and display the results on a computer screen on the bridge of a ship (see Figure 9) as depicted in Figures 10 and 11. There are many possible ways of integrating and presenting the integration of the system.

Figure 9 – Computer display on the bridge of a ship

Figure 10 depicts a ship's horizontal track on a digital chart of Oakland Harbor as well as the ship's roll, settlement, speed, and under-keel clearance. The ship's pilot would look at a computer screen on the bridge of the ship that displays the location of the ship overlaid on a map that outlines permanent obstructions, i.e., shoreline, islands, rocks, etc., such as shown in Figure 10. The screen could indicate a visual flag and/or sound an audible alarm if the ship gets too close to an obstruction.

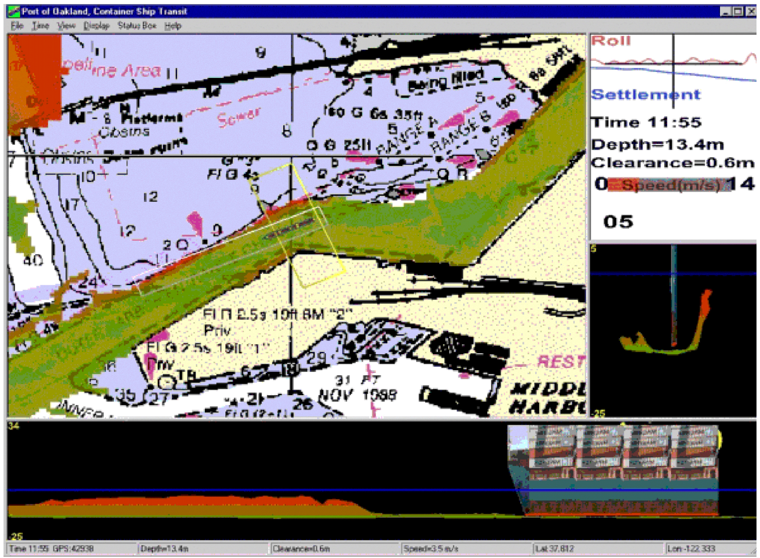

Figure 10 – Ship's horizontal movement, roll, settlement, speed, and under-keel clearance displayed on an electronic chart

By using GPS to position the hydrographic vessel during the bathymetric survey, the bottom of the channel can be accurately related to the bottom of the ship's keel. As previously mentioned, in support of the project, NOAA collected accurate GPS-derived bathymetric data in selected sections of the shipping channel so the mariner will now be able to look at a computer screen on the bridge of the ship and know the exact location of the ship's keel relative to the bottom of the channel. Note that in this example, the field indicates that ship's keel is only 0.6 meters from the bottom of the channel.

Now that the ship is able to transit through the channel and harbor without running aground, the mariner next needs to know precisely where its pier is located. GPS and photogrammetric techniques are used to accurately position the shoreline and piers based on NSRS. Because the pier's location is in the same reference frame as the ship, water level, shoreline, and bottom of the channel, the mariner is able to safely dock the ship even under conditions of poor-to-zero visibility. Figure 11 depicts the *Buttonwood* docking at the USCG facility at Yerba Buena Island.

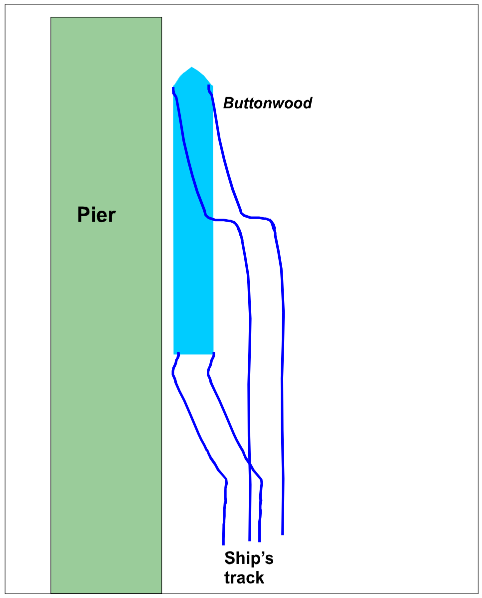

Figure 11 – GPS data charting the *Buttonwood's* track during docking maneuver.

This year, NOAA will initiate discussions to implement partnerships with representatives of the Port of Oakland and the shipping industry to install GPS receivers, computers, and communication equipment on a passenger vessel in San Francisco Bay, integrating GPS results with electronic chart products. The project will demonstrate how NOAA products and services promote safe navigation. This technology transfer effort will enable the Port of Oakland to better conduct business with their clients' shippers, to better interface with NOAA future electronic chart products, and more efficiently and safely plan for future increases in vessel size. The integration of real-time GPS positioning on marine vessels with electronic charts will facilitate the development of accurate docking charts. These charts have the potential to enable large commercial vessels to dock in major harbors under conditions of very poor visibility and will significantly reduce weather-related harbor delays. This project is a major step toward the realization of using electronic charts for safe navigation.

Predicting Water Level Values in the Middle of the Channel

NOAA realizes that mariners need to know what the predicted water level is going to be during transit, i.e., the predicted water level values where the ship is going to be 30 minutes ahead. Therefore, in addition to using GPS to position ships, NOAA will be measuring water levels with a GPS-fitted buoy in San Francisco Bay and computing tidal constituents to provide predicted water level values in mid-channel in addition to the conventional near-shore predictions. Several PORTS are in operation in U.S. harbors. PORTS, developed by NOAA scientists and engineers, is now operational in several U.S. harbors The system measures currents, water levels, and other physical conditions at specific locations in a harbor, such as at the Golden Gate, Alameda, and Richmond in San Francisco Bay. By providing information about actual conditions at specific sites, PORTS allows mariners to use the bay's channels to their fullest extent, while simultaneously increasing safety. More information about PORTS can be obtained on the NOAA CO-OPS web site at

http://www.nos.noaa.gov/programs/coops.html

Mariners can now access PORTS information before entering the bay. Currently, they can only obtain actual water-level values at the specific PORTS location; all other water-level values are based on models. One key ingredient in providing good water-level nowcasts (i.e., real-time predictions at hundreds of locations throughout the bay) is obtaining real-time water level data at strategic locations in the harbor that represent the water level signal propagating throughout the port, i.e., wind-induced water-level changes. Actual water-level measurements obtained at near shore sites strategically located throughout the harbor compared with the forecast water levels can be used to validate and improve the model. Improved water-level models mean that the mariner will more accurately know the separation between the keel and the bottom of the channel. Water-level data from a buoy equipped with a GPS system can provide the data needed to improve and validate the water-level model and eventually update the models in real-time. Comparing GPS-buoy data with forecast model data will enable users to supplement the models with current data when they over-or-under estimate reality. They are not changing the model, just the output.

With the availability of high-accuracy differential GPS results in real-time, it is possible to use GPS to accurately measure the position of a buoy equipped with GPS. NOAA is also transferring this technology to the maritime community. NOAA has installed a GPS buoy system in San Francisco Bay (see Figure 12). NOAA provided the logistics, two GPS receivers, batteries, solar panels, a computer, and modems, and USCG provided a buoy, assisted in modifications of the buoy to equip it with the GPS system, and deployed the buoy. NOAA personnel processed the GPS data and prepared height values, plots, and statistics.

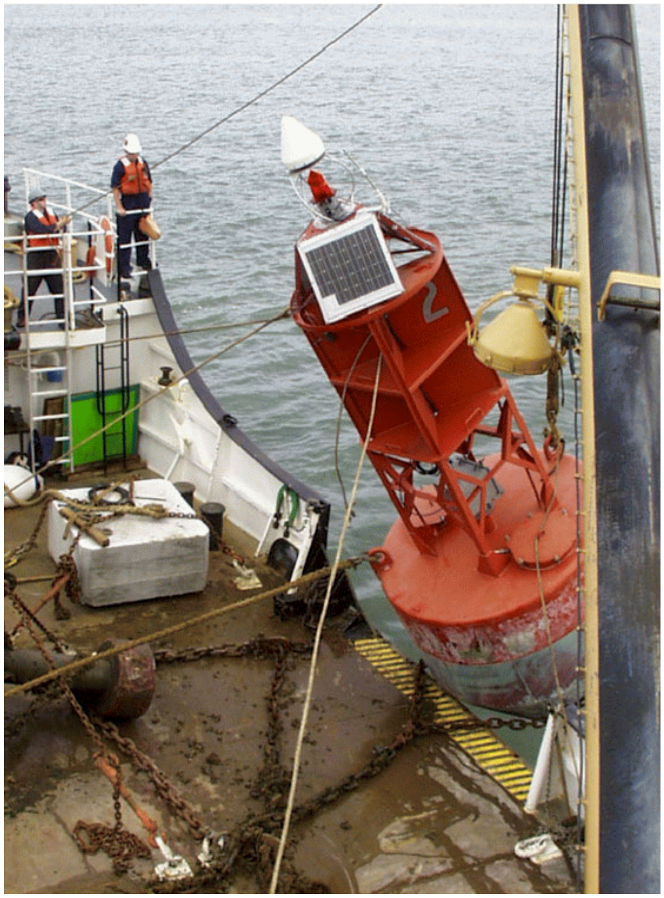

Figure 12 - GPS-fitted buoy being deployed in S.F. Bay

The vertical positions of the buoy in the bay were continuously determined with a precision of 2-3 cm. The solutions showed excellent agreement with the data from a nearby tide gauge and clearly proved the feasibility of remote GPS operations with renewable power and radio modems (see Figure 13). Applications for obtaining real-time water heights in shipping channels or offshore are promising. This project will enhance the efficiency and effectiveness of future water measurements in U.S. harbors including the Great Lakes, as well as other navigable waterways.

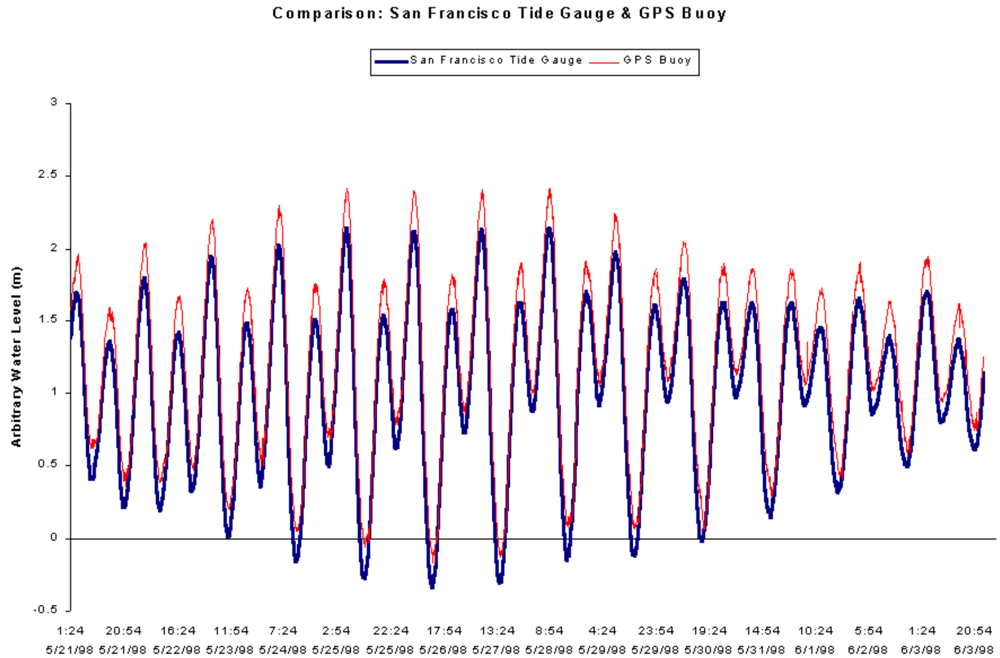

Figure 13 – Comparison of GPS Buoy with Tidal Buoy

The results of the project will be used to improve the design of the GPS buoy system in order to measure actual water-level values. These values will be used to validate water-level models, provide data for testing a new continuous water-level zoning technique for hydrographic surveys (and other applications), and investigate the use of buoys equipped with GPS for detecting real-time directional changes in water currents.

During fiscal year 2001, NOAA will be developing routines to retrieve data from the buoy and post the data in real-time on the web. Eventually, water-level values derived from the buoy will be transmitted to the ship, providing the mariner the most up-to-date water levels.

Conclusion

The key to safe navigation is accurate positioning. NOAA's products and services provide the tools to enable mariners to simultaneously know where they are as well as the things around them. NSRS provides the spatial framework consistency needed to relate objects to one another. GPS provides the capability for acquiring positioning data, and techniques developed by NOAA provide the capability for achieving the levels of positional accuracies required. NOAA proposes a navigational service that uses GPS, remote sensing techniques, and NSRS to provide the mariner with an integrated suite of decision-making tools. The goal is for these products to be provided to the mariner digitally, in real-time, and to be complete, accurate, and up-to-date.

References

Parker, B. B. and L.C. Huff, 1998: Modern Under-Keel Clearance Management, International Hydrographic Review, Monaco LXXV(2), September 1998.

Parker, B. B., 1998: Marine Applications of GPS in the National Ocean Service, Proceedings of the International Symposium on Marine Positioning 1998, Melbourne, Florida, November 30 - December 4, 1998.

Rawson, K. J. and Tupper, E. C., Basic Ship Theory, American Elsevier Publishing Co., Inc., 1968.

Tuell, G., M. Aslaksen, and J. Lucas, 1999: Generation of a High Resolution DEM Using Automated Digital Photogrammetric Techniques, NGS Project Report, April 23, 1999, Silver Spring, Maryland 20910.

Zilkoski, D. B., J. D. D' Onofrio, R. J. Fury, C. L. Smith, L. C. Huff, and B. J. Gallagher, 1999: Centimeter-Level Positioning of a U.S. Coast Guard Buoy Tender, GPS Solutions, John Wiley and Sons, Inc. (At Press).

Zilkoski, D. B. and J. D. D' Onofrio, 1996: "Geodetic Phase of NOS' San Francisco Bay Demonstration Project," Proceedings of GIS/LIS '96 Annual Conference, Denver, CO, November 19-21, pp. 116-127.

Glossary

ATD - Alternate Twin Deck - arrangement used in mounting GPS receivers on container ships.

Bathymetry - the measurement of water depths.

Carrier-phase measurement - at one or both carrier signals (actually being a measurement on the beat frequency between the received carrier of the satellite signal and a receiver-generated reference frequency). Potentially accurate to less than 1 cm.

CO-OPS - Center for Operational Oceanographic Products and Services - an office of NOS.

CORS - Continuously Operating Reference Station - the National CORS is a set of permanent GPS reference stations meeting NOAA geodetic standards for installation, operation, data archiving, and data distribution

DGPS - Differential Global Positioning System - is a positioning technique that reduces the pseudo-range measurement errors in the GPS signal at the location of the user's GPS receiver by using corrections to the received signals which are computed at a nearby GPS reference stations established at a known location.

Dynamic Draft - the combination of vessel's settlement and squat that impacts the under-keel clearance.

Ellipsoid - smooth mathematical surface derived from rotating a best fit ellipse around the Earth's axis of rotation. The ellipsoid provides a convenient surface for spatial computation.

Ellipsoid Height - the distance, perpendicular to the ellipsoid, to a point from the ellipsoid.

GIS - Geographic Information System

GPS - Global Positioning System

Geoid - the equipotential surface of the Earth's gravity field which best fits Mean Sea Level. Note: the geoid surface and Mean Sea Level as measured from tidal stations do not necessarily coincide due to permanent deformations in the sea surface caused by winds, ocean currents, and water density.

Geoid Height - the distance, taken perpendicular to the ellipsoid of reference, from the ellipsoid to the geoid.

Height Modernization - an effort to enhance the vertical component of NSRS which includes a series of activities designed to advance and promote the determination of accurate heights through the use of GPS surveying techniques, rather than by classical, line-of-sight leveling techniques.

MLLW - Mean Lower Low Water.

MSL - Mean Sea Level.

Multipath - GPS signals reflecting off nearby structures or other reflective surfaces en route to the receiver.

NGS - National Geodetic Survey - an office of NOS.

NOAA - National Oceanic and Atmospheric Administration

NOS - National Ocean Service - NOAA administrative component which includes NOAA's primary navigation responsibilities.

NSRS - National Spatial Reference System - a consistent national coordinate system that specifies latitude, longitude, height, scale, gravity, and orientation throughout the Nation, as well as how these values change with time. NSRS is defined and managed by NGS.

NWLON - National Water Levels Observation Network.

OCS - Office of Coast Survey - an office of NOS.

Orthometric height - the height above the geoid, i.e. elevation above sea level. Traditionally orthometric heights have been determined by classical line-of-sight leveling techniques, but may also be derived from the difference between the measured ellipsoid and modeled geoid height at a given point.

PORTS - Physical Oceanographic Real-Time Systems

Photogrammetry - use of aerial photographs for accurate mapping
    Analytical photogrammetry - employs manual stereoplotter
    Soft-copy photogrammetry - digital technique

Pseudo-range (code) measurement - equivalent to the difference of the time of reception (expressed in the time frame of the receiver) and the time of transmission (expressed in the time frame of the satellite) of the navigation satellite signal. Typically accurate to about 1 m.

Relative Positioning
The GPS technique used to determine the relative positions between two or more receivers which are simultaneously tracking the same GPS signals. One receiver, whose coordinates are known, is called a reference or base station, often a CORS. The second receiver, either stationary or moving, is used to determine its own location.

Sea level (Mean) - the arithmetic mean of heights of the water's surface observed hourly over a specific19-year cycle, which effectively averages out the tidal variations.

Selective Availability (SA) - intentional degradation of GPS standard positioning service available for civilian use in single receiver positioning. Originally implemented for security reasons, SA was turned off on May 1, 2000.

Settlement - a speed-dependent, local depression in the water surface around the hull caused by the vessel moving through the water.

Squat - a speed-dependent change in vessel trim (angle of vessel's waterline with respect to the water surface) caused by motion of the vessel's hull through the water.

Subsidence - lowering of the ground surface, often caused by ground water or petroleum draw down.

Under-Keel Clearance - the vertical distance between the lowest point of a ship and the channel bottom.

USCG - U.S. Coast Guard