Improvements to Water Level Reducers for Hydrographic Surveys in Hydrodynamically Complex Tidal Regimes

Gretchen Imahori, W. Michael Gibson, and Kristen Tronvig [1]

National Ocean Service, NOAA

Abstract

Marine Transportation System (MTS) safety and improved technology have placed great demands on the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) to increase the efficiency of processing hydrographic surveys to update our Nation's suite of nautical charts. One major factor affecting processing hydrographic data is existing methodology for determining water level reducers. In any tidal area, water level reducers are the largest vertical correction to sounding data and uncertainties in their determination can dominate the total error budget. Even in areas with a small tidal range, such as the Gulf of Mexico, the total water level variations can be larger than the range of tide and will still affect sounding accuracy. If water level reducers are not properly measured and applied, then hydrographic error budget requirements may not be met. This paper discusses several improvements to water level reducers in order to expedite and increase the efficiency and accuracy of hydrographic survey data for nautical charting purposes.

Currently, NOS utilizes a technique called "discrete tidal zoning", which defines geographic areas of similar tidal characteristics using polygons (or discrete zones), to assign water level reducers to sounding data. This technique provides for the computation of tide corrections, as depth soundings during hydrographic surveys are acquired at all phases of the tide (Tronvig and Gill, 2001). These tides corrections (or reducers) must be then applied to the soundings in order to reduce them to Chart Datum, Mean Lower Low Water (MLLW) (National Ocean Service, June 2002). To meet error budgets, projects should be planned to take into account the appropriate blend of the number of stations, the length of series for datum determination, and the amount of extrapolation using tidal zoning. However, in areas where tidal regimes and other water level effects (i.e. meteorological) are complex, minimizing potential errors using tidal zoning techniques requires additional water level gauging which lengthens the time window for producing final water level corrections. To improve upon the drawbacks for accuracy and efficiency inherent in the use of discrete tidal zoning GPS-tracked buoys**,** Tidal Constituent and Residual Interpolation (TCARI), Kinematic Global Positioning System (KGPS), and the Vertical datum (VDatum) tool may be implemented. However, as NOS prepares to fully implement these new technologies, there are other short-term improvements which may be able to help hydrographers where gauge coverage is inadequate or non-existent. Provisions can also be made to improve questionable

[1] The authors would like to acknowledge the contributions of the following people: Mike Brown, Stephen Gill, Brian Greenawalt, Kurt Hess, Jack Riley

historical stations, where existing datums may be invalid due to physical conditions such as: silting, dredging, uplift and subsidence.

Introduction

The MTS moves over ten trillion dollars of cargo annually. This cargo includes vehicles, clothes and electronics to name just a few. Our economy is dependent on the unremitting flow of these goods through the Nation's ports and as commerce doubles in the next 20 years, there is increasing concern regarding the continuous flow and safety of our ports (Rodney, 1999). Accidents by commercial vessels continue to remain a major concern for NOAA with approximately 3,500 commercial accidents occurring annually and about three quarters of these due to human error. Moreover, with the increase in length, width and draft of cargo ships, room for error with respect to typical port least depths becomes slim and the likelihood of accidents greater. Additionally, the recent realization that our ports have become susceptible targets and are vulnerable to terrorist attacks has only heightened NOAA's awareness to the various fatal impacts on our Nation. Support for maritime commerce, combined with a focus on safe navigation for protection of life, property and the environment, compels NOAA to re-evaluate the accuracy and adequacy of our nation's charts with respect to increasing vessel size and other significant factors. Realizing both the accuracy and coverage benefits of multibeam and other modern hydrographic technologies, NOAA must now ensure that hydrographic data are applied with greater expediency to update navigational products. While NOAA has increased its proficiency of acquiring hydrographic data, it still faces some challenges to incorporate the newest hydrographic data onto the very latest charts.

Over the past few years, NOAA has increased its efforts for developing Electronic Navigational Charts (ENCs) to better support the growing marine transportation infrastructure. At the present rate of production, NOAA expects to develop and maintain over half of the 1000 ENCs necessary for full contiguous coverage of U.S. waters by 2006. Due to public demand for increased ENC output, future budget initiatives will request the necessary resources to complete the task sooner. However, NOAA faces many limiting factors that would not allow it to go to "full production" at this point. NOAA's Office of Coast Survey has begun to examine, discuss, and recommend potential plans to streamline hydrographic, charting and water level production into a more suitable "pipeline" given new improved technologies such as ENCs.

Aside from new technologies arising in the charting forum, gains in acquiring hydrographic data have been substantial. In 2000, NOAA changed from analog to digital side scan sonar and then shortly began its transition to the high speed high resolution Klein 5000 side scan sonar. Data collection more than doubled and NOAA hydrographers found themselves ensconced in the search for better data storage devices. At about the same time, the NOAA hydrographic fleet was equipped with multibeam systems such as the Reson 8101 and then later Reson 8125. While the great advantages of full bottom coverage became clear to hydrographers, NOAA had to face the challenge that came with massive amounts of data. The current production "pipeline" was accustomed to significantly less data than it was now going to receive.

In a recent report assembled by representatives from each division within the Office of Coast Survey (OCS), the group came up with a principle recommendation for OCS's system as a whole and recommendations for a few corresponding areas.
The process of water level corrections was just one of the areas identified as an area of interest to examine the potential, if any, of long-term and short-term improvements.

Conventional water level measurements are typically made at coastal (i.e., shore) locations and offshore water level corrections must be estimated from the coastal measurements through a process referred to as tidal zoning. However, even when well-trained personnel conduct zoning, it often involves subjective procedures. Numerical computer models help, but models have uncertainties that should be reduced by considering actual offshore data for inputs and /or validations. Poor offshore tidal elevation estimates can result in discrepancies at intersections of sounding lines, which may cause a rise in total cost and processing time to resolve. Poor estimates are most detrimental in shallow water where wrecks, obstructions, or shoals may be hazards to navigation and minimizing depth uncertainties is more critical (Earle *et al.*, 2002).

Currently, tide predictions or preliminary observed data from the closest operating tide gauges and preliminary tidal zoning are applied to hydrographic survey data to correct the sounding data to Chart Datum (Mean Lower Low Water). The data from short-term stations established during survey operations must eventually undergo reduction to Chart Datum. Depending upon the number of stations required, the provision of final tide reducers can take up to several months after the beginning of survey operations in order for the data to be collected, tidal datums computed, and tidal zoning schemes adjusted based on the new data. Since predicted tides only represent the astronomical component of water level fluctuations they are typically only useful as a DQA tool. Astronomical forces are usually the dominant contributor to coastal water level fluctuations, but other factors including meteorological (e.g. wind and pressure) and oceanographic effects (e.g., river flow, water density) may be significant. Hydrographers may use predicted tides to consider areas which still need to be surveyed due to unforeseen shoaling, possible obstructions, etc. and can be applied for preliminary cross-line checks, however, use beyond that scope can result in significant errors and uncertainty in sounding quality relative to Chart Datum. Predictions do not include effects from meteorology. Figure 1 shows a two-week plot of predicted versus observed tides at the Grand Isle, LA National Water Level Observation Network (NWLON) station. During a wind-driven storm event, the observed tides at Grand Isle deviated significantly from the predicted tides.

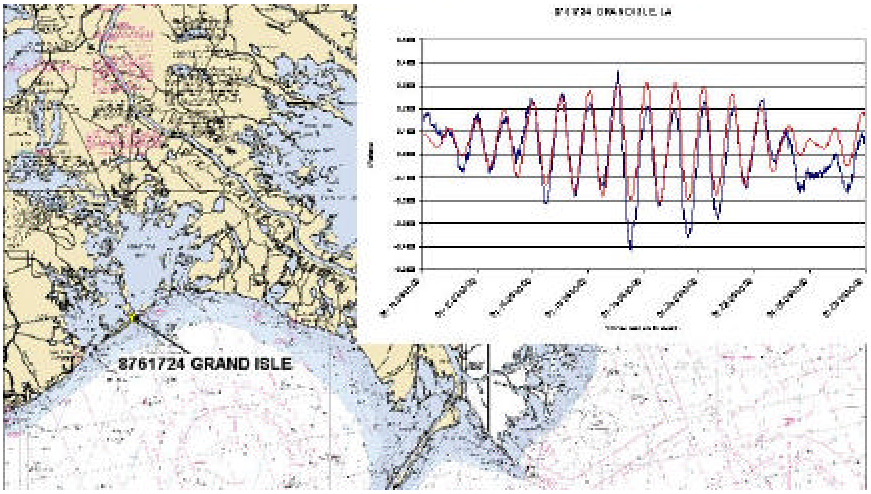

Figure 1. The NWLON station at Grand Isle, predicted (red curve) versus observed (blue curve) tides for two weeks. Predictions do not include effects from meteorology. The observed curve deviates significantly from the observed curve during storms, wind, and other weather events.

Error budget considerations should not be taken lightly and are outlined in Section 4.1.6 of the NOS Specifications and Deliverables (National Ocean Service, 2002). The overall water level error includes error components from water level measurements, the computation of datums and the error in the application of tidal zoning. The error component due to the tidal zoning can "easily exceed 0.20 m if tidal characteristics are very complex or not well-defined and if there are pronounced differential effects if meteorology on the water levels across the survey area." Only in cases where surveying water depths exceed navigational concerns may the magnitude of the total error budget be considered negligible.

Survey areas, which are affected differently by weather events or when two stations have different tide types, may require additional water level stations even if stations are geographically close. Figure 2 shows two stations, Mobile and Dauphine Island, located within the same bay system (Mobile Bay, AL). When there are no weather events, the two stations can be zoned off of each other with a constant phase and range corrector applied. However, the two stations react to the effects of meteorology very differently. Figure 3 shows two NWLON stations, Galveston Pier 21, TX and Grand Isle, LA, that have different tidal characteristics (are different tide types) and react differently to normal weather events.

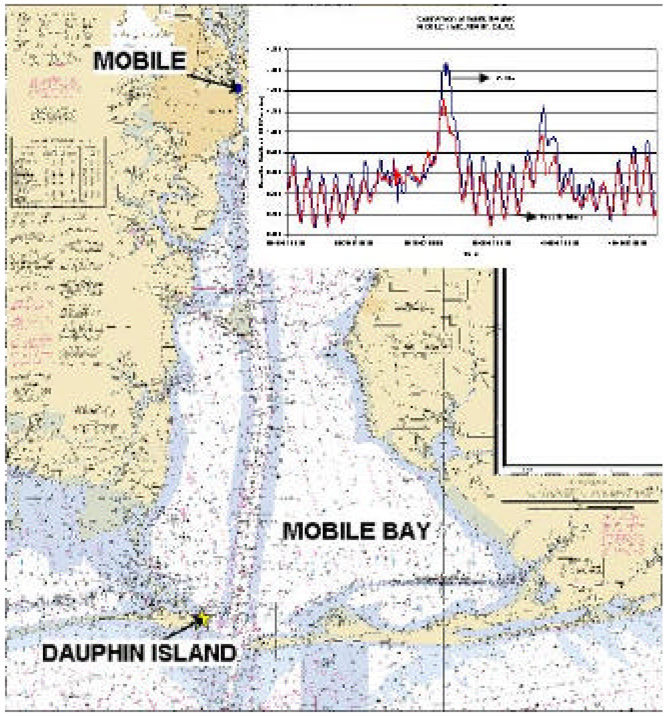

Figure 2. Comparison of two water level stations within the same bay system: Mobile Bay, AL. Dauphin Island is the red curve and Mobile is the blue curve. The two stations can be zoned off of each other with constant phase and range correctors applied, except during storm events. The two stations react very differently to weather events.

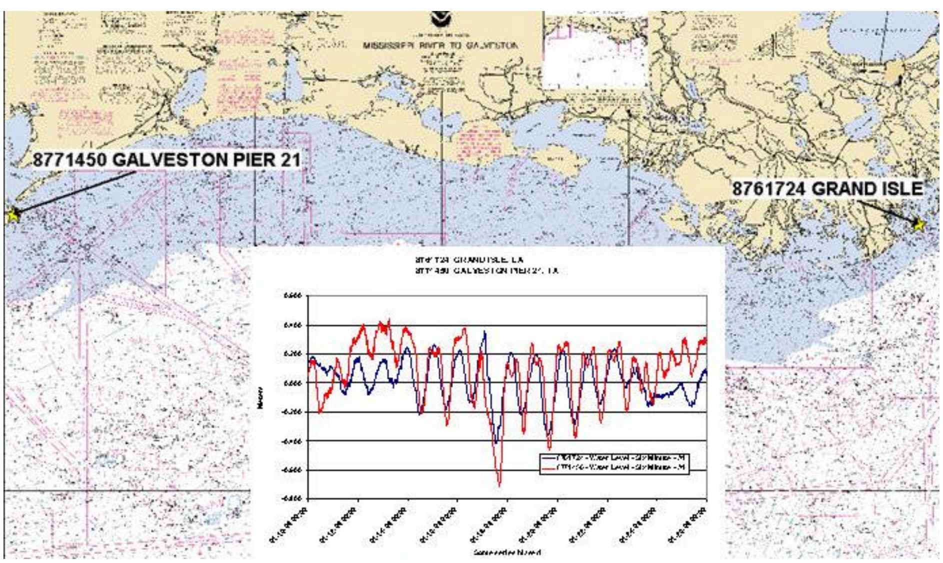

Figure 3. Galveston Pier 21, TX (red curve) versus Grand Isle, LA (blue curve). The two NWLON stations have different tide types and react differently to normal weather effects.

Often times, the installation of subordinate water level stations is required where sufficient data are lacking to fully understand the tidal characteristics of an area as well as where extrapolation through tidal zoning to the closest existing water level station produces unreliable results. Tidal data from subordinate water level stations are frequently used to create tide reducers for final zoning and are critical in refining tidal zoning schemes.

Proposed Long-term Improvements

This paper proposes that field units and contractors apply a procedure that uses a mixture of several methods that will allow them to make final vertical water level corrections during field processing of survey data. Methods to be used include:

- Deployment of dual-frequency GPS for tidal benchmarks;
- Concurrent acquisition of Real-Time Kinematic GPS during survey operations;
- Installation and maintenance of subordinate tide stations with datum connections to geodetic and ellipsoidal datums where necessary for VDatum development, as well as for the development and validation of hydrodynamic and datum surface models;
- Development of gridded hydrodynamic and/or spatial interpolation models for modeling datum surfaces, especially TCARI-based methods, with sufficient accuracy to meet vertical error allowances as stated in the current NOS Specifications and Deliverables (National Ocean Service, 2002).

Survey efficiency and accuracy will benefit by knowing the relationship of MLLW to geodetic datum surfaces everywhere in the survey area prior to operations. The Combination of the ellipsoidal measurements made with GPS, the densification of grids defining the geoidal to mean sea level relationship (provided by National Geodetic Survey (NGS) and new tide stations at critical locations), and improving mean sea level to MLLW relationship (provided by Coast Survey Development Lab (CSDL)) will lead to iterative refining of the VDatum model for the survey area. The end result will be a review and certification process that ensures that IHO-level standards are achieved (Brown, *et. al,* 2003).

GPS-Tracked Buoy

NOAA is currently in Phase II of the Small Business Innovation Research (SBIR) project for the creation of a GPS-tracked buoy (see Figure 4). NOAA is interested in the system's potential for providing real-time water level measurements off shore. The application of this technology will result in offshore measurements that will minimize errors in the extrapolation of data using tidal zoning from shore-based tide stations to the middle of estuaries and bays or to offshore survey areas. This will be particularly useful in areas with complex tidal regimes, such as Block Island Sound or in the areas north of Key West. If the GPS-tracked buoys are successful, uncertainty of off shore "zoned" data that exists with the sole use of fixed near shore systems may be dismissed or verified. The GPS-tracked buoy can also support the TCARI method for the same reason, as well as help to provide or calibrate models of spatial distributions of MLLW relative to the ellipsoid. Deploying GPS buoys can augment the present shore-based tide gauge method of providing vertical correctors by effectively providing additional time series data which more accurately measures the water levels "at location" for sounding reduction (Earle *et. al*, 2002).

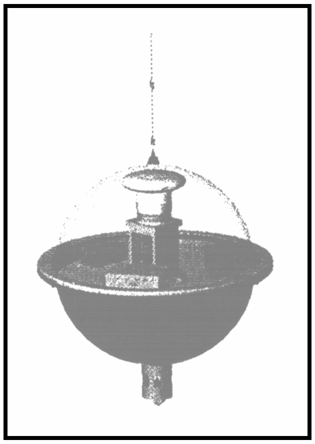

Figure 4. Examples of possible GPS buoy prototype.

TCARI

TCARI can provide an improved method of computing water level correctors to accurately reference hydrographic soundings to Chart Datum (MLLW) using tide gauges and/or GPS-tracked buoys (Hess et al., 1999). This method offers a procedure for "continuous" tidal zoning that improves upon the present discrete tidal zoning and can produce a correction value for any sounding time and position within a survey area bounded by a local network of operating water level stations (shore or buoy). Since it ingests data from all gauges in the network (typically at least three), using a weighted contribution technique, it requires that they all are functioning simultaneously. However, the method should reduce the number of stations required for surveys because the complex changes in tidal characteristics are handled by the interpolation of the tidal constituents and the residuals between predicted and observed tides are usually more coherent over larger areas. If tidal datums are established prior to the survey and the water level gauges are operating in real time, final corrector values can be provided in real-time as the ship moves through the water. The "weighted contribution" algorithm considers the spatial variation in both the astronomic (harmonic) and residual (non-tidal, i.e., primarily meteorological effects) components of the water level signal. Theoretically, this should produce a higher quality water level corrector, especially in areas with complex tidal regimes where errors at the edges of the discrete tidal zones can be quite large. The smooth transition of tide corrections will be particularly beneficial to processing of large volumes of multi-beam data that frequently cross over discrete tidal zones.

KGPS and VDatum

KGPS is potentially the best solution for vertical control for hydrographic surveying (see Figure 6), providing centimeter-level positioning to improve, or otherwise replace, "classic" heave, settlement, and tidal zoning issues. Tide gauges do not have to be operating during the survey (see Figure 5 and note the differences between classical hydrographic surveying and GPS hydrographic surveying), except for quality control or data backup purposes; however, localized Chart Datum models are required to support KGPS height measurements. The software tool, VDatum, when fully developed, will provide a spatial model of MLLW relative to the ellipsoid but today VDatum is operational for only a few U.S. coastal areas. The additional transformation fields required for the remaining coastal areas can be derived using spatial interpolation and tidal models and a combination of valid, previously established datums and bench marks with ellipsoidal references, and new deployments of gauges and/or GPS-tracked buoys to densify and calibrate the models (Wong et al., 2000; Hess et al., these proceedings). Additionally, VDatum helps solve one of the many incompatibility problems with accepting outside source data (or third party data) due to the use of different vertical datums (Parker *et. al,* 2003).

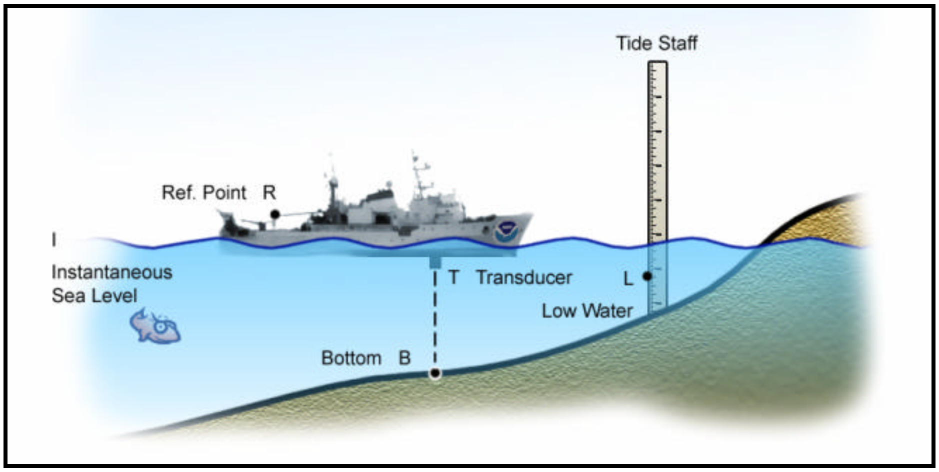

Figure 5. Schematic of Classical Hydrographic Surveying.

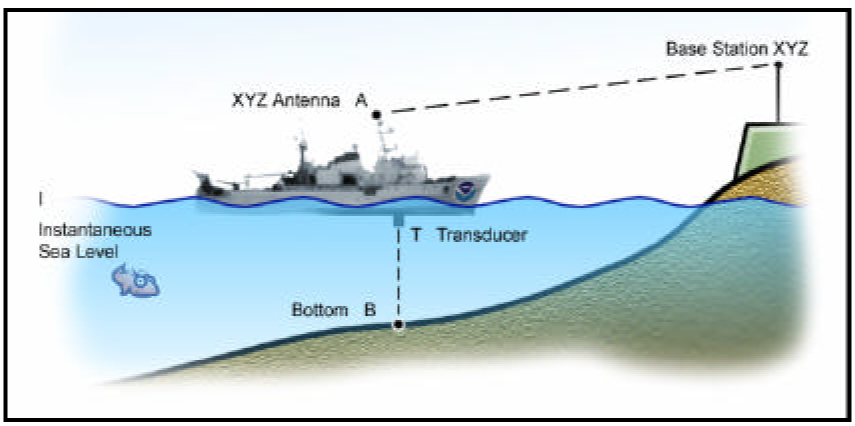

Figure 6. Schematic of GPS Hydrographic Surveying.

Short-term Improvements

As NOS prepares to fully implement these new long-term solutions/technologies, there are other short-term improvements which may be able to help hydrographers where gauge coverage is inadequate or non-existent. Below are several possible solutions to improve efficiency of the present tide gauge provision of vertical sounding correctors:

Short-term improvements for tide stations and tidal zoning:

- Prioritize coastal areas for known high-quality and low-quality knowledge of tidal datums and tidal zoning in context of the latest hydrographic survey plans.
- Continue developing tidal error budgets and closely examining survey areas for how much tidal zoning can be applied to existing NWLON stations and still meet error budgets. Areas completed to date include: Columbia River, East Long Island Sound, St. Johns, Massachusetts, and Virgin Islands.
- Decrease water level reduction process, possibly in near real-time, by using verified 6-minute data relative to MLLW from operating NWLON or short-term stations with known datums where at all possible.
- For upcoming hydrographic survey areas, identify critical historical tide stations with questionable and/or outdated datums due to vertical land movement or changes in tidal characteristics from dredging or silting. Efforts should be made to reoccupy these stations with tide gauges and GPS datum connections prior to survey operations in areas where they would be required.

Short-term solutions for improving the throughput pipeline:

- Provide training and technology transfer for data processing and datum computation to the survey community. This includes data collection, tabulation of tides, computation of monthly means, datum computation techniques, and development of tidal zoning. Historical station summary data and digital tidal zoning can be made available to outside users.

SUMMARY

NOAA is planning on applying the latest in technology to meet increasing user demands for timeliness and accuracy in nautical chart products. An important component of hydrographic surveying is the establishment of the vertical control system to which soundings are reduced and referenced. New technologies and systems are being developed for operational application of datum control to ensure chart production will have improved timeliness and accuracy.

Hydrographers must be careful not to disregard the significance of water level issues, even in areas of low tide ranges. A two-foot range in shallow water could exceed the error budget. Water level fluctuations at any place are not just “tides”, but the combination of the rise and fall of the water surface due to astronomical tides, combined with the effects of high (long period sea swell, seiches, etc.) and low (sea level fluctuations due to atmospheric pressure, and wind stress, etc.) frequency meteorological effects. These can cause variations of several feet in areas where the tide range is small. The present methodology for producing final tide reducers uses a combination of tide gauge measurements during survey operations and the extrapolation of shore-based measurements to offshore areas using discrete tidal zoning. These procedures have efficiency and accuracy limitations, especially in areas of complex tidal regimes.

NOAA is making steady progress in streamlining the process of producing water level corrections for hydrographic surveying. However, this requires continued support for related systems development (RTK, GPS, VDatum, and TCARI models), as well as funding for tide gauge densification, which will greatly reduce or eliminate delays in processing due to waiting for final water level corrections.

References

Brown, M., D. Enabit, M. Higgins, J. Humphrey, G. Imahori, R. Johnson, G. Noll, J. Nyberg, and L. Petze, 2003. Coast Survey Enterprise System Team Report.

Earle, M.D., *et. al*, 2002. GPS Tracked Buoy for Hydrographic Survey Applications. NOAA SBIR Phase I Project Final Report. Neptune Sciences, Inc.

Hess, K.W., R.A. Schmalz, C. Zervas, and W.C. Collier, 1999. Tidal Constituent And Residual Interpolation (TCARI): A New Method for the Tidal Correction of Bathymetric Data. **NOAA Technical Report** NOS CS 4, 99 pp.

Hess, K.W., D.G. Milbert, S.K. Gill, and D.R. Roman, 2003. Vertical Datum transformations for Kinematic GPS Hydrographic Surveys. (this proceedings).

National Ocean Service, 2002. NOS Hydrographic Surveys Specifications and Deliverables, June 2000. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Coast Survey, Silver Spring, Maryland.

Parker, B., D.G. Milbert, K.W. Hess, and S.K., Gill, 2003. National VDatum--The Implementation of a National Vertical Datum Transformation Database (this proceedings).

Rodney, Slater E., *et. al*, 1999. An Assessment of the U.S. Marine Transportation System. A Report to Congress.

Tronvig, K.A. and S.K. Gill, 2001. Complexities of Tidal Zoning for Key West, FL. U.S. Hydro 2001 Conference, Norfolk. (this proceedings).

Wong, C., J. Riley, D. Martin, L. Huff, L. Hall, S. Gill, R. Foote, and E. Carlson, 2000. NOS RTK Team Final Report.

Center for Operational Oceanographic Products and Services
URL: http://www.co-ops.nos.noaa.gov/

Coast Survey Development Laboratory
URL: http://chartmaker.ncd.noaa.gov/csdl/op/tides/cozone.htm

National Geodetic Survey
URL: http://www.ngs.noaa.gov/products_services.shtml

Office of Coast Survey, National Survey Plan. November 2000.
URL: http://chartmaker.ncd.noaa.gov/