The Use of a GPS-Equipped Buoy for Water Level Determination

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***Abstract* - In recent years, Global Positioning System (GPS) receivers have been placed on buoys to determine sea surface height. The Naval Oceanographic Office (NAVOCEANO) has become interested in this application for tides work and has sponsored a series of GPS buoy experiments in Mississippi coastal waters. The primary goal of the experiments was the determination of water level with GPS using the WGS84 reference ellipsoid as a tidal benchmark. Also of importance was the determination of the minimum buoy sensor configuration (aside from GPS) required to accomplish this measurement, and to evaluate RTK GPS performance over time and distance.**

The fully integrated buoy was deployed in 2001, 2002, and 2003. The 2001 RTK results were analyzed for solution availability, solution quality, and solution correlation with other sensor output. Solution availability was high during buoy operational periods; however, the solution quality was hampered by an apparent GPS filter-based anomaly in the receiver RTK processing. Tide gauge comparison indicated sub-decimeter-level water level recovery was attainable. Initial processing of 2002 data produced cm-level differences between RTK and tide gauge water levels. These initial results show great promise for the use of RTK buoys in water level recovery, and more data collection and analysis will be undertaken with the 2003 deployment.

I. INTRODUCTION

A requirement for hydrographic surveying for marine chart production has always been the determination of a physically meaningful vertical surface with which to reference measured depths. This chart datum is realized in the form of some low water level in the survey area. Given tidal, meteorological, etc. effects the traditional approach has been to use local water level gauge data or install gauges (if none exist) for the period of the survey. Since the gauges represent basically discrete measures of water level and the survey area can cover considerable areas, it may be required to estimate vertical datum information by partitioning the coverage area and modeling the water level. This procedure adds to the vertical positioning error budget, which maps into the accuracy of the chart depths.

The Global Positioning System (GPS) has revolutionized positioning and navigation. By measuring the travel time of microwave electromagnetic waves from a number of GPS satellite, all at known locations, a trilateration technique is used to estimate user position to the few meter level. By augmenting this procedure with data from other GPS receivers or GPS correction providers, position estimates as precise as a few millimeters can be achieved under constrained conditions.

GPS can aid hydrography in a number of ways. One obvious application is in the use of survey vessel positioning by onboard GPS. Perhaps less obvious is to place a GPS receiver on a buoy to determine water level in the survey area. Such a process is depicted in Figure 1. The instantaneous sea surface height with respect to the mathematical reference ellipsoid (that is the reference surface for GPS measurements) can be estimated, given that the offset between the GPS antenna and the buoy waterline is measured. The local tidal datum can theoretically then be determined by the reduction of the sea surface values for a minimum of a lunar month. How well (in terms of accuracy, precision, and integrity) the sea surface heights can be measured, if other sensors are required to compensate for buoy motion, and how well the local datum can be established are significant research questions.

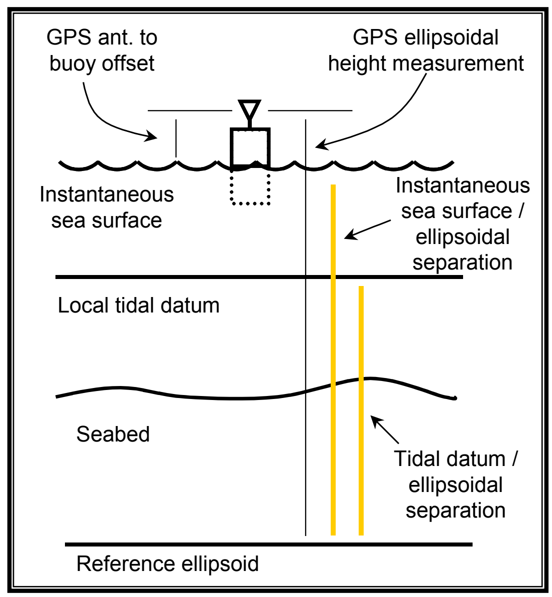

Fig. 1: Measurements from a GPS-enabled buoy.

II. GPS BUOY RESEARCH

The development over the past decade of commercial, carrier phase, differential, kinematic GPS, specifically Real-Time Kinematic (RTK) GPS, has meant that an RTK-equipped buoy can potentially be used to accurately measure water level height above the WGS84 ellipsoid. A number of experiments have been successfully carried out for this purpose. The first example was the calibration of a satellite altimeter with a GPS buoy in the North Sea in 1988, and required the invention of the On-The-Fly (OTF) RTK processing method as a byproduct [1]. Others that have followed include [2], [3], [4], and [5]. The ultimate goals of these experiments and other potential purposes can be classified as:

- Determination of water level with an RTK GPS buoy. Simply put, as an academic question, can this be accomplished and with what caveats? And how would such a buoy compare with a water level gauge in terms of accuracy, cost, etc.
- Determination of water level at locations where installation of a gauge would be difficult. There are scenarios where installation of a conventional tide gauge is not practical. This can be due to distance from shore and / or water depth, or for safety concerns in a hostile environment. In these situations an accurate buoy-mounted sensor would be of great advantage. This raises the potential for buoy-determined water levels to play a role in cotidal and hydrodynamic modeling.
- Determination of water level to establish the separation between tidal datum and GPS datum. Given that GPS is presently the ubiquitous global positioning and navigation technology, with both terrestrial and marine mapping and navigation being referenced to its datum (WGS84) both directly and indirectly, there is great interest in the mapping community to develop transformations between local datums and WGS84. By determining water levels, and therefore chart datum, with GPS, the conversion of chart datum to the ellipsoid can be mapped out. If the same is done with terrestrial datums, this can be a basis for development of seamlessness at the chart / map – sea / land interface.
- Determination of water level for calibration of altimetric sensors on aircraft or spacecraft. Calibration of great and growing interest given the rapid advancement of altimetric sensors designed to determine sea state, sea surface topography, etc. In situ water level measurements from RTK-equipped buoys can provide for not only calibration of these sensors at cross-over points, but perhaps also in data assimilation models. They also complement spaceborne and airborne altimetric data by providing higher sampling rates at their moored locations. This can be crucial to verifying if high frequency variability is removed from the altimetry data properly so as not to alias the measurements.

III. NAVOCEANO RTK BUOY

The Naval Oceanographic Office (NAVOCEANO), which is charged, amongst other responsibilities, with fulfilling the U.S. Navy's hydrographic surveying needs, has recently become interested in using RTK buoys in its hydrographic operations. NAVOCEANO is interested in GPS water level determination as a tide gauge proxy and for determining chart datum / WGS84 ellipsoid separation. Important engineering and operational issues are the minimum buoy sensor configuration requirements, the temporal and spatial performance variability of RTK GPS in coastal marine environments, and the buoy power management strategy. The minimum equipment may also be dependent upon buoy design.

NAVOCEANO deployed a buoy in 2001 and redeployed the same in late 2002, and again in early 2003. Planning Systems Inc. (PSI) was tasked with integrating and operating the buoy, and the Hydrographic Science Research Center (HSRC) was charged with assisting in the system and survey design, and analyzing the collected data. Both deployments were designed to address the above NAVOCEANO objectives.

The buoy itself is shown in Figure 2. The internal configuration for the 2001 deployment is also shown in the figure. Table 1 describes the main components installed in the system. Dual frequency NovAtel OEM4 GPS receivers were used for RTK, and a host of other sensors were incorporated for redundancy comparison and attitude determination. These are three accelerometers, three magnetometers, a tilt sensor, and a pressure sensor. For the 2001 experiment, the buoy was deployed approximately 10 km south of Gulfport, Mississippi, in the Northern Gulf of Mexico, and the reference station was located in Gulfport. For the 2002 test, the reference was again set in Gulfport, and the buoy was placed 50 m away for an initial test, and placed approximately 15 km south of Gulfport. This latter location was also used for the 2003 tests. Figure 3 illustrates these locations. Due to several RTK and power problems encountered in the first and second deployment design, a number of changes were made to the buoy design and operation for the second and third tests. These will be discussed in the results section.

Table 1: Buoy system component descriptions [6].

COMPONENT	DESCRIPTION
Reference Station and Buoy GPS	NovAtel OEM-4 L1/L2, 12 channel, RTK differential capable
Reference Station GPS Antenna	NovAtel Model 503, dual frequency antenna and choke ring with radome
Buoy GPS Antenna	NovAtel Model 600, dual frequency antenna
Radio Modem	FreeWave® DGR-115R 900MHz, spread spectrum
Accelerometers	Crossbow Technologies CXL02LF3 3-axis, ± 2 g, 1-V/g
Magnetometers	Watson Industries, Inc., FGM-301 3-axis, ± 70,000 nT, 20nT/mV
Vertical Reference	Watson Industries, Inc. ADS-C232-1A, dual axis integrated sensor measuring tilt, x/y displacement and x/y angular rate
Pressure Sensor	SenSym Model SX30, 0 – 30 psi

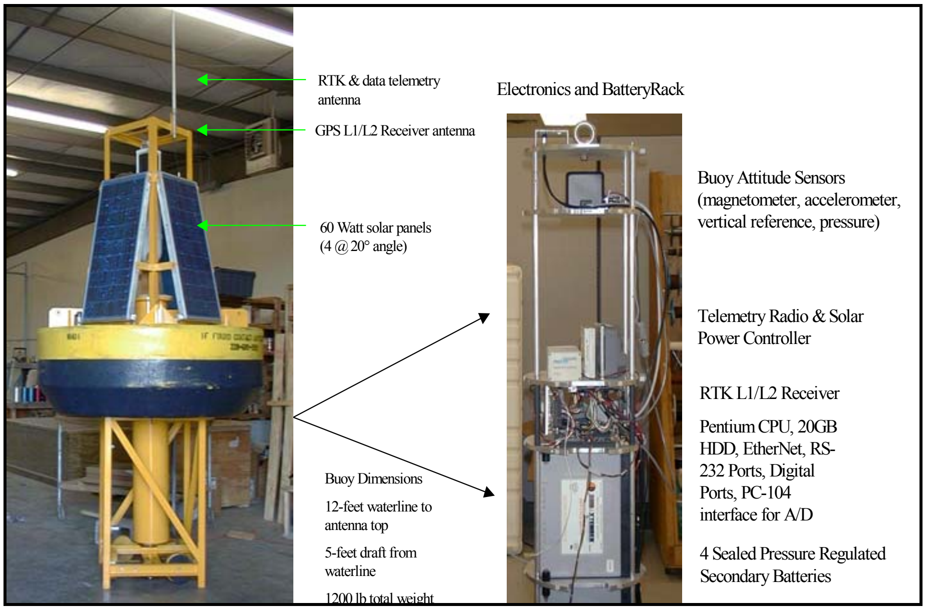

Fig. 2: NAVOCEANO GPS buoy configuration [6].

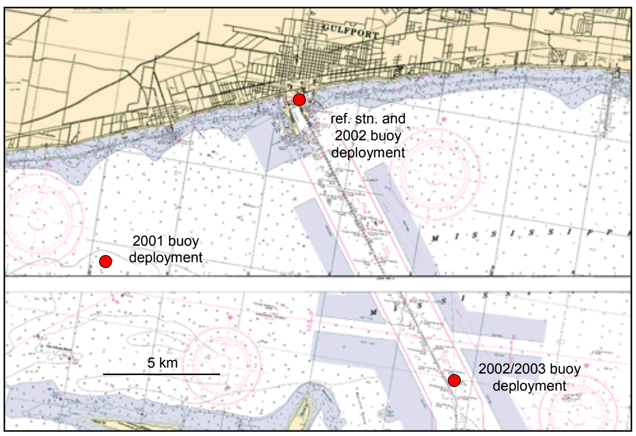

Fig. 3: GPS buoy deployments in Mississippi Sound.

IV. DATA ANALYSIS METHODOLOGY

The buoy collected approximately one month of continuous RTK solutions and other sensor measurements in September 2001. A number of initial analyses were performed on the data, including investigating RTK data quality; correlating RTK height solutions with vertical accelerometer data; correlating RTK height solutions with local tide gauge data. A similar procedure was carried out for 2002 data and planned for the 2003 data.

As will be shown, the RTK solutions from the 2001 dataset indicated problems with the solution. Therefore for the 2002 deployment, receiver upgrades were made and the buoy was collocated with a tide gauge to better control the solution analysis. During the 2002 data collection, power problems arose due to the buoy operating in the local winter. From these experiences, the 2003 deployment is using a reduced power consumption strategy. It is planned for the HSRC to process all of this new data and complete the answers to the original queries posed by NAVOCEANO of determining water levels and chart datum for hydrographic surveys, and to determine the minimum sensor suite necessary to meet water level recovery specifications.

V. 2001 BUOY DEPLOYMENT RESULTS

A primary task of the brief analysis of the 2001 data was to observe the performance of the RTK solutions. This meant not only the apparent precision and accuracy of the estimated positions, but also the integrity of the system. Figure 4 illustrates the availability of RTK solutions (as a percentage) for each survey day in September 2001. There are significant variations from day-to-day, with availability ranging from less than 50 % to almost 100 %. The average was 82 %. Since the GPS receiver was running continuously, as much as 12 hours of data could be lost on a given day. The loss is due to an error in the sensor scheduling program that caused the receiver to power down a number of times. The daily few percent losses were mostly due to an intentionally planned daily system reboot.

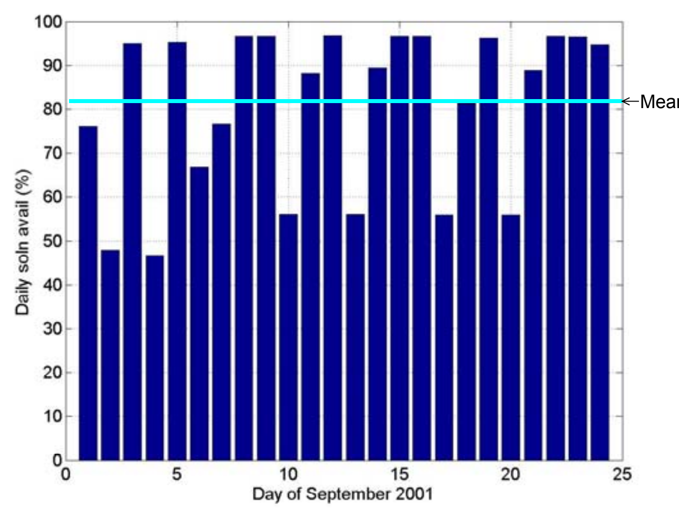

Fig. 4: Buoy solution availability for September 2001 [7].

The RTK height estimates for a single day are shown in Figure 5. 23 September was chosen, as it is a representative sample of the entire dataset, but also contains a carrier phase ambiguity problem. During the period of the shift in height estimation there appears to be incorrectly determined ambiguities. Analysis of the solution quality and type records indicated that the processing engine could not resolve the ambiguities at the beginning of this shift. More problematic were the filter artifacts visible on this day and all other days. After ruling out the approximately 50 minute period phenomenon as being caused by the natural environment, it was concluded that the internal RTK processing filter was most likely at fault. To further ascertain if this was a GPS problem, the vertical accelerometer data was analyzed. Figure 6 clearly shows that the accelerometer did not undergo the dynamics determined by the GPS receiver. Discussion with NovAtel engineers brought no explanations for these artifacts. However, installation of the latest generation NovAtel receiver firmware resolved this problem, as will be further discussed in the 2002 data analysis. As suggested in Figure 3, the processing filter noise is a high frequency signal riding upon the lower frequency water level changes.

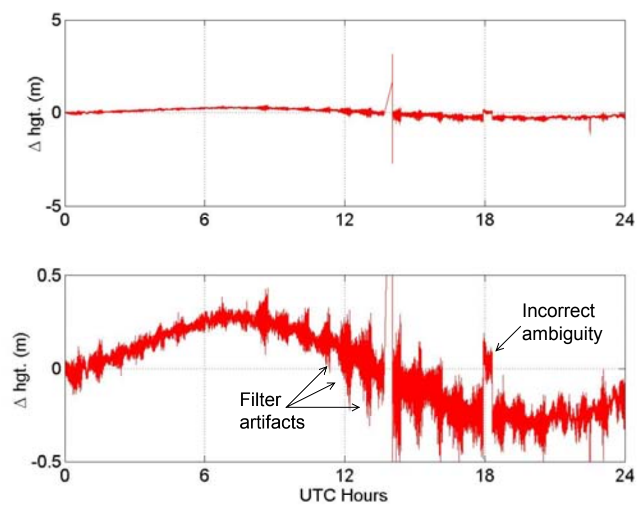

Fig. 5: Buoy height solutions for 23 September 2001 [7].

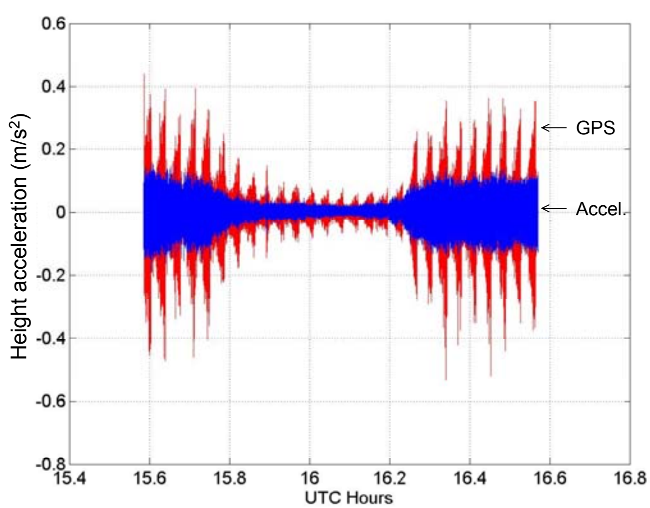

Fig. 6: Buoy height solutions verses vertical accelerometer for 15 September 2001 [7].

To investigate the accuracy of the RTK height solutions and understand determination of chart datum / ellipsoid separation, the RTK-determined water levels were compared against data from a near-by tide gauge. The Waveland, Mississippi tide gauge was located approximately 10 km inshore from the buoy. To reduce the effects of the filter artifacts and the overall noise of the RTK data, low pass Butterworth filtering was performed. The results for 15 September are produced in Figure 7. A bias has been removed from the tide gauge and RTK values for plotting. A distinct phase lag can be seen, which is consistent with the fact that the buoy was offshore and to the east of the reference tide gauge at Waveland, Mississippi. Even so, with a mean bias between solutions of 47.9 cm, the standard deviation difference is only 6.5 cm, with a 2.5 % GPS data loss.

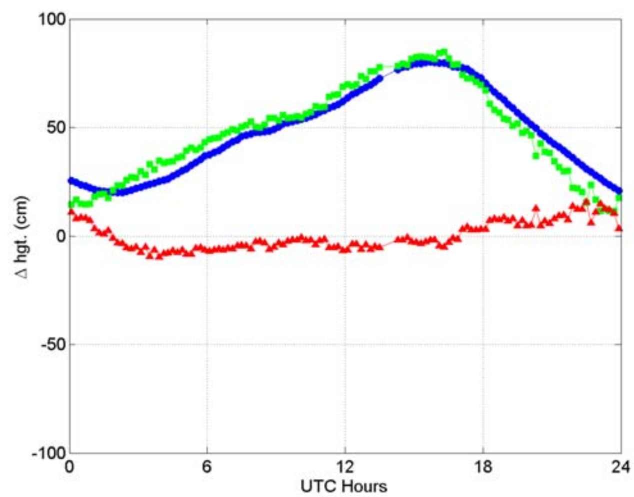

Fig. 7: Buoy height solutions verses tide gauge for 15 September 2001. (Tide gauge: blue circle; filtered RTK: green squares; differences: red triangles.) [8].

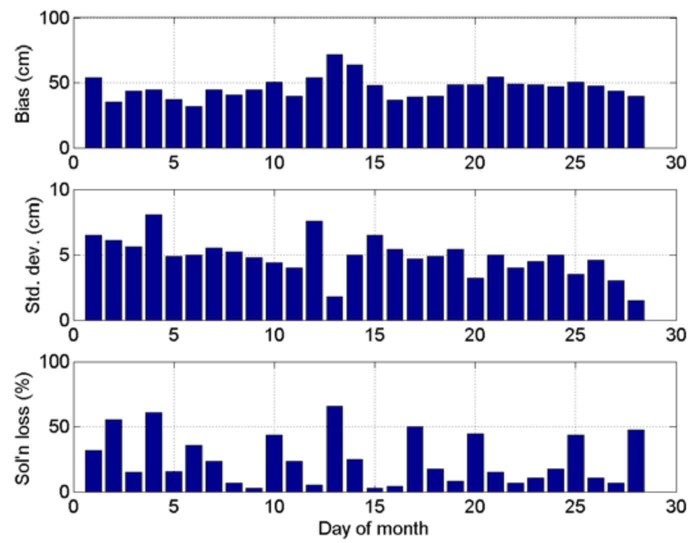

Fig. 8: Summary statistics of buoy height solutions verses tide gauge for September 2001 [8].

Summary statistics for the entire month are given in Figure 8. However, for the most part, a bias of approximately 45 cm was estimated for most days in which the solution loss was low, and for these days the noise of the difference between sensors was near the 5 cm level (1 σ), even with the mentioned phase lag.

To give a more realistic indication of system performance the 15 September 2001 data shown in Figure 7 is revisited. An empirically determined phase shift of +49 minutes has been applied to the RTK heights. (This requires the removal of a portion of the comparison data at either end of the time series.) The resulting standard deviation of the difference between height determination methods is reduced from 6.5 cm to 2.5 cm. A value that is not much larger than the specified precision of typical gauges.

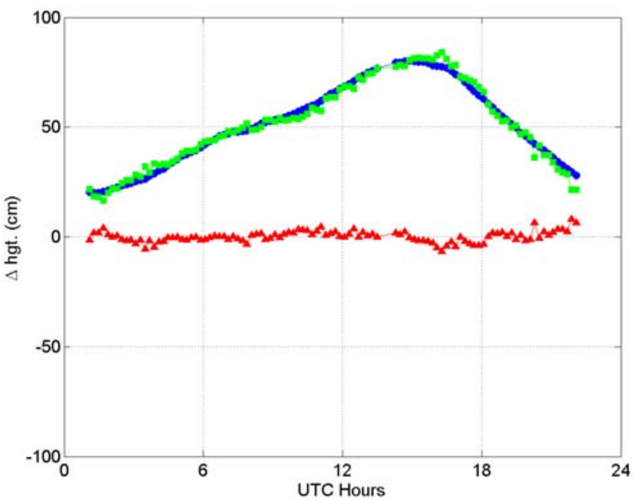

Fig. 9: Buoy height solutions versus tide gauge for 15 September 2001 with phase shift. (Tide gauge: blue circle; filtered RTK: green squares; differences: red triangles.)

VI. 2002 BUOY DEPLOYMENT RESULTS

The year 2002 data processing promised to be more revealing than that of the previous year. Initial bench testing with new firmware showed no indication of the filtering artifacts previously encountered, and the installation of a 100 Mb hard drive meant all raw GPS receiver data could be stored for later post-processing. The reintegrated buoy was first deployed in Gulfport harbor, 50 m from the reference station, to test the system and especially GPS receiver processing firmware. After a successful test, the buoy was placed approximately 10 km offshore, but experienced severe power drain over extended periods of continuous operation. The cause was a combination of overcast weather conditions, not enough winter sunlight hours, and solar panel mounting angle resulting in limited operation. It is intended that the buoy be again deployed in February 2003, but on a reduced duty cycle with the sensors on for one hour and off for approximately three hours. This will allow sustained buoy operation and sampling throughout the local tide cycle over a month.

Data from the harbor deployment was analyzed for RTK performance. Figure 10 illustrates the water level as determined from the short baseline RTK. The data was again filtered with a low pass Butterworth filter, which successfully dampened much of the few-centimeter variability (attributed to receiver noise and wave motion) apparent in the original estimates. However, gross errors in the RTK solution are unavoidably mapped into the filtered water level. The development and use of more robust filters will be carried out in future analysis.

The comparison between the filtered RTK water level and that observed at a tide gauge a few meters away was excellent. With a bias of 112.5 cm removed, the standard deviation of the difference between solutions was 1.2 cm. These results are presented graphically in Figure 11. It is worth emphasizing that in this deployment, unlike the earlier one, the conventional tide gauge was closely collocated so that no phase shift is expected.

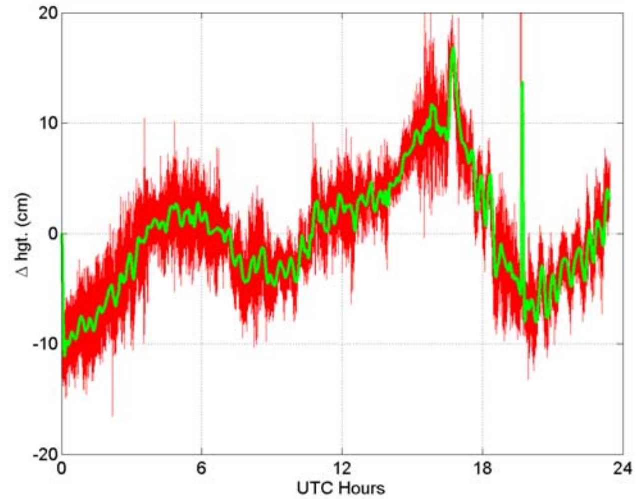

Fig. 10: Buoy height solutions and filtered estimates for 15 November 2002. (RTK: thin red line; filtered RTK: thick green line.) [8].

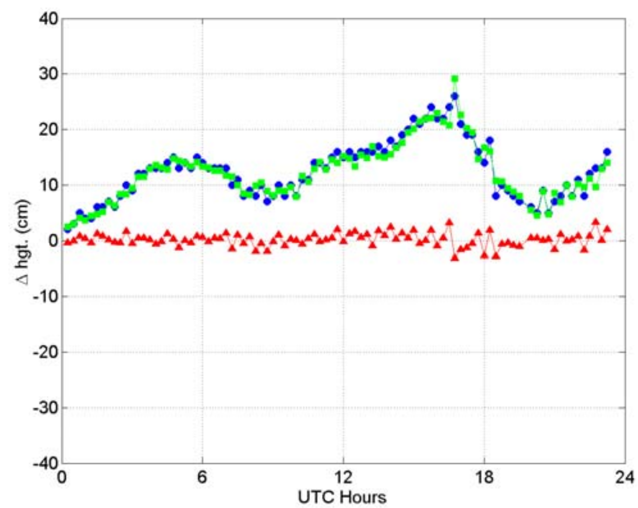

Fig. 11: Buoy height solutions verses tide gauge for 15 November 2002. (Tide gauge: blue circle; filtered RTK: green squares; differences: red triangles.) [8].

VII. CONCLUSIONS AND FUTURE WORK

The determination of water levels with an RTK GPS buoy can potentially provide data for a number of applications. NAVOCEANO understands this potential and has invested resources into an RTK buoy program. The developed buoy has been deployed three times. Brief analysis of the first dataset indicated that the onboard RTK processing was performing below expectations, but daily filtered heights compared with nearby tide gauge data produced standard deviation differences on the order of 5 cm. Standard deviation fell to approximately 2 cm when the phase difference in the tide between the buoy and the conventional tide gauge was taken into account. Initial processing from the 2002 dataset indicates that, with upgraded GPS RTK firmware and a very short RTK baseline, this difference is approximately 1 cm.

The HSRC plans to greatly expand its analysis of the 2002 and 2003 datasets to include correcting the RTK solutions with data from the other sensors to improve the height solutions, while determining the minimum sensor suite required. Also, RTK solution precision and accuracy will be investigated. This work entails analyzing all of the data recovered from the continuing testing. It is also planned that the HSRC will determine the complete integration procedure for using a GPS buoy rather than, or in conjunction with, a tide gauge in NAVOCEANO hydrographic survey operations. This effort points to a significant near-term role for capable GPS-enabled buoys in hydrographic applications.

Acknowledgments

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