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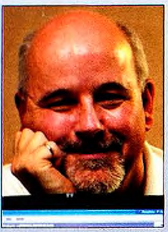

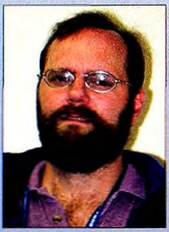

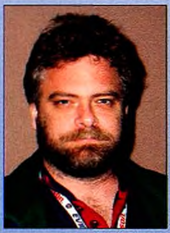

Development of an Operational RTK GPS-equipped Buoy for Tidal Datum Determination

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GPS in differing modes – stand-alone, DGPS, RTK, has been used onboard buoys to determine water levels for a variety of purposes. The rationale for the presented research is to determine the effectiveness of using RTK GPS to recover tidal datums in support of hydrographic survey operations. Data are analysed from a described experimental RTK buoy developed by the U.S. Naval Oceanographic Office to characterise the effectiveness of an RTK GPS-enabled buoy. Results indicate that for the data analysed, under 10 centimetre GPS height determination is possible. The requirements for an operational tidal buoy system based on Commercial Off-The-Shelf (COTS) components are discussed.

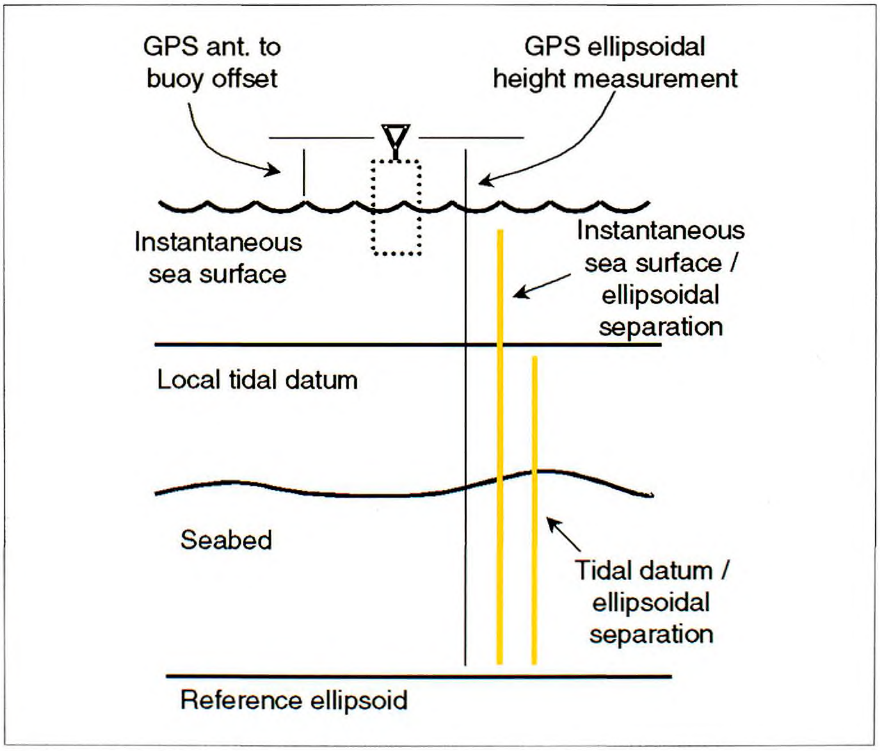

Figure 1: Measurements from a GPS-enabled buoy

Introduction

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. Figure 1 illustrates the GPS buoy / vertical datums geometry. Once the offset between the GPS antenna and the buoy waterline has been applied, the height of the instantaneous water level can be determined with respect to the GPS WGS84 reference ellipsoid. Averaging of the instantaneous height can be used to produce the local tidal datum, e.g., lowest normal tide.

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 (Seeber and Wübbena [1989]). Others that have followed include DeLoach [1995], Parke et al. [1997], Colombo et al. [2000], Moore et al. [2002], and Schueler et al. [2003]. 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 modelling
- **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 crossover 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
- **Determination of instantaneous wave heights.** Similar to the previous application, RTK-equipped buoys can be used to estimate wave height and direction from in situ measurements

The key difference between these experiments is the determination of average water level for tidal datum recovery and instantaneous water level for calibration. Accurate mean water level is inherently easier to obtain than accurate instantaneous water level as it involves noise reduction.

NAVOCEANO Evaluation RTK Buoy

The U.S. 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 substitute and for determining chart datum / WGS84 ellipsoid separation (see Figure 1) – thus allowing for the direct reduction of GPS referenced bathymetry to the local tidal datum. That is, answering the question: Can an RTK GPS-enabled buoy be used to determine tidal datum to 10cm (95 per cent) as specified by the U.S. National Ocean Service (NOS) (NOS [2000])? Important related engineering and operational issues are: the minimum buoy positioning sensor configuration requirements (e.g.,

COMPONENT	DESCRIPTION
Reference station and buoy GPS	NovAtel OEM-4 L1/L2, 12 channel, RTK differential capable
Reference station dual GPS antenna	NovAtel Model 503, 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

Table 1: Buoy system component descriptions (Harrington [2002])

need for tilt sensor, heave sensor, etc.); the temporal and spatial performance variability of RTK GPS in coastal marine environments; the buoy power management strategy (to afford multiple-month standalone operation); and the buoy data communications strategy. The minimum equipment may also be dependent upon buoy design. The novelty of NAVOCEANO requirements is for an RTK GPS buoy that is small enough to be deployed from a survey launch, and robust enough to be deployed for a few months in any coastal region.

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 analysing the collected data. All three deployments were designed to address the primary NAVOCEANO objective of determination of the tidal datum with respect to the GPS vertical datum.

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.

Data Analysis Methodology

For the 2001 experiment, the buoy was deployed approximately 10 km Southwest of Gulfport, Mississippi, in the Northern Gulf of Mexico, and the

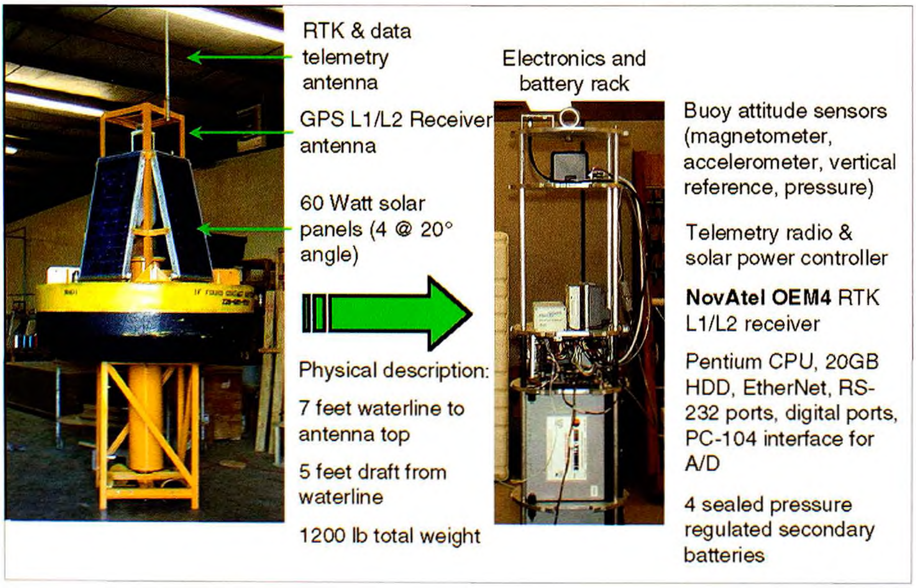

Figure 2: NAVOCEANO GPS buoy configuration (Harrington [2002])

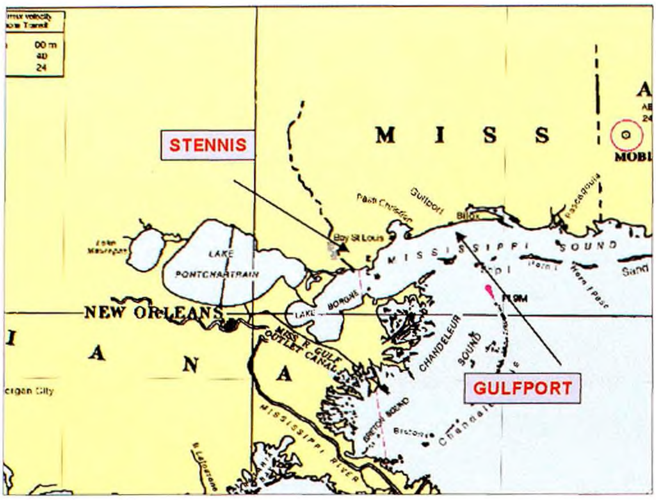

Figure 3: Area of GPS buoy testing off of Gulfport, Mississippi in the northern Gulf of Mexico

reference station was located in Gulfport. In the 2002 testing, the reference was again set in Gulfport, and the buoy was placed 50 m away. For the 2003 test, the reference station was not moved and the buoy was placed approximately 15 km Southeast of Gulfport. Figures 3 and 4 illustrate

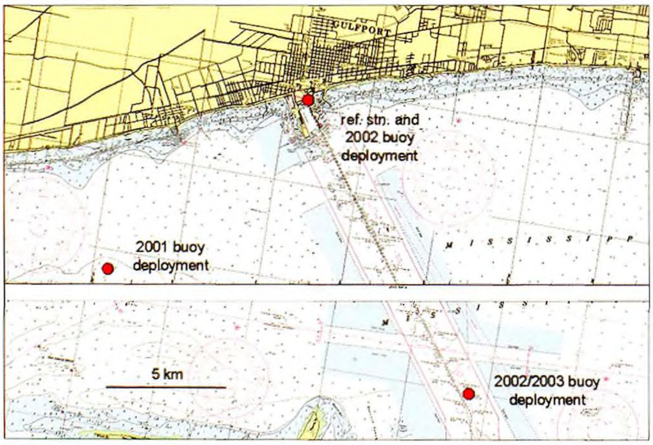

Figure 4: Three GPS buoy deployments

the general location of the experiments, and the specific location of each deployment, respectively. The buoy collected approximately one month of continuous RTK solutions and other sensor measurements in 2001. A number of initial analyses were performed on the data, including investigating RTK data quality; correlating RTK height solutions with vertical accelerometer data; and correlating RTK height solutions with local tide gauge data. The goal of these analyses was to determine if the GPS height solutions, with no corrections from other positioning sensors, followed the tide gauge heights. A similar procedure was carried out for 2002 data and 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 co-located with a tide gauge to better control the solution analysis. During the 2002 data collection, power problems arose due to solar power limitations while operating in the local winter. From these experiences, the 2003 deployment used a reduced power consumption strategy (the system ran on a 25 per cent duty cycle) until sufficient sunlight was available. It is planned for the HSRC to process all of these 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.

2001 Buoy Deployment Results

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. The data gap at ~15 hours was the result of a CPU reset on the buoy that will be further discussed. 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 related vertical accelerometer data was analysed, showing that the accelerometer did not undergo the dynamics determined by the GPS receiver (Bisnath et al.

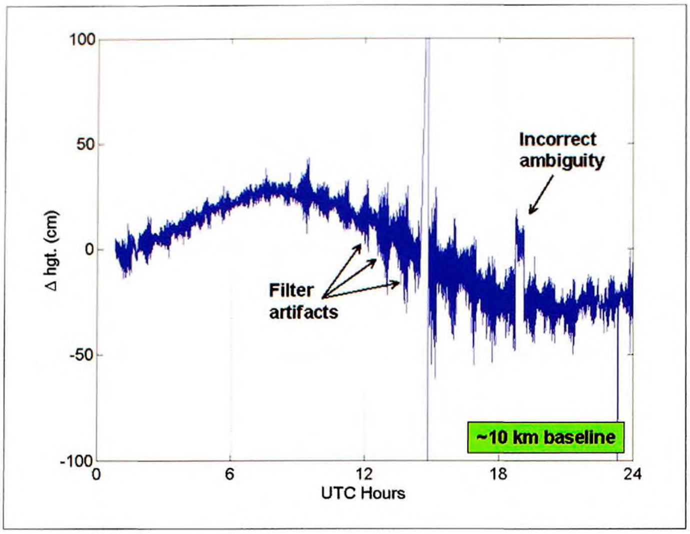

Figure 5: RTK buoy height solutions for 23 September 2001

[2003]). Discussion with NovAtel engineers brought no explanations for these artifacts. However, after installation of the latest generation NovAtel receiver firmware the phenomenon was no longer observed, as will be discussed later in the 2002 and 2003 data analysis sections. As suggested in Figure 5, the processing filter noise is a high frequency signal riding upon the lower frequency water level changes.

Given that averaged water level rather than instantaneous water level is required for the tidal datum determination, the effects of GPS height determination noise, surface waves, and buoy roll can be greatly reduced by passing the data through a moving average filter using data before and after each filtering point. This process parallels the operation of a tide gauge, which damps surface waves by means of a stilling well and measurement averaging. The size (time period) of the filter for this analysis is set to mirror that of the tide gauge. Since the GPS heights also contain GPS-specific artifacts an additional low pass filter is applied to remove spikes in the moving average filtered time series. This second filter simply removes any data points beyond an empirically determined limit for moving average filtered slopes. The comparison of unfiltered and filtered GPS heights for 23 September 2001 is given in Figure 6. The various GPS processing filter artifacts and data gaps have a minimal effect on the filtered height time series.

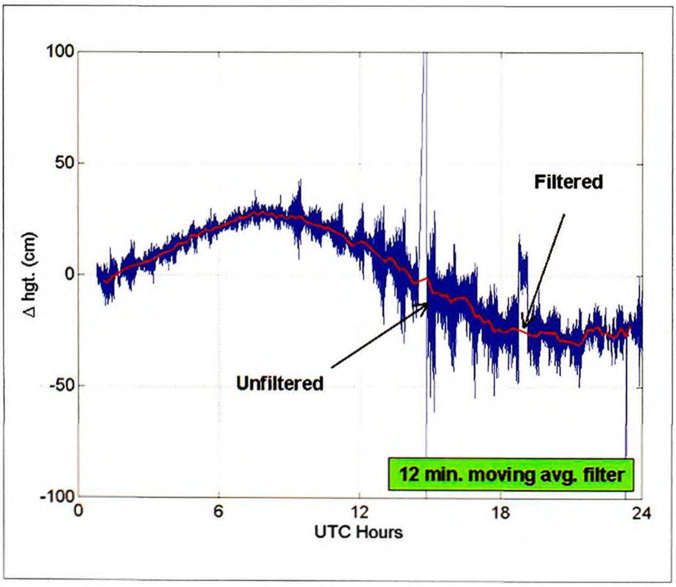

Figure 6: Unfiltered and filtered RTK buoy height solutions for 23 September 2001

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 account for the phase lag between the buoy and tide gauge, an empirical estimate of the lag was determined from the difference between the filtered buoy heights and the gauge over September 2001 and the buoy series shifted in time accordingly. The results for 23 September of the unfiltered GPS versus the gauge are produced in Figure 7. The offset has been removed between the tide gauge and RTK values for plotting. The standard deviation difference is only 4.1cm, with a 95 per cent error (95 per cent percentile) of 7.4cm. This is within the NOS specifications. However, filtering the RTK GPS time series results in far better agreement with the tide gauge. Figure 8 illustrates this with a standard deviation difference of 2.0cm and a 95 per cent error of 3.7cm.

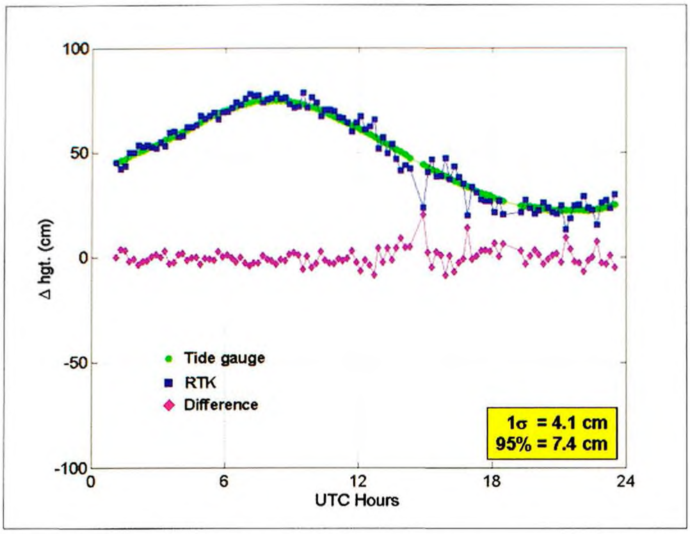

Figure 7: Unfiltered RTK buoy height solutions verses tide gauge for 23 September 2001. (Tide gauge: green circles; unfiltered RTK: blue squares; difference: magenta diamonds.)

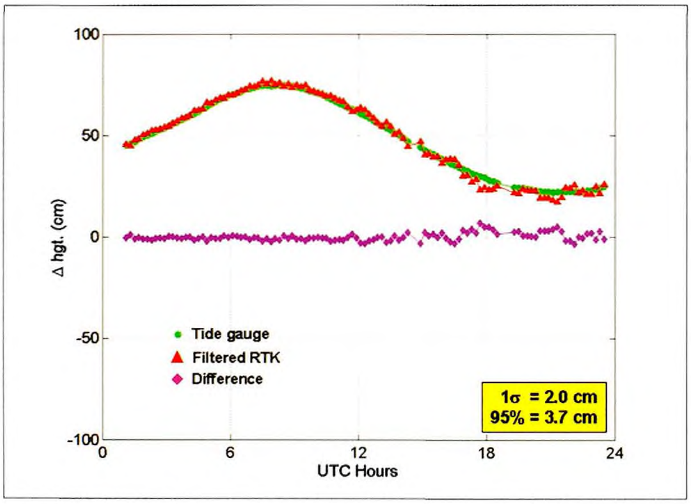

Figure 8: Filtered RTK buoy height solutions verses tide gauge for 23 September 2001. (Tide gauge: green circles; filtered RTK: red triangles; difference: magenta diamonds.)

Unfiltered RTK heights versus tide gauge summary statistics for the entire month of September 2001 are given in Figure 9. The top-left subplot shows the availability of RTK solutions (as a percentage) for each survey day. There are significant variations from day-to-day, with availability ranging from less than 50 per cent to almost 100 per cent. The average was 82 per cent. 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.

The top-right subplot illustrates the consistency of daily offset values estimated between the buoy and gauge. The variations are at the few millimetre level for the most part, indicating that the standard deviation and 95 per cent statistics are very good estimates of the relative accuracy of the GPS determined heights as compared to the gauge heights. The standard deviation and 95 per cent statistics using the unfiltered GPS data are 8.7cm and 16.4cm, respectively.

The filtered GPS heights increase the data loss due to moving average filter edge effects and outlier removal, as can be seen in Figure 10. However the daily offset estimates do not vary significantly from those of the unfiltered. As expected the standard deviation and 95 per cent error are greatly reduced with the filtering to 3.6cm and 5.8cm, respectively. The latter value is well within the 10cm requirement.

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 100Mb hard drive meant all raw GPS receiver data could be stored for later post-processing. The reintegrated buoy was deployed in Gulfport harbour, 50m from the reference station, to test the system and especially GPS receiver processing firmware.

Data from the harbour deployment was analysed for RTK performance. Figure 11 illustrates the water level as determined from the short baseline unfiltered RTK for ten consecutive days in Novem-

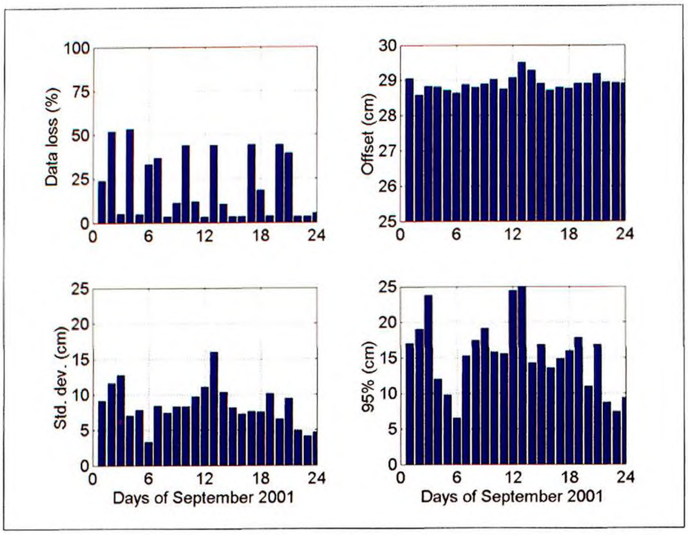

Figure 9: Summary statistics of unfiltered RTK buoy versus tide gauge for September 2001

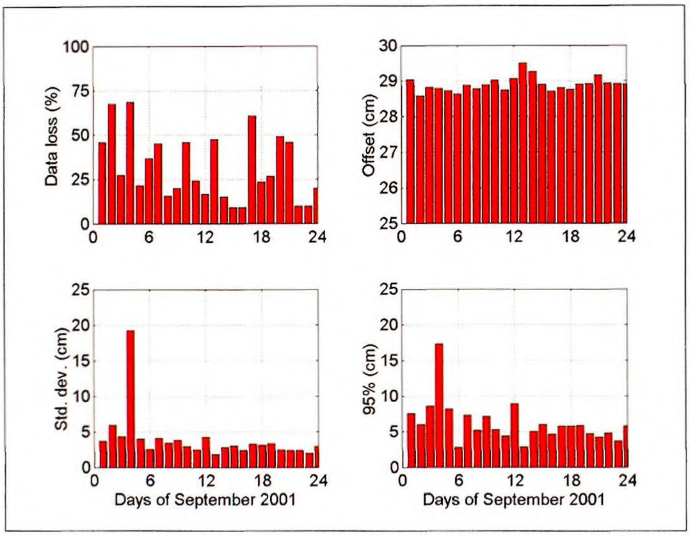

Figure 10: Summary statistics of filtered RTK buoy versus tide gauge for September 2001

ber 2002. Aside from one day with a few per cent data loss, solutions were always fully available. The estimated offset again varied by millimetres from day to day. The standard deviation and 95 per cent statistics using the unfiltered GPS data were 2.3cm and 4.3cm, respectively.

The filtered GPS heights again increase the data loss due to moving average filter edge effects and outlier removal, as can be seen in Figure 12. The daily offset estimates do not vary significantly from those of the unfiltered. The standard deviation and 95 per cent error are reduced with the filtering to 1.6cm and 2.9cm, respectively.

The comparison results between the unfiltered and filtered RTK water level and that observed at a tide gauge a few metres away were, as expected, excellent. The reason for this statement is that relative GPS data processing is baseline length dependent – longer the baseline, the greater the decorrelation of certain error sources, such as atmospheric refraction, which results is lower positioning precision. Further complicating RTK GPS positioning is the fact that there exists a number of different types of RTK GPS solutions. These solution types rely on two components: the combination of GPS carrier phase signals and the estimation of the counts of the ambiguous number of carrier phase cycles in the position solution process. The former combines the carrier phase signals to produce smaller or larger wavelengths, which produce more precise or less precise range measurements. The latter involves either estimating the counts of cycles as real numbers (float ambiguities) or, as they should be, integers (fixed ambiguities). Ideally, narrowlane, fixed ambiguity solutions would be sought, as they produce the most precise solutions. For the results already presented, the unfiltered and filtered 50 m 2002 data were expected to provide high quality height solutions, whereas filtering of the 10 km 2001 data would provide improved heights over the unfiltered solutions, even though all solutions were of the narrowlane fixed type.

2003 Buoy Deployment Results

After the successful harbour test, the buoy was placed approximately 15 km offshore, but experienced severe power drain over extended periods of

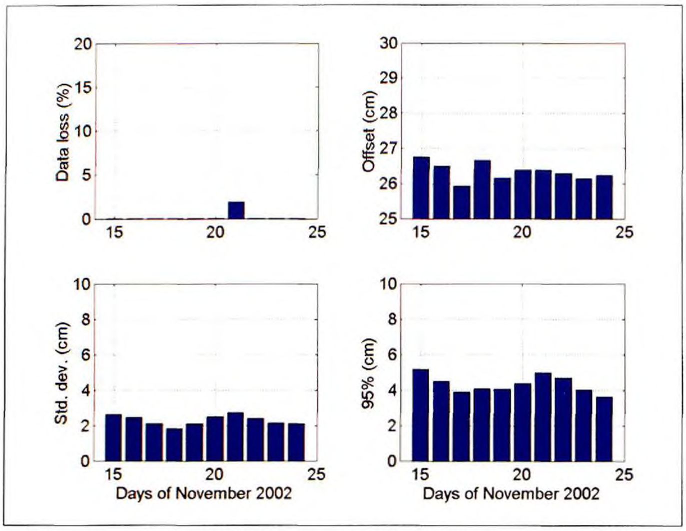

Figure 11: Summary statistics of unfiltered RTK buoy versus tide gauge for November 2002

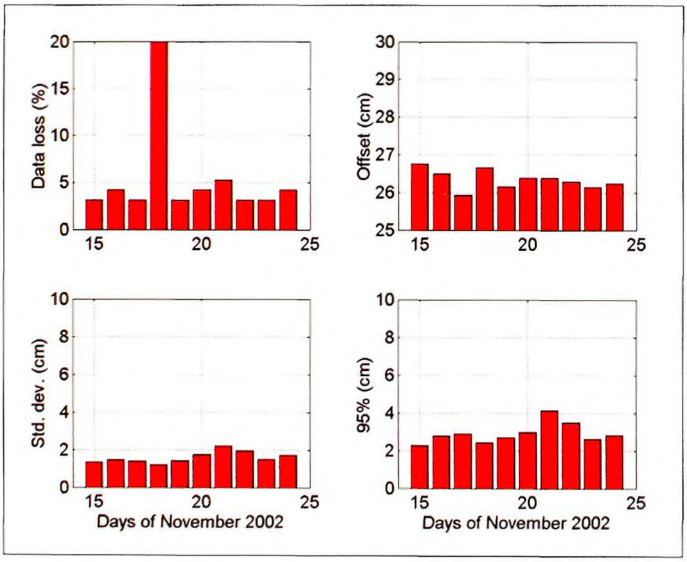

Figure 12: Summary statistics of filtered RTK buoy versus tide gauge for November 2002

continuous operation. The cause was a combination of overcast weather conditions, not enough winter sunlight hours, and solar panel mounting angle resulting in limited efficiency. After a complete system diagnostic the buoy was 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 power management strategy allowed sustained buoy operation and sampling throughout the local tide cycle over many months. In April 2003 the buoy was returned to a full duty for two weeks, the results of which are now presented.

Figure 13 illustrates the results of the unfiltered GPS height comparison against a collocated tide gauge. Since the gauge recorded at one hour intervals, only a limited number of data points were available for comparison. The upper subplots show good data availability and few millimetre variation in daily offset estimates. The standard deviation and 95 per cent error are rather large at 25.0cm and 38.8cm, respectively. Upon inspection of the NovAtel RTK solutions, widelane fixed solutions were produced. This solution type is inherently more noisy than the narrowlane fixed solution.

As can be seen in Figure 14, filtering the GPS solutions greatly improve the tide gauge comparison statistics to 6.3cm and 9.5cm for the standard deviation and 95 per cent error, respectively. The 95 per cent error is within the 10cm requirement of the NOS. Note that the near-constant 8 per cent data loss represents the lack of filtered data at the first and last data point of the day, and would be reduced to 0 per cent with the use of unfiltered data overlapping either end of the day.

Conclusions

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 programme to estimate tidal datum with respect to the GPS reference ellipsoid. The developed buoy has been deployed three times at different distances from an RTK base station. A pair of straightforward low pass filters was devised to filter the RTK height data, and these height time series were compared against tide gauge data. The results indicate that, for these datasets, the filtered RTK heights meet the U.S. National Ocean Service requirement of

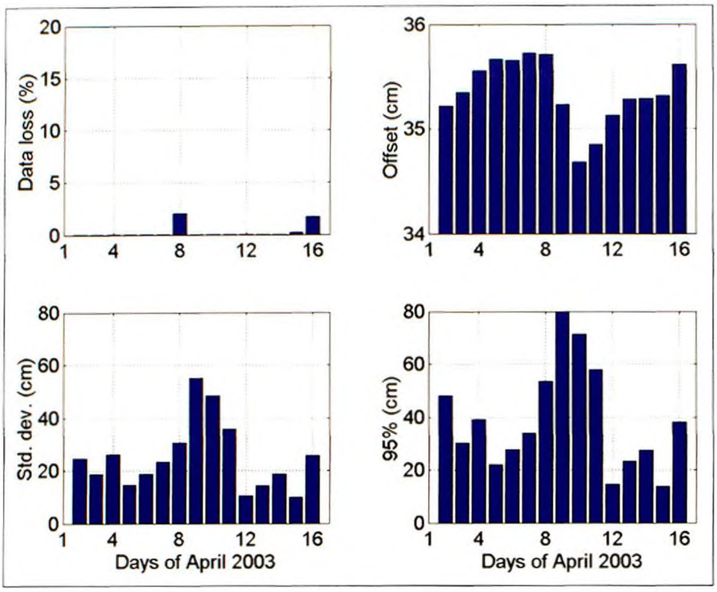

Figure 13: Summary statistics of unfiltered RTK buoy versus tide gauge for April 2003

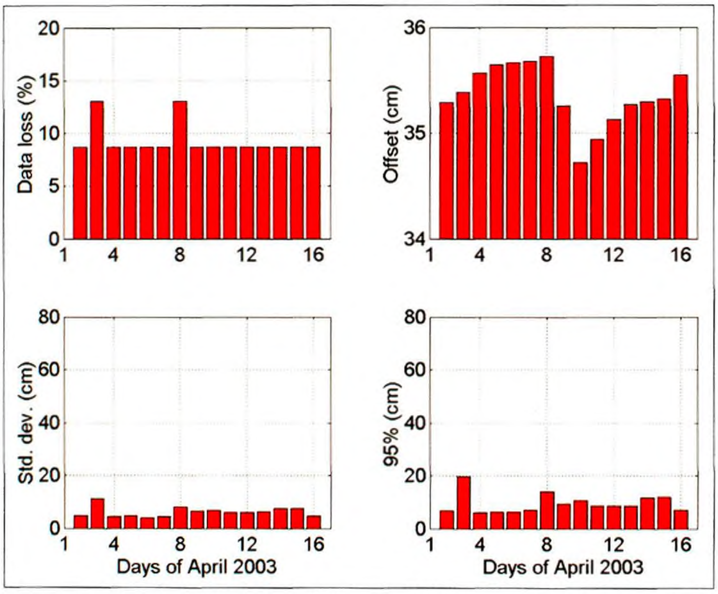

Figure 14: Summary statistics of filtered RTK buoy versus tide gauge for April 2003

Dataset	RTK baseline	1σ (cm)	95 % (cm)
2001	~10km	4	6
2002	~ 50m	2	3
2003	~15km	6	10

Table 2: Summary vertical positioning statistics for the three GPS buoy baselines

10cm 95 per cent (see Table 2). As is well understood, the resulting height accuracy decreases with baseline length.

Future Work

The HSRC is continuing this research in support of the design of an operational RTK GPS buoy comprising COTS components for tidal determination. The components of this design investigation are: analysis of the collected NAVOCEANO buoy data from other sensors; determination of the minimum buoy sensor suite; determination of local chart datum with buoy; survey of potential buoy hull designs; study of potential buoy power management strategies; and survey of potential communication links. This effort points to a significant near-term role for capable GPS-enabled buoys in hydrographic applications.

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These results were presented at the Institute of Navigation 2003 International Technical Meeting, 9-12 September, Portland, Oregon, USA.

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Biographies

Sunil Bisnath is an Assistant Research Scientist at the Hydrographic Science Research Center in the Department of Marine Science at The University of Southern Mississippi. His current research involves the evaluation and improvement of WADGPS and RTK GPS positioning and navigation techniques for marine applications. Sunil received an Honours B.Sc. (1993) and an M.Sc. (1995) in Surveying Science from the University of Toronto and a Ph.D. (2004) in Geodesy and Geomatics Engineering from the University of New Brunswick.

Dave Wells is Professor Emeritus in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, as well as Professor in the Department of Marine Science at The University of Southern Mississippi, and Adjunct Professor at the University of New Hampshire. Dave is also President of HydroMetrica Limited, a company providing hydrographic education and training. Since 1990 Dave has been a member of the FIG/IHO International Advisory Board on Standards of Competence in Hydrographic Surveying, which develops international hydrographic training standards, and assesses and recognises courses which meet these standards.

Stephan Howden received his M.S. in physics from Michigan State University and his Ph.D. in oceanography at the University of Rhode Island. His interests include application of satellite data for oceanographic and earth system studies, western boundary currents, general ocean circulation, earth climate system, coastal oceanography and hydrography.

David Dodd has been involved in surveying for the last 23 years. He received a B.Sc. (1987) and an M.Sc (1994), in Surveying Engineering from the University of New Brunswick in Fredericton, NB, Canada. Dave is currently the co-ordinator of the Hydrographic Program at The University of Southern Mississippi, and enrolled in the doctoral program.

Denis A. Wiesenburg is the Chair and Professor of Marine Science, the University of Southern Mississippi, Stennis Space Center. He has significant experience managing large research projects, including the Chemical Dynamics in Ocean Frontal Areas Project when he was employed with the Naval Ocean Research and Development Activity (NORDA) and the Louisiana-Texas Shelf Circulation and Transport Processes Study (LATEX A) when he was on the research faculty at Texas A&M University. As Chair of the Department of Marine Science, he has overall responsibility for the USM Master of Science degree in Hydrographic Science.

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