Datum Determination and VDatum Model Validation with a GPS Buoy

Ben Hocker, *David Evans and Associates, Inc.*
Nathan Wardwell, *JOA Surveys, LLC*

BIOGRAPHY

Ben Hocker is a Lead Hydrographer at David Evans and Associates, Inc. Marine Services Department based in Vancouver, WA. Mr. Hocker received a Geomatics Technology diploma from the British Columbia Institute of Technology and a BS in Geomatics Engineering from the University of Calgary. Mr. Hocker has over 15 years of hydrographic survey experience working on a variety of projects in Alaska and the Continental US as well as South America.

Nathan Wardwell is a partner of JOA Surveys, LLC and is based in Anchorage, Alaska. Mr. Wardwell received a BS in Environmental Science from Alaska Pacific University and a MS from the University of New Hampshire's Center for Coastal and Ocean Mapping. The majority of Mr. Wardwell's work consists of providing tide support for NOAA hydrographic surveys around Alaska and the Continental US. Currently his interests involve the application of PPK water levels for modifying tidal zoning schemes and deriving ellipsoid referenced tidal datums offshore.

ABSTRACT

Under a charting contract with the National Oceanic and Atmospheric Administration (NOAA), David Evans and Associates, Inc. (DEA) was tasked to evaluate the VDatum model in addition to mapping large portions of Chesapeake Bay. The VDatum software was developed by NOAA to vertically transform geospatial data among a variety of tidal, orthometric and ellipsoidal vertical datums. The goal of the evaluation was the Mean Lower Low Water (MLLW) datum model as applied to convert GPS determined ellipsoid heights to chart datum.

Using a buoy outfitted with GPS and a tilt sensor, tidal datums were computed at six locations distributed throughout the 2009 and 2010 project areas. Data was collected at each location for a minimum of 30-days. Post-Processed Kinematic (PPK) methodologies were used to process the GPS data from the buoy and derive ellipsoid referenced water levels. JOA Surveys, LLC (JOA) computed tidal datums from the ellipsoid referenced water levels using the Tide-by-Tide (TBYT) method of simultaneous comparisons with NOAA's permanent tide station 8635750 Lewisetta, VA. The resulting MLLW datums were within 0.051 m RMSE of VDatum model.

INTRODUCTION

Under a charting contract with the National Oceanic and Atmospheric Administration (NOAA), David Evans and Associates, Inc. (DEA) was tasked to evaluate the National Ocean Service's Vertical Datum Transformation (VDatum) software in addition to mapping large portions of the Chesapeake Bay. The VDatum software was developed by NOAA to vertically transform geospatial data among many tidal, orthometric and ellipsoidal datums[1]. High resolution coastline data and NOAA bathymetry are used to construct a high resolution unstructured grid in an ADvanced CIRCulation (ADCIRC) the tide model to develop tidal datum transformation grids.

The goal of this evaluation was the Mean Lower Low Water (MLLW) datum model as applied to convert GPS determined ellipsoid heights to chart datum. Using the ellipsoid as a reference surface does not fulfill charting goals of referencing measurements to a chart datum such as MLLW or Mean High Water (MHW). These datums were designed to offer a representative surface to the local water level at a particular tide stage. In the case of MLLW, to be a pessimistic depiction of expected water depths for safe navigation at most tide levels. As such, a continuous model is required to convert ellipsoid heights to the tidal plane. The methodology for evaluating the VDatum model offshore consisted of computing tidal datums from ellipsoid referenced water levels measured using a GPS buoy outfitted with a tilt sensor.

GPS buoy data were collected at six different locations between August of 2009 and October of 2010. A minimum of 30-days of data were collected during each deployment. Post-Processed Kinematic (PPK) methodologies were used to process the GPS data from the buoy and compute time-tagged antenna heights. These heights were then corrected by the antenna offset to the water line. Corrected ellipsoid water levels were filtered and the datums were computed using the TBYT method of simultaneous comparisons with the Modified Range Ratio method for deriving tidal datums equivalent to the current National Tidal Datum Epoch (1983-2001) from data series spanning less than 19 years.

The processed buoy data from the first 2010 deployment were checked against water levels measured at NOAA permanent tide station at Lewisetta, VA. To ensure comparisons to the NWLON station at Lewisetta, VA were valid, the published water level results were checked against data collected on the survey vessels as well as manual water level observations. Additionally, the published datum planes at the station were verified using static GPS methods. The computed MLLW datums were then compared to the VDatum model conversion.

BUOY DESIGN

The buoy used for datum determination was an AXYS Technologies, Inc. Hydrolevel™ Mini provided by the Naval Oceanographic Office (NAVOCEANO). This buoy uses the AXYS Technologies Inc. TRIAXYS™ Mini Buoy hull which is a 0.65-meter diameter stainless steel sphere outfitted with a mooring pad-eye and lifting handles (Figure 1). The buoy is sealed using a rubber gasket and 12 stainless steel bolts holding the two halves together. A rubber surround ring protects the flange that seals the two buoy halves. The antennas, obstruction light and cable connections are protected by the lifting handle that is welded to the top of the buoy.

The batteries used for the 2010 deployment changed from the non-rechargeable Lithium Thionyl Chloride platters used in 2009 to rechargeable Lithium Iron Phosphate cells. This improved the usability and safety of the system as well as lowering deployment costs. The new cells did not have the capacity to endure a 30-day deployment requiring a mid-deployment buoy retrieval to recharge the batteries. Also, the system exhibited a definite list during the entire deployment due to the arrangement of the cells within the hull. Each of the new batteries has a nominal voltage of 12 V and a manufacturer quoted capacity of 55 Amp-Hours. The three batteries are secured to the bottom of the buoy hull while the electronics are packaged above and inside a second sealed enclosure. This system uses a Watchman 500 data collection platform to log raw NAVSTAR GPS observables and tilt data while compiling and sending status messages via an Iridium satellite modem. Data was logged to an 8 GB Compact Flash (CF) data card.

Figure 1: Tide Buoy on a calm day.

The GPS sensor used in this buoy is a dual frequency Trimble BD950 board that is streaming data in RT17 format (position, raw observables and ephemeris) at 5 Hz. A NavCom model 2004T dual frequency antenna is mounted on the top of the buoy with the cable sealed in a watertight pass-through. To mitigate data loss files were logged hourly. Depending on the number of satellites tracked the files were approximately 8.2 MB.

The Watchman 500 DCP was heavily taxed by the amount of data to log. The system uses a buffer to capture streaming data while it records information to the flash card. The system could not write data quickly enough as the number of satellites increased over approximately 10. As a result, the buffer overflowed causing a loss of data. This seemed to affect the raw GPS observables, ephemeris data as well as tilt information.

The tilt sensor used was a PNI TCM2.6 tilt corrected compass module. The manufacturer quoted specifications are: 0.8º heading accuracy with 0.1º resolution, 0.2º pitch and roll accuracy with a resolution of 0.1º (range of +/-50º). No confidence level was provided.

An Iridium 9601 Short Burst Data (SBD) modem was used to send buoy status messages that can be monitored remotely. This includes records such as system health, position, battery voltage, memory free-space and many other parameters. It is important to note that the raw GPS observables were not broadcast from the buoy. The only way to download the full resolution GPS and tilt data was to open the buoy and remove the memory card.

The buoy has one-centimeter increment draft marks painted on each the side of the hull. These marks allow for the determination of the Antenna Reference Point (ARP) height above the water surface. The waterline was recorded relative to these marks when the buoy was deployed, and during each visit to monitor the buoy. The mass of the buoy remained constant for the entire duration of the deployment, thus the water line did not change. The waterline in all cases was at the buoy vertical reference, which coincides with the flange joining the two halves of the hull.

REFERENCE STATIONS

Two temporary GPS base stations were installed by DEA to support post-processing of the tide buoy data in both 2009 and 2010 (Figure 2). Each was also used as a base station for post-processing data collected on the hydrographic survey vessels. Each was strategically located near the project site in order to minimize the baseline lengths over the entire project area. These temporary base stations were established using Trimble Net-R5 dual frequency (L1/L2) receivers with Trimble Zephyr Geodetic GPS antennas. Each station was selected to provide a clear satellite visibility with the GPS antennas installed on a rigid steel pole securely attached to a structure. Only NAVSTAR GPS was logged as the receivers on the survey vessels and the buoy did not support GLONASS. The base station receivers were configured to log raw GPS observables at 1 Hz. Data logged included: L1 phase, C/A code, L2 phase, P(Y) code and L2C (CM+CL). Internally logged data was stored in Trimble T01 format and segmented into 24-hour files that were manually downloaded and quality controlled daily.

The fixed position for each base station was determined using the Online Positioning User Service (OPUS), operated by the National Geodetic Survey (NGS). The solutions derived from OPUS were processed using a precise GPS ephemeris and all solutions were in accordance with the passing criteria for the solution statistics established in the NOAA publication *User's Guide for GPS Observations (March 2007)*. The NAD83(CORS96, Epoch 2002) coordinates (Table 1) for each site were derived at the ARP of the Trimble Zephyr Geodetic antennas.

Table 1: Temporary base station coordinates

ARP Coordinates NAD83(CORS96, Epoch 2002) (24 Hour OPUS Solution)			
Station	**Latitude (N)**	**Longitude (W)**	**Ellipsoid h (m)**
SMITH	37º46'50.0590"	76º19'01.2229"	-26.347
TANGIER	37º49'10.0060"	75º59'48.4176"	-31.290
AIRD	38º07'10.2295"	76º20'53.7956"	-22.567
EWELL	37º59'46.2523"	76º01'59.0981"	-31.911

DEPLOYMENT LOCATIONS

Care was taken in the planning of the deployment sites along with consultation with the United States Coast Guard. Sites were selected well outside any areas of heavy vessel traffic while also providing a good distribution for VDatum model validation. It was also important to ensure that the buoy had a clear view of the sky. Although not generally an issue at sea, some deployment sites were situated in the vicinity of navigation aids or existing structures.

The mooring system was configured on site, depending on water depth. For most moorings, the system used a clump weight with 20 feet of ground chain connected to a galvanized cable. The cable length was adjusted to create a 3:1 system (length to water depth). The clump weight was designed not to snag the ground chain as the buoy experienced considerable rotation during the deployments. Figure 2 shows the base stations and buoy deployment locations with respect to the project boundaries.

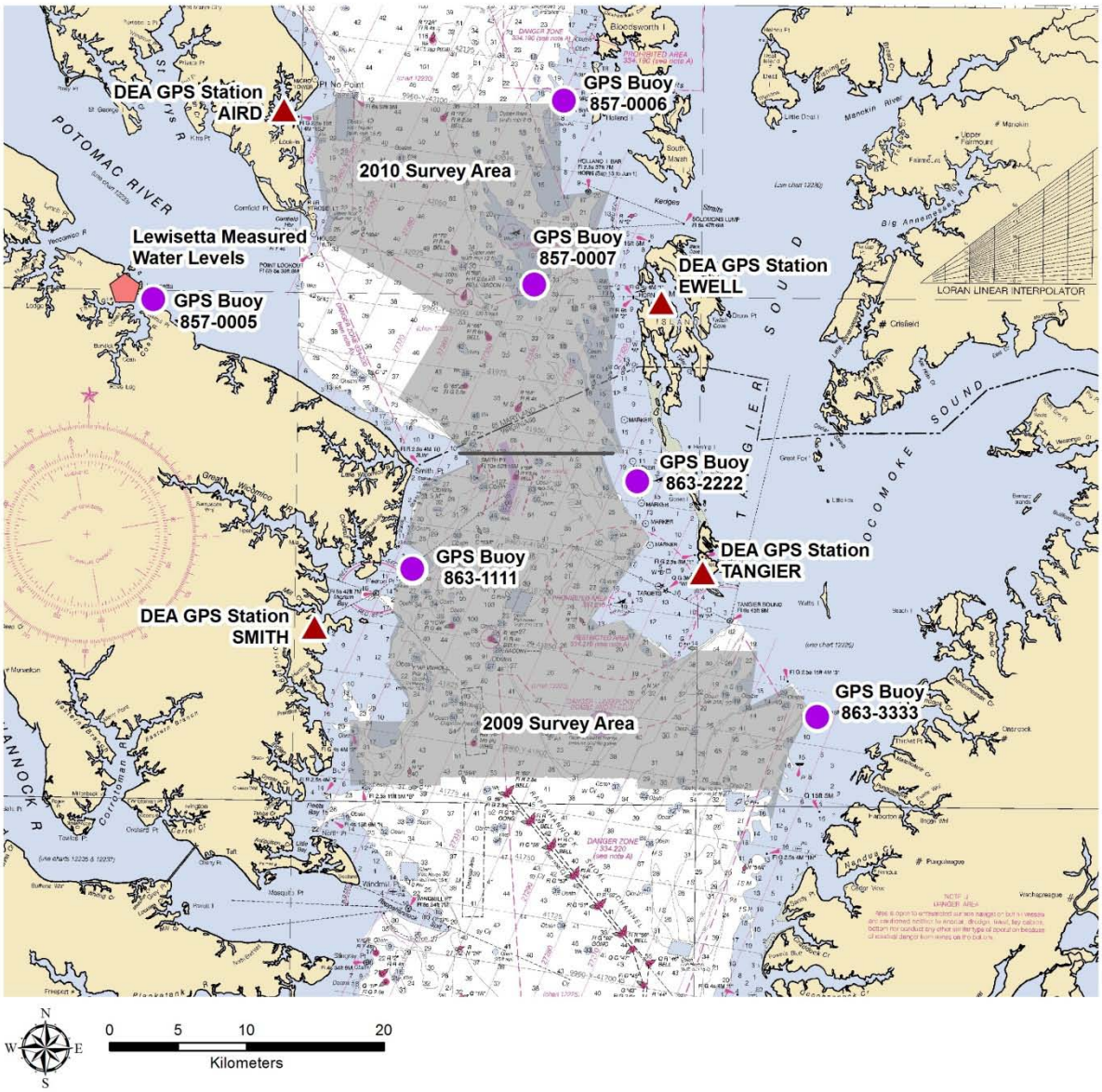


Figure 2: Deployment locations and project areas

DATA PROCESSING

Raw GPS observables were processed in NovAtel's GrafNav software using Post Processed Kinematic (PPK) techniques. The precise ephemeris, clock and IONEX models were also used in the solution. Data from the temporary base stations were used as the master stations in single-base mode using the NAD83(CORS96 Epoch 2002) datum as the reference. For each deployment, the closest base station was selected as the master. Table 2 shows the master to remote baseline lengths for each of the deployments. In some cases the lengths were very long (over 17 km) causing a degradation in accuracy.

Following is information pertaining to the 2010 deployments processing only. Processing of the 3 deployments in 2009 was similar; however, subtle changes in the buoy hardware, software and processing methodologies are outside the intended scope of this paper.

The raw data collected on the buoy was first converted to from the Trimble Real Time (RT17) format to the GrafNav compatible GPB format using the GNSS Converter utility in GrafNav. These files were then merged and processed as 64-file blocks, with each block spanning approximately 3 days (710 MB). GrafNav projects were created for each block of data and processed separately.

The raw base station data was converted from Trimble internal T01 format to RINEX using the Trimble RINEX utility then to GPB using the GrafNav converter. These files were then merged into 3-day blocks that spanned the same time period as the corresponding rover data file block. Since the base data was collected at 1 Hz, it was then re-sampled in GrafNav to match the 5 Hz interval logged by the rover data.

Table 2: Baseline lengths

Deployment	Base Station	Baseline Length (km)
2009-1	SMITH	8.31
2009-2	TANGIER	8.16
2009-3	TANGIER	13.45
2010-1	AIRD	17.21
2010-2	EWELL	16.17
2010-3	EWELL	9.34

The NGS antenna model was used for both the base and rover. The offset between the ARP and the water surface constituted the effective antenna height, and lever arm to be used in the application of the tilt measurements.

Processed data from GrafNav was brought into Caris HIPS version 7 for application of the tilt data. HIPS also provided excellent data visualization tools for quality control and manual editing. An ASCII export was formatted out of GrafNav and imported to HIPS using the Generic Data Parser.

The ASCII tilt data logged by the Watchman 500 was reformatted to a structure that could be merged onto the data in Caris. The compass, pitch and roll values were aligned by time and imported into the HIPS data using the Generic Data Parser.

The buoy tilt sensor measures angular orientation in two axes: pitch and roll. Heading is measured, but not required as the direction of the combined tilt is irrelevant. To determine the effect of buoy pitch and roll on the height of the antenna relative to the water surface, a combined value of tilt was computed that is independent of direction. The angular tilt value was then applied to the lever arm of the antenna height above the water line to determine the difference in height due to buoy orientation.

Due to the buffer overflow during acquisition, there were not only GPS observables missing, but also gaps in the tilt data. These ranged from less than a second to several minutes in some cases. There were also issues with the timing of the tilt sensor data. The PNI sensor is a separate board and is not time synchronized with the Watchman 500. The Watchman 500 is synchronized with the GPS clock every hour to keep the absolute time of the system in check. This resulted in some drift between the tilt sensor's internal oscillator and the Watchman 500 over the course of the deployment. The combined latency between the message recovery from the buffer/decoding/storage and the time discrepancy lead to many messages falling on either side of the 1-second boundary for the logging interval. No data was lost; however, the result was that the frequency of the tilt data appeared to change between 4 Hz and 6 Hz. It could not be determined which integer second the extra reading belonged to due to the message format. As a result, the data was read-in as it was logged, creating some time periods with data that bounced between update rates. This created an additional apparent fluctuating latency in the tilt data. As the effect of the tilt data, particularly on the order of 0.1 second increments, was negligible, this was deemed acceptable.

The primary use of the tilt data is to remove the effects of large or long-term constant pitch/roll angles. As the antenna height above water will always be decreased due to tilt, resolution of this component is important if there are constantly present significant biases. Heave is a much larger contributor to the vertical displacement than the instantaneous tilt. The heave can be, in the simplest case averaged out; however any large or significant long term bias in tilt will result in an offset in the height that can not be removed without reasonably accurate application of the angles to the lever arm. A small timing error will not adversely affect the overall result since the direction of the correction is the same, regardless of angle (lower antenna height).

Figure 3 shows a representative plot of data on a calm day with the exception of a wave event that passed through. The disturbance is apparent in the pitch, roll and computed GPS height. Also seen in Figure 3 is a constant bias in the angular data. This is due to an apparent imbalance of the buoy- the three rectangular batteries and additional power box created a list when the buoy sat in the water that was not present with the circular battery platters used in 2009. Although the offset was negligible, the tilt sensor data worked well to correct for this. For an average of 4 degrees of roll and 3 degrees of pitch, the tilt would be approximately 5 degrees leading to a vertical correction to the antenna height of -0.001 m.

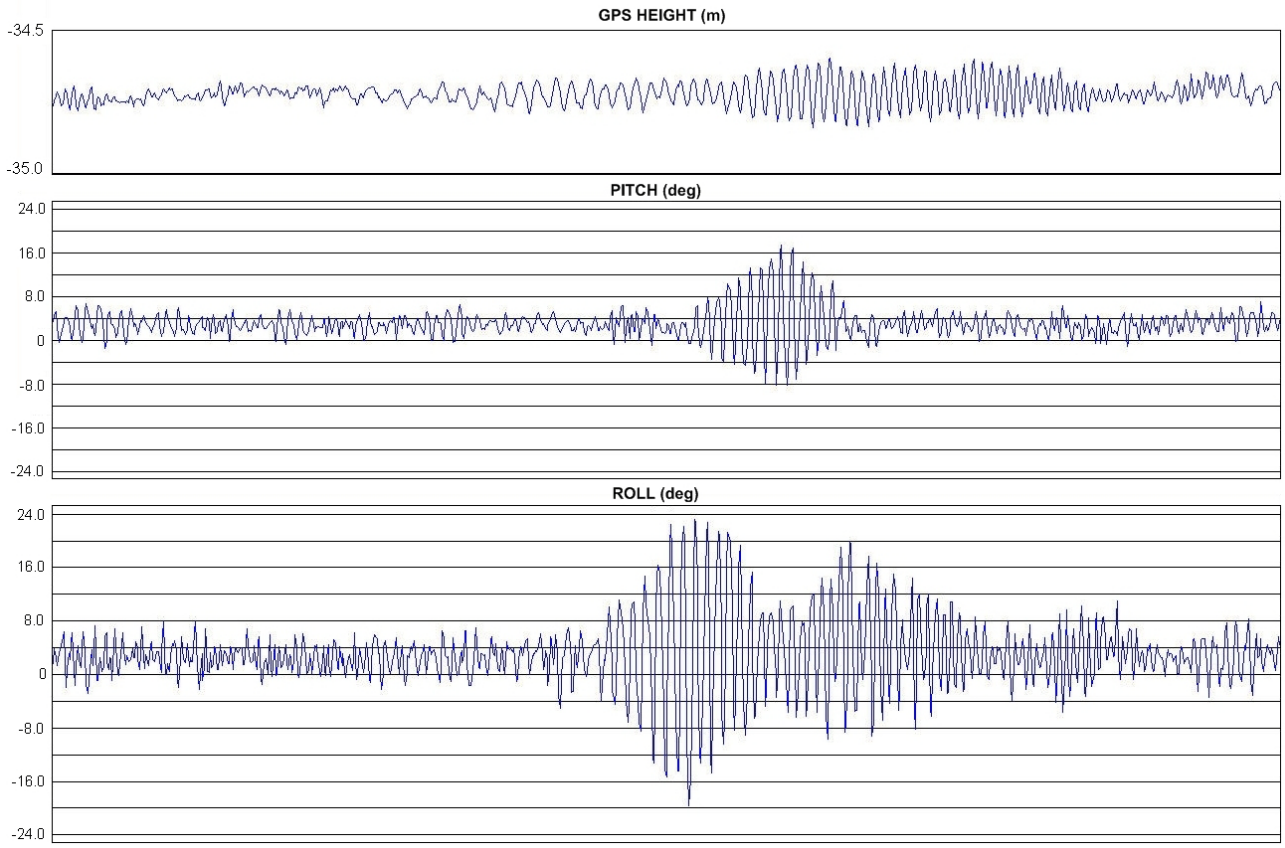


Figure 3: Height, pitch and roll data sample

As the processed PPK results contained a great deal of high frequency signals, a filtering/smoothing algorithm was necessary. Traditional NOAA/CO-OPS tide gauges use an averaging method, taking the mean of 3-minutes of data around each 6-minute interval. The resulting time series is polynomial smoothed prior to picking the high and low water levels used in the datum computation. For the post-processed ellipsoid-referenced water levels from each GPS buoy deployment the averaging step was skipped and the 1 Hz data were frequency filtered. Prior to filtering all gaps were linearly interpolated. The three reasons for doing this are that there is a substantial amount of measurement noise in the data that is not removed by the averaging method (Figure 4). The averaging method is severely biased by the data gaps, whereas the gaps are handled more appropriately by frequency filter. And, the primary goal was to evaluate the VDatum model thus the high and low water levels were of more interest than the six minute water levels.

The frequency filter consisted of a 3rd order Butterworth filter with a cut off frequency of 11 cycles per day (cpd). Considering the majority of the energy in a tidal signal is around 2 cpd, a cut off frequency of 11 cpd easily retained the tide signal. The highest frequency tidal constituent the Center for Oceanographic Operational Products and Services (CO-OPS) uses in their predictions is the shallow water constituent M8 which has a frequency of 7.73 cpd.

The filtering was accomplished in MATLAB using the 'filtfilt' function which filtered the data in both a forward and reverse direction to minimize phase distortion. Outliers in the buoy data are the result of both noise and wave induced buoy vertical motion (heave) and were removed during the filtering process. The Butterworth filter removed a significant amount of the higher frequencies that are preserved by the six-minute averaging filter. These higher frequencies may be the result of local short term water level disturbances and are undesirable when computing high and low values for datum computations.

Figure 4 shows two days of data collected during the second deployment in 2010. The horizontal and vertical scales are the same in both plots. The data collected on August 13th (top plot) is representative of a relatively problem free set of data with approximately 60 centimeters of measurement noise. Note that the Mean Tide Range for at Lewisetta is 37.9 centimeters. The data collected on August 31st (bottom plot) has several long term outages (greater than 1 hour) that were likely caused by the buoy software as the raw observable files were corrupt. The Butterworth filter clearly handled both the measurement noise and the short term outages better than the averaging filter.

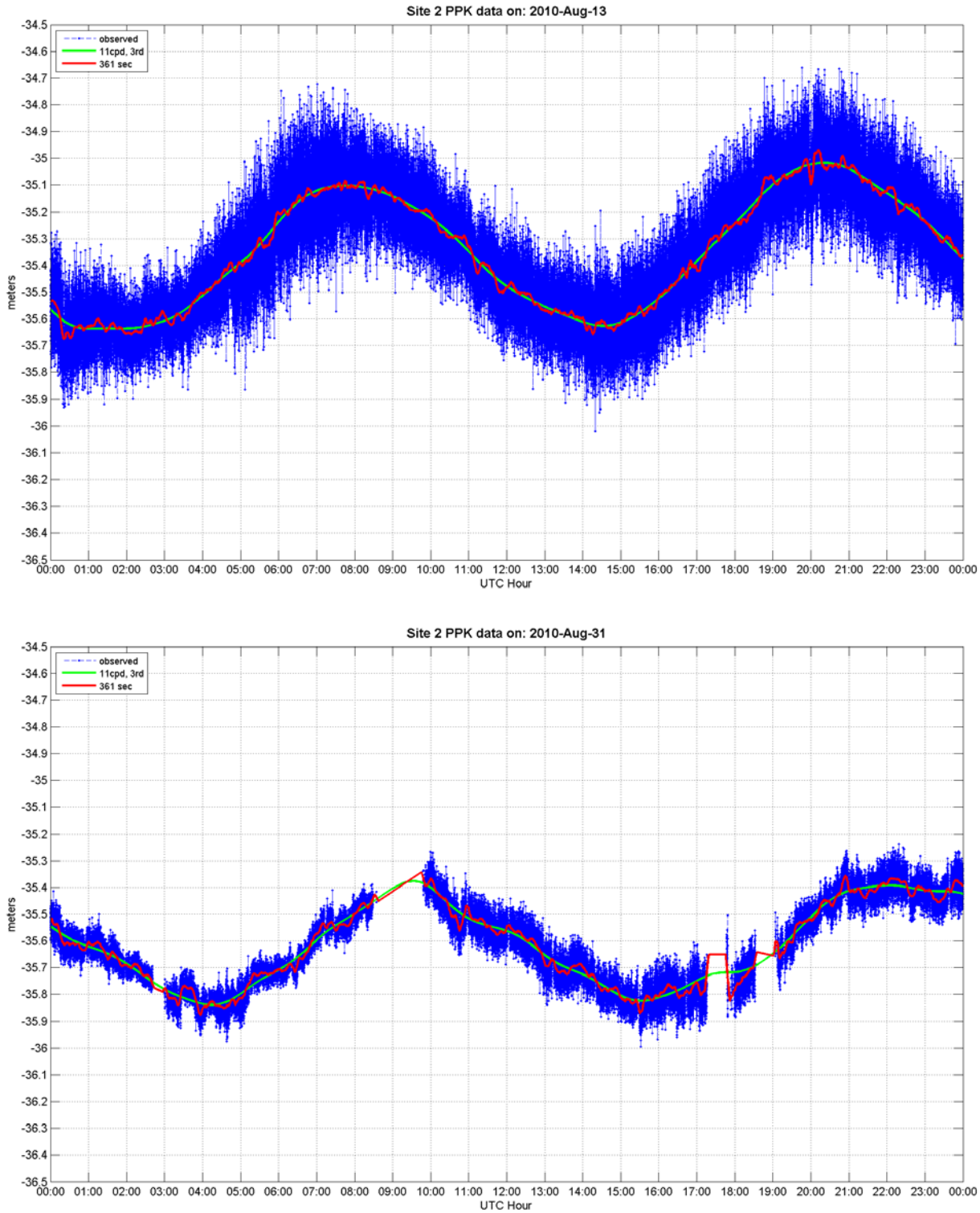


Figure 4: Butterworth (green) and moving average (red) filter results.

NWLON STATION VALIDATION

The active NOAA permanent tide station at Lewisetta, VA is part of CO-OPS's National Water Level Observation Network (NWLON) and served an integral part of the VDatum validation and GPS tides component of the hydrographic survey. To ensure that the station was operating within expected accuracies, and to compare VDatum results in the vicinity of the station, several checks were made by DEA field crews during 2009 and 2010.

As part of the GPS water level quality assurance procedures, a one-hour vessel float observation was acquired adjacent to the tide station. Each of the two hydrographic survey vessels was equipped with an Applanix POS/MV-320 (Version 4) system which recorded dual frequency (L1/L2) raw GPS observables and inertial data at 50 Hz. Applanix POSPAC MMS software was used to post-process the raw GPS and tightly coupled Inertial Measurement Unit (IMU) data to produce a Smoothed Best Estimate of Trajectory (SBET) using advanced forward and backward filtering algorithms. These SBET files contain not only refined position and attitude information, but also ellipsoidal heights. The ellipsoidal heights were reduced to MLLW using a 3-arc second grid created from the VDatum model. The resulting water elevations on MLLW, derived with VDatum and GEOID09 were then compared to the simultaneous water level data measured by the Lewisetta NWLON station. The mean float observation was 2.9 centimeters (+/- 2 cm at 1-sigma) below the CO-OPS observed water levels at Lewisetta.

Table 3: Published elevations compared with GPS survey results

Lewisetta (863-5750)	
Bench Mark	R 462 (PBM)
MLLW (CO-OPS)	1.420 m
MLLW (VDatum GEOID09)*	1.397 m
NAVD88 (NGS Adjusted)	1.169 m
NAVD88 (GEOID09)*	1.153 m
NAD83 (CORS96, 2002 Epoch)*	-33.735 m

*derived from static GNSS observations, OPUS overall RMS 0.013m

Published MLLW water levels for Lewisetta were verified using staff shots (manually measuring the water level relative to a tidal benchmark). The average staff-to-gauge comparison was -1.1 centimeters (+/- 0.4 cm at 1-sigma). Tidal benchmark stability was ensured by running 3rd order levels through three of the tidal benchmarks in the local network for the Lewisetta NWLON. The mark used for the staff observations and the primary bench mark were included in the level run.

Static GPS observations on the primary tidal bench mark R 462 (PID GV0156) were also collected and compared to the NGS published NAVD88 elevation derived from level runs. Static GPS observations were processed using OPUS using the precise ephemeris for consistency with other project comparisons.

CO-OPS and NGS published datum planes show some disagreement with the computed MLLW and NAVD88 datums using the VDatum model (Table 3), but are within expected uncertainties. At Lewisetta, the difference between the NGS published NAVD88 orthometric height (derived from adjusted level observations) and the GPS derived height using GEOID09 is 1.6 centimeters pushing the difference between the CO-OPS MLLW datum and the derived VDatum MLLW to 2.3 centimeters (Table 3). The direction of the difference is also consistent with the GEOID09 separation model, as shown in Figure 5.

It is most likely that the differences observed are mostly related to GPS accuracy and using GEOID models of NAVD88 incorporated in VDatum rather than NGS published NAVD88 elevations from level runs. Use of GEOID models is widely accepted in the survey community and differences are within expected tolerances of both GEOID models and GPS observations.

From these cumulative results, the GEOID model and datum at the Lewisetta NWLON station have been shown to be within expected uncertainties and are valid for comparison purposes.

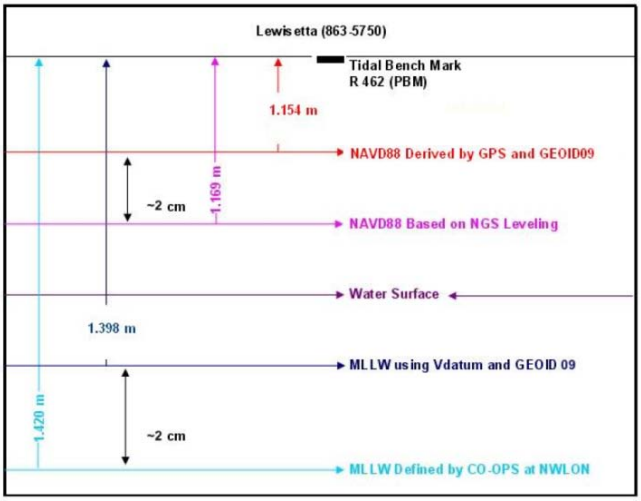


Figure 5: Datum planes

PROCESSED DATA VALIDATION

Figure 6 shows the results of a vessel float at the first deployment site in 2010. This illustrates the vessel results as well as the gauge readings alongside the processed buoy data. Three vessel floats were conducted at the Lewisetta deployment, with the average difference between the gauge water levels and the buoy water levels being -0.032 m.

All of the GPS based observations at the 2010-1 site show an apparent bias of approximately 3 centimeters, with the GPS results lower than the gauge readings for both the buoy and the vessel. This is attributable to the difference in the GEOID09 model from the gauge to the buoy location. The buoy was situated as close to the gauge as possible, but was still approximately 800 meters east. The GEOID model difference of -3.3 centimeters is coincident in direction and magnitude to the differences between the GPS derived water levels and the gauge derived water levels.

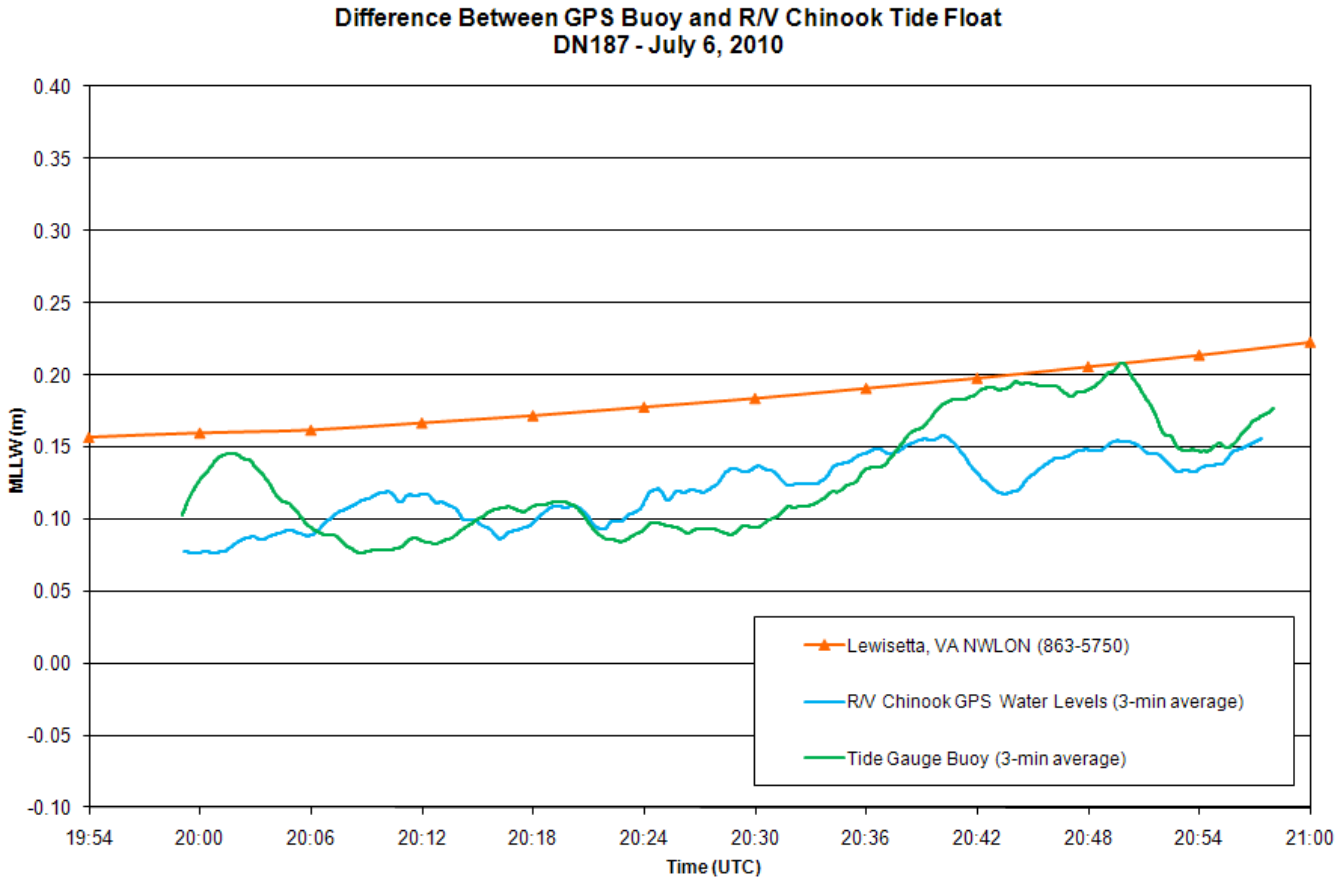


Figure 6: Buoy data compared with vessel and gauge

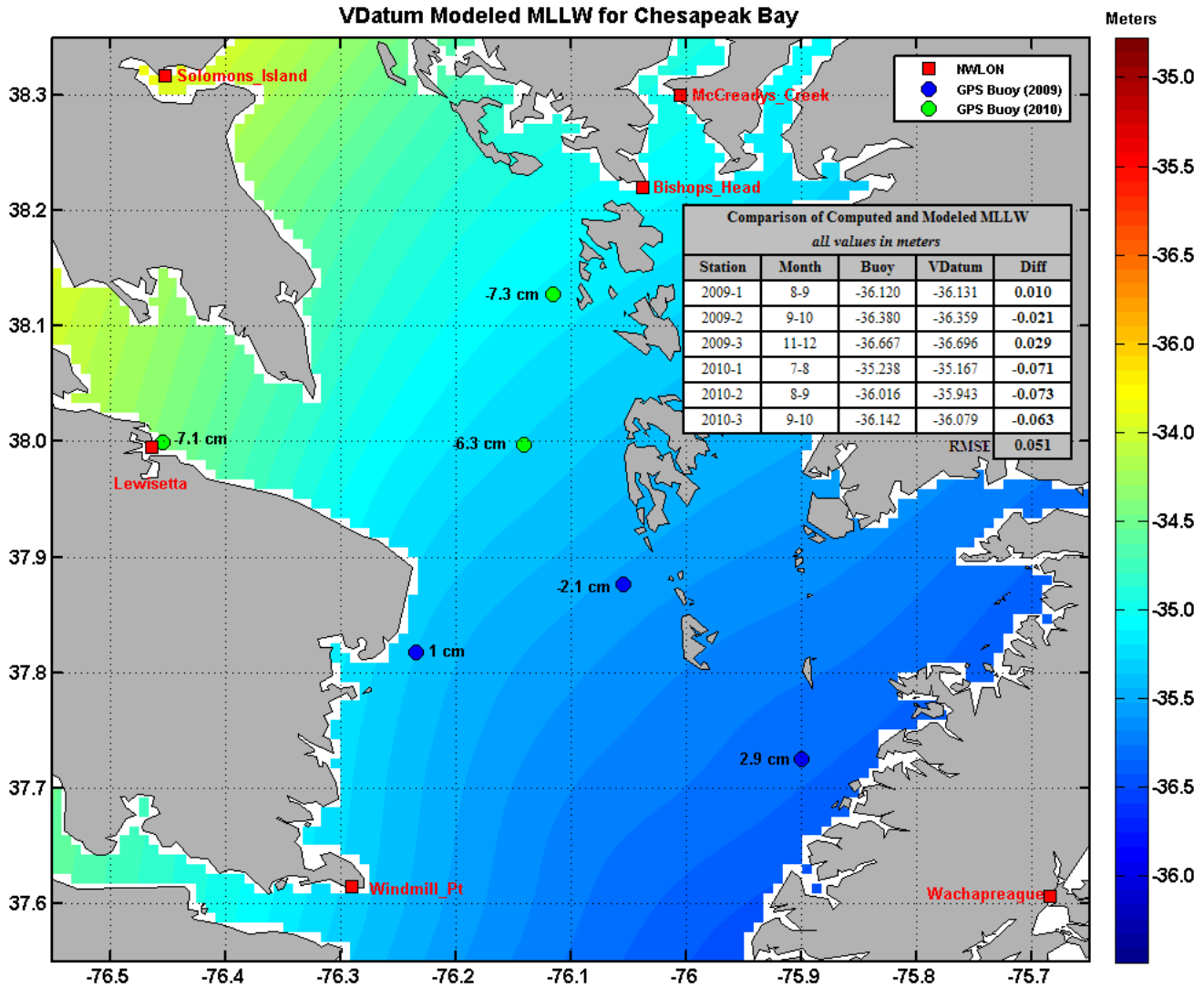
DATUM DETERMINATION AND COMPARISON

The tidal datums computed from the data collected at the six GPS buoy deployment sites were computed in accordance with NOAA Special Publication NOS CO-OPS 2 (NOAA, 2003). Specifically the Tide-by-Tide (TBYT) method of simultaneous observations with the Modified-Range Ratio method for deriving tidal datums equivalent to the current National Tidal Datum Epoch (1983-2001) from data series spanning less than 19 years.

Of primary interest for computing tidal datums is each high and low tidal event during the collection period. These events are used to derive the Diurnal Tide Level (DTL) and the Great Diurnal Range (GT). When using the Modified-Range Ratio Method half of GT is then removed from DTL to determine MLLW. The high and low waters used in all tidal datum computations were picked from the Butterworth filtered PPK solutions.

Traditionally the water level observations and resulting tidal datums at a station are referenced to Station Datum (STND). STND is specific to each site. This datum has historically been either an arbitrary datum assigned to the station or the elevation of the original orifice/sensor "0". STND for this project is NAD83(CORS96 Epoch 2002). The advantage of using this reference ellipsoid as STND instead of an arbitrary datum is that the resulting MLLW datum is the ellipsoid-to-chart datum separation modeled by VDatum.

The agreement between the MLLW datums computed from the GPS buoy data and those modeled using VDatum was very good considering at times the range of the buoy measurements was more than 2 times the published Mean Tide Range for the area in addition to the noise introduced by the buffer size. Overall the root mean square error between the computed and VDatum modeled MLLW datums at the six deployment locations is 0.051 m (Figure 7).



Comparison of Computed and Modeled MLLW
all values in meters

Station	Month	Buoy	VDatum	Diff
2009-1	8-9	-36.120	-36.131	0.010
2009-2	9-10	-36.380	-36.359	-0.021
2009-3	11-12	-36.667	-36.696	0.029
2010-1	7-8	-35.238	-35.167	-0.071
2010-2	8-9	-36.016	-35.943	-0.073
2010-3	9-10	-36.142	-36.079	-0.063
			RMSE	0.051

Figure 7: Variation in MLLW in Chesapeake Bay as modeled by VDatum. GPS buoy deployment locations are represented by the circles and are labeled by the difference between the computed and modeled value for MLLW at the deployment location.

CONCLUSIONS AND RECOMMENDATIONS

The results show that the uncertainty in VDatum, at least in the project area, is much less than the allowable contribution of tides and water levels to a NOAA hydrographic survey. Furthermore the results show that the use of a GPS buoy to establish datums for evaluating the VDatum model is a valid method. However, due to the amount of measurement and processing noise it may not be valid method for calibrating the model.

The hardware used in the buoy performed reliably and was able to collect the necessary data for processing. There were several areas that would benefit from improvement including the timing of the tilt data as well as the placement and duration of the battery pack. Adjustment of the buffer size may reduce the number of corrupt records. The data rate of the Trimble BD950 GPS board could also be reduced to 1Hz to avoid issues with the buffer overflow and not adversely affect the datum results.

The PNI tilt sensor is a tilt corrected compass module. These types of sensors register an apparent tilt that is induced by lateral displacement. Future results may benefit from a higher quality sensor while considering power consumption.

The deployment locations were well distributed throughout the project area and allowed for a good comparison the VDatum model. The location of the reference stations was adequate, however the ellipsoid referenced water levels and resulting tidal datums would benefit from shorter baselines.

ACKNOWLEDGMENTS

Special thanks to Elliot Arroyo-Suarez of the Naval Oceanographic Office. Without Mr. Arroyo-Suarez and NAVOCEANO this project would not have been possible.

Thank you to Peter Van Vugt of AXYS Technologies, Inc. who provided technical support and training for the buoy systems.

This research was funded by the National Oceanic and Atmospheric Administration's (NOAA) Office of Coast Survey (OCS). The authors would like to thank NOAA and the OCS for their support and cooperation.

REFERENCES

Parker, B.P., D. Milbert, R. Wilson, J. Bailey, and D. Gesch, 2001: "Blending Bathymetry and Topography: The Tampa Bay Demonstration Project." *Proceedings, U.S. Hydrographic Conference 2001, Norfolk, VA.*

U.S. Department of Commerce, CO-OPS/NOS/NOAA, September 2003: “Computational Techniques for Tidal Datums Handbook” *NOAA Special Publication NOS CO-OPS 2*

Engineering Division, CO-OPS/NOS/NOAA, December 2009: “User’s Guide for GPS Observations at Tide and Water Level Station Bench Marks”