Tidal Datum Determination and VDatum Evaluation with a GNSS Buoy

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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 GNSS determined ellipsoid heights to chart datum.

Using a buoy outfitted with GNSS and a tilt sensor, tidal datums were computed at three locations bounding the project area in 2009 and work continues in 2010. Data was collected at each location for a minimum of 30-days to maximize the accuracy of the datum computation. Post-Processed Kinematic (PPK) methodologies were used to process the GNSS data from the buoy and compute time-tagged antenna heights. These heights were then corrected by the antenna offset to the water line and the buoy's tilt sensor data was analyzed. Corrected ellipsoid water levels were filtered and the datums were computed using the Tide-by-Tide method of simultaneous comparisons using a control station.

Final results were compared with existing shore-based tide stations, GNSS water levels computed on two survey vessels and the 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 VDatum model 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 vertical datums[1]. To compute the necessary tidal datum values, high resolution coastline data and NOAA bathymetry was used to construct a high resolution unstructured grid which was used in the tide model. ADvanced CIRCulation (ADCIRC) was used as the standard tide model and results were compared to the Center for Operational Oceanographic Products and Services (CO-OPS) gauge observations. A structured marine grid of corrected tidal datums was then created[2]. This structured grid was used to convert the ellipsoid heights derived from GNSS to chart datum.

The goal of this evaluation was the Mean Lower Low Water (MLLW) datum model as applied to convert GNSS 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.

Using a buoy outfitted with GNSS and a tilt sensor, tidal datums were computed at locations bounding the project area in 2009 and work continues in 2010. Data was collected at three locations in 2009 and another three deployments will be completed in 2010. This paper focuses on the data collection and processing methodologies and detailed results from the first deployment of 2010. This deployment was chosen as it was adjacent to the National Water Level Observation Network (NWLON) station at Lewisetta, VA. Results from the 3 previous deployments in 2009 are also presented.

Each deployment collected a minimum of 30-days of data to maximize the accuracy of the datum computation. Post-Processed Kinematic (PPK) methodologies were used to process the GNSS data from the buoy and compute time-tagged antenna heights. These heights were then corrected by the antenna offset to the water line and the buoy's tilt sensor data was analyzed. Corrected ellipsoid water levels were filtered and the datums were computed using the Tide-by-Tide (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 2010 were checked against water levels measured at the nearby NWLON station at Lewisetta, VA. The hydrographic survey vessels were also used to validate the buoy results from both 2009 and 2010.

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 GNSS methods.

The computed MLLW datums were then compared to the VDatum model conversion for that area. Additional comparisons were made to the published MLLW datum at the NWLON station at Lewisetta, VA.

BUOY DESIGN

The buoy used for datum determination was an AXYS Technologies, Inc. Hydrolevel™ Mini provided by the Naval Oceanographic Office (NAVOCEANO).

The 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. The buoy is sealed using a rubber gasket and 12 stainless steel bolts holding the two halves together. A rubber surround ring then 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. Figure 1 shows the buoy on a calm day.

Figure 1: Tide buoy on a calm day

The batteries used for the 2010 deployment have been upgraded 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. However, early testing suggests that the new cells may not have the capacity to endure a 30-day deployment. 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 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 is logged to a 8 GB Compact Flash (CF) data card.

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. This creates data files that are on the order of approximately 8.2 MB per hour, depending on the number of satellites tracked. Files were broken into 1-hour increments to mitigate the data loss should a file become corrupt. A NavCom model 2004T dual frequency antenna is mounted on the top of the buoy with the cable sealed in a watertight pass-through.

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. Unfortunately, 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. Adjustment of the buffer size or data rate should alleviate this issue.

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 GNSS reference 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 reference station for post-processing data collected on the survey vessels for the purposes of hydrography as well. The two base stations installed in 2009 were designated SMITH and TANGIER while the two stations in 2010 were designated AIRD and EWELL. Each was strategically located near the project site in order to minimize the baseline lengths over the entire project area. Base stations SMITH and AIRD were located along the west side of the project area while TANGIER and EWELL were located on the east side. The 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 reference 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 reference position for each 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 coordinates for each site were derived at the ARP of the Trimble Zephyr Geodetic antennas. The coordinates derived from the OPUS solutions and used for the project are referenced to NAD83 (CORS96, Epoch 2002) as shown in Table 1.

Table 1: Reference 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

The buoy was deployed at three locations bounding the survey area for at least 30 days (Table 2). 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.

Table 2: Buoy deployment information

Deployment	Latitude (N)	Longitude (W)	Start Date (UTC)	End Date (UTC)	Duration (Days)
2009-1	31º49'04"	76º14'05"	08/09/2009 20:35	09/10/2009 21:00	32
2009-2	37º52'34"	76º03'18"	09/14/2009 20:03	10/17/2009 07:54	33
2009-3	37º43'31"	75º54'02"	11/21/2009 14:00	12/22/2009 00:00	30
2010-1	37º59'39"	76º27'15"	07/06/2010 19:50	08/06/2009 21:00	31
2010-2	38º07'40"	76º06'56"	08/08/2010 17:48	*09/11/2010*	*34*
2010-3	*38º00'25"*	*76º08'18"*	*09/13/2010*	*10/14/2010*	*31*

Fields in Italics indicate proposed deployment dates and durations at the time of writing

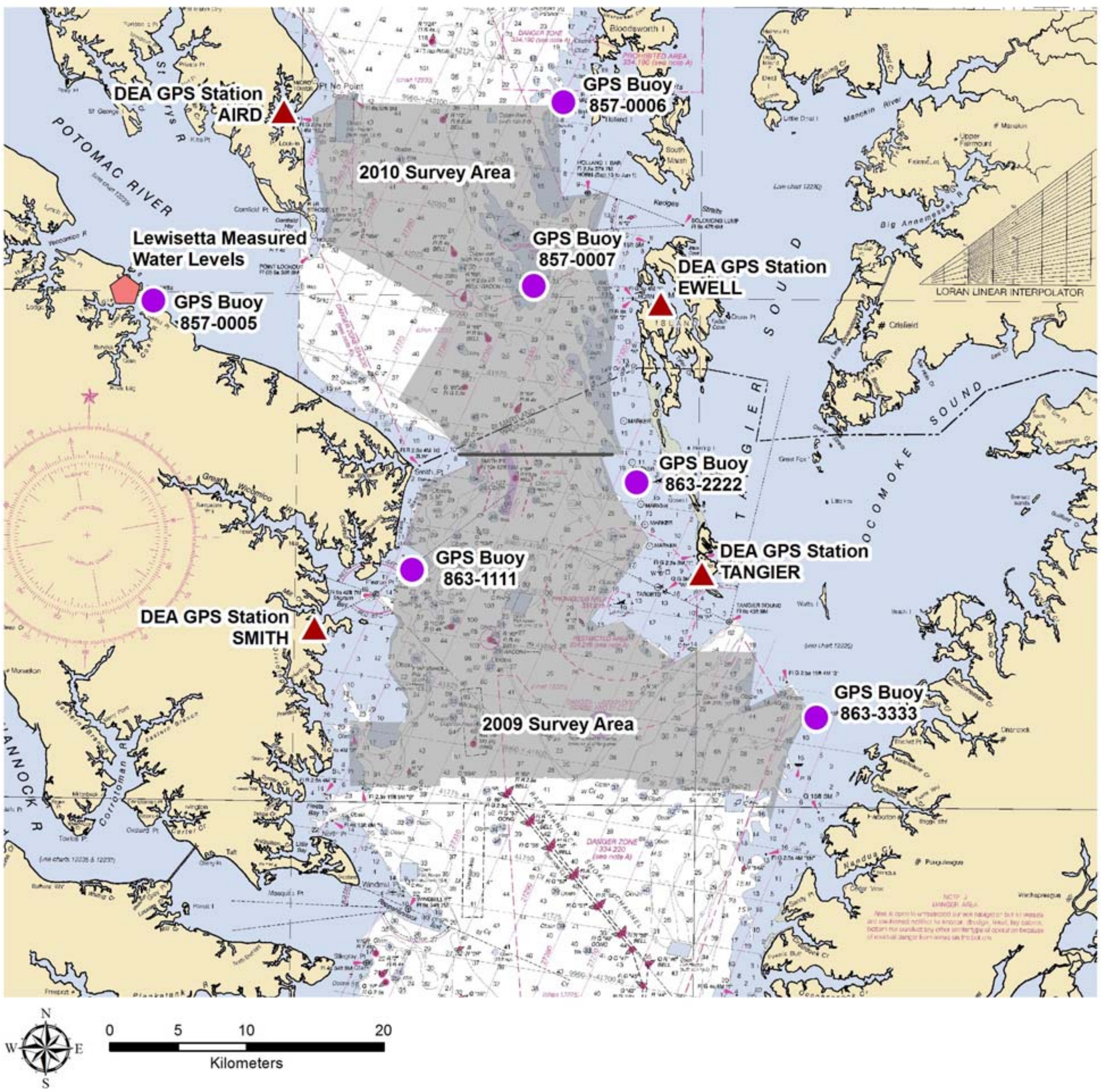

Figure 2: Deployment locations and project area

Figure 2 shows the reference stations and buoy deployment locations with respect to the project boundaries for that survey season.

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 DEA GPS 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 reference station was selected as the master. Table 3 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.

Table 3: Baseline lengths

Deployment	Reference 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

Following is information pertaining to the 2010 deployment 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 GrafNav compatible GPB format. The 668 files (5.52 GB) logged during the first deployment in 2010 were converted from Trimble Real Time format (RT17) to GPB using the GNSS Converter utility in GrafNav. These files were then merged into 64-file blocks to be processed, with each block spanning approximately 3 days (710 MB). Due to the large file sizes, and several limitations in GrafNav, the entire deployment could not be processed at once. 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. The daily files logged at the base station were then merged into a 3-day block that spanned same time period as the corresponding the rover data file. Since the base data was collected at 1 Hz, it was then re-sampled to match the rover data 5 Hz interval in GrafNav.

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.

Once all the data had been brought in, the water surface height was computed. 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 be 4 Hz one second, then 6 Hz the next. 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 both pitch and roll data as well as 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 with the non-rechargeable Lithium Thionyl Chloride configuration. 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.

Data was then smoothed and six-minute tides were extracted from which datums were computed. 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. This, and a 6-minute average, was originally attempted but preserved a high frequency signal in the data. For the final datum computations, a Butterworth filter was implemented. The comparison of the filtering methods is shown in Figure 4.

A 3rd order Butterworth filter with a cut off frequency of 11 cycles per day was found to provide the best results. Considering the majority of the energy in a tidal signal is around the 2 cycles/day, a cut off frequency of 11 cycles/day will easily retain the primary signal. The concern would be at the higher frequency shallower water constituents. NOAA solves for 37 harmonic constituents at their NWLON stations. This group of constituents ranges from the long period Annual and Semi Annual seasonal effects (SA and SSA) to the high frequency shallow water constituent M8 (7.73 cycles/day).

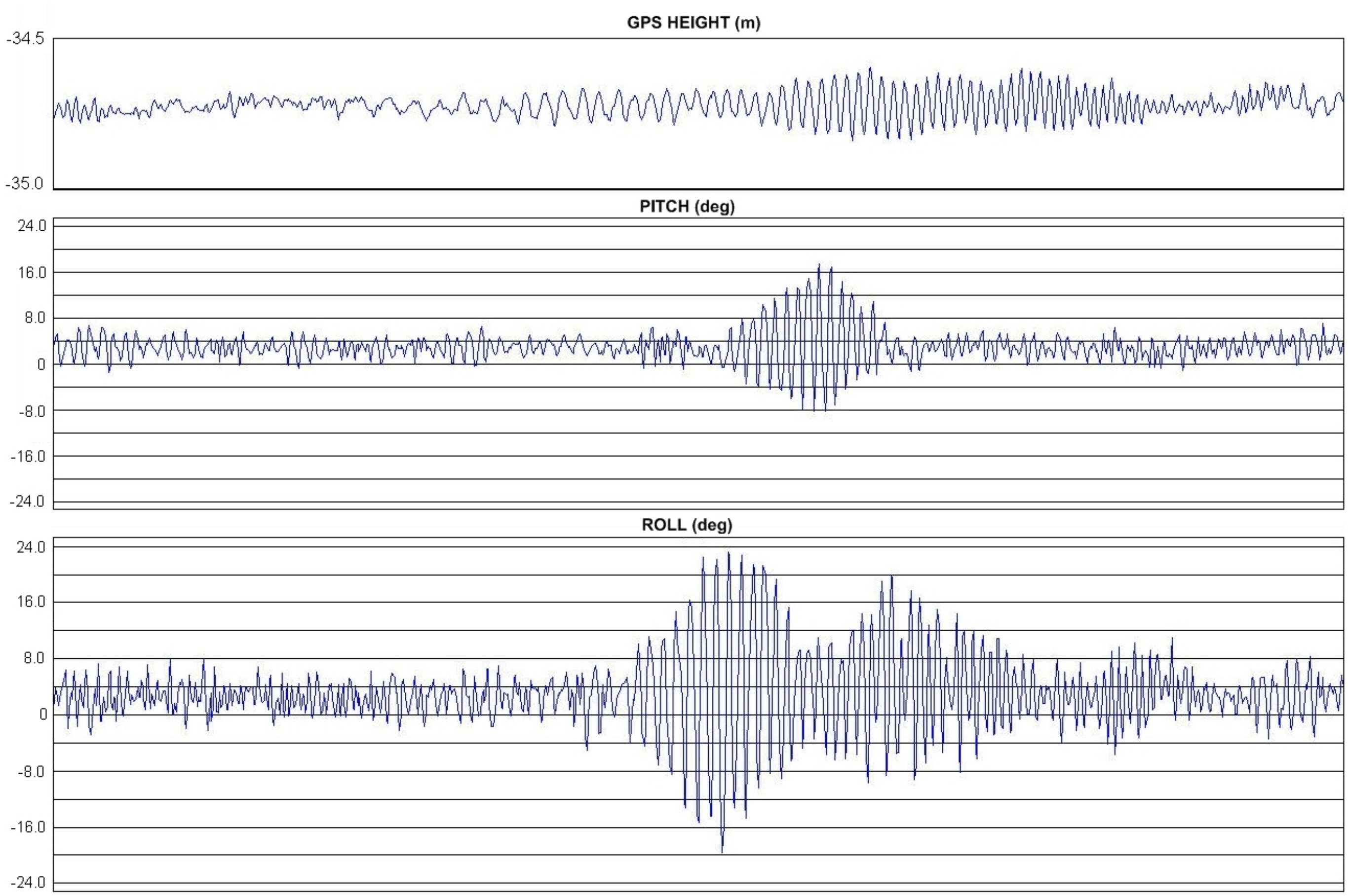

Figure 3: Height, pitch and roll data sample

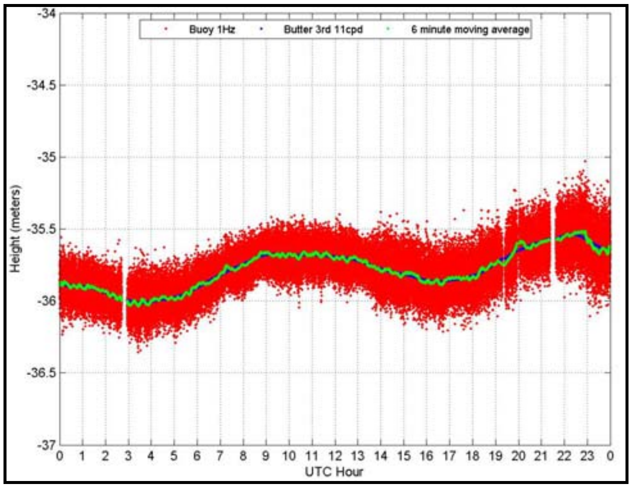

Figure 4: Results of Butterworth filter

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 may be the result of local short term water level disturbances and are undesirable when computing high and low values for datum computations.

Two short term data gaps can be seen in Figure 4, and could have been caused by a gap in the data solution due to poor satellite geometry, tracking as a result of excessive buoy motion (tilt) or missing raw observables. Several long term outages (greater than 1 hour) also occurred and were likely caused by the buoy software as the raw observable files were corrupt. The system logs files in one hour blocks, thus limiting the effects of file corruption. Gaps were filled using a spline interpolation.

DATUM DETERMINATION

The tidal datums computed from the data collected at the four GPS Buoy deployment sites were computed in accordance with NOAA Special Publication NOS CO-OPS 2 (NOAA, 2003). Specifically the 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 the all computations were picked from the 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 (COR96, Epoch 2002). Thus the computed datums are the separations values required to convert ellipsoid referenced soundings to MLLW.

These separations have been computed from GPS Buoy water level data collected at 3 sites in 2009 and 1 in 2010. Table 4 compares the computed MLLW values to the VDatum modeled values. The VDatum values in Table 4 were derived using GEOID09. The average difference between the computed and modeled values is -0.013 m. The range of the differences is 0.100 m.

Table 4: Comparison of Computed and Modeled MLLW values.

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**
			Average	**-0.013**
			1-Sigma	**0.044**

NOAA Special Publication NOS CO-OPS 2 (NOAA, 2003) provides tidal datum uncertainty estimates as a function of data series length. The estimated uncertainty of a tidal datum computed from 1 month of data collected on the East Coast is 3.96 cm at 1-Sigma. Of the four locations at only one does the difference between the computed and modeled MLLW values exceed 3.96 cm. This site is the one located closest to the NOAA NWLON Lewisetta (863-5750).

NWLON STATION VALIDATION

The active NWLON station at Lewisetta, VA (863-5750) is 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. Only the 2009 results are presented as the 2010 checks had not been finalized at the time or writing.

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 NWLON station values logged at the same time by CO-OPS.

Table 5: GPS water level comparison

Lewisetta, VA (863-5750), July 15, 2009			
Time (UTC)	**GPS Water Level (m)**	**Gauge Water Level (m)**	**Difference (m)**
21:06	0.394	0.398	**-0.004**
21:12	0.393	0.408	**-0.015**
21:18	0.362	0.415	**-0.053**
21:24	0.380	0.422	**-0.042**
21:30	0.438	0.429	**0.009**
21:36	0.392	0.436	**-0.044**
21:42	0.419	0.443	**-0.024**
21:48	0.412	0.449	**-0.037**
21:54	0.422	0.458	**-0.036**
22:00	0.420	0.464	**-0.044**
		Average	**-0.029**
		1-Sigma	**0.020**

The mean float observation was 2.9 centimeters below the CO-OPS observed water levels at Lewisetta (Table 5). Checks of the GPS phase center height confirmed correct values were being used and GPS derived water elevations were valid.

To confirm water levels posted by CO-OPS matched tidal bench marks, manual water level observations (staff shots) were made to validate the gauge performance relative to the bench marks. This was accomplished by leveling from a tidal bench mark to the water surface at the even six-minute interval for one hour. To ensure the stability of the mark, it was included in a 3rd order level loop with two other marks, including the primary bench mark. A summary of the staff shot results at each gauge is presented in Table 6.

Table 6: Manual water level comparison

Lewisetta, VA (863-5750), September 28, 2009 (CO-OPS MLLW)			
Time (UTC)	**Staff Shot (m)**	**Gauge Water Level (m)**	**Difference (m)**
17:18	0.330	0.339	**-0.009**
17:24	0.326	0.334	**-0.008**
17:30	0.310	0.325	**-0.015**
17:36	0.306	0.319	**-0.013**
17:42	0.295	0.312	**-0.017**
17:48	0.291	0.304	**-0.013**
17:54	0.286	0.297	**-0.011**
18:00	0.281	0.290	**-0.009**
18:06	0.276	0.285	**-0.009**
18:12	0.276	0.281	**-0.005**
18:18	0.276	0.276	**0.000**
		Average	**-0.011**
		1-Sigma	**0.004**

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 after precise ephemeris files were available to be consistent with other project control comparisons.

Table 7: 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

CO-OPS and NGS published datum planes show some disagreement with the computed MLLW and NAVD88 datums using the VDatum model, but are within expected uncertainties (Table 7). At Lewisetta, the difference between the NGS published (derived from adjusted level observations) NAVD88 orthometric height 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 7). The direction of the difference is also consistent with the GEOID09 separation model, as shown in Figure 5.

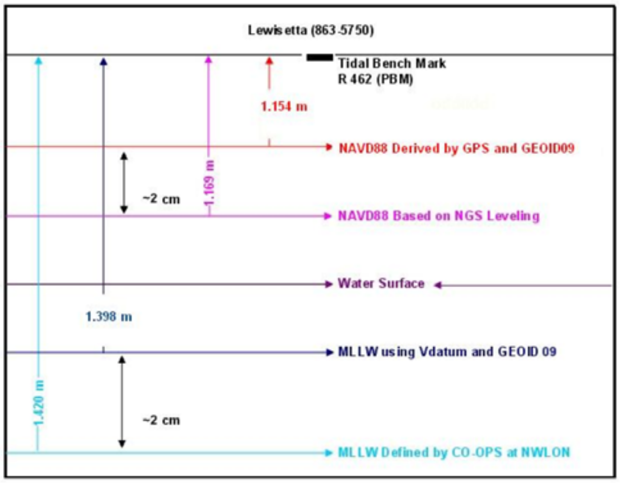

Figure 5: Datum planes

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.

PROCESSED DATA VALIDATION

The processed results of the tilt corrected buoy height data were compared to both the active NWLON stations in the area and data collected by the hydrographic survey vessels. The final datum results were also compared to other gauging stations deployed on the project.

The first deployment in 2010 was intentionally close to the active NWLON station at Lewisetta, VA (863-5750) and is the most valid for comparison. The three

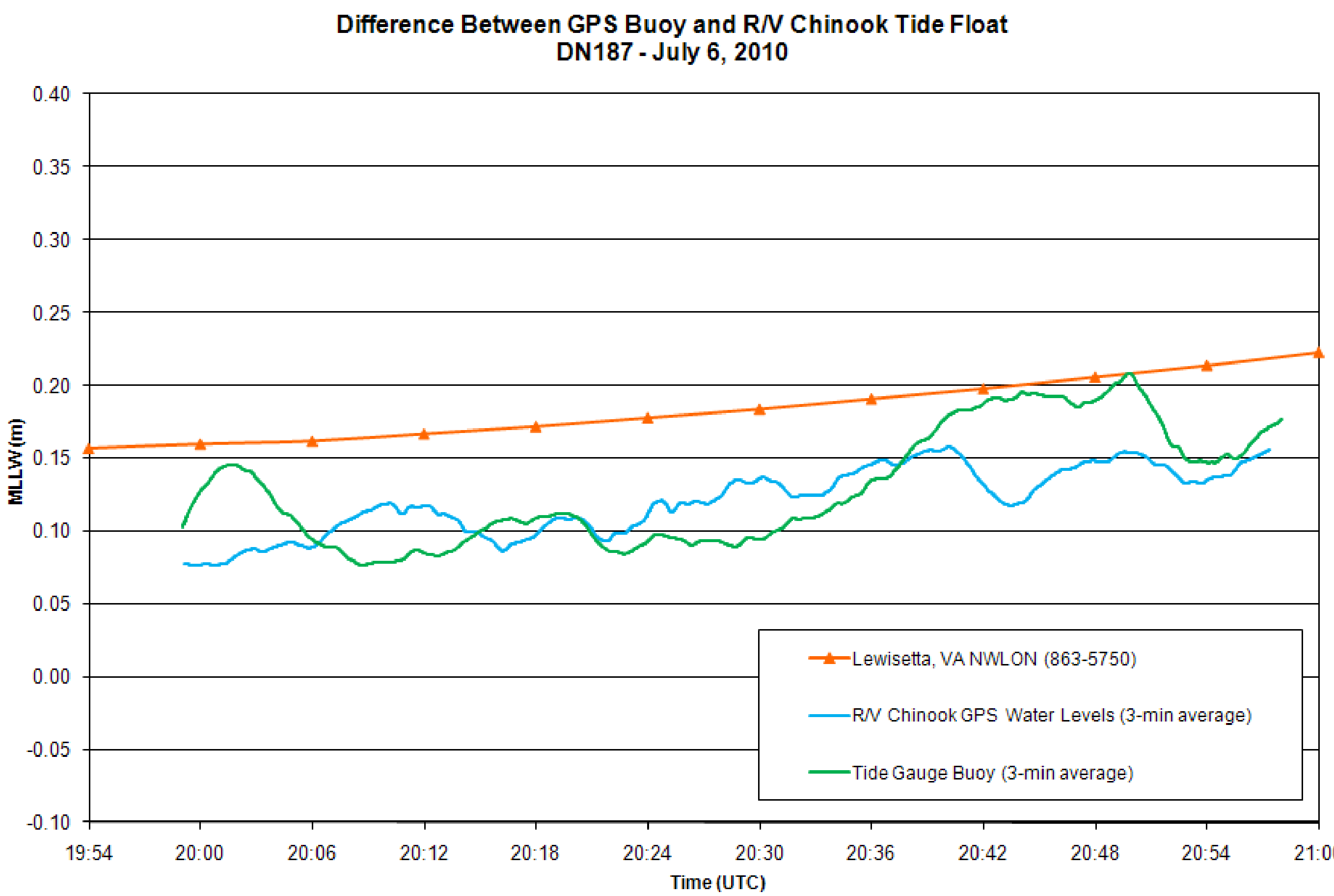

Figure 6: Buoy data compared with vessel and gauge

Table 8: Vessel float results

Date	Vessel	Duration (h:m)	Mean Difference	Buoy Site	Weather
08/14/2009	R/V Theory	00:37	0.035 m	2009-1	Sea state = 3-4' Wind = 15-18 kts
08/21/2009	R/V Theory	00:49	0.011 m	2009-1	Sea State = 1-4' Wind = 15-18 kts
08/21/2009	R/V Chinook	00:39	0.005 m	2009-1	Sea State = 3-4' Wind = 18 kts
09/14/2009	R/V Theory	01:11	0.054 m	2009-2	Sea State = 0-1' Wind = 5-10 kts
10/02/2010	R/V Theory	01:06	-0.083 m	2009-2	Sea State = 3-4' Wind = 10-15 kts
11/21/2009	R/V Theory	01:14	-0.053 m	2009-3	Sea State = 1' Wind = 10 kts
12/12/2009	R/V Theory	01:07	-0.089 m	2009-3	Sea State = 0-1' Wind = 5 kts
07/06/2010	R/V Chinook	01:01	0.009 m	2010-1	Sea State = 0-1' Wind = 0 kts
07/23/2010	R/V Theory	01:18	0.022 m	2010-1	Sea State = 0-1' Wind = 0 kts
08/06/2010	R/V Theory	01:24	-0.080 m	2010-1	Sea State = 0-1' Wind = 10 kts

deployment locations in 2009 were too far from the existing gauges for a direct comparison without applying zoning correctors.

Data collected on the hydrographic survey vessels was also used to validate the computed buoy water levels. At all of the deployment locations during both 2009 and 2010, a minimum of 2 vessel floats were conducted.

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 shown to be -0.032 m.

Table 9: Published elevations compared with GPS survey results

Location	GEOID09 Separation (m)
Lewisetta, VA NWLON (863-5750) N37º59'42.0" W76º27'48.0"	34.890
Deployment 1, 2010 N37º59'39.2" W76º27'15.0"	34.923
Difference	**-0.033**

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 (shown in Table 8) is coincident in direction and magnitude to the differences between the GPS derived water levels and the gauge derived water levels.

Additional vessel floats were conducted in 2009. Table 9 summarizes the results from all the floats in 2009 and 2010.

In addition to the datums computed with the buoy, similar tidal datums have also been computed at three additional sites over the course of the project. Two of the sites consisted of Radar sensors mounted on USCG pilings in the bay and the third is a conventional tertiary tide station installed at Ewell on Smith Island.

Although the station specific information is outside the scope of this paper, the datums from these sites help to quality control both the buoy derived tidal datums and VDatum. The advantages of these sites are that the data series at each is longer than the 1-month series of the buoy deployments and the measurement platforms are stable.

After transferring the water levels measured at the three additional sites to NAD83 (CORS96, Epoch 2002) through static GNSS techniques, the tidal datums on average are 0.090 m lower than the VDatum modeled values. The range of the differences for these three sites is 0.030 m. Table 10 compares the differences for the four buoy sites to the three additional sites (2 Radar and 1 Tertiary).

Table 10: Summary of differences at GPS Buoy, Radar and Tertiary sites.

Summary of Differences *differences in meters*		
	GPS Buoy Sites	**Radar and Tertiary Sites**
Average	-0.013	-0.090
1-Sigma	0.044	0.016
Range	0.100	0.030
Number of Sites	4	3

CONCLUSIONS AND RECOMMENDATIONS

Overall, the project went very well and attained the goal of computing valid tidal datums from GNSS observations. The use of a buoy to compute these datums was shown to be valid and the results compared well to the existing VDatum model. Processed data from the buoy was validated using results from both GPS derived water levels determined by the survey vessels, and measured water levels at an existing CO-OPS gauge.

The active NWLON station at Lewisetta, VA was an integral component to validating the buoy results. Several field checks showed this station to be operating properly. Additionally, the VDatum model in the vicinity of the gauge agreed well with the published MLLW datum plane.

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 long baselines had an impact on the datum uncertainty.

FUTURE WORK

Work on this project continues as the two final deployment locations of 2010 are completed and processed. Different processing methodologies will be analyzed including multi-base solutions and post-processed Precise Point Positioning (PPP). Different techniques to apply tilt sensor data, and the effects of the application of tilt on the final datums will also be reviewed.

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