Article





Chart Datum Transfer Using a GPS Tide Gauge Buoy in Chesapeake Bay

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Abstract

In 2008 NAVOCEANO conducted trials to test the effectiveness of using GPS buoys for water level datum transfers. The GPS vertical positioning evaluation showed that the real-time precise point positioning solutions were not corrected for earth tide, leading to a 10 cm bias relative to three post-processing methods. Ignoring buoy tilt led to errors of up to 10 cm; however, when using 6-minute averaging, the maximum error reduced to ~2 cm. Water level transfer from a tide station 1.3 km away resulted in a datum 12 cm lower than the VDatum model estimate.

Résumé

En 2008, NAVOCEANO a effectué des essais pour tester l'utilité d'utiliser des bouées équipées de systèmes GPS pour les transferts du niveau de référence de l'eau. L'évaluation de la détermination de la position verticale à l'aide du GPS a montré que les solutions de détermination de la position de points précis en temps réel n'étaient pas corrigées pour la marée terrestre, conduisant à un biais de 10 cm correspondant à trois méthodes de post-traitement. L'ignorance de l'inclinaison de la bouée a engendré des erreurs allant jusqu'à 10 cm; toutefois, en utilisant une moyenne de 6 minutes, l'erreur maximum était réduite à approximativement 2 cm. Le transfert du niveau de l'eau depuis une station de marée distante de 1,3 km a donné comme résultat un niveau de référence inférieur de 12 cm, par rapport à l'estimation du modèle de système de référence verticale.

Resumen

En el 2008 NAVOCEANO llevó a cabo pruebas para probar la eficacia del uso de boyas equipadas de un GPS para las transferencias del cero hidrográfico para el nivel del agua. La evaluación del posicionamiento vertical mediante el GPS mostró que las soluciones de posicionamiento preciso puntual en tiempo real no eran corregidas para la marea terrestre, lo que resultaba en una desviación de 10 cm respecto a tres métodos de post-procesado. Ignorar una inclinación de la boya llevó a errores de hasta 10 cm; sin embargo, al utilizar un promedio de 6 minutos, el error máximo quedó reducido a ~2 cm. La transferencia del nivel del agua desde una estación de mareas situada a una distancia de 1,3 km dio como resultado un datum inferior en 12 cm respecto de la estimación del modelo VDatum.

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Introduction

The Naval Oceanographic Office (NAVOCEANO) conducts hydrographic surveys all over the world. These surveys are performed to meet International Hydrographic Organization (IHO) standards. In many situations NAVOCEANO hydrographic surveyors do not have access to local tide gauges or to land where temporary gauges can be established. As a result, NAVOCEANO is investigating the use of GPS buoys to support tidal observations and datum transfers.

The NAVOCEANO GPS buoy transmits filtered three-dimensional position information every 6 minutes. The positions are computed from NavCom dual frequency receivers using Real-Time Gypsy (RTG). The height component takes into account the offset between antenna and water, as well as the buoy tilt, resulting in a water surface elevation relative to WGS 84. The 6-minute filtered solutions, as well as 1-second solutions, are logged on the buoy. One-second raw GPS observations are also recorded on-board.

In July and August of 2008, NAVOCEANO conducted trials to test the effectiveness of using these GPS buoys for water level datum transfers.

A GPS buoy was established in the Chesapeake Bay at approximately 1.3 km from the National Oceanic and Atmospheric Administration (NOAA) Solomons' Island (SI) tide gauge. A Continuously Operating Reference Station (CORS) site (MDSI) was located close to *SI (see Figure 1).*

The NAVOCEANO GPS tide gauge buoys are used to establish a chart datum. Uncertainties associated with the establishment of this datum include:

1. GPS vertical position determination
2. Translation of the position from the antenna to the waterline using static draft and buoy tilt
3. High frequency buoy motion from wave action and heave, mitigated through filtering
4. Datum establishment method, such as the range-ratio water level transfer from a primary tide gauge site. Uncertainties arise from:
   a. Water level transfer algorithm
   b. Similarity of tidal characteristics between the primary and secondary gauge locations
   c. Confidence in chart datum at primary site

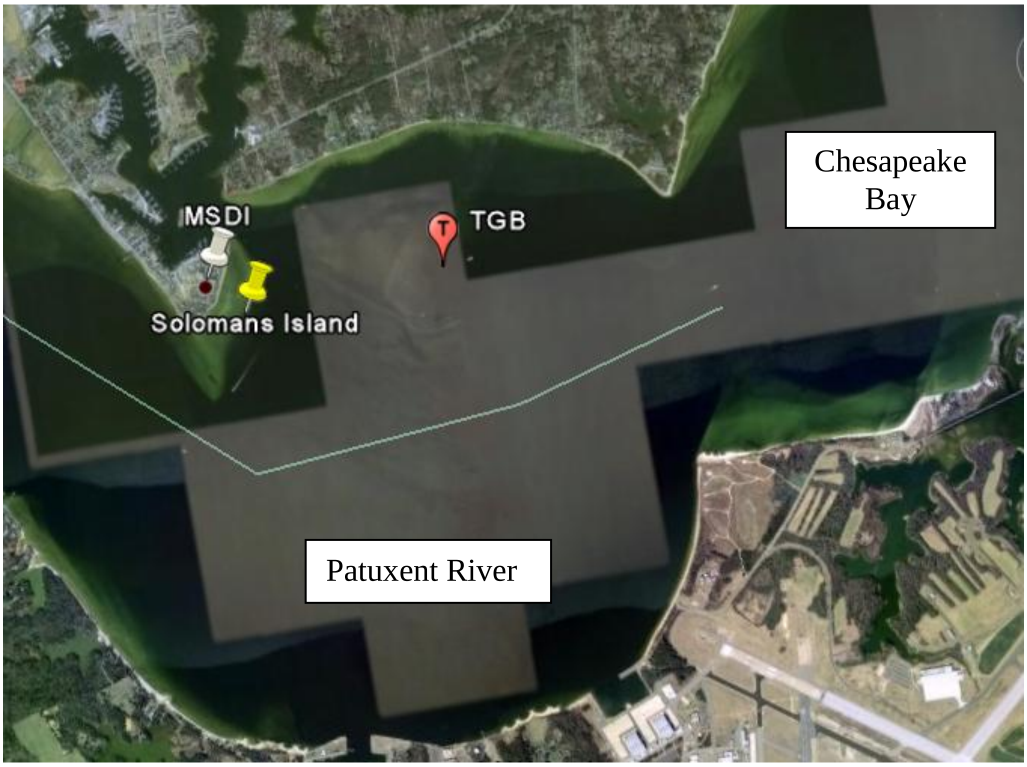

Figure 1: Locations of MSDI CORS site, Solomon's Island Tide Gauge and the GPs Tide Gauge Buoy

These sources of uncertainty are investigated further in this report.

Data from the buoy, MDSI CORS station, and NOAA tide gauges were used to evaluate the effectiveness of using GPS buoys to transfer tidal datums. This paper looks at four aspects of the evaluation: GPS vertical positioning, effect of buoy pitch and roll on the translation of the vertical position to the waterline, effect of averaging on the vertical position, and the transfer of mean lower low water (MLLW) datums relative to the ellipse.

SOLOMON ISLANDS GPS TIFE BUOY DATA EVALUATION

NAVOCEANO intends to use precise point positioning (PPP) for the establishment of chart datums for its hydrographic surveys. It would be preferable to use real-time solutions, negating the need for post-processing. The question is whether or not the real-time solution provides a low enough uncertainty to negate the need for post-processing. This section looks at a comparison between real-time PPP (Real-Time Gypsy [RTG]), post-processed PPP (PP-PPP), and post-processed kinematic (PPK) solutions.

The data for this evaluation were collected between July 17 and August 28, 2008 in the Chesapeake Bay near Solomons' Island NOAA tide gauge. Raw GPS observations and RTG positions were recorded on the NAVOCEANO Tide Gauge Buoy 30 (TGB00030) at 1 Hz. Raw GPS observations were retrieved from the CORS MDSI, located approximately 1.3 km from the buoy. With the short MDSI to buoy baseline, the PPK solution should have provided centimeter level vertical uncertainty, making it an ideal "truth" solution for the comparison of PPP to RTG.

PPK positions of the buoy were computed using MDSI as the base in the software package GrafNav™ Version 8. These results were designated as "PPK" in the analysis. PPK positions were also computed using the University of Southern Mississippi's (USM's) in-house software, and the results were designated as "UFX" (USM ambiguity fixed solution). GrafNav™ was also used to compute the post-processed PPP solutions, and these results were designated as "PPP" in the analysis. The real-time buoy results used in the comparisons were extracted from the internally recorded real-time PPP solutions, and designated as "RTG" in the analysis.

All GPS positions were determined relative to the L1 phase center of the buoy antenna. The ITRF00 (epoch 1997) station coordinates for MDSI were also relative to the antenna L1 phase center. No antenna offsets were used in the processing. The base station coordinates used for MDSI were:

Latitude	= 38 19 08.10042 N
Longitude	= 076 27 13.96371 W
Ellipsoid height	= -17.994 m.

The RTG buoy height was represented by the "altitude" field from the buoy record. This height did not contain an offset to the water line and was not adjusted for buoy tilt. The horizontal position in the RTG record had a resolution of 0.0001° (was approximately 10 m); therefore, only position heights were used in the comparisons.

The PPK results were to be used as the "truth" for a comparison of results between RTG and PPP. However, due to problems with observations at MDSI, the PPK results were inconsistent, making its use as the "correct" buoy height problematic.

Figure 2 depicts the results for day of year (DOY) 214 (August 1, 2008). The height values resulting from each of the four processing methods (UFX, PPK, PPP, and RTG) are plotted against time in hours of the week. The results very clearly show the semidiurnal tide, which ranges by approximately ±0.4 meters. The PPK results from GrafNav™ have several large excursions from the other results. The UFX results (USM PPK) are not as adversely affected by the observation problems at MDSI. For the most part, the PPP and UFX agree, as does the PPK when it is settled. The RTG results appear to follow a similar trend to the other solutions; however, there is a significant deviation between 124 and 129 hours. The RTG solution also deviates from the others at hour 133 (low tide), where it is lower, and at hour 139 (high tide), where it is higher. It is suspected that the solid earth tide algorithm was not applied during the RTG computations, leading to the high and low tide deviations. However, this does not account for the deviations between 124 and 129 hours.

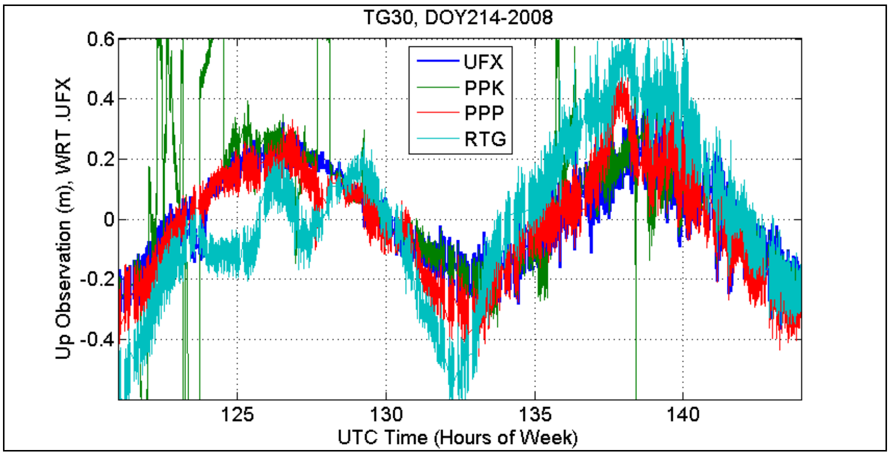

Figure 2 Buoy heights for DOY 214; UFX (USM PPK) mean height removed from all observations

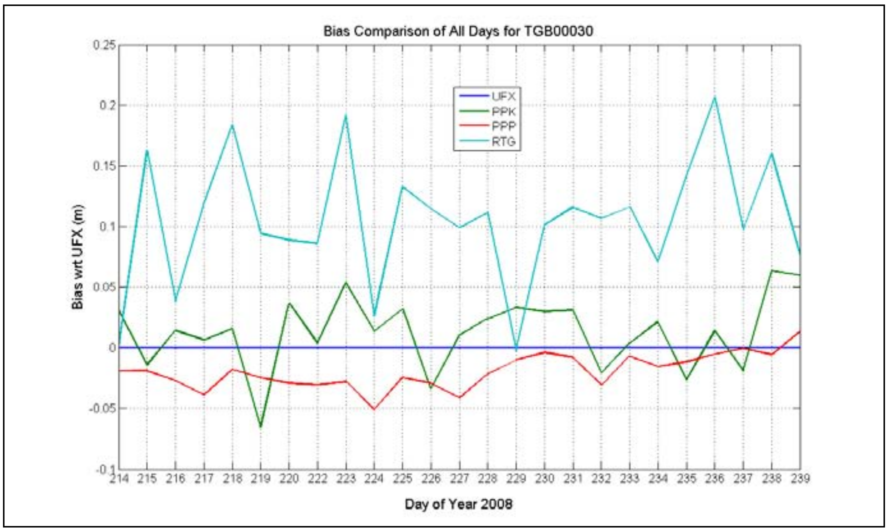

Figure 3: Bias Comparison for all days.

A total of 25 days were processed using all four techniques (UFX, PPK, PPP and RTG). *Figure 3* displays the average difference (bias) between UFX and the other solutions for each day. On average, the PPP solution is between 0 and -5 cm. The PPK solution is between ±5 cm. The RTG solutions range between 0 and 20 cm, averaging to approximately +10 cm, likely due to solid earth tides.

Due to issues with the MDSI observations, it is not possible to define a reliable "truth" for a definitive evaluation of the different methods. However, all indications are that the PPP results are far more consistent than the RTG results. It is suspected that the RTG offsets would translate directly into a datum determination. For example, the averaged height difference for the period between DOY 219 and 227 was 11 cm. If this 7-day period was used for a water level transfer, the resulting datum would be higher than one computed from any of the other height determination methods. The effect of this difference is addressed in more detail in the water level transfer section of this study.

EFFECT OF TILT ON BUOY DRAFT

The NAVOCEANO tide gauge buoys are used for determining chart datum at the buoy location from observations of the waterline height. The GPS-derived heights are translated to the waterline from the antenna phase center. This evaluation looks at two aspects of this process:

1. What is the vertical offset between the L1 phase center and the waterline?
2. How much effect does the buoy tilt have on the waterline determination?

One day of data from the NAVOCEANO tide gauge buoy (TGB) TGB00030 from the Solomons' Island 2008 study was used for this evaluation. August 15 (DOY 228); was selected because of its variety of sea states. The following fields were extracted from the 1 Hz data records (RTG version B [RGB] file type) for this evaluation:

Field	Attribute
2	Date in yymmdd
3	UTC time in hhmmss
12	Antenna altitude in meters, wrt ellipse
13	Altitude corrected for draft, pitch, and roll
18	Pitch in degrees
19	Roll in degrees

1.1 Vertical Offset

An evaluation of the difference between antenna altitude and the altitude adjusted for draft and tilt indicated that the draft value was incorrectly entered into the buoy configuration. The static draft (without tilt) should have been 0.425 m. *Figure 4* shows the difference between the recorded antenna height and the computed waterline (draft) for DOY 228. The plotted draft showed a maximum separation of 0.365 m, rather than the expected 0.425 m (6 cm error), as well as smaller draft values when the buoy was tilted. The smallest draft (0.30 m) occurred when the buoy tilt was the greatest. A correction for the 6 cm static draft error would increase the distance from the ellipse to the waterline and consequently increase the ellipse-to-datum separation, determined from the erroneous data *(See Figure 5)*.

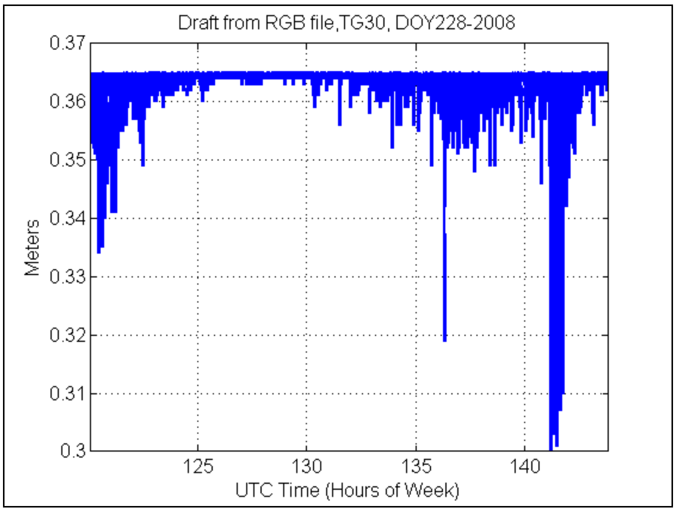

Figure 4: Draft from RTG file, antenna altitude - corrected altitude, for DOY 228

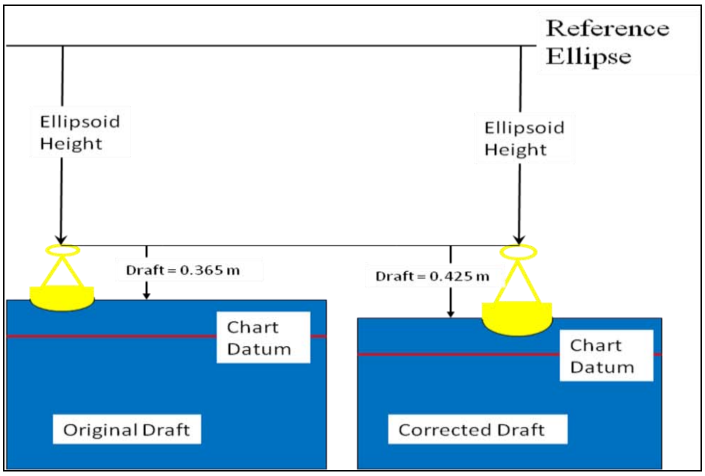

Figure 5: Effect of draft error

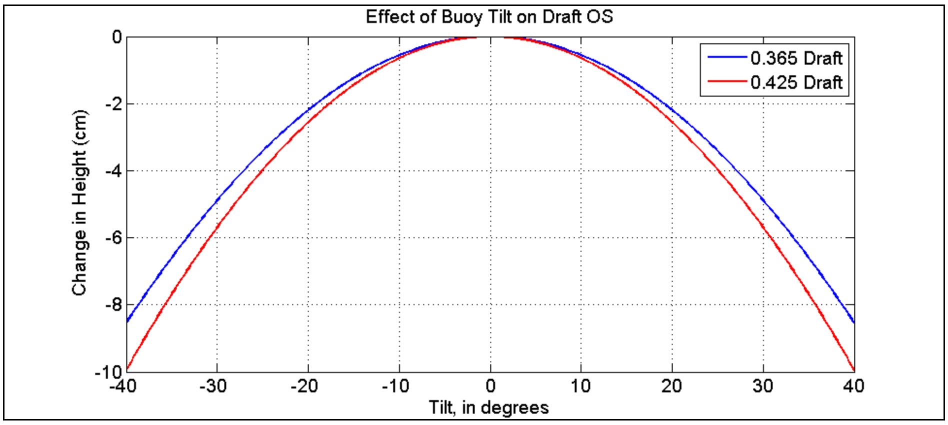

Figure 6: Epoch-to-epoch effect of tilt on antenna to waterline separation

1.2 Effect of Buoy Tilt

The distance from the antenna phase centre to the waterline (draft) is reduced whenever the buoy experiences a tilt. This evaluation was performed to determine the magnitude of that effect, given the length of the static draft. An evaluation was performed using theoretical pitch and roll values, as well as actual observations from the buoy for DOY 228. The theoretical evaluation looked at the effect on both the incorrect (0.365 m) and correct (0.425 m) draft values.

An estimation of the buoy tilt was derived from the pitch and roll observations and applied to the draft using the following:

$$Tilt = sqrt(roll^2 + pitch^2)$$
$$draft = offset * \cos(tilt)$$

The resulting corrected altitude values were compared to the observations from the recorded file and found to be within ±2 mm.

A change in height resulting from tilt values from -40 to +40 degrees is shown in *Figure 6*. This plot contains two graphs, one with a 0.365 m draft and the other with a 0.425 m draft. The height change varies from 0 cm at 0° to -8.3 cm (0.365 m draft) and -10 cm (0.425 m draft) at ±40°.

Figure 7 shows the buoy tilt for DOY 228. It shows a wide range of tilt, from less than 5° up to 35°. If no tilt is taken into account, the draft is a constant 0.365 m. With tilt, the draft varies from 0.365 m to 0.300 m, a difference of up to 7 cm, for DOY 228. *Figure 8* shows the difference between applying and not applying tilt. Notice that the periods of greater tilt correspond to periods of lesser antenna-to-waterline separation.

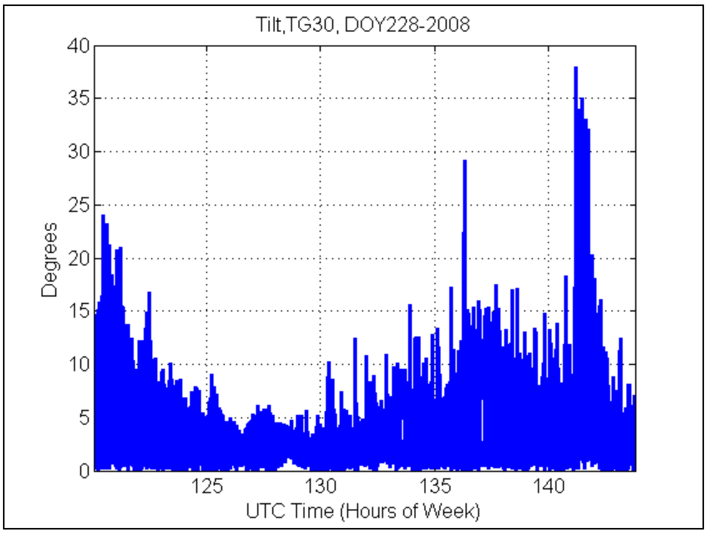

Figure 7: TGB00030 tilt for DOY 228

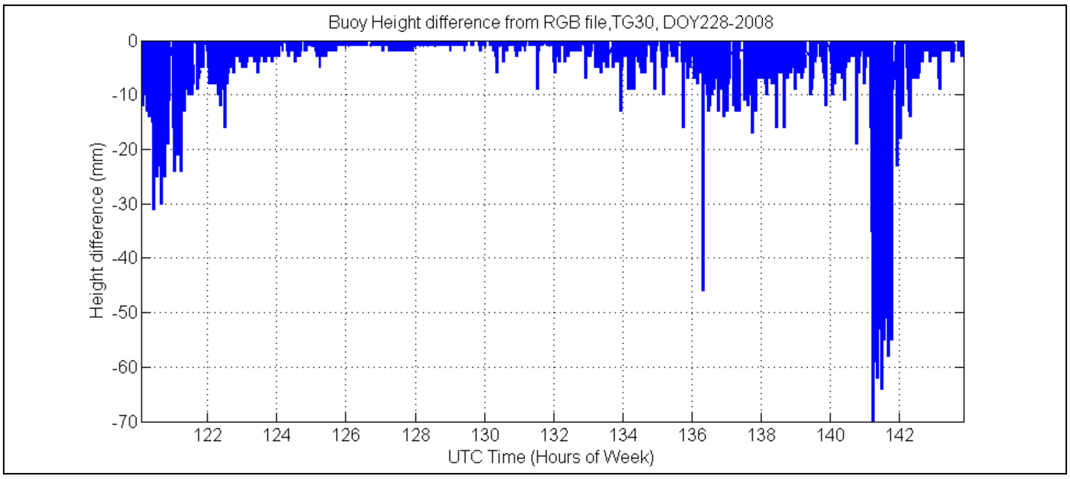

Figure 7 : TGB00030 tilt for DOY 228

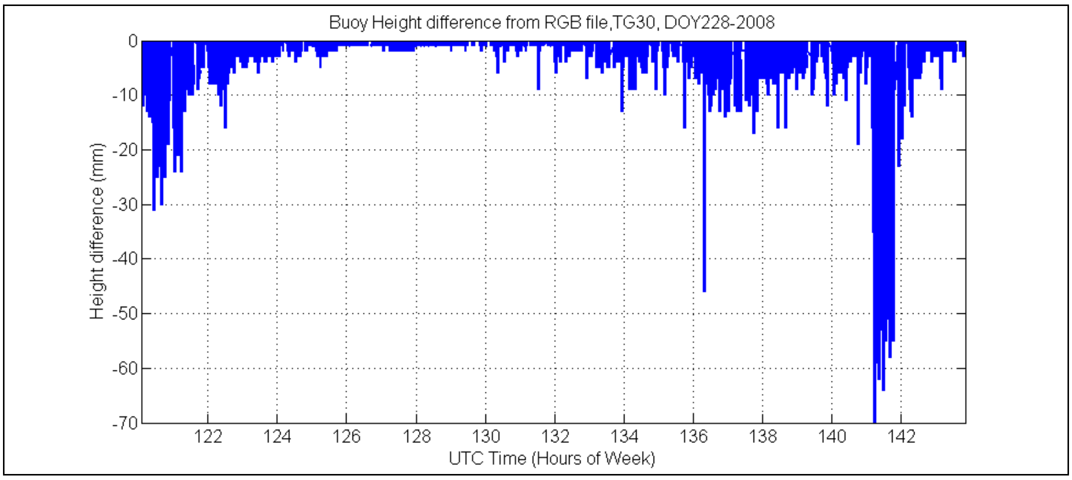

Figure 8: Difference between applying and not applying tilt to the draft for DOY 228

This evaluation showed the expected error resulting from ignoring buoy tilt. Tilt always reduced the distance between the phase centre and the waterline. A tilt of 40 decreased the draft by ~10 cm. Ignoring tilt would lead to an overall increase in the antenna to waterline distance, the result of which would be an increase in the ellipsoid-to-datum separation. Averaging water level height observations, as is done with most tide gauges, reduces the effect of this error, which is the subject of the next section.

EFFECT OF AVERAGING

The intended use of the GPS buoys is for the determination of chart datum. As with most tide gauges, the observations will be averaged to remove the short-term water level effects such as heave.

For this evaluation, the RTG heights were averaged over 6-minute time periods. *Figure 9* depicts the averaged antenna and waterline heights for DOY 228. *Figure 10* shows the difference between using the tilt to derive an antenna-to-waterline separation and using a constant (0.365 m). Note that the y-axis units are in millimeters. The greatest differences are during times of high buoy motion.

Figure 11 and Figure 12 show the effects of averaging. *Figure 12* is simply an enlarged version of Figure *11*. The blue line (full time series) is the error from the full dataset when not using the tilt. The red line (6-minute average) is the error from the averaged dataset when not using the tilt. The difference between the two is significant. The error decreases from a maximum of ~70 mm to a maximum of ~15 mm.

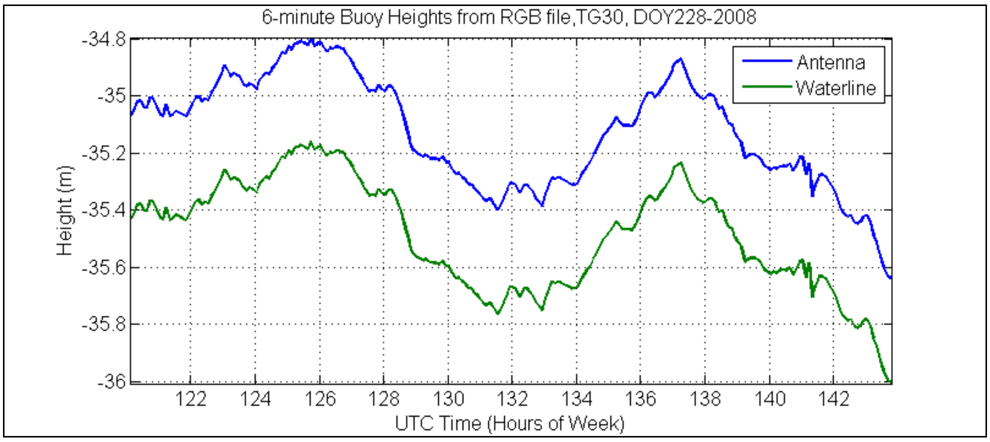

Figure 9: Six-minute average buoy heights for DOY 228

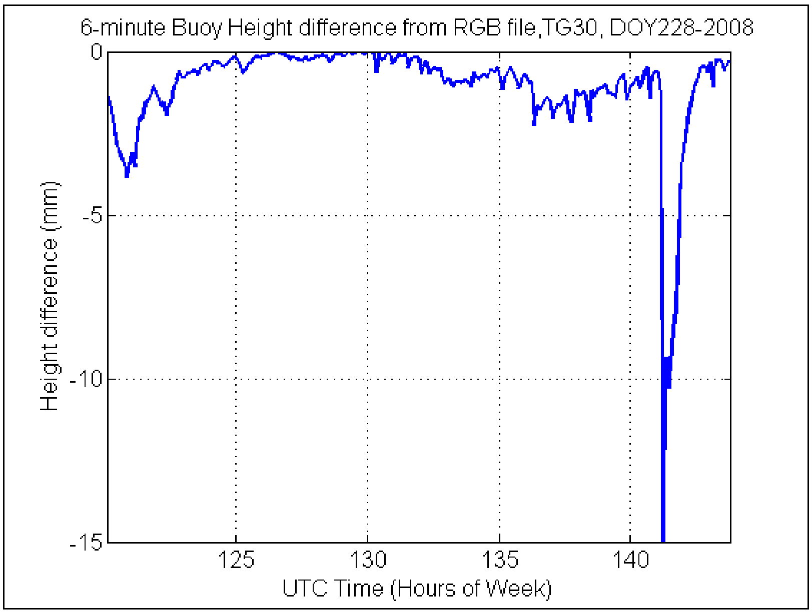

Figure 10: Difference between constant draft and tilt corrected draft for DOY 228, in mm

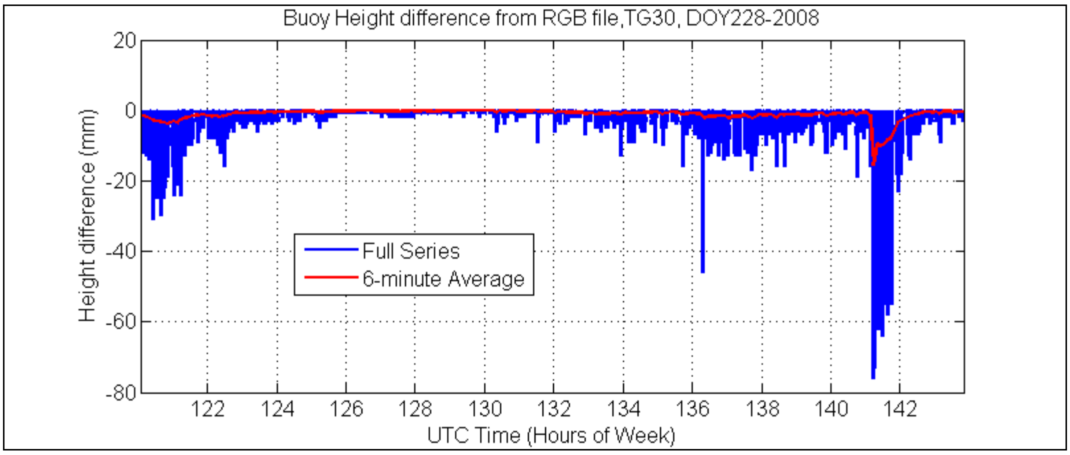

Figure 11: Difference between tilt corrected and not tilt corrected buoy heights, with and without averaging

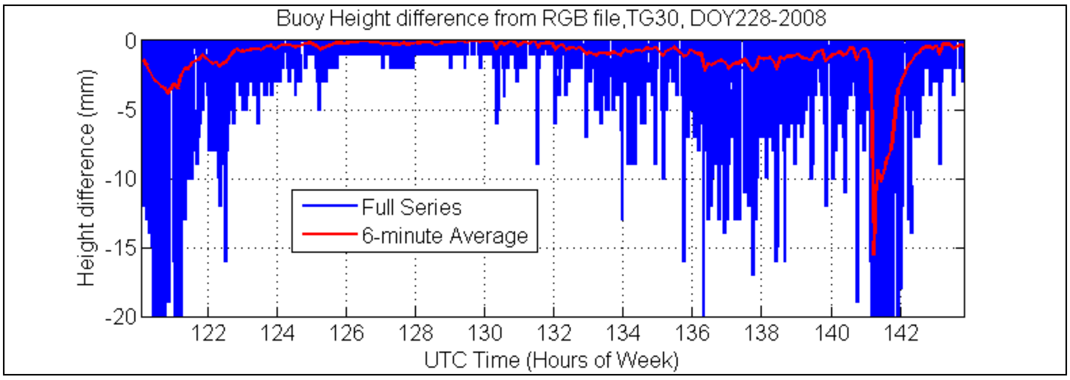

Figure 12: Difference between tilt corrected and not tilt corrected buoy heights, with and without averaging, zoom

For 25 days in August 2008, from the Solomons' Island TGB00030, the maximum difference went below –5 mm on only three occasions. The -15 mm deviation shown in *Figure 12* was the largest.

Ignoring the pitch and roll of the buoy will introduce an error bias in the results of up to 10 cm for a ±40° tilt. This is reduced drastically by 6-minute averaging to ~2cm.

WATER LEVEL TRANSFER EVALUATION

The determination of ellipsoid to chart datum separation at a tide buoy location requires the transfer of a water level datum from a known location (primary gauge) to the buoy. The uncertainty associated with the resulting buoy datum will depend on similarity of the tidal character between sites, observation time period, and the buoy water level height determination.

NAVOCEANO uses the in-house software package "NAVOTAS" to perform tide-related functions such as picking daily highs and lows and performing water level transfers. The NOAA-modified range ratio method [NOAA 2003] is used for the transfer.

The NAVOTAS software was used to transfer the Solomons' Island (SI) gauge datum to the buoy location using daily tidal highs and lows. The procedure was first tested using daily highs and lows from NOAA's Bishops' Head (BH) tide station (38 km away, see *Figure 13*). The highs and lows for BH, relative to MLLW, were converted to International Terrestrial Reference Frame (ITRF) ellipsoid heights by applying a separation value determined from NOAA's VDatum software (version 2.1.1.3). The primary gauge (SI) data were not adjusted from MLLW. The resulting datum (relative to ITRF) for BH was -37.24 m. The value determined from VDatum was -37.25 m, a difference on 1 cm. This validated the datum transformation methodology. See reference NOAA, 2007 for more information on VDatum.

It was not necessary to relate the primary gauge datum to the ITRF reference ellipsoid. A datum transfer relative to MLLW of the primary station resulted in a MLLW datum at the remote site relative to its height reference, which was the ellipsoid. Consider the GPS height observations to be similar to a tide staff, with staff zero on the ellipsoid.

Daily highs and lows at the buoy were selected from the RTG water level determinations and as such included the RTG and draft biases discussed in the previous sections. A datum for TGB00030 was determined from SI and BH for the 7-day period between July 6 and July 14, 2008 (DOY 219 to 227). The datum derived from SI, at a range of about 1 km, was -36.04 m. The datum derived from BH, at a distance of approximately 37 km, was -36.08 m. The datums agreed with each other to within 4 cm for the selected 7-day time period.

The chart datum (MLLW), geoid (GEOID03), and ellipsoid (ITRF00) relationships for Solomons' Island, TGB00030, and Bishops' Head were established using VDatum (see *Figure 14*).The datum-to-ellipse separation was -35.96 m at SI and -36.00 m at the buoy, a difference of 4 cm. The chart datum for both SI and the buoy were almost identical (0.26 m) with respect to the geoid. The majority of the deviation between the datums with respect to the ellipsoid was due to a change in the geoid/ellipsoid separation (geoid height), over the 1.3 km distance, with no difference attributed to the geoid/chart datum separation.

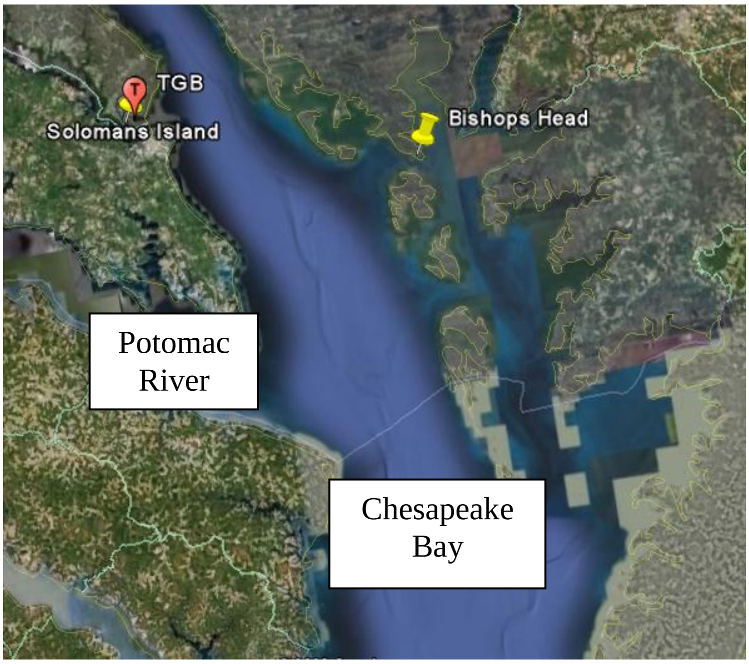

Figure 13: Locations of Solomon's Island and Bishop's Head tide gauges

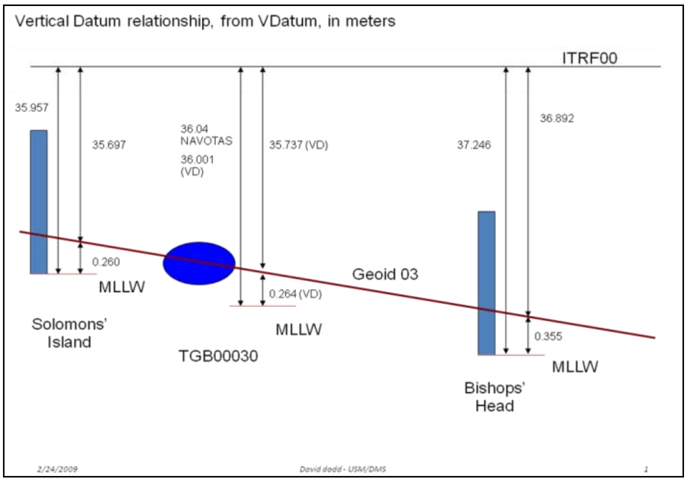

Figure14: Vertical Datum relationship between Solomons' Island, TGB00030, and Bishops' Head

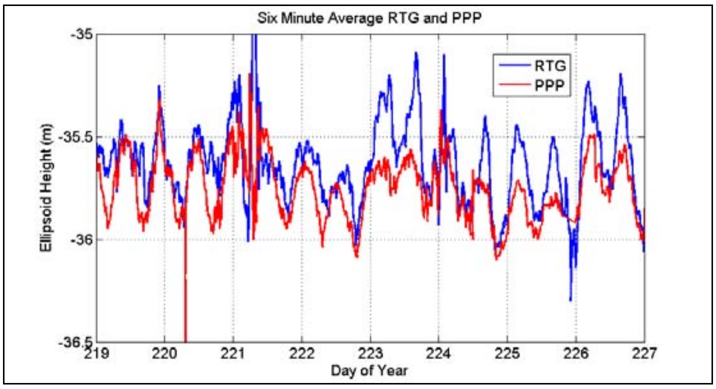

Figure 15: Comparison of RTG and PPP 6-minute water line solution. RTG corrected for 6 cm draft error

The datum of -36.04 m established at the tide buoy using the NAVOTAS water level transfer software was derived from the RTG waterline heights. The previous sections showed that these RTG heights were biased from the post-processed solutions (~11 cm) and by the draft error (6 cm). The 6 cm draft error would translate directly into the translated datum. The effect of the RTG bias difference was not as evident; therefore, a datum transfer was performed using the PPP solution.

Figure 15 shows the averaged solutions for the waterline from both the PPP and RTG processes for the 7-day period. The PPP solution was averaged over 6 minutes and a draft of 0.425m applied. The RTG solution was corrected for the 6 cm draft error. The two solutions are reasonably close at low tide but much farther apart at high tide. This may be attributed to inadequately applied earth tide in the RTG solution. The averaged low water values differed by 2 cm. The average high water values differ by 16 cm. The RTG solution was higher in both cases.

Using averaged 6-minute PPP heights and applying the correct draft (0.425 m), NAVOCEANO analysts determined the NAVOTAS solution for the MLLW datum was -36.12 m. This was 8 cm lower than the RTG solution of -36.04 m, and 6 cm was attributed to the draft error (corrected = -36.10), leaving a 2 cm difference. This indicated that the 11 cm RTG bias did not have a significant effect on the water level transfer. This can be attributed to the alignment of the low water observations and that it was a MLLW datum that was being transferred.

Figure 16 shows the RTG, PPP, and VDatum chart datum determinations. VDatum is higher than both RTG and PPP by 10 cm and 12 cm respectively. One possible explanation for this difference is that the VDatum models may not have adequately accounted for the low water variation between SI and the buoy. As mentioned earlier, the VDatum MLLW variation between SI and the buoy is only 4 mm.

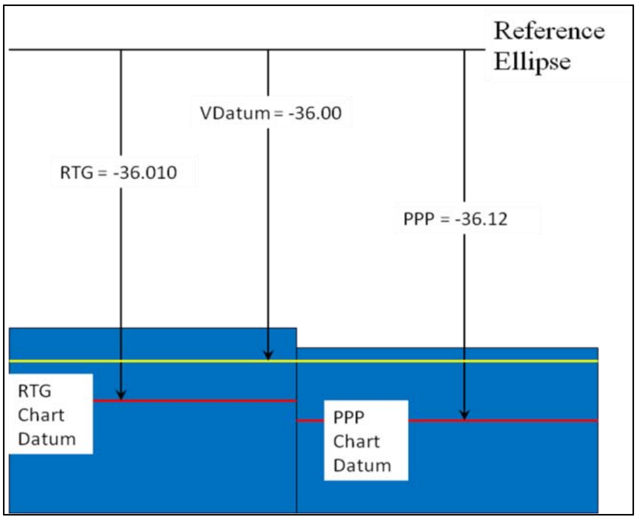

Figure 16: VDatum, RTG, and PPP derived datum comparison. RTG corrected for the 6 cm draft error

UNCERTAINTY

A significant omission from this paper thus far is a discussion on uncertainty. Bias offsets have been quoted without standard deviations and chart datum determination comparisons have been made without detailing associated uncertainties in the methods and results. In order to assign reasonable uncertainty estimates to the water level transfer process, all contributions must be understood.

The evaluation of the epoch-to-epoch GPS solutions looked at the bias between the RTG and USM fixed solution, without indicating standard deviations. The bias was 10 cm with a 1σ standard deviation of 11 cm. These statistics were relative to the difference between the RTG and USM solutions. However, the epoch-to-epoch solutions were averaged to determine a six-minute tidal value, complicating the uncertainty contribution of the GPS solution. The averaging process removed the effects of wave action and dampened some of the GPS noise effects. A standard deviation attached to the average would be an indication of sea-state. The 1σ standard deviation varied from a few centimetres on calm days up to a decimetre on a rough day (DOY 228).

The actual water-level transfer only used the daily highs and lows; therefore, the GPS uncertainty and averaging effect for one six-minute epoch would contribute to the uncertainty of a particular high or low. The uncertainties attached to these highs and lows propagate into the datum determination.

Another contributor to the water-level determination uncertainty is the transfer process itself, the modified range-ration method. In a recent study conducted for NAVOCEANO, water-level transfer between Solomons' Island (SI) and Bishops' Head (at 38 km) was determined using seven days of observations, for one year (October 2007 through September 2008). The results showed a 95% root-mean-square uncertainty of 5 cm, assuming the SI datum to be correct.

NOAA has developed some uncertainty estimates for their VDatum process [NOAA 2009]. The standard deviation estimate for an ITRF to MLLW transformation in the Chesapeake is 5.8 cm, or approximately 12 cm at 95%. Given this and the uncertainties associated with the GPS buoy estimate, the discrepancies between VDatum and the water-level transfer of 10 to 12 cm are within the combined uncertainties of the two methods. This uncertainty requires a more detailed evaluation.

CONCLUSION

The GPS tide buoy evaluation compared heights derived from real-time (RTG), post- processed precise point positioning (PPP), post-processed kinematic (PPK), and USM's post-processed kinematic solutions (USM PPK). The results very clearly showed the semidiurnal tide, which ranged by approximately ±0.4 meters. The RTG results followed a trend similar to that of the other solutions; however, there were significant biases where the RTG results were higher at high tide and lower at low tide. This was attributed to the solid earth tide. For the most part, the three post-processed solutions agreed. In a comparison with the USM PPK results, on average, the PPP solutions were within 0 and -5 cm. The PPK solutions were within ±5 cm, and the RTG solutions were between 0 and +20 cm, with an average of ~+10 cm.

Ignoring the pitch and roll of the buoy will introduce an error in the epoch-to-epoch results of up to 10 cm for a 40° tilt (+ or -). This is reduced drastically by 6-minute averaging to ~2cm. Therefore, with averaging, the buoy pitch and roll can be ignored for these buoys. As the distance from the GPS antenna to the waterline increases, the effect of the tilt error will also increase.

The final section of this study looked at the use of NAVOTAS to transfer tidal datums, relative to the ellipsoid, from a known site to the NAVOCEANO GPS tide gauge buoy. The VDatum estimate for the tide buoy location was -36.00 m. The NAVOTAS determination using a water level transfer and taking into account established errors was -36.12 m, a difference of 12 cm. The water level transfer methodology was validated using data from a known station (Bishops' Head) as the secondary station. The GPS height comparison and results appear sound, leading to the conclusion that the discrepancy is due to sensitivity of the VDatum models in this region.

GPS tide gauge buoys can play an important role in offshore water level monitoring. Models used to determine the relationship between chart datum and a reference ellipsoid, such as those used in VDatum, are well defined at tide gauge locations along the land/sea interface; however, they lack in-situ observations in the offshore. Further studies should be conducted to validate and strengthen the datum transformation models and resolve any differences between NAVOTAS and VDatum. In order to use real-time GNSS, further investigation is required to resolve the discrepancies between the real-time and post-processed solutions, concentrating on the application of solid earth tide algorithms. The final chart datum must be accompanied by an estimation of uncertainty; therefore, every stage of the process must be evaluated in order to determine an overall uncertainty for the final result.

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Biographies

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Gail Smith is the supervisor of the Tides and Geodesy section at the Naval Oceanographic Office and has 22 years of experience in hydrographic surveying and data processing. She holds a BS degree from Mississippi State University.

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