

## **Further Investigations of VDatum to NAD83 Vertical Separations Using United States Geological Service (USGS) Coastal Water Levels Gage and Hydrolevel Buoy.**

Uchenna Chizaram Nwankwo, Stephan Howden and David Wells

The University of Southern Mississippi

The US National Oceanic and Atmospheric Administration (NOAA) has alerted users of VDatum in southeastern Louisiana and western Mississippi about VDatum uncertainties ranging from 20-50 cm. The implication of this is that special order through order 1b hydrographic surveys using VDatum may not be within the IHO vertical uncertainty budget. Two United States Geological Service (USGS) coastal water levels gages near the border between Louisiana and Mississippi had been used to investigate VDatum uncertainties in these regions and results were found to be within the VDatum published regional uncertainty of  $\pm 0.17$  m. Further investigations have been conducted using a third USGS coastal water levels gage, at Delacroix in coastal waters east of the Mississippi River, and an AXYS Hydrolevel buoy deployed at Chandeleur East (east of the Chandeleur Islands). A static GNSS survey was conducted at Delacroix to determine the ellipsoidal height of the station. The GNSS outputs from the Chandeleur East buoy were used to determine the instantaneous ellipsoidal heights of the buoy. Tidal datums were transferred to both sites from NOAA tide gages close to the sites. The transferred datums were then compared to VDatum results at the sites.

## Introduction

Three reference datums to which hydrographic observations may be referenced are: ellipsoidal, orthometric and tidal datums. Horizontal positions required during hydrographic operations, are commonly provided by the Global Navigation Satellite System (GNSS), which also provides vertical measurements referenced to an ellipsoid (North American Datum 83 (NAD83) for the United States). Land based tide gages are referenced to leveling benchmarks which have orthometric/ellipsoidal datums while the tides observed using the gages are referenced to tidal datums (Mean Lower Low Water (MLLW) for the United States) (Parker et al, 2003). The advent of GNSS tide has made reduction of hydrographic soundings to the ellipsoid possible. Coordinate transformation tools can be used to transform the reduced sounding from ellipsoidal datum to tidal or orthometric datums.

A vertical transformation tool (VDatum) was developed by NOAA's National Ocean Service (NOS) for the transformation of elevations from one reference datum to another. In the development of the tool, numerical models were generated to model the hydrodynamics of different areas. For areas where the hydrodynamics could not be adequately modeled, Tidal Constituents and Residual Interpolation (TCARI) was used for interpolations (Hess, et al., 2003). VDatum can transform between 36 datums. The tool has enhanced the reduction of hydrographic sounding to chart datum and in the delineation of Marine boundaries (Parker, 2002). However, on the VDatum website, NOAA's warning about the tool reads:

*“Important: Transformation Uncertainties in the ‘Louisiana / Mississippi - Eastern Louisiana to Mississippi Sound’ Regional Model, have been found to range from 20 to 50 cm in particular locations from the Mississippi River Delta north to Lake Pontchartrain. These issues most likely can be attributed to subsidence, newly established datums, and changes to the understanding of NAVD88 based on new versions of the GEOID. The VDatum Team is currently looking at resolving these uncertainties”.*

This uncertainty is high when compared to published VDatum uncertainty of 17 cm and so it is imperative to localize areas where VDatum uncertainty is larger than published. To achieve this goal, three USGS water level gages and an AXYS Hydrolevel buoy (<http://axystechnologies.com/wp-content/uploads/2014/12/Hydrolevel-Buoy.pdf>) were utilized in the region highlighted by NOAA (Figure 1). The results of the VDatum uncertainty investigations from USGS stations at the CSX Railroad bridge over the East Pearl River and the Highway 90 bridge over the Rigolets were reported in the 2018 Hydrographic conference at Vancouver Canada. We are reporting the latest analysis at one USGS tide gage near Delacroix LA (073745257 Crooked Bayou NW of L. Cuatro Caballo) and a Hydrolevel buoy, Chandeleur East, deployed east of the Chandeleur Islands (Figure 1), in a partnership with the Naval Oceanographic Office (NAVO) Leidos (a national security, health and engineering solutions company). NAVO provided a HydroLevel buoy for the project and Leidos, who were conducting a hydrographic survey in the area, deployed and recovered the buoy.

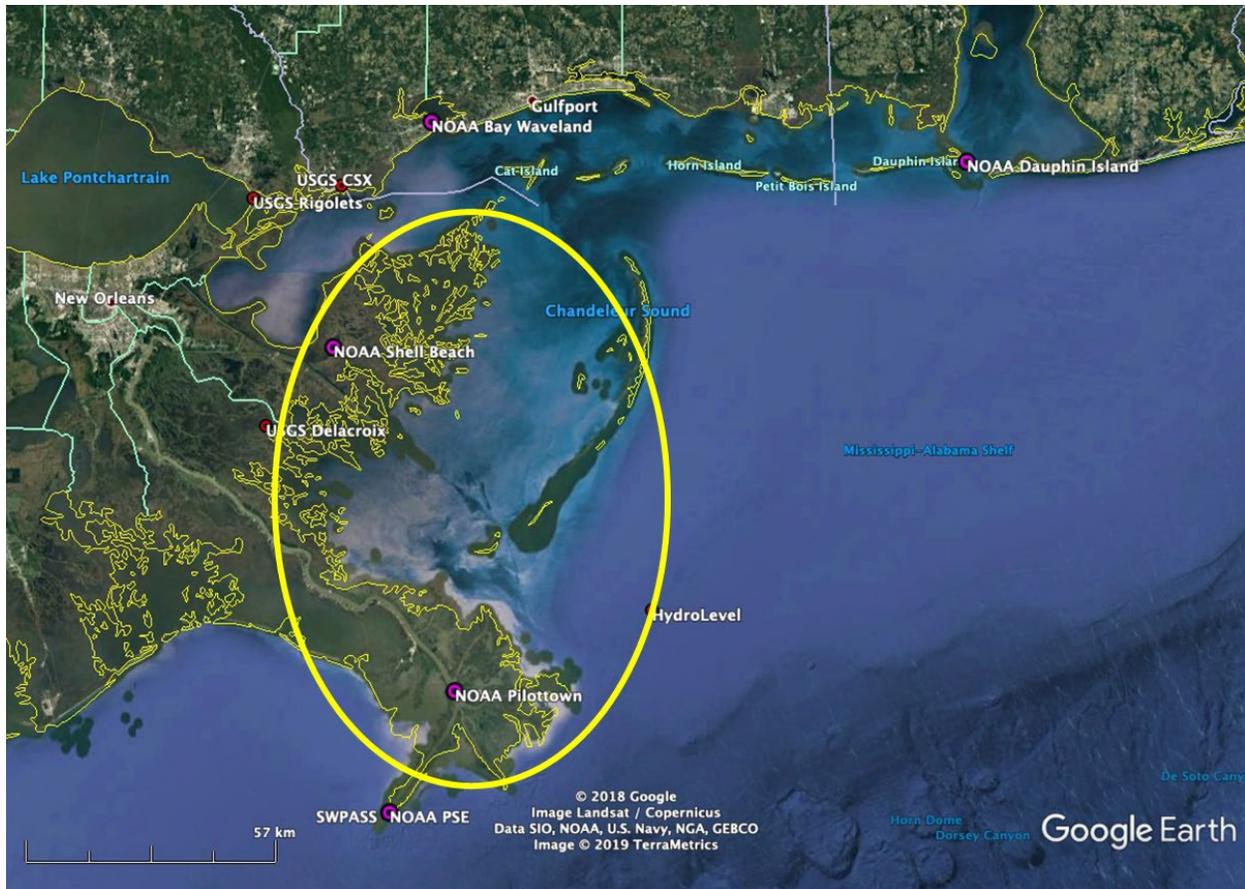


Figure 1: Figure showing suspected VDatum uncertainty critical area represented by the oval. In addition to the area within the oval NOAA is concerned about VDatum in the broader region.

## Methodology

The methods for determining the vertical separations between the NAD83(2011) ellipsoid and the tidal datums at the USGS water level gage and the moored HydroLevel buoy were similar in concept, though differed in detail. Although the methods at both the USGS water level gage and the HydroLevel buoy utilized GNSS observations, at the USGS platform the GNSS observations were in static mode to obtain the vertical separation between the NAD83(2011) ellipsoid and the gage zero, while for the Hydrolevel buoy the GNSS observations were in kinematic mode to measure the separation between the NAD83(2011) ellipsoid and the water level. Both methods utilized tidal datum transfers from a NOAA NWLON primary gage following Evans et al., (2003).

### USGS Water Level Station 073745257

The equipment used for the survey on the USGS water level station included a Trimble Zephyr Geodetic model 2 antenna, a Trimble GNSS NetR8 receiver, antenna pole, solar panel, protective case for the receiver and external battery, I-beam spirit levels, and survey grade measuring tape.

USGS provided the NAD27 horizontal coordinates and vertical gage datum offsets from a topside reference mark for the Delacroix station, from which we could measure a GNSS antenna vertical offset and from NAVD88(Table 1)

Table 1: USGS station information for station 073745257, Crooked Bayou near Delacroix, Louisiana

Latitude (NAD27)	29° 42' 29.0"N
Longitude (NAD27)	089° 43' 10"W
Gage Zero from NAVD88	-4.20 ft, (-1.28 m)
Gage Zero from Platform Reference Mark	-14.07 ft, (-4.29 m)
Water Level Reporting Interval	15 min

Access to the USGS station was by boat. Upon getting to the site, we discovered the frame supporting the water level gage datalogger, on which we could fasten the pole for the GNSS antenna, extended about 2 m above the platform (Figure 2). To effectively mount the GNSS antenna, and to prevent multipath we increased the length of the GNSS antenna pole by joining it to a second pole making it 3.69 m above the reference mark located near the floor of the platform (Table 2). The receiver and an external battery were used to augment the built-in receiver battery and were housed in a datalogger box to keep them safe from the environment. A solar panel was installed to ensure the batteries were charged throughout the survey period.

A measuring tape was used to determine the length of the GNSS antenna pole from the antenna reference point (ARP) to the base of the pole. The pole was erected vertically using a plumb level. An I-beam spirit level and measuring tape were used to tie the base of the pole to the station's reference point indicated by two grooves on a piece of aluminum angle iron bolted to the platform. The offset between the station's reference point and gage datum (Table 1) was provided by USGS.

A GNSS survey then allows for the ellipsoid height of the gage water level datum to be determined by adding the ellipsoid height found for the GNSS antenna to the measured antenna pole length, the measured antenna pole base vertical offset from the gage reference mark, and the USGS provided vertical offset from the gage reference mark to the gage datum.

A static GNSS survey was conducted from July 12, 2018 to July 18, 2018 at the USGS water level station. The GNSS receiver was configured to collect data at 1Hz. Only Global Positioning System (GPS) and Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) constellations were tracked. On the day of the deinstallation, all offsets were measured again to ensure nothing changed during the data collection period.

Raw data from the Trimble receiver were saved in .00T format. This was converted to Rinex version 3.0.5.0, using is a Trimble Business Center utility to convert the .00T files to Rinex format. The files were eventually post-processed in static mode in both forward and backward directions using Novatel Waypoint Software GrafNav version 8.70 to minimize residuals and have better resolution of integer ambiguities. A Differential GNSS method was applied using SBCH Continuously Operating Reference Station (CORS) which was which was about 17.3 km.

The USGS published vertical separation between NAVD88 and the USGS gage datum allowed for our methods to check this value by 1) Finding the ellipsoid separation of the gage datum, 2) Running the NGS GEOID 12B model (or equivalently NOAA's VDatum tool) to find the ellipsoid to NAVD88, and 3) NAVD88 separation from the gage separation. If this value differed from the published NAVD88 to gage zero by more than the uncertainties indicated, it would suggest that the gage datum had moved vertically. If the NAVD88 to gage separation from the present survey had become larger, that would be consistent with subsidence.

Three months of 15 min, approved water level data (January 2, 2017 to April 3, 2017), relative to gage datum, were used for the datum transfer to ensure that the uncertainties of the transferred datums were below 0.05 m, as determined from Swanson (1974). The water level data were converted from feet to meters and the time stamps were converted to Universal Coordinated Time (UTC) (Figure 3).



Figure 2: Figure showing GNSS setup at Delacroix station.

The NOAA primary gage chosen for the tidal datum transfer was the one at Shell Beach, LA, which has NOAA Station ID number 8761305. Water levels from this gauge were downloaded for the same period as the USGS gage. The particular type of tidal datum transfer depends upon the type of tide in the region (Evans et., al 2003). In the northern Gulf of Mexico, the tides are diurnal, which means that the Modified Range Ratio (MRR) should be used (Evans et. al, 2003). To verify that the tides are diurnal at the USGS gage a harmonic analysis was run on the water level data using UTide (Codiga, 2011). From the computed form number which, is the quotient between the sum of the diurnal primary constituents (K1 and O1) and semi-diurnal primary constituents (M2 and S2) we ascertained that the region experiences diurnal tide because form number at the two sites was greater than 1.

The datums were transferred from the primary gage to the USGS using two techniques: an in-house USM software and a NOAA online tidal datum transfer tool. The in-house USM software required finding peaks (high and low water levels) in both times series and matching the peak found in one time series to a corresponding peak in the other time series. Then, using the higher high and lower low water values, a MRR program written in Microsoft Excel, was used to calculate the datums at the subordinate station. The NOAA online tidal datum transfer tool required formatting the water levels data so that it will have two columns; a date-time column water level column.

### Chandeleur East HydroLevel Buoy

The equipment used for this part of the study was a HydroLevel buoy from AXYS Technologies that uses GNSS receivers to measure water level to the ellipsoid taking into account the rotational and translational tilts of the buoy (e.g., Bamford, 2013). NAVO partnered with USM on this project as a means to test out the system in the northern Gulf of Mexico and provided the buoy, and personnel to help deploy it, and to process the data, providing water levels to the NAD83(2011) ellipsoid. Leidos provided the time on their survey vessel to deploy and recover the buoy.

The buoy was vandalized twice, with someone cutting the buoy from its mooring. The first time Leidos was able to recover and redeploy it. The second time Leidos just recovered it. Although the intent was for at least a 30-day water level record, the result was too short water level records.

NOAA tide station 8735180 Dauphin Island was used as the primary tide station for the tidal datum transfer. As for the USGS gage, the MMR method was used for the datum transformation. The transferred datums are relative to the NAD83(2011) ellipsoid. These can then be directly compared to the VDatum NAD83(2011) to tidal datum separations.

## **Results**

### USGS Water Level Station 073745257

The estimated ellipsoidal height of the antenna after post-processing the raw GNSS data is -18.67 (m) with respect to the NAD83(2011) ellipsoid (Table 2). Using the estimated antenna ellipsoidal height, the gage datum was reduced to the NAD83(2011) ellipsoid by incorporating both the measured offsets at the station and the offsets provided by USGS (Table 2). The reduced gage datum ellipsoidal height was found to be -26.65 m.

id	Parameters	Source	Delacroix (m)
a	GNSS Antenna Ellipsoidal height NAD83	GrafNav8.7	-18.67 +/- 0.03
b	Antenna above reference mark	USM data	3.69 +/- 0.01
c	Reference mark above gage datum	USGS	4.29 +/- 0.01
d	Gage datum ellipsoid height	$a - b - c$	-26.65 +/- 0.03

Table 2: Table showing the offsets measured at the station including the offsets provided by USGS

Besides the gage datum to reference mark offset, USGS also provided the separation between the gage datum and NAVD88 (Table 1). We estimated the corresponding separation from the ellipsoidal gage

datum height and found a difference of about 14 cm that is NAVD88 was found to be 14 cm higher above gage than it was when the USGS surveyed the gauge in 2016.

Parameters	Source	Value (m)
Gage datum ellipsoid height ( $N_g$ )	USM result	-26.65 +/- 0.03
NAVD88 separation ( $N_{NAVD88}$ )	GEOID12B	-25.23 +/- 0.03
Gage datum from NAVD88 ( $h_1$ )	$N_g - N_{NAVD88}$	-1.42 +/- 0.04
Gage datum from NAVD88 ( $h_2$ )	USGS	-1.28
Difference in gage datum to NAVD88	$h_1 - h_2$	-0.14

Table 3: Table showing the comparison of gage datum to NAVD

between USM results and the offset provided by USGS.

The plot of the water levels from the USGS station is shown on (Figure 3). The tidal datums and uncertainties for the USGS water level gage, from the datum transfer using the water levels records are shown in (Table 4). The transferred datums were with respect to the gage datum. Corresponding datums from the online datum calculator were also shown on (Table 4). The differences in the datums show that both results agree to Swanson's three months uncertainty estimate for the Gulf coast.

Table 4: Table showing transferred datums using manual method (USM) and online datum calculator method (NOAA).

Comparison of datum transfer results			
Datum	USM (m)	NOAA (m)	USM – NOAA (m)
DTL	1.49 +/- 0.05	1.45	0.04
MLLW	1.37 +/- 0.05	1.32	0.05
MHHW	1.61 +/- 0.05	1.58	0.03
Gt	0.23 +/- 0.05	0.26	0.03
MSL		1.44	

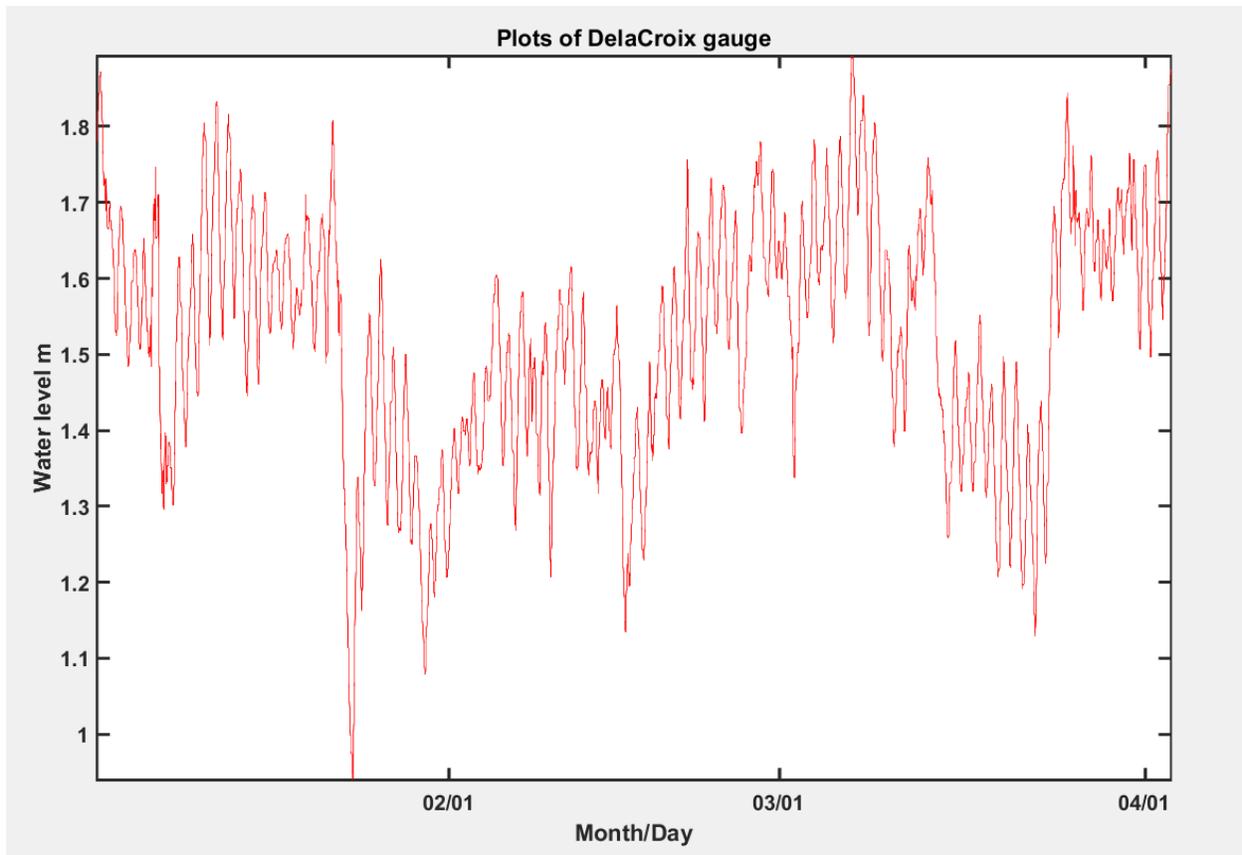


Figure 3: Figure showing water level plot at Delacroix station from January 1, 2017 – April 3, 2017.

The reference for the transferred datums was transformed to NAD83(2011) ellipsoid using the ellipsoidal height of the gage datum (Table 5). The NOAA VDatum tool was used to determine the tidal datums at the station (Table 2). The differences between the datums were computed. It can be seen in (Table 5) that the residuals for Gt and MHHW were not within NOAA published VDatum uncertainty of 17 cm. Note that the Mean Diurnal Tidal Level from VDatum is 11 cm higher than our result and the Great Diurnal Range is double our result.

Table 5: Table showing comparisons of datums from VDatum and our manually transferred datums at Delacroix station using method A.

Datum	Delacroix m	NOAA Vdatum m	Delacroix – Vdatum m
DTL	-25.16+/-0.06	-25.05+/-0.17	-0.11+/-0.18
MLLW	-25.28+/-0.06	-25.28+/-0.17	-0.00+/-0.18
MHHW	-25.04+/-0.06	-24.82+/-0.17	-0.22+/-0.18
GT	0.23+/-0.06	0.46+/-0.17	-0.23+/-0.18

### Chandeleur East HydroLevel Buoy

Two plots were represented on (Figure 4): 1) raw ellipsoidal water level height which includes outliers (red plot) 2) ellipsoidal water levels height after statistically removing outliers (blue plot) and also shown in more detail in (Figure 5). Outliers were water levels records which were not within two standards deviations of the mean water level.

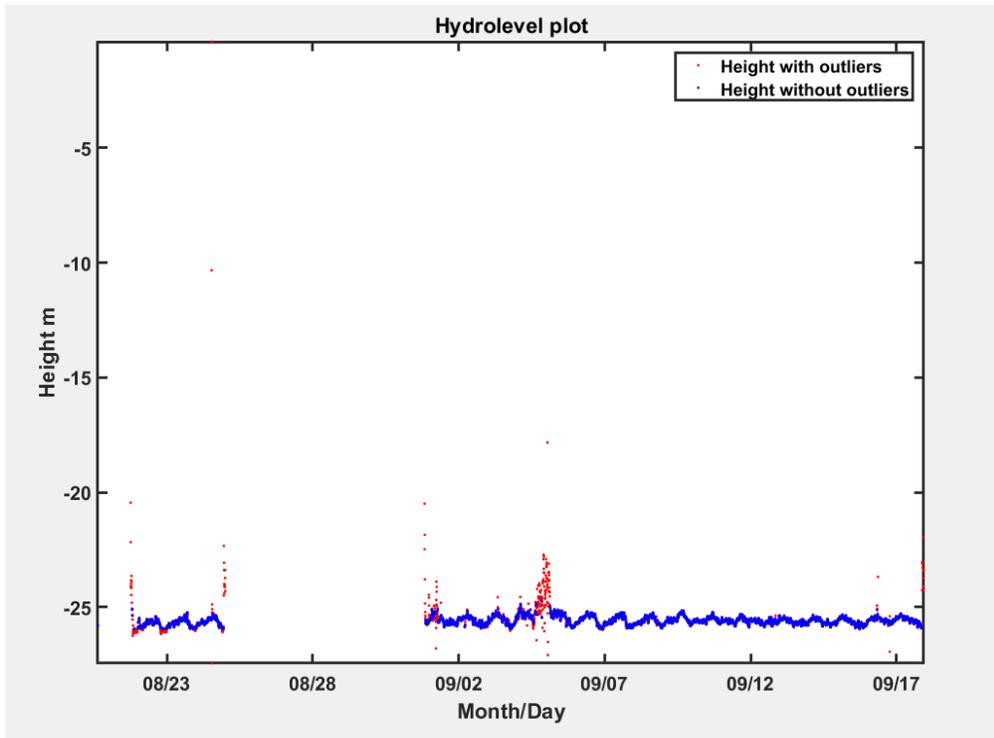


Figure 4: Figure showing water levels plots with and without outliers at the buoy .

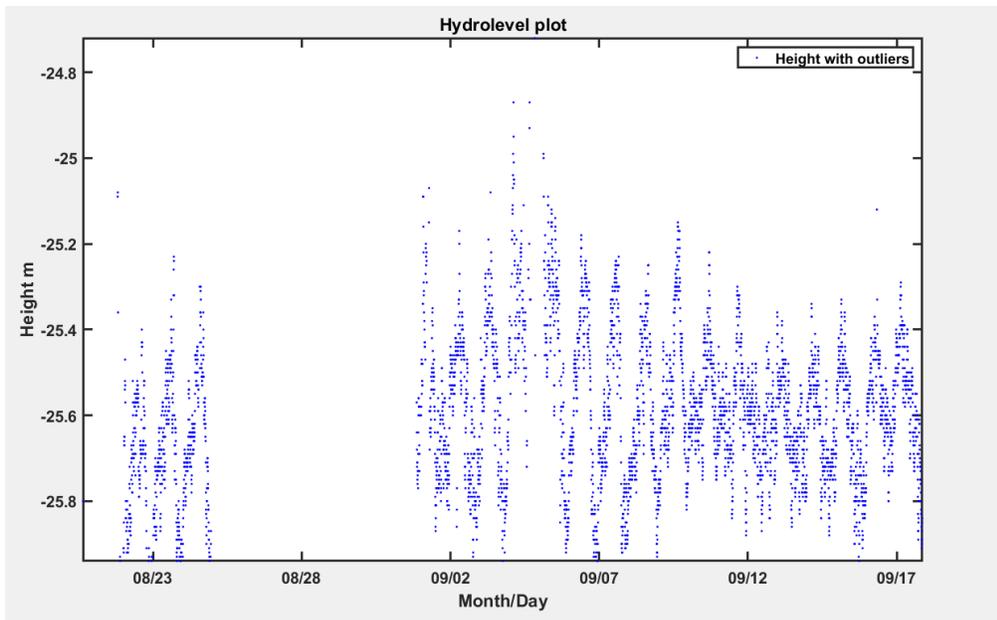


Figure 5: Figure showing water levels plots without outliers at the buoy .

The result of the transferred datums using water levels with outliers removed and a NOAA station at Dauphin Island is shown on (Table 6). We could not check our results with the online datum calculator

because, the tool breaks when there is a gap greater than 3 hours. Tidal datums at the buoy location were determined using VDatum and the results were compared to our results as shown in table 6. Besides Gt, the other datums were not within NOAA published VDatum uncertainty of 17 cm. Gt at the neighboring NOAA tide stations were computed (Table 7) compared well with the Gt we estimated. DTL from VDatum is 40 cm below our results.

Table 6: Table showing comparisons of datums from VDatum and our manually transferred datums at the buoy.

Datum	Chandeleur East buoy m	NOAA Vdatum m	Chandeleur East buoy – Vdatum m
DTL	-23.63+/-0.06	-24.03+/-0.17	0.40+/-0.18
MLLW	-23.81+/-0.06	-24.22+/-0.17	0.41+/-0.18
MHHW	-23.45+/-0.06	-23.83+/-0.17	-0.38+/-0.18
GT	0.36+/-0.06	0.39+/-0.17	-0.03+/-0.18

Table 7: Table showing comparisons of great diurnal range at NOAA tide stations and from VDatum.

Great Diurnal Range								
Station	Shell Beach NOAA		Pilot Station East NOAA		Pilot Town NOAA		Dauphin Island NOAA	
	Vdatum	SBCH	VDatum	PSE	VDatum	PT	VDatum	D I
Values	0.46	0.45	0.37	0.36	0.31	0.26	0.37	0.37
Difference	0.01		0.01		0.05		0.00	

## Discussion

### USGS Water Level Station 073745257

The analysis of the water level data at the USGS water level station 073745257 aided the investigations of VDatum uncertainties southwards of the previously analyzed USGS stations at CSX Railroad and the Rigolets. Although the USGS station at Delacroix was not within the most critical area that NOAA wanted to examine, some of the results were more than 17 cm different from our results.

The static GNSS survey carried out was similar to the two previous sites we had analyzed. However, at this site, there were no structures in the vicinity shading the GNSS signals captured by the antenna. Using the signals recorded by the receiver, the ellipsoidal height of the antenna with respect to NAD83(2011) was established. This was done to determine the ellipsoidal heights of both the reference mark on the platform and the gage datum. We could not independently determine the offset between the gage datum and reference mark that was provided to us by the USGS.

The comparison between our results and VDatum outputs is shown on (Table 5). The uncertainties for VDatum outputs MHHW and Gt were not within the NOAA published VDatum uncertainty of 17 cm. We deduced that VDatum overestimates Gt at the station. We hypothesize that the overestimation of Gt at

Delacroix by Vdatum may be due to the underlying tidal model having too much hydrodynamic connectivity to NOAA tidal station at Shell Beach. We also hypothesize that the station is subsiding. The last GPS survey of the gage by the USGS was in 2016 (USGS personal communication) and this would imply a subsidence rate of about 47 mm/yr which is very high. We assume that the separation provided by USGS is correct. It is important to note, however, that subsidence can only affect tidal datum-ellipsoid separations if it 1) changes the local geoid or 2) affects the local range of the tide both of which are unlikely at this level of discrepancy.

### Chandeleur East HydroLevel Buoy

The Chandeleur East buoy deployment is the furthest offshore analysis we have conducted so far in this project. Also, it is the only station located within the region identified as critical by NOAA. In the datum transfer operation, the closest NOAA tide station (Pilot Station East) was not used because the station's datums have high uncertainties. Therefore, Dauphin Island station was chosen instead of Pilot Station East. Comparison of VDatum outputs and our transferred datums (Table 6) shows that the discrepancies (many of which are above 17 cm) are due to an offset in DTL. This subsequently affected MLLW and MHHW values. This implies that all the datums at the site would have been within VDatum published uncertainty if DTL was adequately estimated by VDatum. This is considered a preliminary analysis because the buoy was operational for only a period of three weeks.

### **Conclusions**

The VDatum uncertainty investigation project was a response to the warning by NOAA about the degraded uncertainties in VDatum in southeastern Louisiana and western Mississippi. The results reported here are the continuation of previous analysis related to this project. USGS water gages were used for this project. We not only investigated VDatum uncertainties at these USGS gages but also, established tidal datums on them. We found a deviation of 14 cm when we compared our NAVD88 to gage datum separation with that provided by USGS. This was an indication of subsidence. Also, we noted that VDatum overestimates great diurnal range at the Delacroix station. Analysis at the buoy station supported NOAA's claim about the increased VDatum uncertainties in the region indicated as critical region. However, our analysis was based on the water records from a buoy deployed for a period of about 3 weeks.

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