NOAA Technical Memorandum NOS 38

AN ASSESSMENT OF THE REVISED VDATUM FOR EASTERN FLORIDA, GEORGIA, SOUTH CAROLINA, AND NORTH CAROLINA

Silver Spring, Maryland
October 2016

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Coast Survey Development Laboratory

Office of Coast Survey
National Ocean Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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AN ASSESSMENT OF THE REVISED VDATUM FOR EASTERN FLORIDA, GEORGIA, SOUTH CAROLINA, AND NORTH CAROLINA

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EXECUTIVE SUMMARY

VDatum is a datum transformation software tool developed by NOS that provides conversions between tidal, orthometric, and ellipsoidal vertical reference systems. An updated VDatum application was created and made available to the public via the VDatum website in December 2014 for East Florida, Georgia, South Carolina, and North Carolina. Modernized coverage extends along the U.S. coast from the Fort Lauderdale, Florida vicinity to the North Carolina/Virginia Border providing enhanced datum transformations capabilities and reducing the uncertainties in many areas. These new regions supersede the previous version that became operational from 2005 to 2010.

The updated application covers five VDatum sub regions:

1) North Carolina - Inland waterways and sounds
2) North Carolina - Coastal shelf
3) Georgia/South Carolina/North Carolina - Sapelo Island GA to Holden Beach NC
4) Florida/Georgia - Coastal waterways, Fort Lauderdale FL to Sapelo Island GA
5) Florida/Georgia - Shelf, Fort Lauderdale FL to Sapelo Island GA

Several enhancements are incorporated in the updated application:

- 119 new tide stations have been added to the database and new datums have been computed for many existing stations.
- Revised digital coastline information and the U.S.'s Exclusive Economic Zone (EEZ) delimitation boundary have been incorporated.
- Users request for expanded datum conversion coverage for various intra-coastal waterways, additional inlets and bays, and the farther offshore regions, except where the EEZ limits, have been included.
- Higher spatial resolution grids were created that allow depiction of narrow channels like intra-coastal waterways and inlets.
- For the North Carolina applications, the three previous VDatum regions were updated and consolidated into two regions: North Carolina Coastal Shelf and North Carolina Inland Waterways and Sounds.
- During this update process, model results were used for the first time as guidance in defining non-tidal areas.
- Three out of the four VDatum regions not previously meeting the 10cm or below Maximum Cumulative Uncertainty (MCU) threshold were reduced to meet the strategic goal.
- Overall, the accuracy of the new modeled tidal datum is significantly improved relative to the old model.
    - In the Florida/Georgia regions, a total of 12 new stations were added to the area within the original grid, and showed an average tidal field RMS error at these stations of 11.5 cm. At these locations, the observed and modeled tidal datum difference will be reduced to approximately zero.
    - In North Carolina, the new tidal models reduced the uncertainty by approximately half.
- The Topography of the Sea Surface field also showed dramatic improvements.

- 41 new stations were added in the generation with absolute differences between new and old fields in the values realized at these stations ranging from 2.1 cm to a maximum of 30.8 cm.
- Differences recognized between the new and old grids can predominantly be attributed to the addition of new gauges, except one instance where a new datum relationship was established.

- These changes in the Topography of the Sea Surface field, emphasize the importance of new gauging to better characterize the spatial variability of the data starved TSS fields.

Key Words: tides, elevation, datums, VDatum, Florida, Georgia, South Carolina, North Carolina, coast, orthometric, grids, NAVD88, model, U.S. Army Corps of Engineers

1. **INTRODUCTION**

VDatum is the National Ocean Service's (NOS's) vertical datum transformation software tool that provides spatially-varying conversions between tidal, orthometric, and ellipsoid-based three-dimensional reference frames. The software can convert any ellipsoidally-referenced vertical elevation to the North American Datum of 1983 (NAD 83) by parametric models, NAD 83 to the North American Vertical Datum of 1988 (NAVD 88) by a gridded geoid model, NAVD 88 to the Mean Sea Level (MSL) by a gridded sea surface topography model, and MSL to any tidal datum with a set of gridded tidal datum transform fields. Data for the parametric models were obtained from the geodetic literature, and the gridded data were generated by spatial interpolation of known values at numerous locations and by the use of tidal datum fields derived from hydrodynamic models. The following will discuss the update of the VDatum application created for Eastern Florida, Georgia, South Carolina, and North Carolina covering the U.S. coast from the Fort Lauderdale, Florida vicinity to the North Carolina/Virginia Border. Figure 1 illustrates the regions covered by this update.

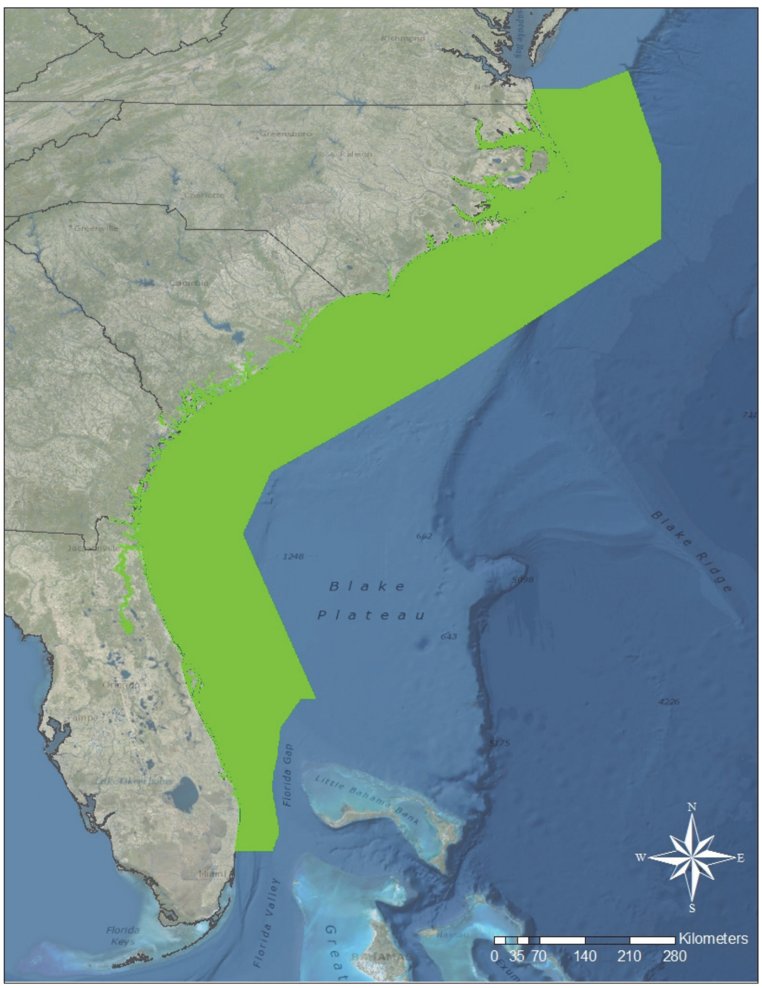

Figure 1. Illustration of the area covered by the East Florida, Georgia, South Carolina, and North Carolina update.

1.1. East Florida, Georgia, and South Carolina

Recently, VDatum was developed for east Florida (Yang et al., 2012) and included two regional applications (i.e., a set of GTX transformation grids and a bounding polygon): one for southern Georgia and east Florida, and the other for northern Georgia, South Carolina, and southern North Carolina. These VDatum applications became operational in 2010. After certain problems were identified by the U.S. Army Corps of Engineers, a revised version was developed (Hess et al., 2013) for the southern Georgia and eastern Florida VDatum, and consisted of two regions instead of the original single region. The new regions were the Georgia-Florida inland waterways region and the Georgia-Florida continental shelf region. This version became operational in April 2012.

Since that update, several developments have occurred. Data from new tide stations have been added to the database, and new datums have been computed for many existing stations. Revised digital coastline information and a digitized file of the U.S.'s Exclusive Economic Zone (EEZ) have become available (http://www.nauticalcharts.noaa.gov/csdl/mbound.htm). For these reasons, it was decided to update the VDatum application data sets for the following three existing VDatum regions: (a) Florida-Georgia waterways, the (b) Florida-Georgia continental shelf, and (c) the Georgia-South Carolina region. As a result, revised tidal datum fields were generated. Two topics dictated the extent of the new fields. The first was the inclusion of numerous tide stations in the upper reaches of rivers which created several difficulties. The second was the revision of the outer boundary extension to consistently reach 75 km offshore and the consideration to only include within the extents of the U.S. Exclusive Economic Zone (EEZ). These later revisions were handled relatively easily. Figures 2 and 3 demonstrates new coverage (green) and old coverage (red hash marks) for the East Florida and the Georgia/South Carolina/North Carolina Regions. Notice the extension in the upper reaches of rivers, the outer boundary extension to 75 km, and the consideration of the U.S. Exclusive Economic Zone (EEZ) to the south.

1.2. North Carolina

The previous North Carolina VDatum was developed and became operational in 2005 (Hess et al., 2005). To evaluate the possible change in local datums since then, the new tidal datums from recently-collected water level data were compared with the previous model datums. Results indicated significant datum differences at certain locations. In addition, many users have requested datum conversions in the new regions such as the farther offshore region, intra-coastal waterways, and additional inlets and bays, which were not covered by the previous North Carolina VDatum. Thus new gridded fields of tidal datums were needed for the North Carolina coastal area. Figure 4 shows new coverage (green) and old coverage (red hash marks) for the North Carolina Region. Notice the extension in the farther offshore region, intra-coastal waterways, and additional inlets and bays (e.g. Albemarle Sound), which were not covered by the previous North Carolina VDatum.

Tidal datum grids for these new regions were derived from tidal water levels simulated by a hydrodynamic model. In order to obtain new tidal datum fields, a new hydrodynamic modeling system was needed to cover the requested waterways and to reflect tidal change induced by the changes in shoreline and water depths.

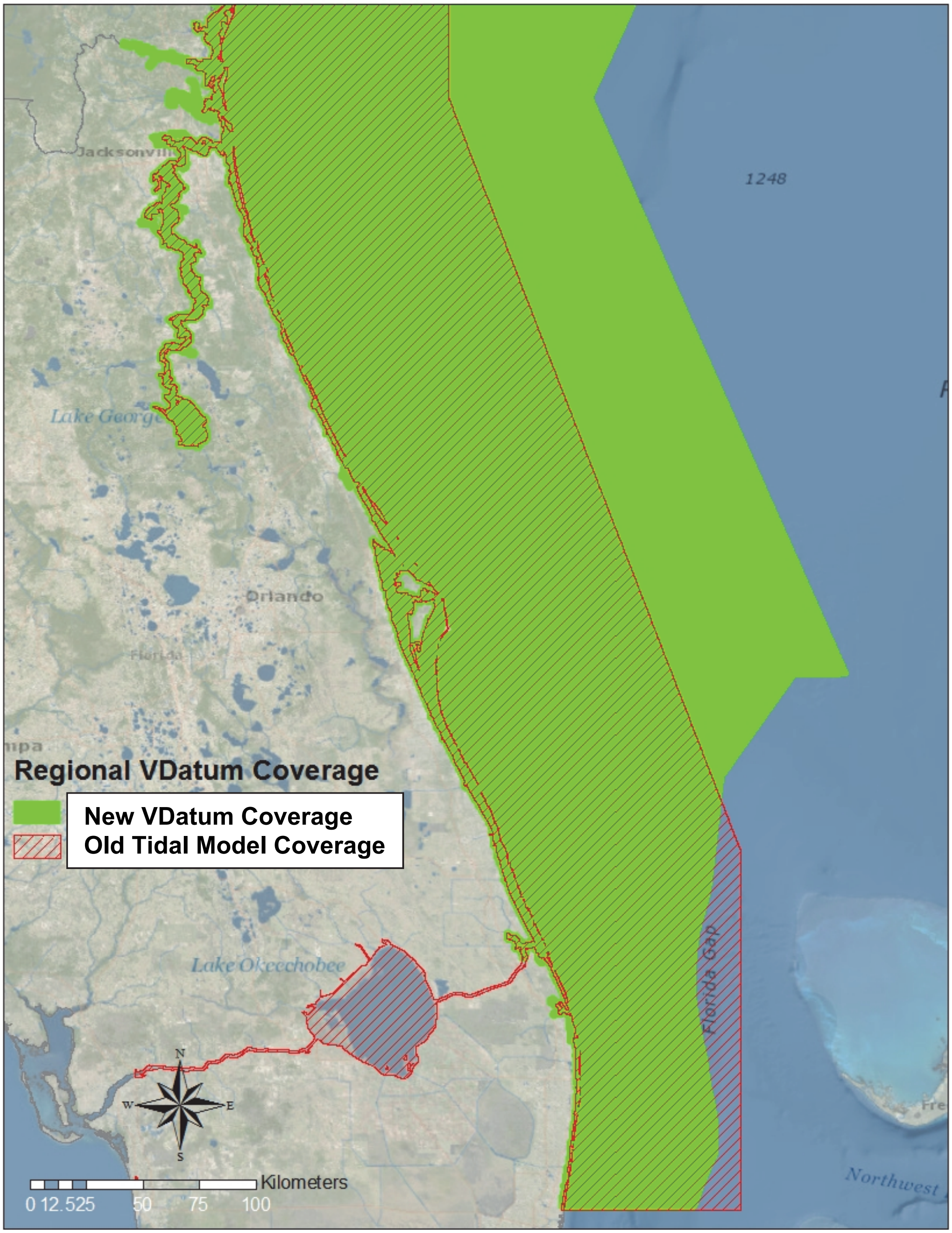

Figure 2. Illustrates new coverage (green) and old coverage (red hashed lines) for the East Florida Regions. Notice the extension in the upper reaches of rivers and the outer boundary extension to 75 km offshore and the consideration of the U.S. Exclusive Economic Zone (EEZ) to the south.

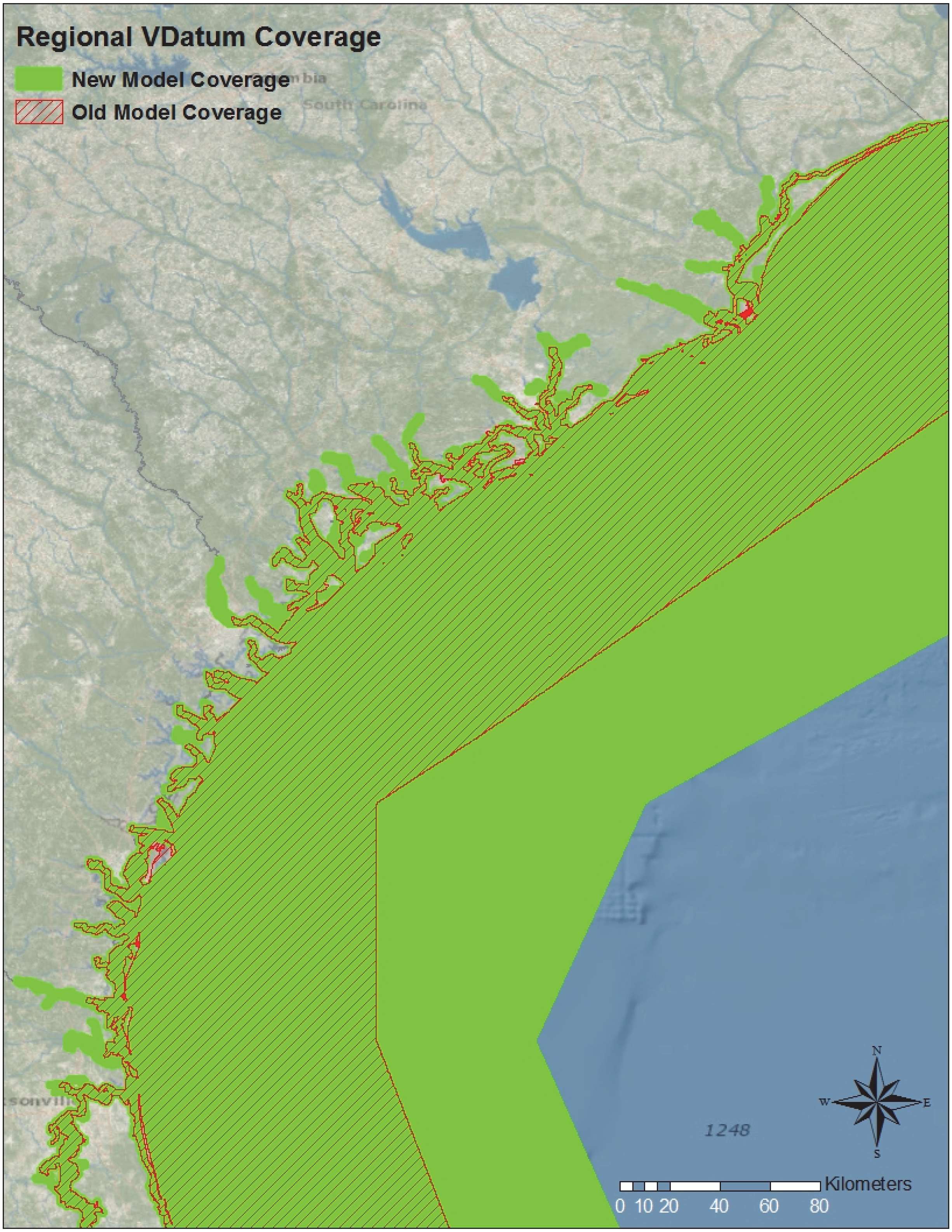

Figure 3. Illustrates new coverage (green) and old coverage (red hashed line) for the Georgia/South Carolina/North Carolina Region. Notice the extension in the farther offshore region, intra-coastal waterways, and bays, which were not covered by previous Model.

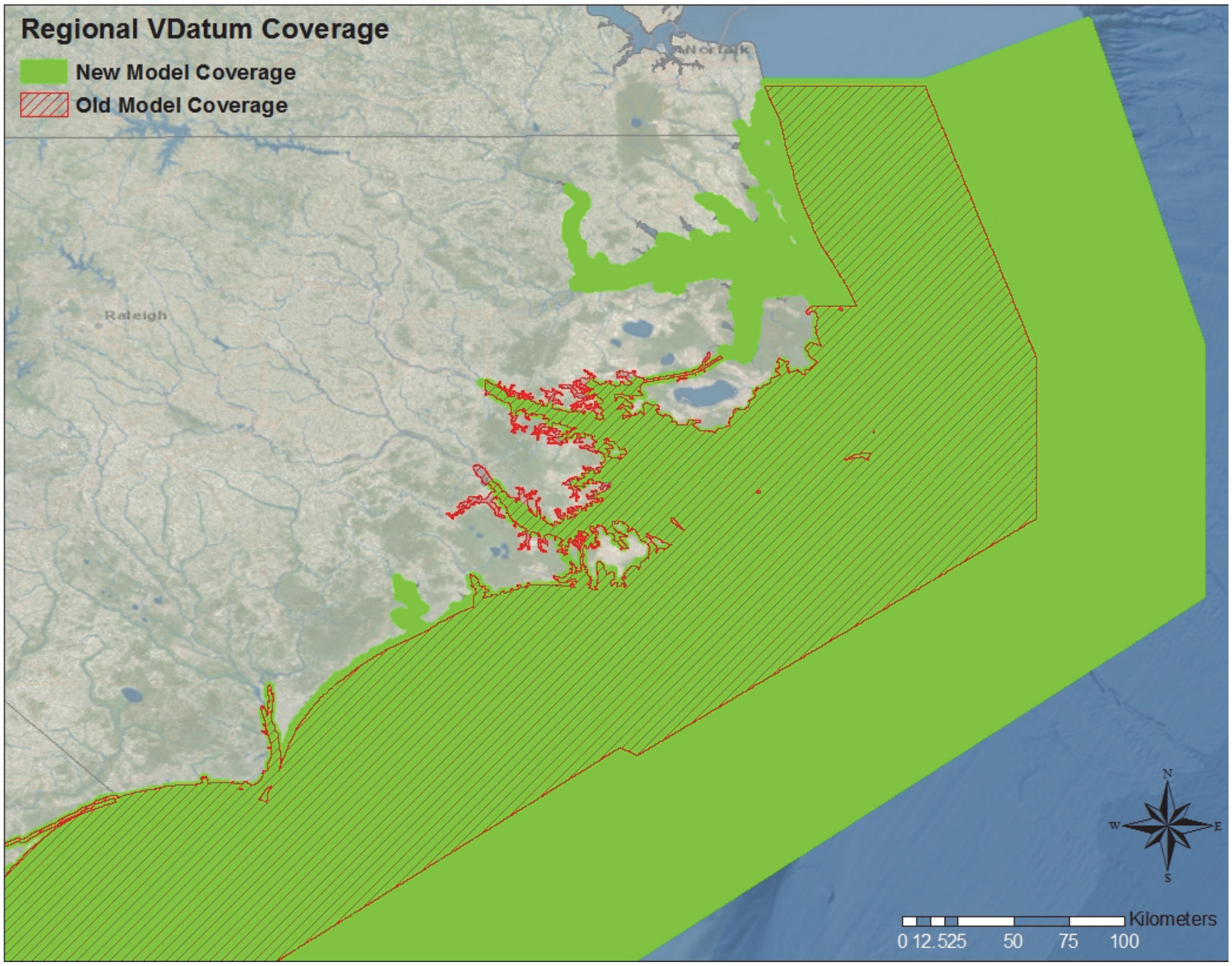

Figure 4. Illustrates new coverage (green) and old coverage (red hashed line) for the North Carolina Region. Notice the extension in the farther offshore region, intra-coastal waterways, additional inlets and bays, which were not covered by previous NORTH CAROLINA VDatum.

2. DEVELOPMENT OF THE REVISED VDATUM FILES

2.1. Tidal Grids

2.1.1. East Florida, Georgia, and South Carolina

Extension into Rivers
At the outset of the current (2014) revision, it was noted that not all the existing locations having tidal datum information were used in the previous versions of VDatum. Therefore, it was decided to include all tide stations within the inland portions of each VDatum region. In retrospect, this decision created several problems, some of which were not encountered in previous VDatum developments. These aspects are discussed below.

Shoreline
The inclusion of tide stations in the upper reaches of rivers required, in many cases, the expansion of the digitized shoreline file to include the additional rivers. Most of the new shoreline was generated by a direct request to the National Geodetic Survey (NGS) and was made available from the Continually Updated Shoreline Product (CUSP) web portal. The new shoreline data covered only portions of the rivers, and had to be manually integrated with the existing shoreline file for the region.

Tide Station Locations
Using the revised shoreline file, the positions of the tide stations in the Center for Operational Oceanographic Products and Services (CO-OPS) database was checked to make sure that the station was located inside a body of water. However, numerous stations were found to lie on land. Using CO-OPS station descriptions and satellite images, their positions were then manually revised to their true locations.

Grid Generation for Added River Areas
New unstructured triangular grids for the added river areas were constructed in the ADCIRC (Advanced CIRCulation) format using the SMS software. Since it was decided not to make additional hydrodynamic model runs, no bathymetry was used. Also, the gridded position of the intracoastal waterway near the South Carolina-North Carolina border was found to not match that in the North Carolina hydrodynamic model grid, so some adjustment in its position was made in the Georgia/South Carolina/North Carolina grid.

Non-tidal Areas
Some of the areas within the east Florida inland waterways VDatum region are designated by CO-OPS as being non-tidal. That is, their mean tide range is less than 0.3 ft (0.9 cm). In a few areas, especially around Port Canaveral, FL., the precise location of the polygon was altered to better account for the presence of canals and docking facilities. In addition, one tide station (872-1832 at Melbourne, Indian River, FL) had significant tidal range, but since it was located in a non-tidal area, it was ignored in the development of the tidal datum fields.

Method for Estimating Datums
For the stations in the added river grids, a completely new method to estimate datums had to be developed. First, each datum field was interpolated using the TCARI method with the following

boundary conditions: the uncorrected, model-derived values from the existing model grid. Then, this set of uncorrected grids is fused with the existing uncorrected grid. Next, the error values at all tide stations were generated using the latest datum values. Then, a field of errors was interpolated over the fused grid. Finally, the error field was added to the uncorrected datum field to obtain the final, corrected field. Several new computer programs had to be written to manipulate the grid data.

Method for Estimating Uncertainty
The standard VDatum method for estimating uncertainty cannot be used for the stations within the new grid, because they have no uncorrected tide model values to use for comparison. Therefore, jackknifing was used. With this approach, the error at each station is the difference between the observed value, and the value of the spatially-interpolated (using TCARI) datum field that was generated using all stations except the one for which the estimate is made. At this time, it is unknown how jackknifing based error and the standard comparison error are related. In addition, at some stations located far upstreams that have very small tidal ranges, jackknifing produced unreasonably large errors. Therefore, at those stations (there were 22) the error at the adjacent downstream station was substituted. This produced more reasonable statistical error results.

New Bounding Polygon
During VDatum development, it was decided to extend the offshore region of coverage out to 75 km, from the existing 25 nmi (46 km). Therefore, the bounding polygon was revised outward accordingly. Also, the border with the North Carolina VDatum regions was moved southward so its new position fell in a portion of the coast with relatively simple geography. In addition, it was also decided to restrict coverage to within the U.S.'s Exclusive Economic Zone (EEZ). This was accomplished using a digitized EEZ polygon. Finally, the Florida coastal region's Bounding Polygon was revised to have constant latitude along the southern boundary. This required a corresponding adjustment of the Bounding Polygon for the Southern Florida VDatum Region.

2.1.2. North Carolina

Shoreline and Bathymetric Data
The development of the hydrodynamic model grid for the new North Carolina VDatum coverage required shoreline and bathymetric data. NGS provided up-to-date high-resolution North Carolina shoreline which combines NOAA/CUSP (Continually Updated Shoreline Product) shoreline and the Office of Coast Survey (OCS) chart shoreline. Compared to the old shoreline, the new shoreline indicates significant changes, especially in Pamlico Sound and some inlets. In addition, the new shoreline includes more intra-coastal waterways and coverage farther inland for river channels. These new features would play an important role in improving model usability.

In order to make the shoreline ready for grid generation, much work was done to clean up thousands of unimportant features and redistribute segments. The designed auto-clean-up and auto-spacing scripts helped save substantial time and effort compared with manual clean up. The triangular grid was then generated from the processed shoreline using the SMS software. The resulting high resolution (~10 m) grid has a reasonable number of nodes (~250,000) and is able to resolve important channels, inlets, and bays.

The triangulated irregular grid was further populated with up-to-date bathymetric data. The bathymetric data was mainly from three sources. The OCS sounding data were used for most of the NC coastal regions. A global bathymetry-topography database SRTM30_PLUS from Scripps Institution of Oceanography was used for the far offshore region. The sounding data from the U.S. Army Corps Engineers' Wilmington District were used for the intra-coastal waterways. Compared to the old model grid bathymetry, the new grid has significant changes around the inlets. In additions, in the middle of Pamlico Sound, a large data gap in the old grid is filled in the new grid.

Sub-Regions and Rectangular Marine Grids
The previous North Carolina VDatum region was separated into three sub-regions, confined by three bounding polygons: North Carolina north (the northern part of coastal shelf), North Carolina central (the southern part of coastal shelf), and North Carolina Pamlico (Pamlico Sound). In the new version, we separate the North Carolina VDatum region into two sub-regions: North Carolina coastal shelf and North Carolina inland waterways and sounds. The offshore distance of the coastal shelf VDatum coverage is extended from the previous ~25 nautical miles (46 km) to the current ~75 km. The southern boundary of the new bounding polygons also extends ~80 km toward the southwest of the original bounding polygons. Cape Fear River and the related intra-coastal waterways are newly added into the new North Carolina VDatum coverage. The resolution of the rectangular marine grids is increased by approximately five times. Grid cell size decreased from the previous 0.0025 degrees (~250 meters) to the current 0.0005 degrees (~50 meters). The new marine grids are able to resolve narrow channels like intra-coastal waterways and inlets.

Non-tidal areas
Regions with a mean tidal range less than 0.3 ft are designated by CO-OPS as non-tidal. Previous VDatum non-tidal regions were mainly defined based on the observed tides at sparsely distributed stations. In this project, model results were used for the first time as guidance in defining non-tidal areas.

The MHW and MLW fields from the model were first corrected by adding the error fields interpolated from the model-data discrepancy at tide stations. The mean tidal range field was then derived by calculating the mean of the corrected MHW and MLW fields. The 0.3 ft contour line of the corrected mean tidal range field was used as the boundary of the non-tidal polygons. The new method integrates the model results with the observations and is able to produce more accurate non-tidal polygons.

2.2. Topography of the Sea Surface

The Topography of the Sea Surface (TSS) is defined as the elevation of the North American Vertical Datum of 1988 (NAVD88) relative to mean sea level (MSL). This grid provides compensation for the local variations between a mean sea level surface and the NAVD88 geopotential surface over the East Florida, Georgia, South Carolina, and North Carolina Regions. The TSS grid generation for the East Florida, Georgia, South Carolina, and North Carolina Regions covers five VDatum sub regions:

1) North Carolina - Inland waterways and sounds
2) North Carolina - Coastal shelf
3) Georgia/South Carolina/North Carolina - Sapelo Island Ga. to Holden Beach N.C.
4) Florida/Georgia - Coastal waterways, Fort Lauderdale Fla. to Sapelo Island Ga.
5) Florida/Georgia - Shelf, Fort Lauderdale Fla. to Sapelo Island Ga.

A positive value specifies that the NAVD88 reference value is further from the center of the earth than the local mean sea level surface. All data are based on the most recent National Tidal Datum Epoch (1983-2001). The direct method utilized, obtaining NAVD 88-to-MSL values, includes calculating orthometric-to-tidal datum relationships at NOAA tide gauges where elevation information has been compiled. Data for the direct method were supplied by CO-OPS and NGS.

Next, a continuous surface for each VDatum region was generated representing inverse sea-surface topography. Here, inverse indicates the TSS definition for VDatum inversed the nominal TSS convention (i.e. MSL relative to an equipotential surface). A grid mesh covering the entire area of benchmarks and water level stations with a spatial resolution similar to that of the tidal marine grids is created. Breaklines are inserted to represent the influence of land. A sea surface topography field is generated using the Surfer© software's minimum curvature algorithm to create a surface that honors the data as closely as possible. The maximum allowed departure value used was 0.0001 meters. To control the amount of bowing on the interior and at the edges of the grid, an internal and boundary tension of 0.3 was utilized. Once the gridded topography field has been generated, null values are obtained from the marine tidal grids and are inserted to denote the presence of land. The spatial resolution for two North Carolina TSS grids (inland waterways and sounds and coastal shelf) is 0.0005 degree in both latitude and longitude direction. The spatial resolution for the other three TSS grids (Georgia/South Carolina/North Carolina - Sapelo Island Ga. to New River N.C., Florida/Georgia - Coastal waterways and Florida/Georgia - Shelf) is 0.001 degree in both latitude and longitude directions.

3. OBJECTIVE ANALYSIS

In order to better understand the changes that occurred between old and new VDatum regions, an objective analysis was performed and will be covered hereafter. In order to understand general uncertainty estimate changes for each region, a comparison was performed between new and old estimates. Table 1(a) and (b) depict the uncertainty estimates for each individual transformation grid, source data, and the maximum cumulative uncertainty (MCU) spanning the transformation of ellipsoidal to tidal datum of highest uncertainty, for the old VDatum and new VDatum regions respectively. Table 1(c) illustrates differences realized, derived based on new uncertainty estimates minus old uncertainty estimates. It should be noted that since the North Carolina VDatum model transitioned from three to two regions, the older North Carolina – Coastal Central was utilized, since it depicted the highest uncertainty. It should also be noted that the new North Carolina VDatum coverage has been significantly expanded relative to the old one. A more energetic tidal region (Cape Fear Estuary) with higher uncertainties has been added into the new coverage. More detailed comparison in uncertainty for North Carolina is in 3.1.2. All region's MCU decreased, except for the Georgia/South Carolina/North Carolina VDatum region, where a 2.3 cm increase was noticed. All other regions experienced MCU decrease ranging from 0.1cm to 3.9 cm. In three out of four VDatum regions which previously had an uncertainty greater than 10cm, the goal to meet or reduce below the 10cm threshold was accomplished. The Georgia/South Carolina/North Carolina VDatum region uncertainty increase can most likely be attributed to the expansion into areas previously not modeled and the high variability in datums, especially in upper reaches of rivers and estuaries.

3.1. Tidal Grids

3.1.1. East Florida, Georgia, and South Carolina

A few objective analyses of the datum errors were completed to assess improvement in the East Florida, Georgia, South Carolina VDatum product. A comparison of the new tidal datum values at the 193 tide stations that are in both the original grid and the revised grid shows a very small increase in overall RMS errors: approximately 0.1 cm (Appendix, Section B). This shows that the new tidal datums have changed little from the previous VDatum. With the addition of the new grids, a total of 119 new stations were added to the total used to develop the VDatum GTX files. This represents a 61% increase on the number of tide stations used. Forty two new stations were added for the Florida/Georgia – Inland Waterways, one new station in the Florida/Georgia – Shelf, and 76 stations in the Georgia/South Carolina region.

A total of 12 new stations were added to the area within the original grid, and were not used to develop the original grid. The RMS error at these stations averaged 11.5 cm (Appendix, Section C). At these locations, the observed and modeled tidal datum difference will be reduced to approximately zero.

The mean error for Florida/Georgia – Coastal Waterways for 6 six new stations ranged from -6.3 cm with a standard deviation of 8.4 cm for MHW to 9 cm with a standard deviation of 9.8 cm for MLLW. The maximum MLLW error ranged from 12.4 cm for MHW to 18 cm for MLLW at station 8721164. The Root Mean Square Errors (RMSEs) for MHHW, MHW, MLW, and MLLW are 11.8 cm, 10.5 cm, 12.1 cm, and 13.3 cm, respectively for these 6 stations. The Florida/Georgia – Coastal Shelf has only one new station. The errors ranged from -12.1cm for MLLW to 14 cm for MHHW.

Table 1. Uncertainty Estimates for; a.) new VDatum Regions, b.) original VDatum Regions, and c.) Difference in uncertainty between new vs. old.

a.)

New Uncertainty Estimates (2015/01/30)									
REGION	**TRANSFORMATION**							**SOURCE DATA**	**MCU**
	NAVD88 to MSL	MSL to MHHW	MSL to MHW	MSL to MTL	MSL to DTL	MSL to MLW	MSL to MLLW	All Tidal Datums	
North Carolina – Inland Waterways and Sounds	4.6	3.8	3.5	1.5	1.8	2.6	2.8	1.5	8.7
North Carolina – Coastal shelf	4.7	2.7	2.6	0.5	1	2.9	3.7	1.5	8.4
Georgia/South Carolina/North Carolina– Sapelo Island GA to Holden Beach NC	9.4	7.4	7	2.6	2.8	9.4	9.5	1.4	14.8
Florida/Georgia – Coastal Shelf, Fort Lauderdale FL to Sapelo Island GA	4.1	5.4	4.6	1.9	1.7	4.4	4.3	1.4	9.2
Florida/Georgia – Inland Waterways, Ft Lauderdale FL to Sapelo Island GA	4.5	6.1	5.5	1.4	1.7	6.2	6.4	1.4	10

b.)

Old Uncertainty Estimates (2013/12/03)									
REGION	**TRANSFORMATION**							**SOURCE DATA**	**MCU**
	NAVD88 to MSL	MSL to MHHW	MSL to MHW	MSL to MTL	MSL to DTL	MSL to MLW	MSL to MLLW	All Tidal Datums	
North Carolina – Pamlico Sound	7.7	4.3	4	1.2	1.7	3.7	3.5	1.7	11.9
North Carolina – Coastal North	0	0.6	0.5	0.2	0.4	0.2	0.3	1.5	7.9
North Carolina – Coastal Central	0.8	3.2	3	0.2	0.5	3.2	3.4	0.9	8.5
Georgia/South Carolina/North Carolina – Sapelo Island GA to Holden Beach NC	4.9	8.3	7.6	6.1	6.5	7.2	7.5	1.6	12.5
Florida/Georgia – Shelf, Fort Lauderdale FL to Sapelo Island GA	9.1	5.1	4.3	1.7	1.8	4.3	4.3	1.5	13.1
Florida/Georgia – Inland Waterways, Ft Lauderdale FL to Sapelo Island GA	3.7	6.5	5.7	3.4	4	5.3	5.8	2.1	11.1

c.)

Differences in Uncertainty Estimates									
REGION	**TRANSFORMATION**							**SOURCE DATA**	**MCU**
	NAVD88 to MSL	MSL to MHHW	MSL to MHW	MSL to MTL	MSL to DTL	MSL to MLW	MSL to MLLW	All Tidal Datums	
North Carolina – Inland Waterways and Sounds	-3.1	-0.5	-0.5	0.3	0.1	-1.1	-0.7	-0.2	-3.2
North Carolina – Coastal shelf	3.9	-0.5	-0.4	0.3	0.5	-0.3	0.3	0.6	-0.1
Georgia/South Carolina/North Carolina– Sapelo Island GA to Holden Beach NC	4.5	-0.9	-0.6	-3.5	-3.7	2.2	2	-0.2	2.3
Florida/Georgia – Coastal Shelf, Fort Lauderdale FL to Sapelo Island GA	-5	0.3	0.3	0.2	-0.1	0.1	0	-0.1	-3.9
Florida/Georgia – Inland Waterways, Ft Lauderdale FL to Sapelo Island GA	0.8	-0.4	-0.2	-2	-2.3	0.9	0.6	-0.7	-1.1

The mean error for the Georgia/South Carolina region for 5 new stations ranged from 0.6cm with a standard deviation of 7.2 cm for MHHW to 14.2 cm with a standard deviation of 4.9 cm for MLLW. The maximum error ranged from 13.9 cm for MHW to 22.3 cm for MLLW at station 8721164. The RMSEs for MHHW, MHW, MLW, and MLLW are 7.2 cm, 7.3 cm, 4.8 cm, and 4.9 cm, respectively for these 5 stations.

Finally, the spatial resolution of the GTX grids increased from 0.0015 degree to 0.0010 degree. So in the latitudinal direction, spacing was reduced from 166 m to 111 m.

3.1.2. North Carolina

The ADCIRC barotropic model was used to simulate tidal water levels over the new unstructured grid. The simulated tidal water levels were then used to derive tidal datum fields. The modeled tidal datums were validated by comparing them with datums derived from the observed water levels at CO-OPS tide stations.

Both the new model and the old model were evaluated by statistical analysis of error which is defined by uncorrected modeled datum minus observed datum. Within the new model grid domain, tidal datums (MHHW, MHW, MLW, and MLLW) at 44 tide stations (9 along the NC Atlantic coast and 35 located in the inland waterways and sounds) were analyzed (Table 1a). The root mean square errors (RMSEs) of MHHW, MHW, MLW, and MLLW are 2.7 cm, 2.6 cm, 2.9 cm, and 3.7 cm, respectively for 9 Atlantic coastal stations. The RMSEs of MHHW, MHW, MLW, and MLLW are 3.8 cm, 3.5 cm, 2.6 cm, and 2.8 cm, respectively for 35 inland waterway stations.

In order to evaluate the new model performance relative to the old model, the RMSEs of old modeled datums vs. old data (Appendix, Section B) and new modeled datums vs new data (Appendix, Section A) were compared for 26 common stations located within both the old model grid domain and the new model grid domain. The RMSEs of the old modeled MHHW, MHW, MLW, and MLLW are 5.7 cm, 4.7 cm, 5.8 cm, and 5.7 cm, respectively. The RMSEs of the new modeled MHHW, MHW, MLW, and MLLW are 3.3 cm, 2.9 cm, 2.7 cm, and 3 cm, respectively. In general, the new model reduced the uncertainty by approximately half. For particular stations (e.g. 8652678, 8656084, and 8656467), the new model reduced the errors by approximately 10 cm.

Tidal datums derived from the recently-collected water levels at 5 new tide stations were also used for evaluation. These observed datums were not used in the old version of the NC VDatum. However, the old modeled datums were extracted at these 5 locations and compared with the observed datums and the new model datums. The mean error when compared to the old model for 5 new stations (Appendix, Section C) ranged from -2.4 cm for MHW with a standard deviation of 6.7 cm to 5.1 cm for MLLW with a standard deviation of 7.2 cm. As a result, the RMSEs of the old modeled MHHW, MHW, MLW, and MLLW are 8.1 cm, 6.4 cm, 6.6 cm, and 8.2 cm, respectively for these 5 stations. The RMSEs of the new model MHHW, MHW, MLW, and MLLW are 1.8 cm, 1.5 cm, 1.6 cm, and 2.7 cm, respectively for these 5 stations (Appendix, Section A). Particularly at new station 8656201, the errors of the old modeled MHHW, MHW, MLW, and MLLW are 16.3 cm, 12.7 cm, 13.1 cm, and 15.3 cm, respectively. The errors of the new modeled

MHHW, MHW, MLW, and MLLW are significantly reduced to 2.8 cm, 0.7 cm, 0.6 cm, and 1.3 cm, respectively.

In summary, the accuracy of the new modeled tidal datums is significantly improved relative to the old model. The higher resolution of the new North Carolina model grid and incorporation of the new shoreline and bathymetric data should mainly contribute to this improvement.

3.2. Topography of the Sea Surface

The data used to compile TSS grids were compared against the TSS grid product, to generalize internal consistency. The difference between NAVD88 and MSL for each tide station was computed. The mean and standard deviations for these differences between NAVD88 to MSL relationships for each of the sub regions was less than 0.001 m.

To assess the improvement in the VDatum TSS product, a comparison of new stations not utilized in the original development were examined against that of the old grid (Appendix, Section D). Summary statistics for each region are provided in Table 2. In the Florida/Georgia –Shelf region, 1 new station was included in this update. The difference realized between the new and old product was 30.8 cm. 15 new stations were added to the Florida/Georgia Coastal Waterways grid. A minimum difference of -6.3 cm and a maximum difference of 10.4 cm were realized. The mean difference was 2.7 cm with a standard deviation of 4.2 cm. The Georgia/South Carolina sub region had 13 new stations added for development. A minimum difference of -4.6 cm and a maximum difference of 29.9 cm were realized. The mean difference was 7.9 cm with a standard deviation of 10.5 cm. No new stations were included in the North Carolina Shelf grid development. 12 new stations were added to the North Carolina Inland Waterways region. A minimum difference of -2.1 cm and a maximum difference of 10.3 cm were realized. The mean difference was 3.3 cm with a standard deviation of 3.6 cm.

In an effort to try and understand changes that occurred between the new vs. old grids, the two were differenced to obtain a qualitative perspective. To drive the exploration, a difference threshold of 5 cm was utilized to serve as a starting point for interrogation of changes. For all sub regions, the exceeded threshold could be attributed to new station data except for one instance. Notable regions where tide stations presented a visible change were for the western reaches of the Pamlico Sound near the Tar and Neuse Rivers (Figure 7) where two gauges were added, and in the state of Georgia where 9 additional gauges were included in development, Figure 6. The exception was in the Florida/Georgia – Shelf sub region where a TSS relationship change of 30.8 cm occurred at the Dayton Beach Shores Station. This is apparent as shown in Figure 5 for the location north of Cape Canaveral.

Table 2: Statistics for difference at newly added tide stations, computed against the old TSS grid

Stats Location	# of New Tide Stations	Mean (m)	Standard Deviation (m)	RMS (m)
Florida/Georgia Shelf	1	0.308	NA	NA
Florida/Georgia - Coastal Waterways	15	0.027	0.042	0.049
Georgia/South Carolina	13	0.079	0.105	0.129
North Carolina – Coastal Shelf	0	NA	NA	NA
North Carolina - Inland waterways	12	0.037	0.038	0.052

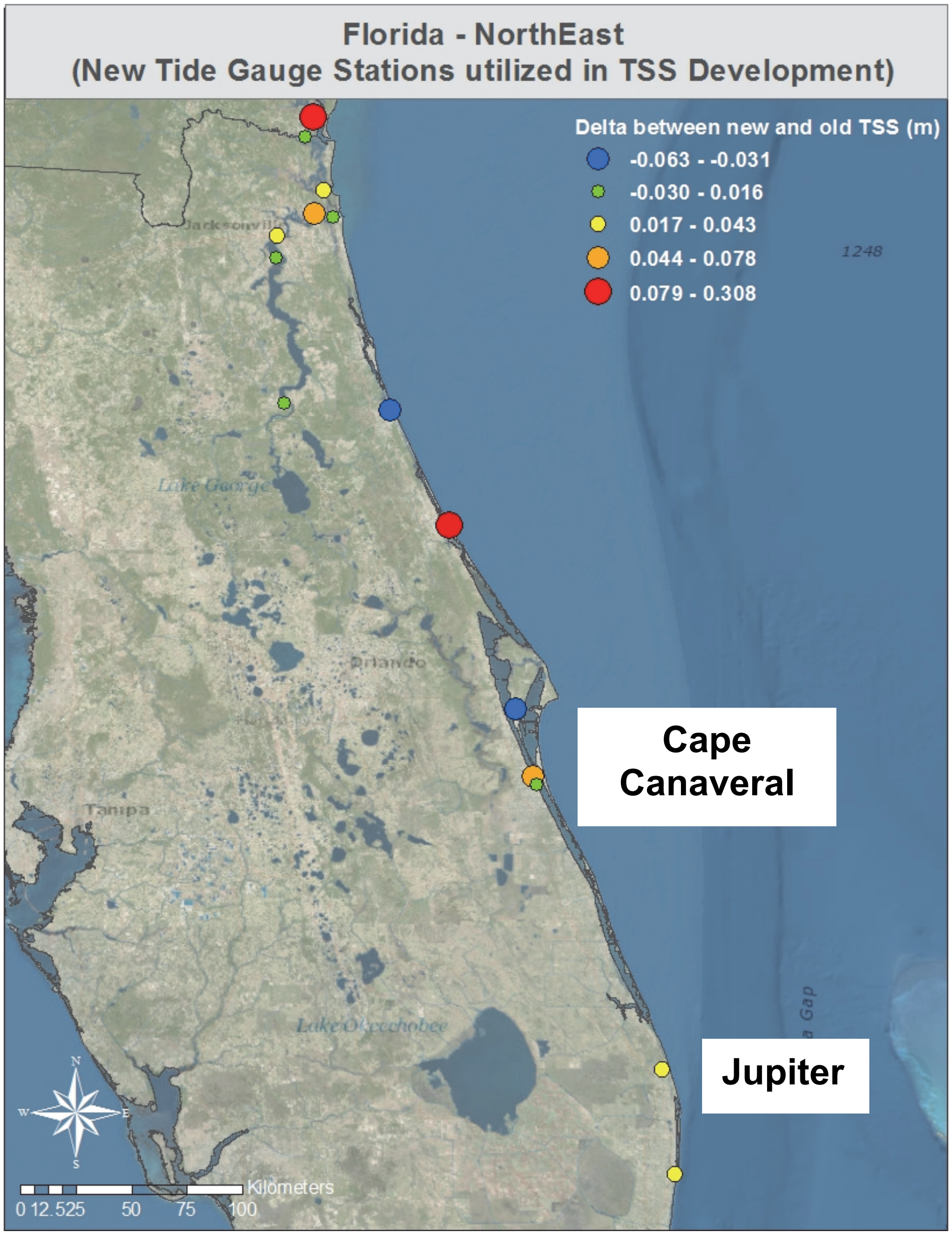

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Figure 5. Difference (m) between the original TSS field and the new TSS field at new tide gauge stations utilized in TSS Development for both the Florida – Inland Waterways and Florida – Coastal Shelf Regions

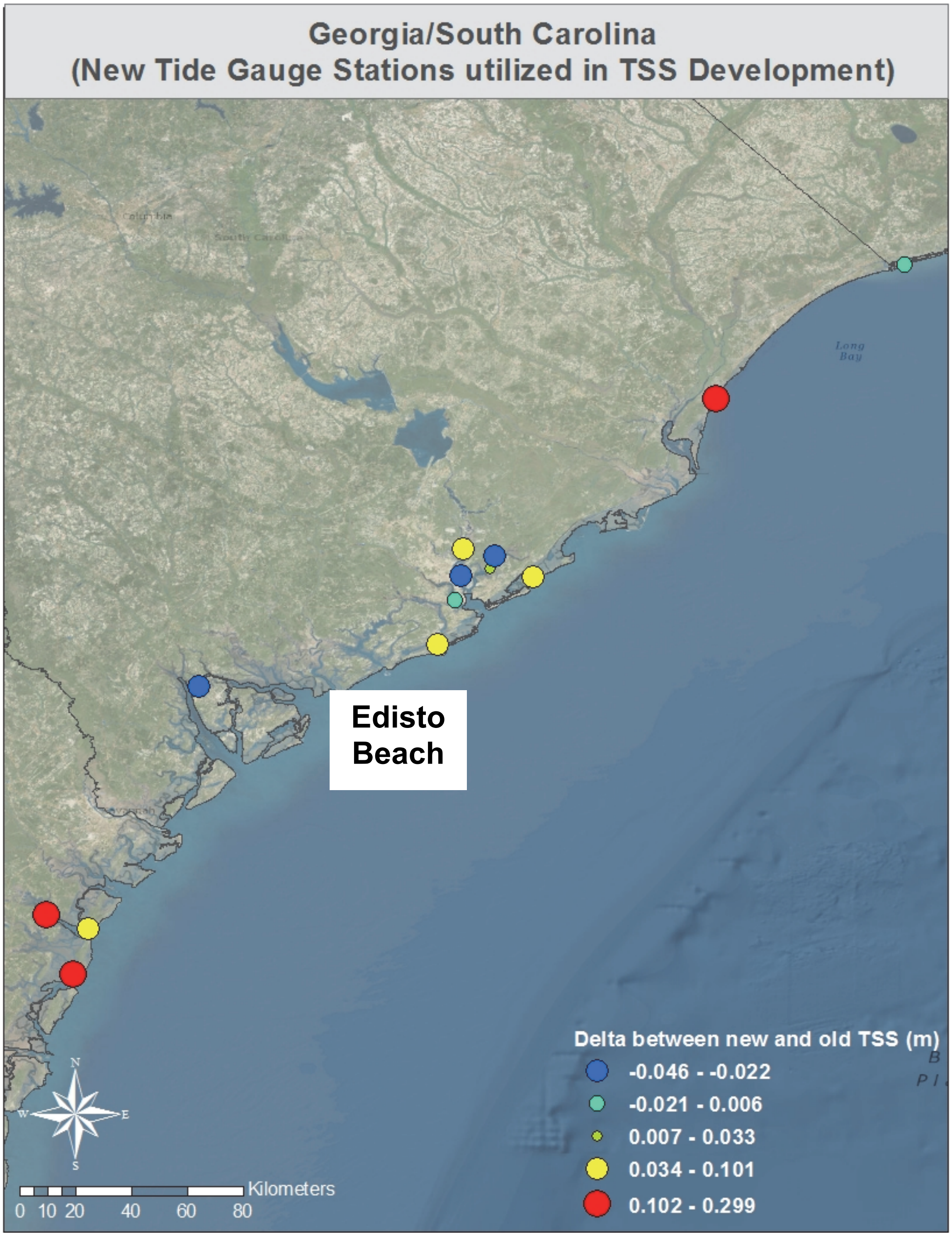

Figure 6. Difference (m) between the original TSS field and the new TSS field at new tide gauge stations utilized in TSS Development for both the Georgia/South Carolina Region.

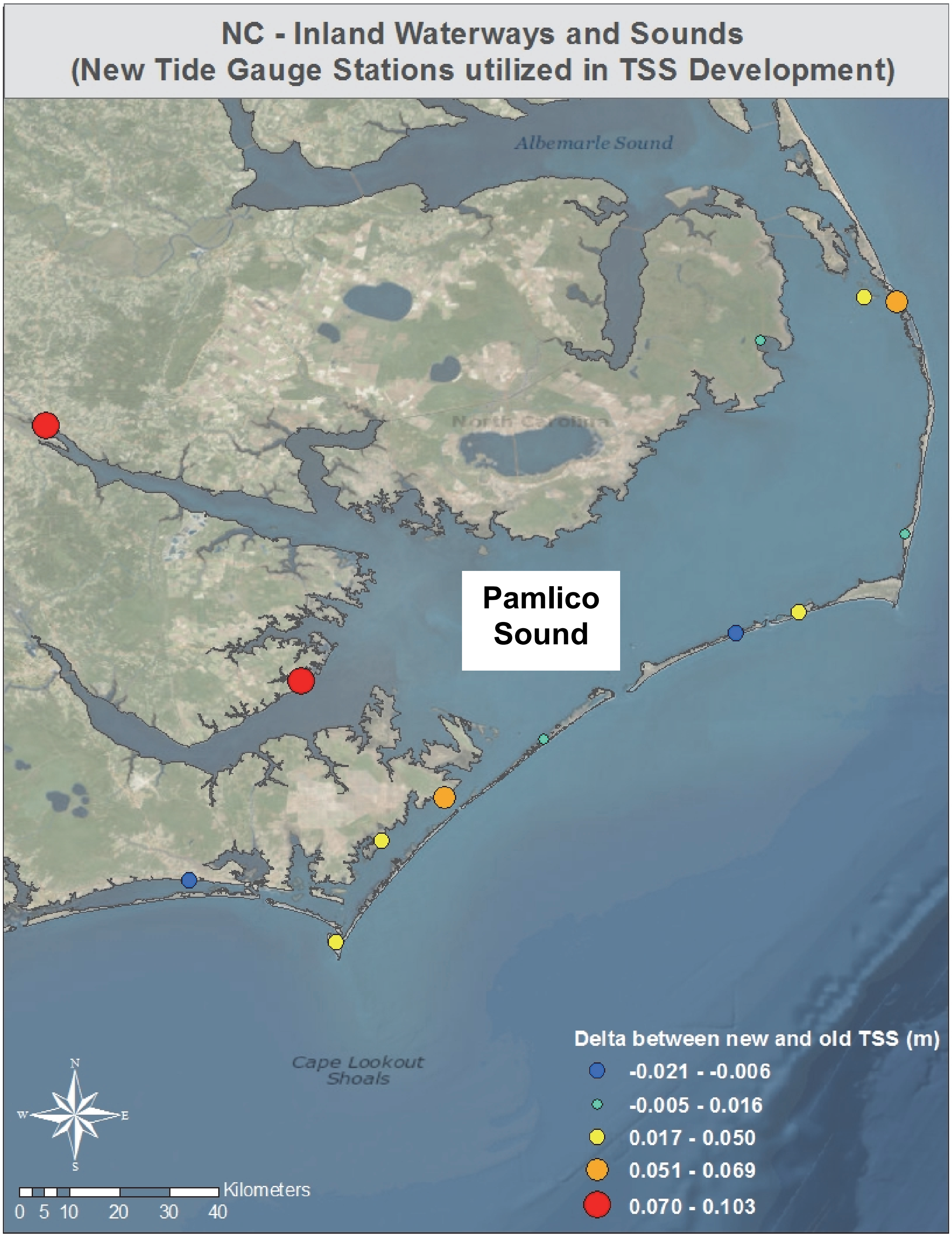

Figure 7. Difference (m) between the original TSS field and the new TSS field at new tide gauge stations utilized in TSS Development for the North Carolina Inland Waterways and Sounds Region.

4. SUMMARY

A few years ago, VDatum files were created for a region covering Florida, Georgia, South Carolina and North Carolina extending along the U.S. coast from approximately the North Carolina/Virginia Border. southward through South Carolina and Georgia, and ending on the western end in the Florida panhandle at Apalachicola Bay. The Florida/South Atlantic Bight became operational in 2010 and the North Carolina grids in 2005.

Since these updates, several developments have occurred. New tide stations have been installed, new data have been added to the database, and new datums have been computed for many existing stations. Revised digital coastline information and a digitized file of the U.S.'s Exclusive Economic Zone (EEZ) have become available. In addition, many users have requested datum conversions in the new regions such as farther offshore, intra-coastal waterways, additional inlets and bays, which were not covered by the previous VDatum regions. For these reasons, it was decided to update the VDatum application data sets for the following existing VDatum regions: (a) Florida-Georgia waterways, (b) the Florida-Georgia continental shelf, and (c) the Georgia/South Carolina/North Carolina region. For the North Carolina applications, the three previous VDatum regions were updated with two regions: Coastal Shelf and Inland Waterways and Sounds. As a result, revised tidal datum fields were generated and made available to the public via the VDatum website in December 2014. The VDatum uncertainty website was also updated to reflect the changes in the data.

The new VDatum Regions provide expanded coverage for Albemarle Sound, the intra-coastal waterways in southern North Carolina, upstream regions in South Carolina and Georgia, and farther offshore extent except where limited by the EEZ. Higher spatial resolution grids were created to resolve narrow channels like intra-coastal waterways and inlets. During this update process, model results were used for the first time as guidance in defining non-tidal areas.

Prior to the update, four out of five previous stations had maximum cumulative uncertainties greater than 10 cm. Following the update, three out of the four VDatum regions are 10cm or below the maximum cumulative uncertainty (MCU) threshold. Overall, the accuracy of the new modeled tidal datums is significantly improved relative to the old model. In the Florida/Georgia regions, a total of 12 new stations were added to the area within the original grid, that were not used to develop the original grid. The average RMS error at these stations is 11.5 cm. In North Carolina, the new model reduced the uncertainty by approximately half. For particular stations (e.g. 8652678, 8656084, and 8656467), the new model reduced the errors by approximately 10 cm. The Topography of the Sea Surface (TSS) field also showed dramatic improvements. Forty-one new stations were added in the generation of the TSS and their absolute differences were between 2.1 and 30.8 cm, indicating an improved TSS field was created with the new station input. Differences recognized between the new and old surfaces can predominantly be attributed to the addition of new gauges, except one instance where a new datum relationship was tabulated. The new VDatum Regions that became operational in December 2014 should provide enhanced datum transformation capabilities and greatly reduce the uncertainties in areas with new stations.

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APPENDIX A. STATISTICAL ANALYSIS

A. Error statistics of new modeled tidal datums vs new observed datums in North Carolina.

1. North Carolina: 26 common stations. New Data 2014

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.008	0.023	0.033	0.033	0.073	8656841
2	MHW	0.001	0.023	0.029	0.029	0.064	8656841
3	MLW	-0.002	0.022	0.027	0.027	0.072	8656841
4	MLLW	0.013	0.022	0.03	0.027	0.088	8656841

2. North Carolina: 5 new stations. New Data 2014

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.012	0.017	0.018	0.015	0.028	8656201
2	MHW	0.007	0.01	0.015	0.015	0.033	8653951
3	MLW	-0.005	0.01	0.016	0.017	0.036	8653951
4	MLLW	0.013	0.022	0.027	0.026	0.051	8653365

B. Comparison of errors in three VDatum Region (Florida waterways, Florida shelf, and Ga./S.C.) using stations available for both times
(Original, uncorrected grid vs old, new datum values)

1. Florida/Georgia – Coastal Waterways: 97 common stations. Original Data 2010

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	0.0343	0.0469	0.0666	0.0571	0.2540	8720305
2	MHW	0.0290	0.0416	0.0582	0.0504	0.2190	8720305
3	MLW	0.0064	0.0340	0.0463	0.0458	0.2070	8720398
4	MLLW	0.0188	0.0388	0.0537	0.0503	0.2350	8720398

New Data 2014

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	0.0362	0.0484	0.0679	0.0574	0.2540	8720305
2	MHW	0.0310	0.0423	0.0591	0.0504	0.2190	8720305
3	MLW	0.0069	0.0346	0.0472	0.0467	0.2060	8720398
4	MLLW	0.0193	0.0402	0.0551	0.0516	0.2350	8720398

2 Florida/Georgia – Coastal Shelf: 11 common stations. Original

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.0343	0.0343	0.0383	0.0170	0.0620	8720194
2	MHW	-0.0275	0.0275	0.0308	0.0140	0.0490	8720291
3	MLW	0.0004	0.0163	0.0222	0.0222	0.0550	8720291
4	MLLW	0.0118	0.0205	0.0251	0.0221	0.0450	8722105

New Data 2014

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.0333	0.0333	0.0376	0.0175	0.0620	8720194
2	MHW	-0.0262	0.0262	0.0299	0.0144	0.0490	8720291
3	MLW	-0.0001	0.0159	0.0218	0.0218	0.0550	8720291
4	MLLW	0.0121	0.0208	0.0253	0.0222	0.0450	8722105

3. Georgia/South Carolina: 85 common stations. Original

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	0.0507	0.0713	0.0976	0.0834	0.3260	8665589
2	MHW	0.0522	0.0664	0.0922	0.0760	0.3010	8665589
3	MLW	0.1053	0.1084	0.1278	0.0725	0.3260	8666017
4	MLLW	0.1288	0.1307	0.1491	0.0751	0.3790	8666017

New Data 2014

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	0.0513	0.0720	0.0984	0.0840	0.3260	8665589
2	MHW	0.0528	0.0670	0.0931	0.0766	0.3010	8665589
3	MLW	0.1050	0.1081	0.1279	0.0730	0.3260	8666017
4	MLLW	0.1286	0.1306	0.1492	0.0757	0.3788	8666017

4. North Carolina: 26 common stations. Original

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.03	0.045	0.057	0.049	0.116	8656841
2	MHW	-0.02	0.037	0.047	0.043	0.1	8656841
3	MLW	0.015	0.043	0.058	0.057	0.176	8656467
4	MLLW	0.039	0.049	0.057	0.043	0.122	8656841

New Data 2014

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.044	0.063	0.081	0.076	0.163	8656201
2	MHW	-0.024	0.048	0.064	0.067	0.127	8656201
3	MLW	0.029	0.051	0.066	0.067	0.131	8656201
4	MLLW	0.051	0.066	0.082	0.072	0.153	8656201

C. Errors at new stations: new datums vs original uncorrected grid

1. Florida/Georgia – Coastal Waterways 6 stations

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.0707	0.1096	0.1179	0.0944	0.1412	8722213
2	MHW	-0.0633	0.0983	0.1050	0.0837	0.1236	8721164
3	MLW	0.0724	0.1117	0.1214	0.0974	0.1621	8721164
4	MLLW	0.0897	0.1232	0.1327	0.0978	0.1803	8721164

2. Florida/Georgia – Coastal Shelf 1 station

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	0.1400	0.1400	0.1400	0.0000	0.1400	8722491
2	MHW	0.1255	0.1255	0.1255	0.0000	0.1255	8722491
3	MLW	-0.1340	0.1340	0.1340	0.0000	0.1340	8722491
4	MLLW	-0.1210	0.1210	0.1210	0.0000	0.1210	8722491

3. Georgia/South Carolina 5 stations

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	0.0059	0.0549	0.0719	0.0716	0.1392	8667411
2	MHW	0.0116	0.0545	0.0737	0.0728	0.1492	8667411
3	MLW	0.1255	0.1255	0.1342	0.0476	0.2035	8667411
4	MLLW	0.1415	0.1415	0.1499	0.0494	0.2225	8667411

4. North Carolina 5 stations

	Datum	Mean (m)	Mean Abs (m)	RMS (m)	StD (m)	Max (m)	@station
1	MHHW	-0.044	0.063	0.081	0.076	0.163	8656201
2	MHW	-0.024	0.048	0.064	0.067	0.127	8656201
3	MLW	0.029	0.051	0.066	0.067	0.131	8656201
4	MLLW	0.051	0.066	0.082	0.072	0.153	8656201

D. TSS Errors at new stations: new grid vs. original grid

1. Florida/Georgia - Shelf, Fort Lauderdale FL to Sapelo Island GA: 1 new station

ID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value of previous grid (m)	Difference (m)
8721120	29.14667	-80.96333	0.242	-0.066	0.308

2. **Florida/Georgia - Coastal waterways, Fort Lauderdale FL to Sapelo Island GA : 15 new stations**

ID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value of previous grid (m)	Difference (m)
8720757	29.61500	-81.20500	0.050	0.113	-0.063
8721611	28.40500	-80.69670	0.184	0.215	-0.031
8721832	28.10000	-80.61170	0.237	0.234	0.003
8720774	29.64330	-81.63170	0.014	0.009	0.005
8720224	30.39500	-81.43170	0.185	0.174	0.012
8720333	30.22830	-81.66330	0.027	0.013	0.014
8679964	30.72000	-81.54830	0.121	0.105	0.016
8720143	30.50330	-81.47170	0.149	0.117	0.032
8722488	26.95170	-80.10330	0.312	0.278	0.034
8722718	26.52670	-80.05330	0.295	0.252	0.043
8720226	30.32000	-81.65830	0.078	0.035	0.043
8720198	30.40670	-81.51000	0.176	0.121	0.055
8721808	28.13330	-80.62500	0.295	0.231	0.064
8678124	31.01481	-81.45597	0.151	0.073	0.078
8679511	30.79670	-81.51500	0.178	0.073	0.104

3. **Georgia/South Carolina - Sapelo Island GA to Holden Beach NC : 13 new stations**

ID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value of previous grid (m)	Difference (m)
8667633	32.50250	-80.78410	-0.051	-0.005	-0.046
8664945	32.86000	-79.93830	-0.012	0.012	-0.024
8664545	32.92670	-79.83000	0.013	0.035	-0.022
8659897	33.86500	-78.50670	0.112	0.106	0.006
8665495	32.78330	-79.95670	0.060	0.054	0.006
8664782	32.88500	-79.84500	0.070	0.037	0.033
8664515	32.94830	-79.93170	-0.013	-0.087	0.074
8666767	32.64000	-80.01500	0.151	0.064	0.087
8673171	31.72303	-81.14170	-0.048	-0.142	0.094
8664941	32.85670	-79.70670	0.149	0.048	0.101
8674301	31.57500	-81.19000	0.121	-0.089	0.210
8662006	33.43170	-79.11670	0.199	-0.013	0.212
8672875	31.76670	-81.27830	0.062	-0.237	0.299

4. North Carolina - Coastal shelf

No New Stations

5. North Carolina - Inland Waterways and Sounds : 12 new stations

ID	Latitude (deg)	Longitude (deg)	NAVD 88 to MSL (m)	TSS Derived Value of previous grid (m)	Difference (m)
8656467	34.72500	-76.80330	0.055	0.076	-0.021
8654572	35.17133	-75.81744	0.018	0.024	-0.006
8653951	35.35014	-75.51203	0.014	0.014	0.001
8652905	35.69830	-75.77330	0.020	0.010	0.009
8655353	34.97939	-76.16308	0.030	0.014	0.016
8656201	34.79675	-76.45547	0.074	0.047	0.027
8656841	34.61330	-76.53830	0.141	0.101	0.040
8654467	35.20864	-75.70417	0.068	0.022	0.045
8652648	35.77670	-75.58500	0.071	0.021	0.050
8652678	35.76833	-75.52667	0.124	0.062	0.062
8655875	34.87500	-76.34333	0.104	0.036	0.068
8653365	35.54500	-77.06170	0.114	0.011	0.103
8654875	35.08528	-76.60044	0.092	0.003	0.090