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FL2101-TB-C Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project

Quality Assurance Report Produced for the National Oceanic and Atmospheric Administration, National Geodetic Survey

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1. EXECUTIVE SUMMARY

Dewberry was tasked with developing a consistent and accurate topographic and bathymetric (topobathymetric) elevation dataset derived from high-accuracy light detection and ranging (lidar) technology for the National Oceanic and Atmospheric Administration (NOAA) Tampa Bay, Florida project area.

The lidar data were processed and classified according to NOAA's Shoreline Mapping Statement of Work (SOW), Version 14A, and the project instructions for this specific task order. Topobathymetric digital elevation models (DEMs) were produced for the project area. Project components were formatted based on two tile grids: lidar data was tiled according to a 500 m by 500 m tile grid, with a total of 3,181 tiles produced; DEM, intensity, and DZ orthos data were tiled according to a 5,000 m by 5,000 m tile grid, with a total of 48 tiles produced. Approximately 225 sq. miles of coverage is provided.

Digital orthoimagery was acquired for the project area. Imagery was tiled according to a 1,000 m by 1,000 m tile grid. A total of 893 imagery tiles were produced.

1.1 The Project Team

Dewberry served as the prime contractor for the project. In addition to project management, Dewberry was responsible for LAS classification, all lidar products, breakline production, Digital Elevation Model (DEM) production, and quality assurance. Dewberry was also responsible for ortho-imagery production, including ortho-rectification, and quality assurance of the ortho-mosaics, including horizontal accuracy testing.

Dewberry's survey team completed ground surveying for the project and delivered surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the lidar-derived model. They also verified the GPS base station coordinates used during lidar data acquisition to ensure that the base station coordinates were accurate. Survey reports were delivered to NGS as part of a separate survey data package.

Dewberry completed lidar data acquisition and data calibration for the project area.

Dewberry acquired the digital imagery, performed all ground control survey for the imagery, and performed the aerotriangulation of the raw image frames.

NOAA derived the initial shoreline files from the delivered topobathymetric lidar point cloud and the digital imagery. The shoreline files were then sent back to Dewberry for clean-up and attribution.

1.2 Survey Area

The NOAA Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping project area covers approximately 225 square miles. There are 3,181 500 m x 500 m lidar tiles, 48 5,000 m x 5,000 m DEM tiles, and 166 3,000 m x 3,000 m ortho tiles delivered for the project area. The project area boundary and overview are shown in Figure 1.

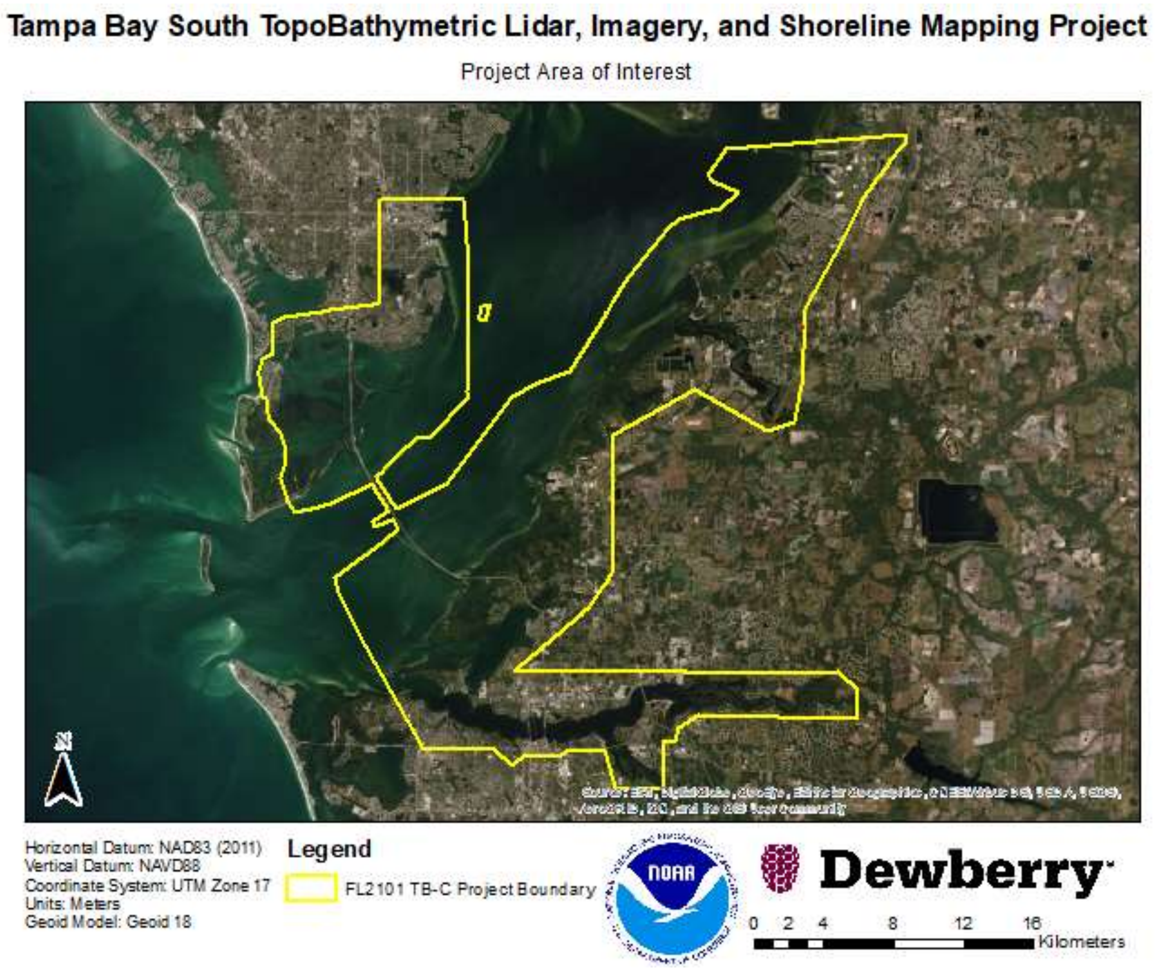

Figure 1. The left image shows Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping project area outlined in yellow.

1.3 Date of Survey

The lidar aerial acquisition was conducted from January 26, 2021 thru February 27, 2021.

1.4 Coordinate Reference System

Data produced for the project were delivered in the following reference system:

Horizontal Datum: North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011))

Vertical Datum: North American Vertical Datum of 1988 (NAVD88)

Coordinate System: UTM zone 17

Units: Meters

Geoid Model: Geoid18

1.5 Lidar Vertical Accuracy

For the Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain is **5.6 cm** and the non-vegetated vertical accuracy (NVA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **10.9 cm**.

For the Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in submerged topography is **15.3 cm** and the bathymetric vertical accuracy (BVA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **29.9 cm**.

For the Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project, the tested vegetated vertical accuracy (VVA) of the classified lidar data computed using the 95th percentile is **14.7 cm**.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and topobathymetric DEM data are found in sections 3.1.1, 5.4 and 6.3 of this report.

1.6 Ortho-Mosaic Horizontal Accuracy

For the Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project, the tested horizontal accuracy at the 95% confidence level of the ortho-mosaics computed using $RMSE_{xy}$*2.448 is **32.7 cm**.

Additional accuracy information and statistics for the ortho-mosaics are found in the section 8.2 of this report.

2. LIDAR ACQUISITION CONTROL

Dewberry acquired and calibrated the lidar data for this project. Acquisition was started January 26, 2021, and completed on February 27, 2021.

2.1 Lidar Acquisition Static Control

Five existing NGS monuments were used to control the lidar acquisition for the Tampa Bay project area. The coordinates of all base stations used for acquisition control are provided in Table 1. All control and calibration points were also provided as part of the previously delivered survey package.

Table 1. Base stations used to control lidar acquisition

Station Name	NAD83(2011), UTM 17, m		NAD83(2011), m
	Easting (x)	Northing (y)	Ellipsoid Height (Z)
FLIB	318604.224	3085269.696	-16.018
FLD7	365837.983	3094577.355	-12.821
STPT	339690.62	3072487.102	-17.964
FLAI	332961.765	3037384.646	-10.813
GSPS	366513.217	3040875.869	-5.648

2.2 Airborne Kinematic Control

Airborne GPS data were processed using the Applanix PosPac software suite. Flights were flown with a minimum of six satellites in view (13° above the horizon) and with PDOP less than 4. Distances from base station to aircraft were kept to a maximum of 40 km.

The GPS average residuals for all flights were 3 cm or better, with no residuals greater than 10 cm recorded.

GPS processing reports for each mission were provided as part of the previously delivered survey package.

2.3 Generation and Calibration of Raw Lidar Data

Availability and status of all required GPS and laser data were verified against field reports and any data inconsistencies were addressed.

Subsequently the mission points were output using Teledyne Geospatial's CARIS software suite. After applying the initial system calibration in CARIS, the refined swath to swath alignment was done using Bayesmap Stripalign and then shifted to control. This aligned data was then reviewed for any remaining interswath relative accuracy issues.

Data collected by the lidar unit was reviewed for completeness, acceptable density, and to make sure all data were captured without errors or corrupted values. All GPS, aircraft trajectory, mission information, and ground control files were reviewed and logged. A supplementary coverage check was carried out (Figure 2) to ensure that there were no unreported gaps in data coverage.

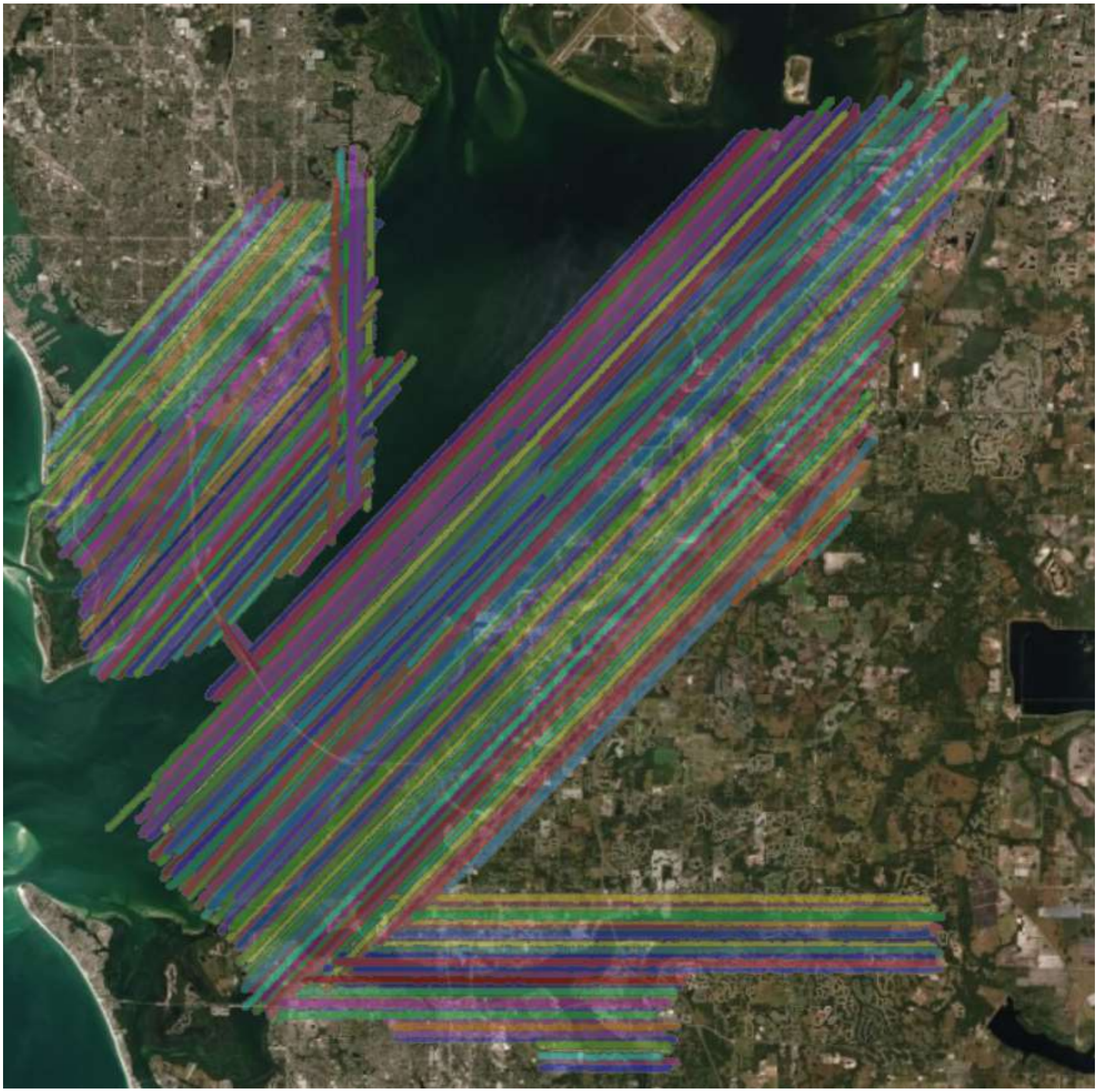

Figure 2. Lidar swath output showing complete coverage.

2.4 Boresight and Relative accuracy

The initial point cloud data for each mission calibration were inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the lidar unit or GPS. Roll, pitch and scanner scale were optimized during the calibration process until relative accuracy requirements were met (Figure 3).

Relative accuracy and internal quality were checked using at least 3 regularly spaced QC blocks in which points from all lines were loaded and inspected. Vertical differences between ground surfaces of each line were displayed. Color scale was adjusted to flag errors that were not within project specifications (Figure 4). Cross sections were visually inspected across each block to validate point to point, flight line to flight line, and mission to mission agreement.

The following relative accuracy specifications were used for this project (topographic portions):

- ≤ 6 cm maximum difference within individual swaths (intra-swath); and
- ≤ 8 cm RMSDz between adjacent and overlapping swaths (inter-swath).

A different set of QC blocks were generated for final review after any necessary transformations were applied.

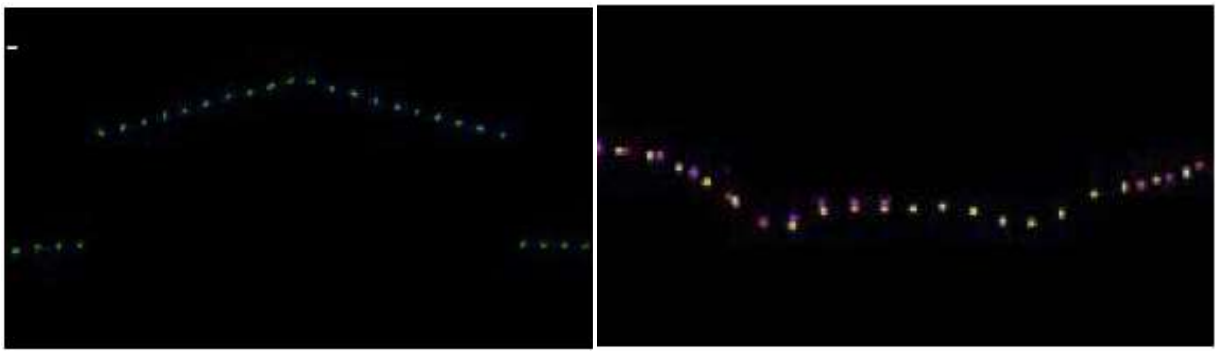

Figure 3. Profile views showing results of roll and pitch adjustments.

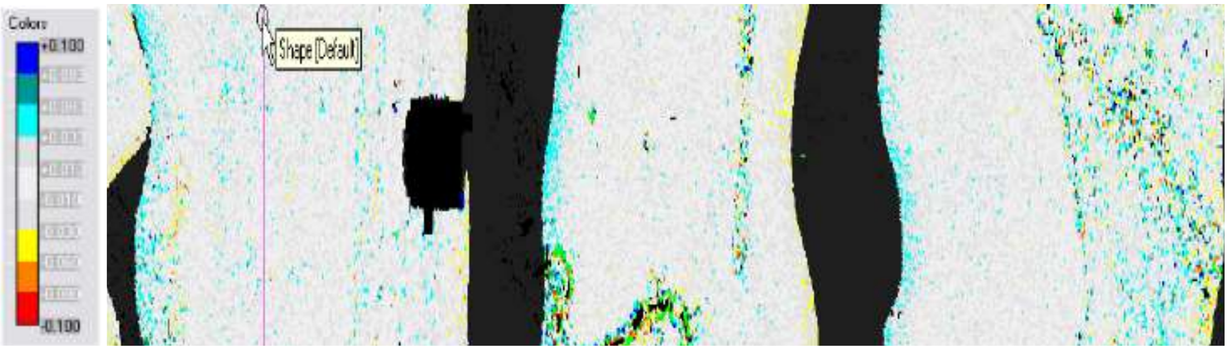

Figure 4. QC block colored by vertical difference between swaths to check accuracy at swath edges.

2.5 Refraction Correction

Bathymetric data must have a refraction correction applied. This process corrects the horizontal and vertical (depth) positions of each data point by accounting for the change in direction and speed of light as it enters and travels through water. The initial automated refraction correction for this dataset was performed by Dewberry using Teledyne CARIS BASE Editor software. Additional local refraction corrections were performed using a Dewberry proprietary toolset in select areas where bathymetric/topographic domain differentiation in the point cloud was particularly complex (e.g., some nearshore areas).

2.6 Preliminary Vertical Accuracy Assessment

Dewberry performed a preliminary RMSE$_z$ error check in the raw lidar dataset against GPS static and kinematic data and compared the results to project specifications. The lidar data was examined in non-vegetated, flat areas away from breaks. An automated grounding routine was used by the provider to classify an initial ground surface for this analysis.

The calibrated Tampa Bay South dataset was tested to 0.022 m RMSE$_z$ and 0.043 m vertical accuracy at the 95% confidence level when compared to 5 GPS static checkpoints (Table 2) surveyed by Dewberry. The results of the preliminary vertical accuracy assessment conducted by Dewberry are summarized in Table 3.

The calibrated lidar data products collected by Dewberry met or exceeded the requirements set out in the Statement of Work. The quality control requirements defined by Dewberry's quality management program were adhered to throughout the data acquisition stage.

Table 2. Static GPS points used for the preliminary vertical accuracy assessment.

Number	NAD83(2011) UTM zone 17, m		NAVD88 Geoid 18B, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
1 LI GCP	329824.115	3062310.572	-22.641	-22.6546	-0.014
2_LI_GCP	338218.108	3070453.712	-22.932	-22.9173	0.015
3_LI_GCP	360685.188	3070381.412	-22.378	-22.4032	-0.025
4 LI GCP	347545.804	3057875.727	-22.235	-22.2708	-0.036
5_LI_GCP	347230.917	3045153.262	-22.161	-22.1517	0.009

Table 3. Summary of vertical accuracy assessment results.

Land Cover Type	# of Points	RMSE$_z$ (m)	NVA (m)	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Project Specification	**-**	**0.100**	**0.196**	**-**	**-**	**-**	**-**
Non-Vegetated Terrain	5	0.022	0.043	-0.010	0.022	-0.036	0.015

3. LIDAR PROCESSING & QUALITATIVE ASSESSMENT

3.1 Initial Processing

Dewberry performed vertical accuracy validation of the swath data, inter-swath relative accuracy validation, intra-swath relative accuracy validation, verification of horizontal alignment between swaths, validation of the refraction correction, and confirmation of point density and spatial distribution. This initial assessment allowed Dewberry to determine whether the data was suitable for full-scale production. Details are provided in the following sections.

3.1.1 Final Swath Vertical Accuracy Assessment

Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to further processing. Swath vertical accuracy was tested using 30 non-vegetated (open terrain and urban) independent survey checkpoints. Checkpoints were compared to a triangulated irregular network (TIN) created from the raw swath points. (Only checkpoints in non-vegetated terrain can be tested against raw swath data because the data has not undergone classification to remove vegetation, buildings, and other artifacts from the ground surface.) Dewberry used LP360 software to test the swath lidar vertical accuracy.

This raw lidar swath dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSE$_z$ vertical accuracy class. Actual NVA accuracy was found to be RMSE$_z$ = 6.5 cm, equating to ± 10.8 cm at the 95% confidence level. Project specifications required a NVA of 19.6 cm based on the RMSE$_z$ (10 cm) x 1.96. The swath data for the Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project satisfied these criteria. Table 4 shows calculated statistics for the raw swath data.

Table 4. NVA at the 95% confidence level for raw swaths.

Land Cover Type	# of Points	RMSE$_z$ (m)	NVA (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Project Specification	-	**0.100**	**0.196**	-	-	-	-	-	-	-
Non-Vegetated Terrain	30	0.065	0.127	-0.004	0.006	-1.558	0.066	-0.243	0.115	5.047

Checkpoint LI_NVA_19 was removed from the raw swath vertical accuracy testing due to its location outside the boundary.

Checkpoint LI_NVA_26 was removed from the raw swath vertical accuracy testing due to its location beneath a power line. Though LI_NVA_26 i located in open terrain, the overhead power lines were modeled by the lidar point cloud. Because the point cloud was not yet classified to remove vegetation, structures, and other above-ground features from the ground model, these high points produced erroneous elevation values during the swath vertical accuracy testing. Therefore, this point was removed from the final calculations. Once the data underwent classification, the power lines were removed from the final ground classification and LI_NVA_26 was usable in the final vertical accuracy testing, the results of which are reported in Section 5 of this report.

Table 5 illustrates the effect of the power line on the apparent positional accuracy of the lidar data by comparing the surveyed elevation of LI_NVA_26 with the elevation of the surface generated from the raw swath data (which includes the power line). Table 6, with its much smaller delta z value, demonstrates that the effect of the power line is removed following classification of the lidar data.

Table 5. Vertical accuracy information for checkpoint removed from raw swath assessment.

Point ID	NAD83(2011) UTM Zone 17N, m		NAVD88 Geoid 18B, sft		Delta z (sft)
	Easting (x)	Northing (y)	Survey z	Lidar z	
LI_NVA_26	339139.517	3043239.013	-21.125	-18.707	2.418

Table 6. Vertical accuracy information for checkpoint in final classified lidar.

Point ID	NAD83(2011) UTM Zone 17N, m		NAVD88 Geoid 18B, sft		Delta z (sft)
	Easting (x)	Northing (y)	Survey z	Lidar z	
LI_NVA_26	339139.517	3043239.013	-21.125	-21.069	0.056

3.1.2 Interswath Relative Accuracy

According to the SOW and *ASPRS Positional Accuracy Standards for Digital Geospatial Data*, data required to meet 10 cm accuracy class standards must have an interswath (between-swath) relative accuracy of 8 cm $RMSD_Z$ or less.

Prior to classification, Dewberry validated the precision of the lidar calibration by creating delta-Z (DZ) rasters to visualize interswath accuracy. These rasters were generated with 1 m cell resolution based on the maximum difference in elevation. Undifferentiated only returns in non-vegetated areas of overlap between flight lines were analyzed. Each pixel of the raster was colorized according to the resulting value. Cells where overlapping flight lines were within 8 cm of each other were colored green, cells where overlapping flight lines had elevation differences between 8 cm and 16 cm were colored yellow, and cells where overlapping flight lines had elevation differences greater than 16 cm were colored red. Pixels that did not contain points from overlapping flight lines were designated as NoData and left empty.

Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across 1 linear meter) are expected to appear yellow or red in the DZ rasters. Bathymetric areas can also appear yellow or red due to factors like different tidal stages between missions. Large or continuous sections of yellow or red pixels following terrain features or land cover zones are typically reflective of variable or unfavorable (e.g., vegetated) conditions for DZ measurements, whereas large or continued sections of yellow or red pixels following flight line patterns can indicate acquisition or calibration issues. The interswath DZ rasters for Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project are shown in Figure 5. Based on visual inspection, no issues with swath-to-swath calibration were noted.

Figure 5. Interswath DZ raster for the Tampa Bay South TopoBathymetric lidar data.

Dewberry also delivers DZ orthoimagery created from the final classified data for validation of interswath relative accuracy. Additional details about this product are provided in Section 4.4 of this report.

3.1.3 Intraswath Relative Accuracy

According to the SOW and *ASPRS Positional Accuracy Standards for Digital Geospatial Data*, data required to meet 10 cm accuracy class standards must have an intraswath (within-swath) relative accuracy of 6 cm maximum difference or less.

Dewberry validated the intraswath relative accuracy prior to classification by generating and reviewing DZ rasters. These rasters were generated with 1 m cell resolution based on the maximum difference in elevation between undifferentiated only returns in non-vegetated areas of single flight line coverage. Each pixel of the raster was colorized according to the average difference in elevation between overlapping points. Cells where the maximum elevation difference between points was within 6 cm were colored green, and cells where the maximum difference was greater than 6 cm were colored red.

Areas of vegetation and steep slopes (slopes with 6 cm or more of valid elevation change across 1 linear meter) are expected to appear red in the DZ rasters, as are areas of bathymetric coverage since bathymetric returns are typically not only returns. Overlap areas can also appear red due to different acquisition conditions between missions. Large or continuous sections red pixels following terrain features or land cover zones are typically reflective of variable or unfavorable (eg., vegetated) conditions for DZ measurements, whereas large or continued sections of red pixels in flat, relatively featureless areas can indicate sensor issues. An example of the intraswath DZ rasters for Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project are shown in Figure 6. Based on visual inspection, no issues with hard surface repeatability were noted.

Figure 6. Intraswath DZ raster for the Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project. This image depicts a spatial subset of the dataset; flat, open areas are predominantly shaded green as they are within 6 cm whereas sloped and/or vegetated terrain is shaded red, as data in these locations exceeds 6 cm maximum difference. Buildings and spurious "only returns" (i.e., noise) also appear as red pixels.

3.1.4 Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Dewberry reviews point cloud profiles in areas of overlap to identify horizontal shifts or misalignments between swaths on roof tops and other elevated planar surfaces. Figure 7 shows an example of the horizontal alignment between swaths for Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project; no horizontal alignment issues were identified.

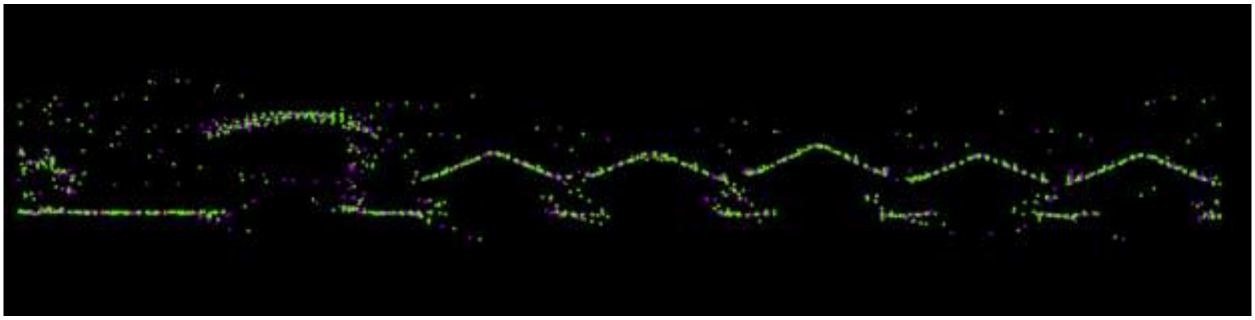

Figure 7. Two separate flight lines are differentiated by color (green/purple) to determine whether horizontal misalignments are present. This is a representative example; there is no visible offset between these flight lines.

3.1.5 Point Density

The required Nominal Point Spacing (NPS) for this project is no greater than 0.58 meters, which equates to a Nominal Point Density (NPD) of 3 points per square meter (ppsm) or greater; however, it is understood that a required NPD may not be met in the bathymetric domain due to environmental conditions. Density calculations were performed using data located in the geometrically usable center portion (typically ~90%) of each swath. LAS dataset statistics yielded a NPD of 4.43 ppsm (equivalent to an NPS of 0.48 meters), which meets project specifications.

Spatial distribution was reviewed to verify that there was no clustering of points or unacceptable void areas. This evaluation was based on the number of 1-meter cells in the dataset that contained at least one lidar point. No distribution anomalies were noted.

3.2 Data Classification and Editing

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data were validated, the lidar dataset was moved into processing and production. These steps included refraction extent creation to define the land/water interface and constrain void polygons used during DEM creation, automated and manual editing of the lidar tiles, QA/QC, and final formatting of all products.

3.2.1 Point Cloud Processing

Dewberry utilized CARIS and TerraScan software for processing. The acquired raw point clouds were imported into CARIS for conversion to LAS format and output with an initial classification schema based on stored sensor data. The LAS were tiled according to the project tile grid. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine classified any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. Points along flight line edges that were geometrically unusable were flagged as overlap and classified to a separate class so that they would be excluded from the initial ground algorithm. After points that could negatively affect the ground were removed from class 1, the ground layer was extracted from this remaining point cloud using an iterative surface model.

After the initial automated ground routine, each tile was imported into TerraScan and a surface model was created. Dewberry analysts visually reviewed the topo-bathymetric surface model and corrected errors in the classification such as vegetation, buildings, bridges, and grounded water column or surface that were in ground classes following the initial processing. Analysts also looked for features that were present in the point cloud but not reflected in the ground model, including obstacles to marine navigation.

The withheld bit was set for points deemed to be outliers, blunders, or geometrically unreliable outside the flight line overlap areas.

The final classification schema is detailed in

Table 7.

Table 7. Final classification schema used in delivered lidar data.

Class	Definition
1	Unclassified, used for all other features that do not fit into the Classes 2, 7, 18, 40, 41, 42, 43, 44, 45, 64, or 65. Includes vegetation, buildings, etc.
2	Bare-Earth Ground
7	Low Noise
18	High Noise
40	Bathymetric Point
41	Water Surface
42	Derived Water Surface, used in computing refraction
43	Submerged Object
44	IHO S-57 Object, not otherwise specified
45	Water column
64	Submerged Aquatic Vegetation
65	Excluded Temporal Surface

After manual classification, the LAS tiles were peer reviewed and then underwent a final independent QA/QC (detailed in Section 3.3). After the final QA/QC and corrections, all headers, appropriate point data records, and variable length records, including spatial reference information were updated, and verified using proprietary Dewberry tools.

3.2.2 Submerged Objects

Submerged objects were identified during editing and review of the lidar data. Any submerged objects identified were classified as submerged objects (class 43). Per client request, class 43 was used to create the final DEM product. Therefore, attempts were made to eliminate voids in the final DEM due to submerged object classifications. Some marine objects were partially exposed above the water surface. Per discussions with NOAA, these partially exposed objects were fully classified as class 43-submerged object. No points were classified as class 44 (IHO S-57 object).

3.2.3 Temporal Changes

Changes in the bathymetric bottom surface can result from differences between collection periods due to factors such as currents moving sediment. Dewberry did identify some temporal changes in this project. Any competing ground surfaces were analyzed for continuity, and areas that did not represent the most recent and/or continuous surface were classified into class 64- temporal.

When temporal changes were discovered in the dataset, the following order of priorities was maintained:

1. Use most recent flight lines to model bathy bottom data.
2. Use older flight lines if it will provide full coverage, will prevent ridges/abrupt changes in the data, or represents better water clarity (i.e. bathy returns) than more recent data.
3. If ridge/abrupt change is unavoidable or boundaries for #1 or #2 are not definable, then use more recent data to full extent and fill in with older/earlier collect where necessary.

3.3 Lidar Qualitative Assessment

Dewberry's qualitative assessment of lidar point cloud data utilized a combination of statistical analyses and visual interpretation. Methods and products used in the assessment included profile- and map view-based point cloud review, pseudo image products (e.g., intensity orthoimages), TINs, DEMs, and point density rasters. This assessment looked for incorrect classification and other errors sourced in the LAS data.

3.3.1 Visual Review

During QA/QC, reviewers checked for consistent and correct classification. They looked for anomalies in the data, areas where structures or vegetation points may not have been classified properly to produce a bare-earth model, areas where bathymetry was not classified correctly to produce an accurate submerged topography model, scan pattern artifacts, flight line ridges, and other classification errors. Any issues identified were returned to the appropriate stage of the production process for corrections.

3.3.2 Formatting

After the final QA/QC was performed and all corrections were applied to the dataset, all lidar files were updated to the final format requirements as defined in the SOW. These requirements are detailed in Table 8.

Table 8. Lidar final format requirements

Parameter	Requirement
LAS Version	1.4
Point Data Record Format	6
Coordinate Reference System	NAD83 (2011) UTM zone 17, meters and NAVD88 (Geoid 18), meters in WKT Format
Global Encoder Bit	17 (for Adjusted GPS Time)
Time Stamp	Adjusted GPS Time (unique timestamps)
Intensity	16 bit, recorded for each pulse
Overlap and Withheld Points	Overlap (Overage) and Withheld flags, properly set

4. DERIVATIVE LIDAR PRODUCTS

NOAA required several derivative lidar products to be created. Each type of derived product is described below.

4.1 Void Polygons

Void polygons delineating areas of extremely sparse or no valid bathymetric returns have been created for this project area. The polygons reflect void areas greater than or equal to 9 square meters in area and were utilized to constrain interpolation in the bathymetry domain in the final merged topo-bathymetric DEM.

4.2 Total Propagated Uncertainty

A confidence layer that reports the total propagated uncertainty (TPU) of all ground and submerged topography points within each 1-meter grid cell has been created for the entire project area on a per-tile basis. The TPU reflects the aggregate spatial uncertainty from all measurement sources at the 95% confidence level, and accounts for measurement errors (e.g., GPS, IMU, lidar sensor) as well as environmental factors via the TPU model used by Teledyne Optech's CARIS software. The pixels of the confidence layer are aligned with the corresponding pixels in the final topobathymetric DEMs, enabling reporting of TPU for each topobathymetric DEM grid cell. The TPU layer is tiled according to the DEM tile grid.

4.3 Normalized Seabed Reflectance

Intensity orthoimages representing normalized seabed reflectance have been created for the entire project area on a per-tile basis. Each 1-meter grid cell has an associated 8-bit intensity value that has been normalized to account for attenuation due to depth and swath-to-swath variability in acquisition. The intensity layer extents are the same as the extents for the final topo-bathymetric DEMs so that the pixels align, showing the lidar intensity at each bathymetric DEM grid cell. The intensity rasters are tiled according to the DEM tile grid.

4.4 DZ Orthoimages

RGB orthoimages depicting the vertical positioning of overlapping swaths relative to each other (i.e., interswath relative accuracy) have been created for both green and NIR laser channels for the full project area. In areas of overlap, each 1-meter grid cell has a color based on the maximum delta-Z present in that cell. The imagery is 8-bit and 3-band such that cells don't represent an actual DZ value, but rather a color that indicates whether the DZ value falls within the required specifications. Cells with a maximum DZ value less than 8.0 cm are colored green, cells with a maximum DZ value between 8.0 and 16.0 cm are colored yellow, and cells that have a maximum DZ value greater than 16.0 cm are colored red. In non-overlap areas, cells are populated with 8-bit intensity values. The DZ orthoimage layer extents are the same as the extents for the final topo-bathymetric DEMs so that the pixels align. The DZ orthoimages are tiled according to the DEM tile grid.

5. LIDAR POSITIONAL ACCURACY

5.1 Background

Dewberry quantitatively tested the vertical accuracy of the lidar to confirm adherence of the dataset to project specifications. Discrete surveyed (real-world) checkpoint elevation coordinates were compared to the surface elevation values at the corresponding X and Y coordinates on TIN surfaces created from the unclassified (swath) and classified lidar data. Relative accuracy testing determined how consistently the lidar data was collected and enabled extrapolation of the point-based absolute accuracy results to the broader dataset. I.e., if the relative accuracy of the dataset was found to be within specifications *and* the dataset passed absolute vertical accuracy requirements at the locations of survey checkpoints, the vertical accuracy results were considered valid throughout the whole dataset with high confidence. Dewberry used LP360 to test the swath lidar vertical accuracy, TerraScan to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different methods were used to validate the vertical accuracy for the project.

Dewberry also tested the horizontal accuracy of lidar datasets when checkpoints were photo-identifiable in the intensity imagery. Photo-identifiable checkpoints included checkpoints located at the ends of paint stripes on concrete or asphalt surfaces or checkpoints located at 90 degree corners of different reflectivity, e.g. a sidewalk corner adjoining a grass surface. The XY coordinates of checkpoints as viewed in the intensity imagery were compared to surveyed XY coordinates for each photo-identifiable checkpoint. The horizontal differences were used to compute the tested horizontal accuracy of the lidar.

5.2 Survey Vertical Accuracy Checkpoints

Dewberry surveyed 55 checkpoints for the project. Survey checkpoints were located within bare earth/open terrain, grass/weeds/crops, brush/low trees, forested/fully grown, and submerged topography land cover categories. Checkpoints were evenly distributed throughout the project area to cover as many flight lines as possible. The locations of the QA/QC checkpoints used to test the positional accuracy of the dataset are shown in Figure 8. A complete list of survey checkpoints was provided in the previously submitted survey report.

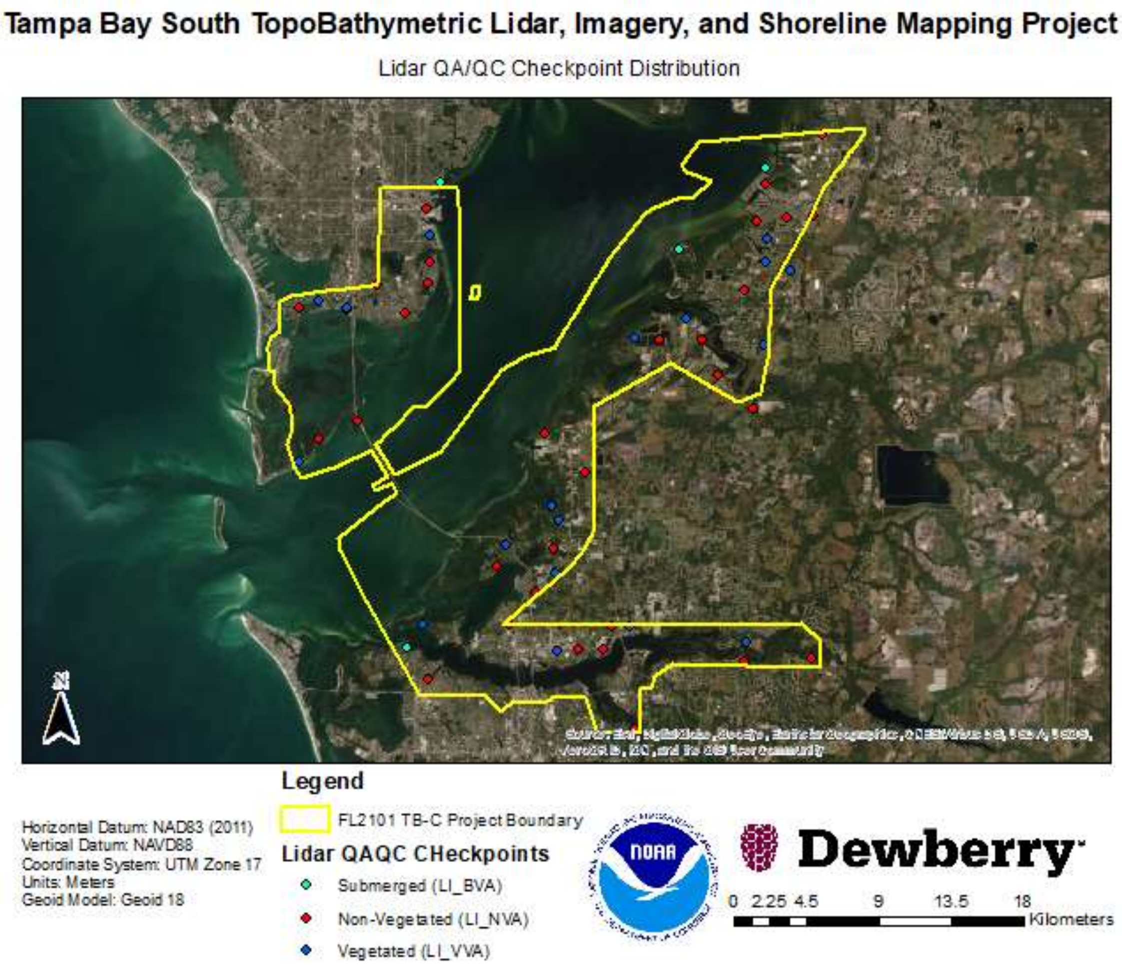

Figure 8. Location of all surveyed checkpoints

Dewberry surveyed 55 checkpoints for vertical accuracy testing. While reviewing the coordinates of the survey checkpoints against the field sketches and lidar intensity imagery, Dewberry identified issues with two checkpoints located outside the boundary.

Three checkpoints were removed from the classified lidar vertical accuracy testing. LI_BVA_2, LI_VVA_4, LI_NVA_5, and LI_NVA_19 were all located outside the AOI (Table 9). Even without these three checkpoints, there were enough total checkpoints and enough checkpoints per land cover category to satisfy project requirements.

Table 9. Checkpoints removed from vertical accuracy testing

Point ID	NAD83(2011) UTM Zone 17N, m		NAVD88 Geoid 18B, ft		Delta z, ft
	Easting (x)	Northing (y)	Survey z	Lidar z	
LI BVA 2	339891.402	3074088.875	-24.916	outside	outside
LI_NVA_5	363091.256	3072012.407	5.198	0.000	-5.198
LI_NVA_19	359345.847	3060052.688	3.947	0.000	-3.947
LI_VVA_4	361607.226	3068596.431	4.325	0.000	-4.325

5.3 Vertical Accuracy Test Procedures

NVA reflects the calibration and performance of the lidar sensor. NVA was determined with checkpoints located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas. In these locations it is likely that the lidar sensor detected the bare-earth ground surface and random errors are expected to follow a normal error distribution. Assuming a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_z$) of the checkpoints x 1.9600. For the Tampa Bay Topobathy lidar project, the vertical accuracy specification is 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

BVA was determined with check points located only on submerged topography. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_z$) of the checkpoints x 1.9600. The $RMSE_z$ for the BVA is a depth-dependent value that considers increasing uncertainty with depth using two uncertainty coefficients. Because all the bathymetric checkpoints for the Tampa Bay project were surveyed at less than 1 m below the water surface, the $RMSE_z$ specification is 30.0 cm. For the Tampa Bay Topobathy lidar project, bathymetric vertical accuracy specification is 58.8 cm or less based on an $RMSE_z$ of 30.0 cm x 1.9600.

VVA was determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas. In these locations there is a possibility that the lidar sensor and post-processing may yield elevation errors that do not follow a normal error distribution. VVA at the 95% confidence level equals the 95th percentile error for all checkpoints in all vegetated land cover categories combined. The Tampa Bay Topobathy lidar project VVA specification is 30.0 cm based on the 95th percentile. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the VVA. In addition to the combined VVA, separate assessments were conducted for tall grass/weeds/crops and fully forested land cover categories.

The relevant testing criteria are summarized in Table 10.

Table 10. Vertical accuracy acceptance criteria

Land Cover Type	Quantitative Criteria	Measure of Acceptability
NVA	Accuracy in open terrain and urban land cover categories using $RMSE_z$ *1.9600	19.6 cm
BVA	Accuracy in submerged topography using $RMSE_z$ *1.9600	58.8 cm
VVA	Accuracy in vegetated land cover categories combined at the 95% confidence level	30.0 cm

The QA/QC vertical accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed X, Y, and z coordinates for discrete checkpoints in accordance with project specifications.
2. Dewberry interpolated the bare-earth lidar DTM to determine a lidar surface z coordinate for every surveyed X and Y coordinate.
3. Dewberry computed difference between each surveyed z coordinate and lidar surface z coordinate.

4. The resulting differences were analyzed by Dewberry to assess the accuracy of the data. The overall descriptive statistics of each dataset were computed to assess any trends or anomalies. The results are provided in the following section.

5.4 Vertical Accuracy Results

Table 11 summarizes the tested vertical accuracy of the classified lidar LAS files.

Table 11. Classified lidar vertical accuracy results

Land Cover Type	# of Points	NVA (m)	BVA (m)	VVA (m)
Project Specification		**0.196**	**0.588**	**0.300**
NVA	30	0.109		
BVA	4		0.299	
VVA	17			0.147

The topographic portion of this DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSE_z Vertical Accuracy Class. Actual NVA accuracy was found to be RMSE_z = 5.6 cm, equating to ± 10.9 cm at 95% confidence level. Actual VVA accuracy was found to be ± 14.7 cm at the 95th percentile. The bathymetric portion of this DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for an 18.5 cm RMSE_z Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be RMSE_z = 15.3 cm, equating to ± 29.9 cm at 95% confidence level.

The VVA 5% outliers are listed in Table 12. Descriptive statistics for all categories are presented in Table 13.

Table 12. VVA 5% outliers

Point ID	UTM zone 17N NAD83(2011), m		Ellipsoid Heights, NAD83(2011), m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
LI_VVA_15	338856.015	3046690.781	-23.839	-23.546	0.293

Table 13. Classified lidar vertical accuracy descriptive statistics

Land Cover Type	# of Points	RMSE_z (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	30	0.056	0.004	-0.003	0.213	0.056	-0.245	-0.100	0.125
BVA	4	N/A	0.023	0.006	1.885	0.086	5.724	-0.110	0.293
VVA	17	0.153	0.115	0.128	-0.558	0.116	-0.368	-0.032	0.237

Figure 9 and Figure 10 show histograms illustrating the distribution of discrepancies between the survey checkpoint elevations and the corresponding lidar surface elevations.

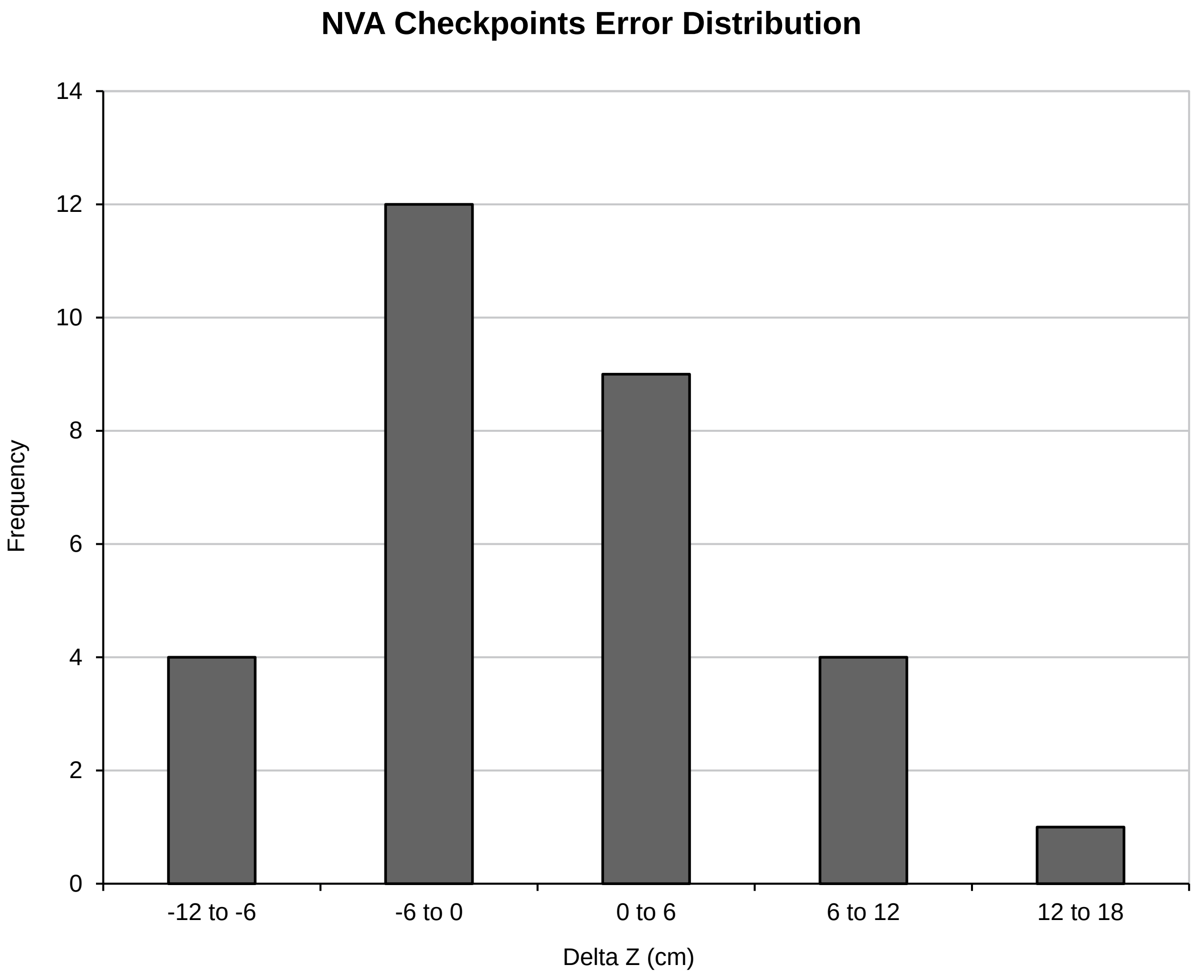

Figure 9. Distribution of elevation discrepancies between non-vegetated surveyed checkpoints and lidar surface. All individual NVA checkpoints meet NVA requirements.

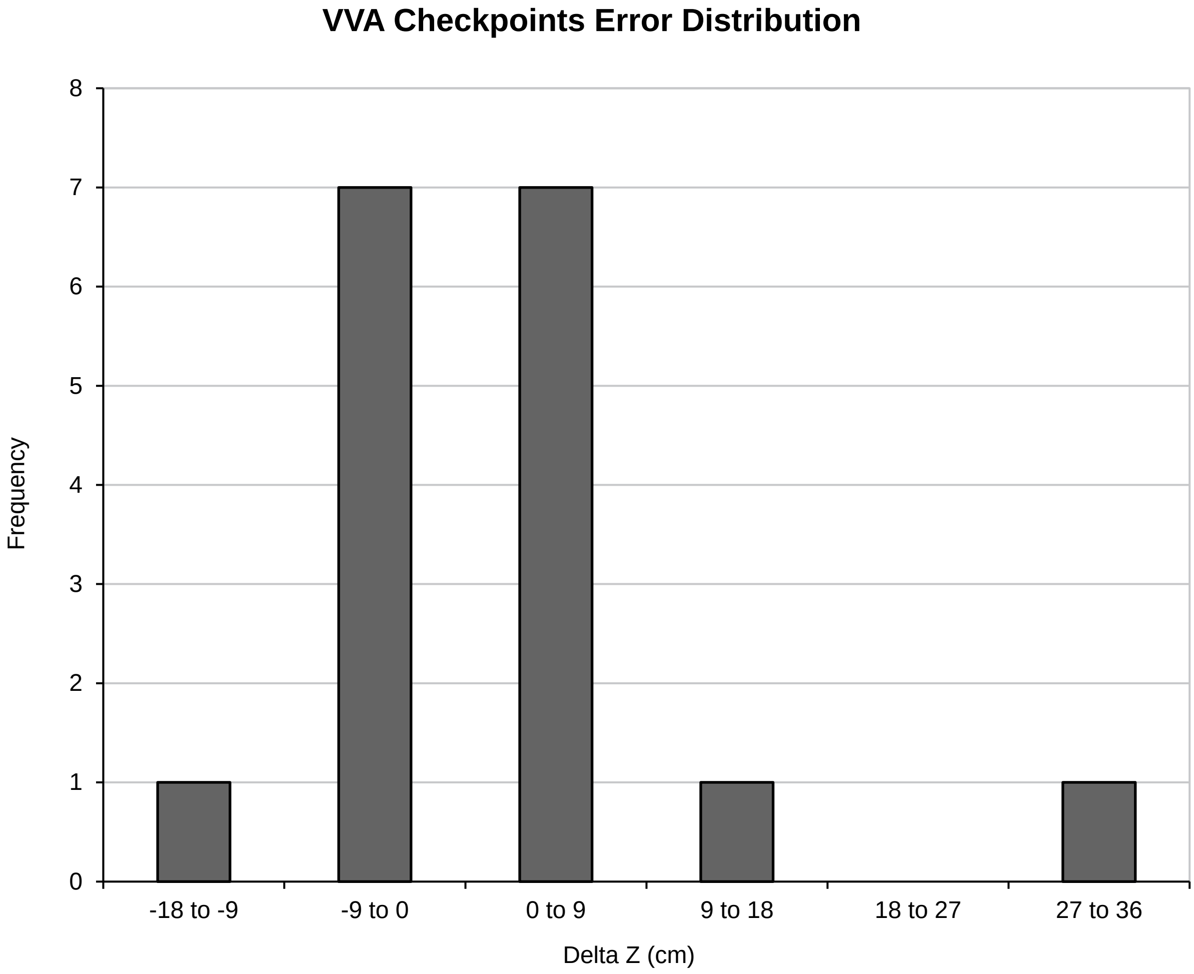

Figure 10. Distribution of elevation discrepancies between vegetated surveyed checkpoints and lidar surface. The dataset meets the VVA specification, with one VVA checkpoint falling outside of the specification.

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the Tampa Bay Topobathy lidar project satisfies the project’s pre-defined vertical accuracy criteria.

5.5 Horizontal Accuracy Test Procedures

Horizontal accuracy testing requires well-defined checkpoints that can be visually identified in the dataset. Elevation datasets, including lidar datasets, do not always contain well-defined checkpoints suitable for horizontal accuracy assessment. Dewberry reviewed all NVA checkpoints to determine which, if any, of these checkpoints were located on photo-identifiable features in the intensity imagery. This subset of checkpoints was used for horizontal accuracy testing.

The horizontal accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry’s team surveyed X, Y, and z coordinates for discrete checkpoints in accordance with project specifications. Dewberry targeted half of the NVA checkpoints for location on features that would photo-identifiable in the intensity imagery.

2. Following initial processing, Dewberry located the photo-identifiable features in the intensity imagery.
3. Dewberry computed the differences in X and Y values between the surveyed coordinates and the lidar coordinates of the photo-identifiable feature.
4. Horizontal accuracy was assessed based on these data using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. The results are provided in the following section.

5.6 Horizontal Accuracy Results

Eleven checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. Due to the small number of available checkpoints, the results reported herein are not considered statistically significant.

Horizontal accuracy at the 95% confidence level (Accuracy$_r$) is computed by the formula:

$$\text{Accuracy}_r = \text{RMSE}_r \times 1.7308$$

where:

$$\text{RMSE}_r = \sqrt{\text{RMSE}_x^2 + \text{RMSE}_y^2}$$

The lidar horizontal accuracy results are detailed in Table 14.

Table 14. Horizontal accuracy of the classified lidar data at the 95% confidence level

Land Cover Type	# of Points	RMSE$_x$ (m)	RMSE$_y$ (m)	RMSE$_r$ (m)	Accuracy$_r$ (m)
Project Target	**-**	**0.410**	**0.410**	**0.580**	**1.000**
Non-Vegetated Terrain	11	0.111	0.103	0.151	0.262

This dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSE$_x$/RMSE$_y$ horizontal accuracy class which equates to a positional horizontal accuracy of ± 1 meter at the 95% confidence level. Using 11 photo-identifiable checkpoints, positional horizontal accuracy of this dataset was found to be RMSE$_x$ = 11.1 cm and RMSE$_y$ = 10.3 cm, which equates to ± 26.2 cm at the 95% confidence level.

6. DEM PROCESSING & QUALITATIVE ASSESSMENT

6.1 DEM Production Methodology

Dewberry utilized a proprietary routine to generate DEM products. ArcGIS, LP360, LAStools, and proprietary tools were used for QA/QC.

The DEM bare earth surface was sourced from the final classified lidar points in bare earth classes—class 2 for subaerial ground, class 40 for submerged topography (bathymetry), and class 43 for submerged objects. Void polygons were enforced in the final raster to delineate areas larger than 9 square meters where no valid bathymetric returns were acquired. The DEM was reviewed for any issues requiring corrections, including remaining calibration issues, lidar point misclassification, and processing artifacts. After corrections were applied, the DEM was split into tiles per the project tiling scheme. The formatting of the DEM tiles was verified before a final qualitative review was conducted by an independent review department within Dewberry.

6.2 DEM Qualitative Assessment

Dewberry performed a comprehensive qualitative assessment of the bare earth DEM deliverables to ensure that all tiled DEM products were delivered with the proper extents, were free of processing artifacts, and contained the proper referencing information. Dewberry conducted the review in ArcGIS using a hillshade model of the full dataset with a partially transparent colorized elevation model overlaid. The tiled DEMs were reviewed at a scale of 1:5,000 to look for artifacts caused by the DEM generation process and to verify correct enforcement of void areas.

6.3 DEM Vertical Accuracy Results

The same checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products. DEMs were created by averaging the elevations of ground points within each pixel, which may result in slightly different elevation values at each survey checkpoint when compared to the linearly interpolated TIN created from the source LAS. The vertical accuracy of the DEM was tested by comparing the elevation of a given surveyed checkpoint with the elevation of the horizontally coincident pixel in the DEM. Dewberry used LP360 to test the DEM vertical accuracy.

The survey checkpoints used to test this topobathymetric dataset are listed in the previously delivered ground survey report previously delivered. Table 15 summarizes the tested vertical accuracy results from the final DEM dataset.

Table 15. DEM vertical accuracy results

Land Cover Type	# of Points	NVA (m)	BVA (m)	VVA (m)
Project Specification		**0.196**	**0.588**	**0.300**
NVA	30	0.112		
BVA	4		0.304	
VVA	17			0.151

The topographic portion of this DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 5.7 cm, equating to ± 11.2 cm at 95% confidence level. Actual VVA accuracy was found to be ± 15.1 cm at the 95th percentile. The bathymetric portion of this DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for an 18.5 cm $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 15.5 cm, equating to ± 30.4 cm at 95% confidence level.

The VVA 5% outliers are listed in Table 16. Descriptive statistics for all categories are presented in Table 17.

Table 16. VVA 5% outliers

Point ID	UTM zone 17N NAD83(2011), m		NAVD88 Geoid 12B, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
LI_VVA_15	338856.015	3046690.781	0.614	0.916	0.302

Table 17. Classified lidar vertical accuracy descriptive statistics

Land Cover Type	# of Points	$RMSE_z$ (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	30	0.057	-0.003	-0.003	0.203	0.058	0.119	-0.109	0.136
BVA	4	0.088	0.027	0.004	1.967	0.086	6.458	-0.113	0.302
VVA	17	0.155	0.121	0.131	-0.418	0.112	-1.042	-0.019	0.240

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the Tampa Bay South TopoBathymetric Lidar, Imagery, and Shoreline Mapping Project satisfies the project’s pre-defined vertical accuracy criteria.

7. METADATA

Project level metadata files were delivered in XML format for all project deliverables including lidar, DEMs, imagery, and void polygons. All metadata files are FGDC compliant and were verified to be error-free according to the USGS MetaParser utility.

8. ORTHOIMAGERY

Dewberry acquired four-band (Red, Green, Blue, and Near-Infrared or RGBNIR channels) digital imagery covering the project area. Dewberry performed the aerotriangulation and ortho processing of image frames.

8.1 Orthoimagery Processing and Qualitative Assessment

A 2m DEM derived from the 2018 Florida Peninsular lidar (Pinellas and Manatee counties) and the 2017 Hillsborough County lidar project was used to orthorectify the imagery. Seamlines were auto-generated and then reviewed prior to creating the orthoimage tiles. Four-band (RGBNIR), 8-bit, uncompressed orthoimage tiles (3000 m x 3000 m) in GeoTIFF format with 25 cm Ground Sample Distance (GSD) were created for the project area. All ortho-mosaics have the same coordinate reference system as the lidar data:

Horizontal Datum: North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011))

Coordinate System: UTM zone 17

Units: Meters

Once the orthoimagery mosaics were created, all formatting was verified for adherence to project parameters. Tiles were loaded into ArcGIS to verify completeness, continuity, and integrity. A combination of manual review and data reviewer tools were used to identify any usability and quality issues, such as voids, misalignments, warped features, and smears. Corrections were applied where necessary.

8.2 Orthoimagery Accuracy Results

Horizontal accuracy testing requires well-defined checkpoints whose surveyed coordinates can be identified and re-measured in the orthoimagery for comparison. Dewberry used 30 checkpoints to compute the horizontal accuracy of the orthoimagery.

Horizontal accuracy at the 95% confidence level (Accuracy_r) is computed by the formula:

$$\text{Accuracy}_r = \text{RMSE}_r \times 1.7308$$

where:

$$\text{RMSE}_r = \sqrt{\text{RMSE}_x^2 + \text{RMSE}_y^2}$$

The results of the horizontal accuracy calculations are provided in Table 18.

Table 18. Orthoimagery horizontal accuracy results

Land Cover Type	# of Points	$RMSE_x$ (m)	$RMSE_y$ (m)	$RMSE_r$ (m)	$Accuracy_r$ (m)
Project Specification		**0.600**	**0.600**	**0.850**	**1.470**
Results	30	0.155	0.108	0.189	0.327

This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 60 cm $RMSE_x$/$RMSE_y$ Horizontal Accuracy Class. Using 30 photo-identifiable checkpoints, actual positional accuracy for this dataset was found to be $RMSE_x$ = 15.5 cm and $RMSE_y$ = 10.8 cm, which equates to +/- 32.7 cm at 95% confidence level.

8.3 Orthoimagery Deliverables

In addition to the imagery frames, photo-center shapefiles, orthomosaic tiles, and orthoimagery tile grid, several imagery reports and pieces of documentation were delivered to NOAA as part of the imagery deliverables. These include:

- Exterior Orientation (EO) files
- Camera Calibration files
- Terrestrial Calibration files
- Boresight Calibration files
- Airborne Positional and Orientation Report (APOR)
- Aerotriangulation (AT) Report
- Electronic Exposure Data (EED) files
- Tabulation of Aerial Photography
- Photographic Flight Reports
- Ground Control Report
- Flight Line Maps
- Metadata in XML format for the image frames and ortho-mosaic tiles