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Indian River Lagoon Topobathy Shoreline

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) Indian River Lagoon (IRL) 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 were tiled according to a 500 m by 500 m tile grid, with a total of 8,786 tiles produced; DEM data was tiled according to a 5,000 m by 5,000 m tile grid, with a total of 136 tiles produced. Approximately 615 sq. miles of coverage is provided.

Digital orthoimagery was acquired for the project area. Imagery was tiled according to a 3,000 m by 3,000 m tile grid. A total of 344 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 performed all ground control survey for the imagery. Digital Aerial Solutions, LLC (DAS) acquired the digital imagery and performed the aerotriangulation and orthorectification.

NGS 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 Indian River Lagoon topobathymetric lidar survey project area covers approximately 615 square miles and was divided into four blocks. There are 8,786 500 m x 500 m lidar tiles, 136 5,000 m x 5,000 m DEM tiles, and 344 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. Shows the Indian River Lagoon Shoreline mapping collection area, outlined in yellow.

1.3 Date of Survey

The lidar aerial acquisition was conducted from February 24, 2022 through June 1, 2022.

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

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

Coordinate System: UTM zone 17

Units: Meters

Geoid Model: Geoid18 (Geoid18 was used to convert ellipsoid heights to orthometric heights)

1.5 Lidar Vertical Accuracy

For the Indian River Lagoon Bathymetric Lidar project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain is **4.4 cm** and the non-vegetated vertical accuracy (NVA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **8.6 cm**.

For the Indian River Lagoon Bathymetric Lidar project, the tested $RMSE_z$ of the classified lidar data for checkpoints in submerged topography is **14.8 cm** and the bathymetric vertical accuracy (BVA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **29.1 cm**.

For the Indian River Lagoon Bathymetric Lidar project, the tested vegetated vertical accuracy (VVA) of the classified lidar data computed using the 95^{th} percentile is **20.7 cm**.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and topobathymetric DEM data are found in sections 5 and 6 of this report.

1.6 Ortho-Mosaic Horizontal Accuracy

The tested horizontal accuracy at the 95% confidence level of the ortho-mosaics computed using $RMSE_{xy}$*2.448 is **31.3 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 completed on June 1, 2022.

2.1 Airborne Kinematic Control

Airborne GPS data was processed using the PosPac PP-RTX software suite. Flights were flown with a minimum of 12 satellites in view (10° above the horizon) and with PDOP less than 2.

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

2.2 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, initially with default values from Teledyne or the last mission calibrated for the system. The initial point generation for each mission calibration was verified within Microstation/TerraScan for calibration errors. If a calibration error greater than specification was observed, the appropriate roll, pitch and scanner scale corrections were calculated. The point data were then regenerated with the new calibration values and validated internally again to ensure that the errors were fully addressed.

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.

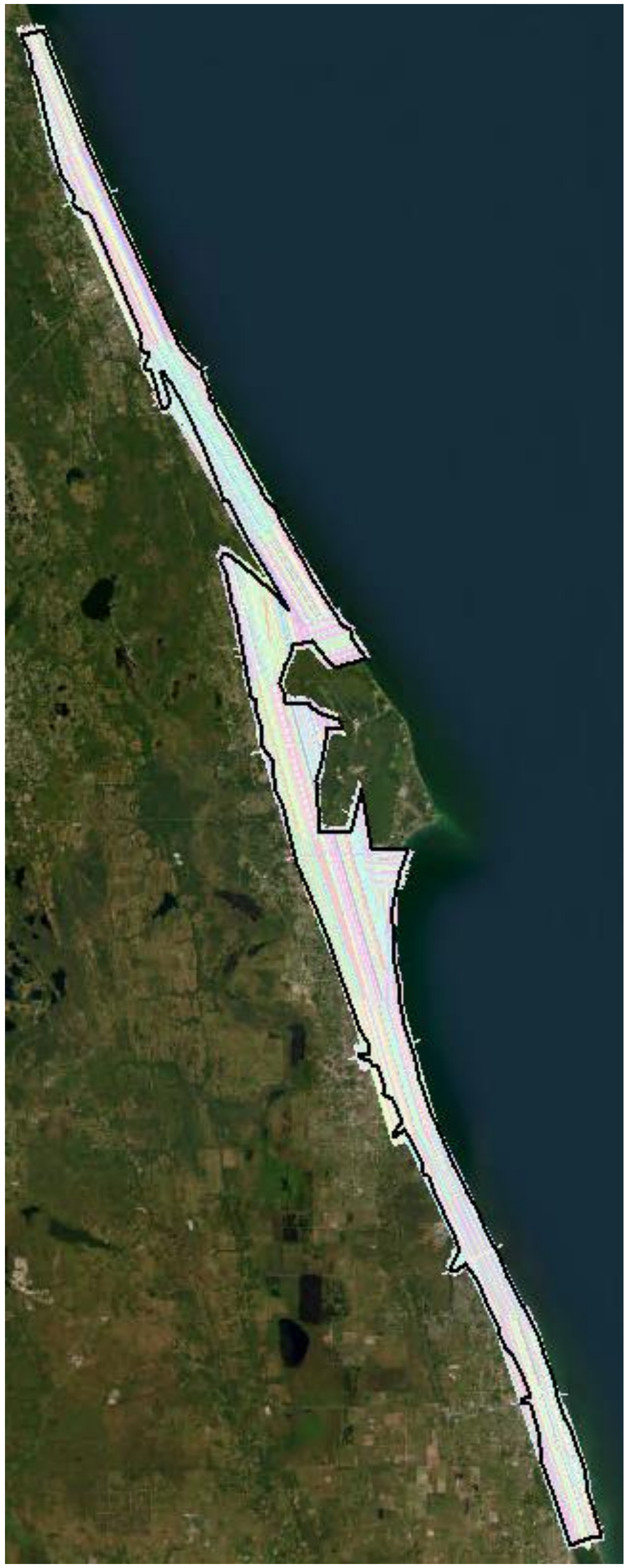

Figure 2. Lidar swath output showing complete coverage.

2.3 Boresight and Relative accuracy

The initial points 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:

- ≤ 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.

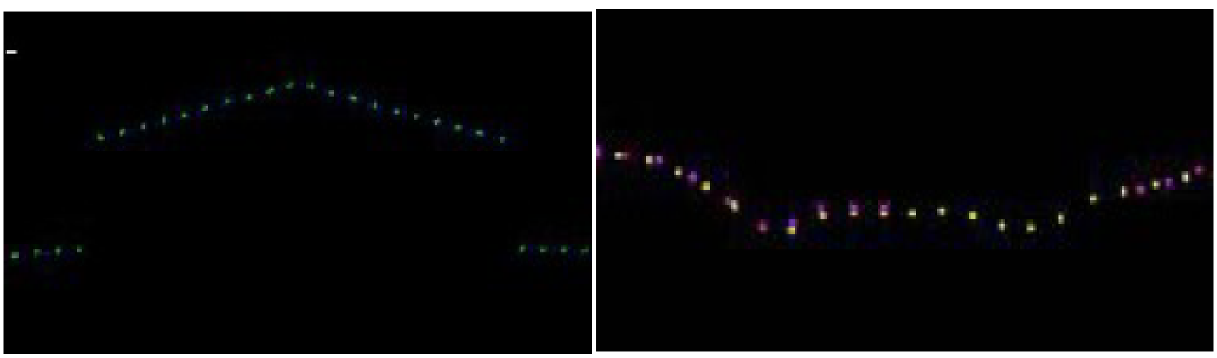

Figure 3. Profile views showing results of roll and pitch adjustments.

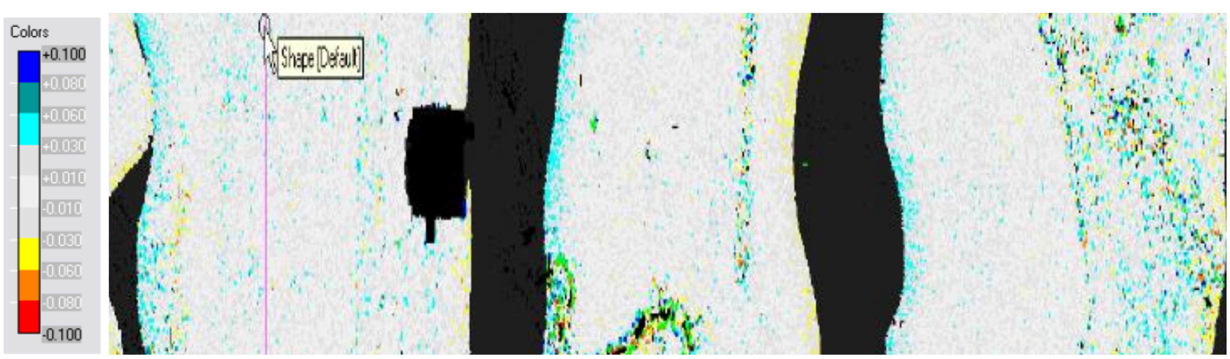

Figure 4. QC block colored by vertical difference between swaths to check accuracy at swath edges.

2.4 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 Indian River Lagoon lidar dataset was tested to 4.9 cm $RMSE_z$ and 0.097 m vertical accuracy at the 95% confidence level when compared to 33 GPS static checkpoints (Table 1) surveyed by Dewberry. The results of the preliminary vertical accuracy assessment conducted by Dewberry are summarized in Table 2.

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

Table 1. Static GPS points used for acquisition provider's preliminary vertical accuracy assessment.

Number	NAD83(2011) UTM zone 17, m		Ellipsoid Heights, NAD83(2011), m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
GCP1	504559.582	3216632.613	-26.169	-26.174	-0.005
GCP2	569660.329	3039603.290	-25.549	-25.615	-0.066
GCP3	513256.147	3205236.067	-27.133	-27.170	-0.037
GCP4	564683.966	3054634.638	-24.520	-24.510	0.010
GCP5	521809.539	3192250.446	-22.336	-22.292	0.044
GCP6	558841.262	3070445.397	-27.076	-27.125	-0.049
GCP7	523931.811	3178960.055	-26.819	-26.731	0.088
GCP8	548709.463	3084875.655	-24.228	-24.230	-0.002
GCP9	526498.944	3164609.527	-27.683	-27.672	0.011
GCP10	541634.292	3100242.782	-19.756	-19.816	-0.060
GCP11	524012.516	3155621.011	-26.206	-26.191	0.015
GCP12	535580.838	3120255.503	-25.759	-25.798	-0.039
GCP13	538189.678	3136811.141	-27.341	-27.173	0.168
GCP15	522775.232	3149861.992	-26.085	-26.088	-0.003
GCP16	518493.931	3166183.858	-26.099	-26.136	-0.037
GCP17	513905.478	3188438.979	-26.761	-26.780	-0.019
GCP18	539569.134	3141782.800	-25.636	-25.698	-0.062
GCP19	533151.270	3144319.201	-27.510	-27.542	-0.032
GCP20	562932.950	3046701.850	-24.428	-24.485	-0.057
GCP21	558448.069	3063053.683	-25.987	-26.003	-0.016
GCP22	554987.782	3080334.762	-26.837	-26.842	-0.005
GCP23	547333.020	3095049.302	-27.177	-27.184	-0.007
GCP24	537185.785	3110285.153	-21.180	-21.173	0.007
GCP26	509401.144	3211272.869	-27.096	-27.105	-0.009
GCP27	513332.666	3196986.047	-24.777	-24.859	-0.082
GCP28	516044.651	3193040.299	-27.165	-27.139	0.026
GCP29	523809.704	3172780.506	-26.842	-26.853	-0.011
GCP30	534349.651	3172308.153	-27.028	-27.118	-0.090
GCP31	502054.068	3226425.846	-24.017	-24.021	-0.004
GCP32	497365.149	3233463.792	-27.371	-27.422	-0.051

Number	NAD83(2011) UTM zone 17, m		Ellipsoid Heights, NAD83(2011), m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
GCP33	493941.088	3245044.433	-25.292	-25.288	0.004
GCP34	488499.605	3253619.781	-25.133	-25.129	0.004
GCP35	485264.626	3266203.775	-27.603	-27.587	0.016

Table 2. 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	33	0.049	0.097	-0.011	0.049	-0.090	0.168

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 45 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 proprietary 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 $RMSE_z$ = 4.5 cm, equating to ± 8.9 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 Indian River Lagoon Bathymetric Lidar Project satisfied these criteria. Table 3 shows calculated statistics for the raw swath data.

Table 3. 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	45	0.045	0.089	-0.010	-0.008	0.149	0.045	-0.093	0.076	-0.568

3.1.2 Interswath Relative Accuracy

The Interswath accuracy, or overlap consistency, measures the variation in the lidar data within the swath overlap. Interswath accuracy measures the quality of the calibration and boresight adjustment of the data in each lift. Dewberry reviews the overlap consistency of the lidar dataset during multiple stages of production. Each review is performed by an initial reviewer and then reviewed by a second reviewer to verify the overlap consistency meets expectations. After calibration, Dewberry uses a proprietary software to generate a point statistics interswath raster. The interswath raster is reviewed for any systematic interswath errors that should be considered of concern. If issues are identified, it will be corrected by the calibration team. The interswath rasters are symbolized by the following ranges:

- +/- 0-8 cm: **Green**
- +/- 8-16 cm: **Yellow**
- +/- 16 cm: **Red**

Once the initial ground macro has been run on the dataset, Dewberry uses LP360 to generate swath separation images. The swath separation images are generated using the same settings as the final deliverable swath separation images outlined in 4.4 DZ Ortho Images and in accordance with USGS Lidar Base Specification v2022 Rev A. If the lidar dataset is heavily vegetated, Dewberry will generate swath separation images using the last return of ground points only to better confirm no offsets are present in the bare earth DEM. If issues are identified, dependent on the cause of the issue, it will be corrected by recalibrating the affected data or classifying the impacting points to withheld.

Lastly, the final deliverable swath separation images are generated using LP360. A final review is performed by the final product producer and then verified by a member of the quality management team prior to sending to USGS.

3.1.3 Intraswath Relative Accuracy

The intraswath accuracy, or the precision of lidar, measures variations on a surface expected to be flat and without variation. Precision is evaluated to confirm that the lidar system is performing properly and without gross internal error that may not be otherwise apparent. Dewberry reviews the precision of the lidar dataset during multiple stages of production. Each review is performed by an initial reviewer and then reviewed by a second reviewer to verify the precision of the lidar meets expectations. Dewberry performs an intraswath accuracy review for each mission within 1-2 days of collection. The precision of the lidar dataset is then reviewed before calibration on the lidar dataset to ensure no systematic errors.

Dewberry uses a proprietary software to generate point statistics intraswath rasters. Swath data in non-overlap areas were assessed using only first returns in non-vegetated areas. To measure the precision of a lidar dataset, level or flat surfaces were assessed. If the lidar dataset is located in area with sloped or steep terrain, a slope raster will be used in conjunction with the intraswath raster to ensure only level or flat surfaces are being assessed. The intraswath raster is reviewed for any systematic intraswath errors that should be considered of concern.

The intraswath rasters are symbolized by the following ranges:

- 0-6 cm: **Green**
- >6 cm: **Red**

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 5 shows an example of the horizontal alignment between swaths for Indian River Lagoon Bathymetric project; no horizontal alignment issues were identified.

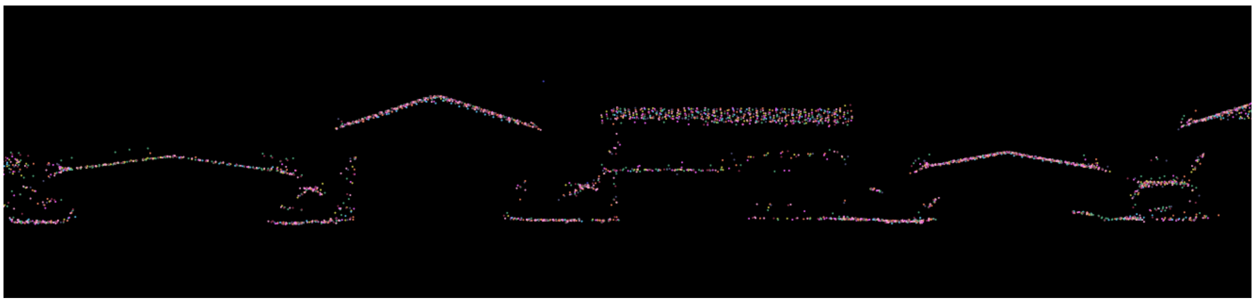

Figure 5. Separate flight lines are differentiated by color to determine whether horizontal misalignments are present. This is a representative example; there is no visible offset between these flight lines.

3.1.5 Point Density

The required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.58 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 3 points per square meter (ppsm) or greater; however, it is understood that a required ANPD may not be met in the bathymetric domain due to environmental conditions. Density calculations were performed using only first return data located in the geometrically usable center portion (typically ~90%) of each swath. LAS dataset statistics yielded an average bathymetric ANPS of 0.4 meters (equivalent to an ANPD of 6.25 ppsm), exclusive of bathymetric void areas, 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, 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 ground 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 4.

Table 4. 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, 9, 17, 18, or 20. 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
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 that were identified were classified to 43 (Figure 6).

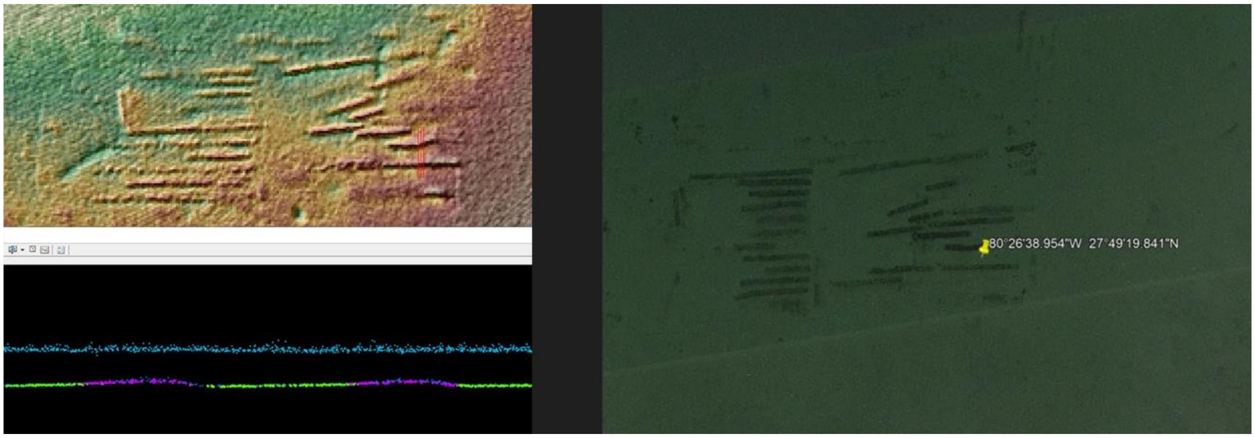

Figure 6. The image on the left shows a DEM with a lidar profile across submerged objects (class 43, purple). The image on the right in Google Earth imagery from January 2021.

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. Class 65 was utilized in temporal change areas, mostly along the coast where different flight dates collected during both low tide and high tide.

3.2.4 Synthetic Points

Generally, class 42 represents synthetic water surface points which are those points that are artificially generated by the CARIS Base Editor processing software for the CZMIL SuperNOVA sensor. These are created during the detection of the water surface to ensure consistency in the refraction correction. This section outlines the general workflow that describes the water surface detection logic. Additionally, there were instances where the early workflow in CARIS placed a synthetic flag on uncertain points often from the deep channel (channel 8 as identified in the user data bit) but additionally on points where there was a higher degree of uncertainty on the return or refraction correction value. With later updates these uncertainties have largely been resolved with fewer points containing that synthetic flag and less reliance on class 42. Under the current IRL data, there are class 42 points that are under the water surface or classified bathymetric bottom.

The water surface detection algorithm builds a localized mean water level elevation in each grid cell (if possible) based on the water shots which are assigned to each cell. A separate mean water level elevation is generated based on the IR channel, the deep channel or possibly the shallow channels (if the shallow channel parameter box is set, the IR/Deep channels are ignored). Note that this process is fully automated in its decision making based on the waveform of the pulse. The method for detection of water surface using the IR channel was prioritized for the IRL lidar collection however, due to water conditions, we do know that the deep channel first return was often used.

The IR mean water level elevation is set for the grid cell if all the following are true:

- The total number of valid IR shot elevations is greater than 2
- The percentage of valid IR shots to the total number of valid IR shots in the grid cell is greater than or equal to n% (n% comes from the “Valid percentage of shots in water grid cell” option, the default is 75%)
- 100% of valid IR shots are water shots
- Less than 5% of valid IR water shots have multiple returns

If all the above conditions are true, the mean water level elevation is computed from the valid IR water shot elevations and set for the current cell, making it a qualified grid cell for the IR channel.

The Deep mean water level elevation is set for the grid cell if all the following are true:

- The total number of valid Deep shot elevations is greater than 2
- The percentage of valid Deep water shot elevations to the total number of valid Deep shots in the grid cell is greater than or equal to n% (n% comes from the “Valid percentage of shots in water grid cell” option, the default is 75%)
- 100% of valid Deep shots are water shots

If all the above conditions are true, the mean water level elevation is computed from the valid Deep water shot elevations and set for the current cell, making it a qualified grid cell for the deep channel.

The Shallow channel mean water level elevation is set for the grid cell if all the following are true:

- The total number of valid shallow elevations is greater than 2
- The percentage of valid shallow return elevations to the total number of valid shallow returns in the grid cell is greater than or equal to n% (n% comes from the “Valid percentage of shots in water grid cell” option, the default is 75%)
- 100% of valid shallow return elevations are water shots
- The standard deviation from the mean is low enough. There are user options to configure this, but if the standard deviation is too high, there is too much variance in the valid shallow elevations for the mean to be considered reliable.

If all the above conditions are true, the mean water level elevation is computed from the valid shallow water return elevations and set for the current cell, making it a qualified grid cell for shallow channels.

The above logic and settings are biased towards open water and assume that there will be strong IR/Deep coverage throughout. It is also assumed that the quality of the data in the IR/Deep channels is high. In cases where a grid cell cannot be qualified on the IR or deep channel, the “Water Grid Cell Search Radius” can be used to look for neighboring qualified grid cells to use instead. In open water, the water surface is consistent, so using a neighboring qualified grid cell is unnecessary. However, in challenging environments which have variable elevations near each other, using a neighboring qualified grid cell may result in a wrong mean water level elevation being used in the local grid cell. It is also worth noting that along the coast, it is highly probable that a grid cell will contain both land and water shots. As such, the above mean water surface detection logic may not be able to generate a mean water level elevation in the local grid cell and will always have to rely on a neighboring qualified grid cell. In such cases, a water surface control file can be used to explicitly define the water surface along the coastline.

Areas of extremely shallow water present additional challenges; therefore, the above logic may be too restrictive in determining the water surface because there may not be a lot of cases where the local area is 100% water, or there may be unreliable IR/Deep coverage. Using neighboring grid cells may not work if none can be found in range. It is also possible that if a neighboring grid cell is found, it may not be at the correct elevation. This is another case where a water surface control file can be utilized.

Class 42 generation for CZMIL is further described in a separate memo that was delivered to NOAA.

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 5.

Table 5. 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 NAD83 (2011) ellipsoid, 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
Synthetic and Withheld Points	Synthetic and Withheld flags, properly set including all noise classes flagged as withheld

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 Confidence Layer

A confidence layer that reports the standard deviation 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. Each 1-meter grid cell has an associated standard deviation value, in meters. The confidence layer extents are the same as the extents for the final topobathymetric DEMs so that the pixels align, showing the confidence of each topobathymetric DEM grid cell. The standard deviation rasters are tiled according to the DEM tile grid.

4.3 Normalized Seabed Reflectance

The intensity normalization process is done by creating a histogram of intensity values calculated for each flight line to derive the mean values. The flight line with highest intensity value serves as a reference flight line. The difference between the mean value of the reference flight line to all other flight lines is calculated. This difference is added to the points of the corresponding flight lines. As a result, the average value for each flight line matches the reference flight line. The normalized intensity image is created in Python using the revised intensity information.

Dewberry's intensity normalization process is further described in a separate memo that was delivered to NOAA.

Normalized 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 16-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 topobathymetric DEMs so that the pixels align, showing the lidar intensity at each bathymetric DEM grid cell. The normalized 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 do not 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 topobathymetric DEMs so that the pixels align. The DZ orthoimages are tiled according to the DEM tile grid.

4.5 Low Confidence Layers

Manually collected polygons outlining areas of low confidence, temporal offsets, or data anomalies are included with this dataset. The polygons represent areas that are potentially less accurate than surrounding environments. Reasons for the delineation of these areas may range from reduced ground returns in heavy vegetated or flooded areas, data voids or other data anomalies, flightline ridges present in the bare earth surface but below the interswath relative accuracy specification, or temporal differences present in marshy or wet environments. A field is included in the attribute table for the shapefile explaining the reason for each polygon.

4.6 Flightline Extents Shapefile

Flightline extents are delivered as polygons in an Esri shapefile, delineating actual coverage of each swath used in the project deliverables. Dewberry delivered this shapefile using USGS's provided template so that each polygon contains the following attributes:

- Lift/Mission ID (unique per lift/mission)
- Point Source ID (unique per swath)
- Type of Swath (project, cross-tie, fill-in, calibration, or other)
- Start time in adjusted GPS seconds
- End time in adjusted GPS seconds

Prior to delivery, a final flightline shapefile is created from the final, tiled point cloud deliverables to ensure all correct swaths are represented in the flightline shapefile. The flightline shapefile is then reviewed for complete coverage and correct formatting.

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.

Horizontal accuracy testing requires survey checkpoints located such that the checkpoints are photo-identifiable in the intensity imagery. No photo-identifiable checkpoints were surveyed for this project, so the horizontal accuracy was not tested.

5.2 Survey Vertical Accuracy Checkpoints

Dewberry surveyed 95 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 7. A complete list of survey checkpoints was provided in the previously submitted survey report.

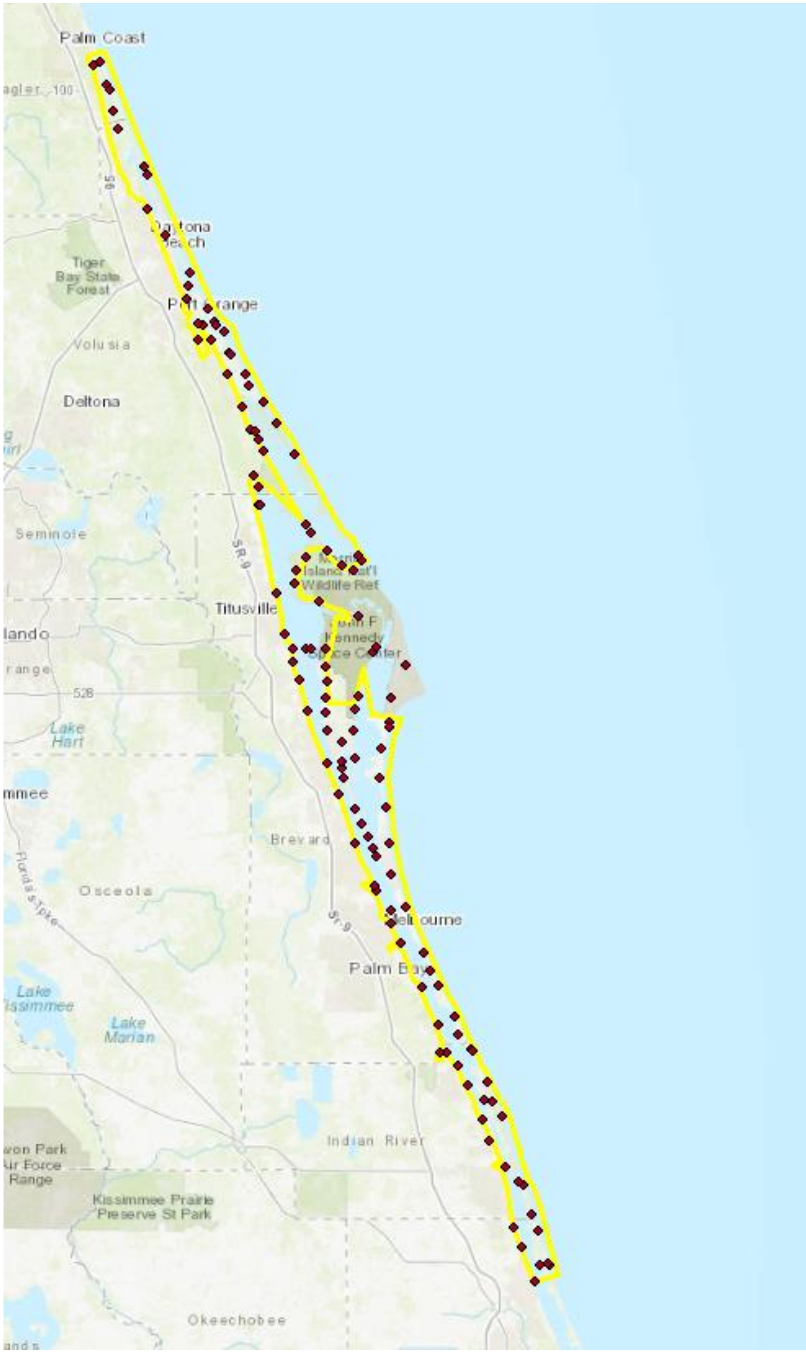

Figure 7. Location of all surveyed checkpoints

Dewberry surveyed 95 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 six NVA or VVA checkpoints, and three BVA points. NVA 13, NVA 18, VVA 8, VVA 9, VVA 10, and VVA 15 checkpoints were located outside of the project AOI, and no data was collected in these areas.

Three BVA checkpoints were removed from the classified lidar vertical accuracy testing. BVA 9 (Figure 8) had a boat parked above the point during acquisition. BVA 10 was collected on a boat ramp, and where data was acquired there was no bathymetric bottom coverage (Figure 9). BVA 8 was collected in a tidepool with rocks and submerged aquatic vegetation, and the resulting DZ is skewed higher (Figure 10).

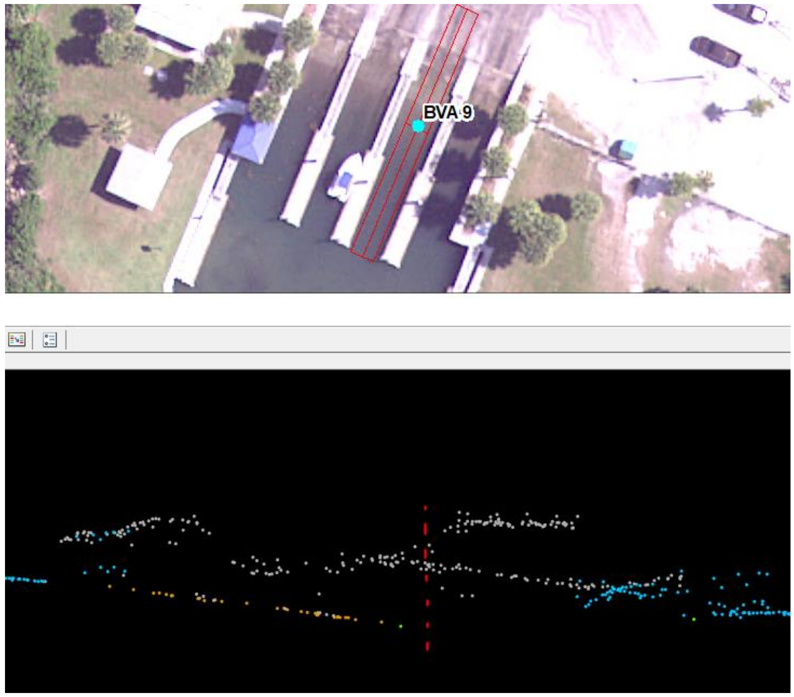

Figure 8. BVA 9 was collected on a boat ramp, and the data show a boat parked above where this survey point was located.

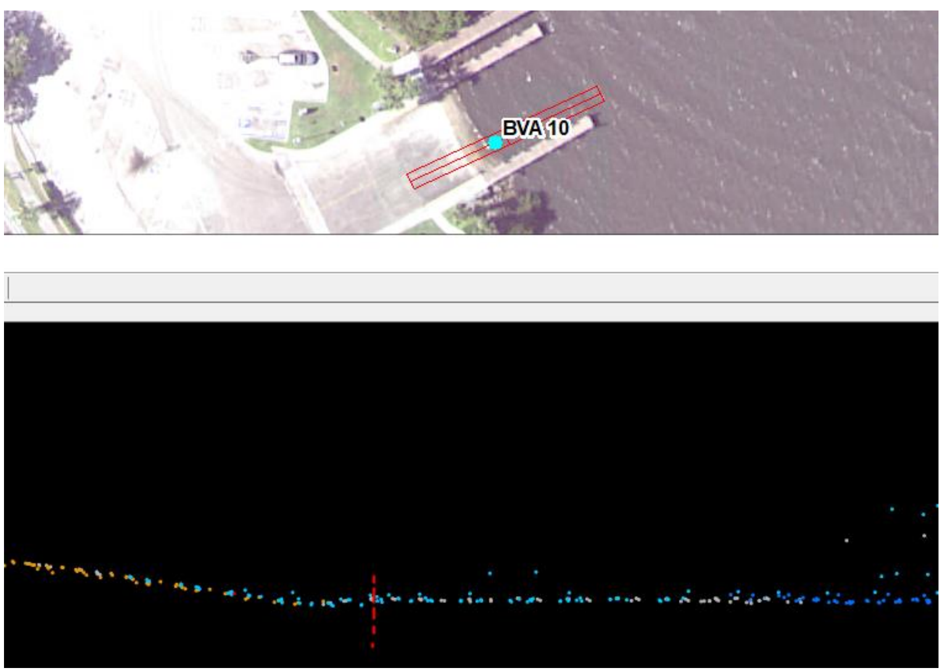

Figure 9. BVA 10 was collected on a boat ramp, and there was no bathymetric coverage in the data.

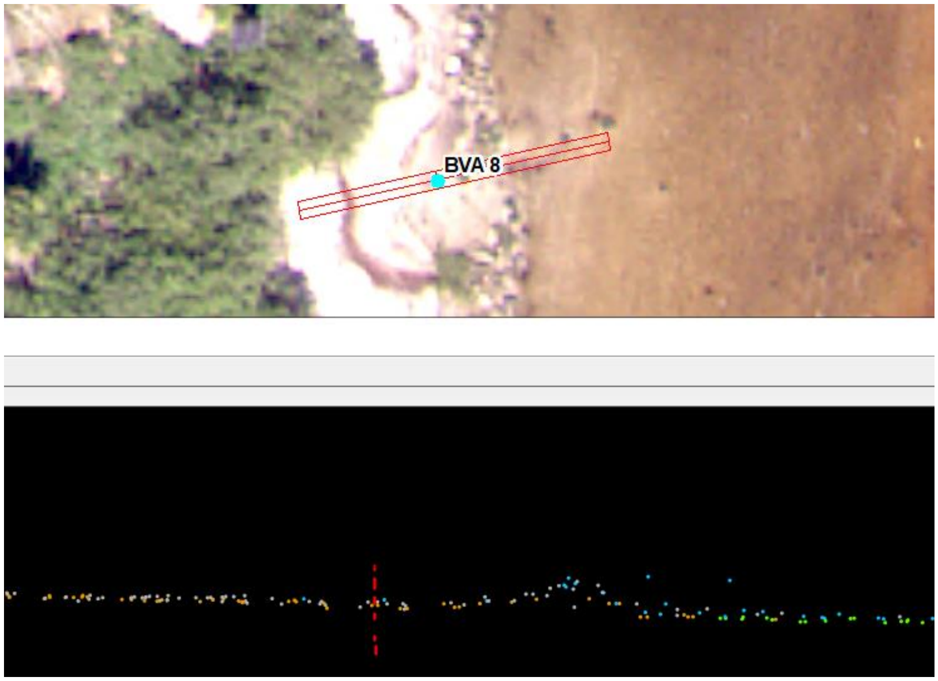

Figure 10. BVA 8 was collected in a tidepool containing rocks and submerged aquatic vegetation, and the resulting DZ is skewed higher.

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 Indian River Lagoon Bathymetric 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 accounts for increasing uncertainty with depth using two uncertainty coefficients. For the Indian River Lagoon Bathymetric 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 95^{th} percentile error for all checkpoints in all vegetated land cover categories combined. The Indian River Lagoon Bathymetric lidar project VVA specification is 30.0 cm based on the 95^{th} percentile. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95^{th} 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 6.

Table 6. 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 7 summarizes the tested vertical accuracy of the classified lidar LAS files.

Table 7. 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	46	0.086		
BVA	7		0.291	
VVA	33			0.207

The topographic portion of this lidar 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 $RMSE_z$ = 4.4 cm, equating to ± 8.6 cm at 95% confidence level. Actual VVA accuracy was found to be ± 20.7 cm at the 95th percentile. The bathymetric portion of this lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 30.0 cm $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 14.8 cm, equating to ± 29.1 cm at 95% confidence level.

The VVA 5% outliers are listed in Table 8. Descriptive statistics for all categories are presented in Table 9.

Table 8. Lidar 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	
VVA 23	537129.264	3116489.291	-27.559	-27.350	0.210
VVA 31	555173.610	3080018.276	-27.689	-27.479	0.210

Table 9. 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	46	0.044	-0.005	-0.006	0.105	0.044	-0.093	0.076	-0.570
BVA	7	0.148	0.124	0.077	1.107	0.088	0.054	0.255	-0.940
VVA	33	N/A	0.055	0.047	0.769	0.078	-0.068	0.210	-0.133

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the Indian River Lagoon Bathymetric project satisfies the project's pre-defined vertical accuracy criteria.

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.

Dewberry's process for generating the final topobathymetric DEMs includes using LAStools ('blast2dem' function) to generate DEMs from the final classified lidar points in bare earth classes—class 2 for bare-earth ground, class 40 for submerged topography (bathymetry), and class 43 for submerged objects. At this step, every point classified as 2, 40, or 43 is used and represented in the interim DEM. A density grid is then generated to identify pixels intersecting the input lidar points (classes 2, 40, and 43). Pixels which are Null/NoData and do not intersect or contain an input lidar point are then identified and aggregated to build the void polygon, which is used to enforce voids/limit interpolation in the final DEMs. The initial void polygon then goes through a cleaning and smoothing process to eliminate jagged edges and close small holes within the void polygon.

It is during the smoothing and cleaning process that grounded lidar points, typically along the terminal edge of bathymetry, become aggregated within the final void polygon, resulting in their omission from the final topobathymetric DEMs. Typically, it is individual, non-aggregated pixels which are removed from the final DEMs.

Dewberry's process utilizes the 9 square meter threshold in both the minimum void size enforced in the final DEMs and as the threshold for eliminating small holes within void polygons. Dewberry's process does allow for manipulation and change of several parameters, including an internal gap measurement between points, the small hole fill within void polygon threshold, and the overall minimum void size threshold, all of which could be modified.

Dewberry's topobathymetric DEM generation process is further described in a separate memo that was delivered to NOAA.

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 86 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 ArcMap 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 10 summarizes the tested vertical accuracy results from the final DEM dataset.

Table 10. DEM vertical accuracy results

Land Cover Type	# of Points	NVA (m)	BVA (m)	VVA (m)
Project Specification		**0.196**	**0.588**	**0.300**
NVA	46	0.088		
BVA	7		0.284	
VVA	33			0.203

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 $RMSE_z$ = 4.5 cm, equating to ± 8.8 cm at 95% confidence level. Actual VVA accuracy was found to be ± 20.3 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 a 30.0 cm $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 14.5 cm, equating to ± 28.4 cm at 95% confidence level.

The VVA 5% outliers are listed in Table 11. Descriptive statistics for all categories are presented in Table 12.

Table 11. VVA 5% outliers

Point ID	UTM zone 17N NAD83(2011), m		NAVD88 Geoid 18, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
VVA 17	515121.652	3182631.576	0.732	0.946	0.214
VVA 23	537129.264	3116489.291	0.707	0.910	0.203

Table 12. 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	46	0.045	-0.006	-0.012	0.118	0.045	-0.094	0.090	-0.635
BVA	7	0.145	0.121	0.067	0.988	0.087	0.048	0.245	-1.164
VVA	33	N/A	0.051	0.026	0.647	0.082	-0.069	0.214	-0.448

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the Indian River Lagoon Bathymetric 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

Digital Aerial Solutions, LLC (DAS) was tasked by Dewberry to acquire four-band (Red, Green, Blue, and Near-Infrared or RGBNIR channels) digital imagery covering the project area and to perform the aerotriangulation and processing of the imagery.

8.1 Orthoimagery Processing and Qualitative Assessment

The imagery was collected using a Leica ADS100 sensor. The surface model generated from the lidar dataset collected for this project was used as the orthorectification reference surface. Four-band (RGBNIR), uncompressed orthoimage tiles (3000 m x 3000 m) in GeoTIFF format at 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 North

Units: Meters

The orthomosaic formatting was verified for adherence to project parameters. Tiles were loaded into ArcGIS or Global Mapper software to verify completeness, continuity, and integrity. A manual review was performed 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 45 checkpoints to compute the horizontal accuracy of the orthoimagery.

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

$$Accuracy_r = RMSE_r \times 1.7308$$

where:

$$RMSE_r = \sqrt{RMSE_x^2 + RMSE_y^2}$$

The results of the horizontal accuracy calculations are provided in Table 13.

Table 13. Orthoimagery horizontal accuracy results

# of Points	$RMSE_x$ (Spec=0.450 m)	$RMSE_y$ (Spec=0.450 m)	$RMSE_r$ (Spec=0.636 m)	$ACCURACY_r$ ($RMSE_r$ x 1.7308) Spec=1.101 m
45	0.146	0.106	0.181	0.313

This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 45 cm $RMSE_x$/$RMSE_y$ Horizontal Accuracy Class. Using 45 photo-identifiable checkpoints, actual positional accuracy for this dataset was found to be $RMSE_x$ = 14.6 cm and $RMSE_y$ = 10.6 cm, which equates to +/- 31.3 cm at 95% confidence level.

8.3 Orthoimagery Deliverables

In addition to the image strips, ortho-mosaic tiles, and orthoimagery tile grid, several imagery reports and pieces of documentation were delivered to NOAA as part of the imagery deliverables. These include:

- 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