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Great Lakes Benthic Mapping in Northern Green Bay

Quality Assurance Report Produced for the National Oceanic and Atmospheric Administration, Office for Coastal Management National Ocean Service

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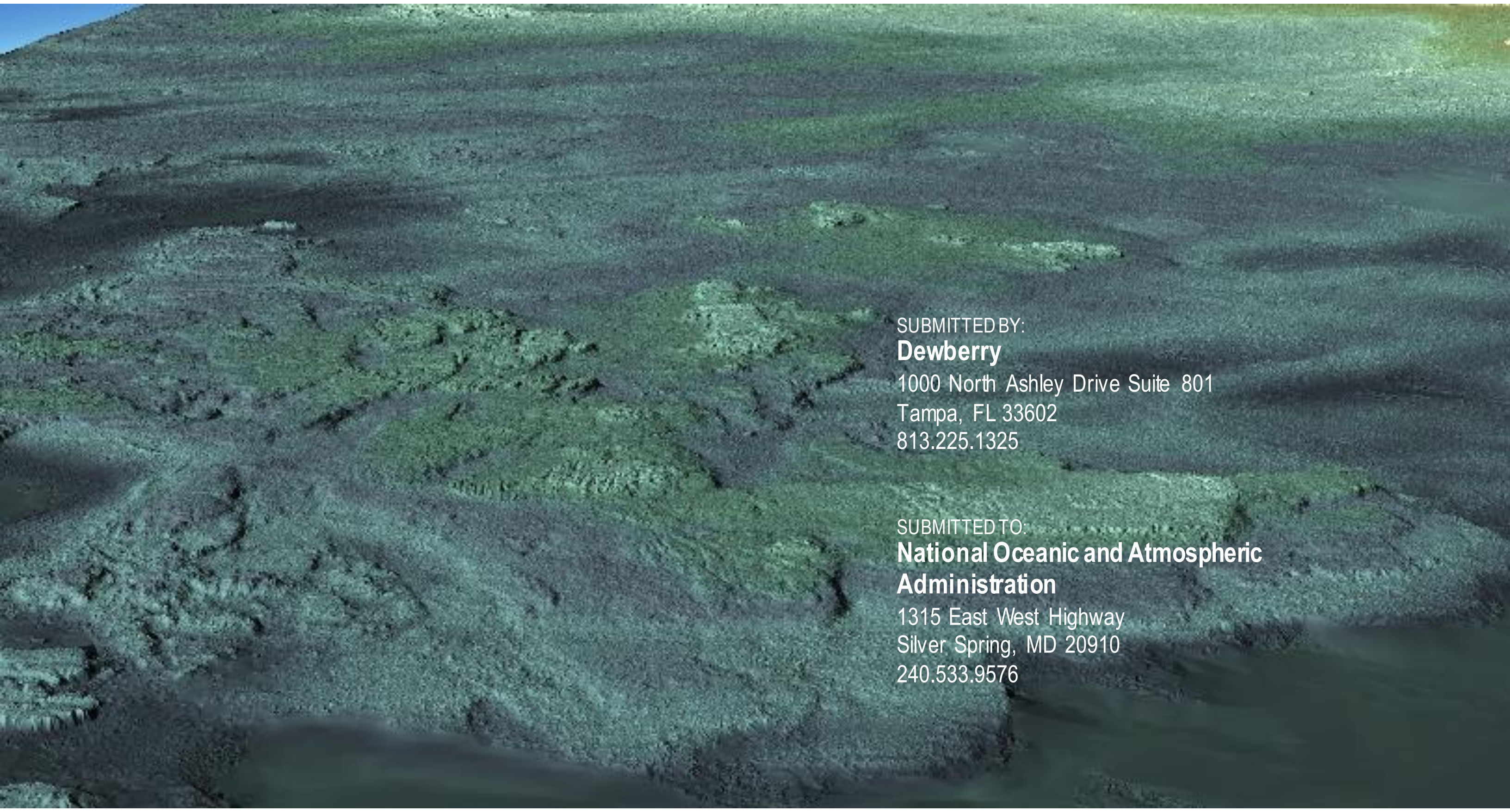

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1. EXECUTIVE SUMMARY

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) Green Bay Topobathy 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 one tiled grid: tiled according to a 500 m by 500 m tile grid, with a total of 2,630 tiles produced. Approximately 219 sq. miles of coverage is provided.

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, Digital Elevation Model (DEM) production, and quality assurance.

Dewberry's survey team, which included Ayres, 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.

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

1.2 Survey Area

The Green Bay Topobathy Project area covers approximately 219 square miles. There are 2,630 500 m x 500 m tiles delivered for the project area. The project area boundary and overview are shown in Figure 1.

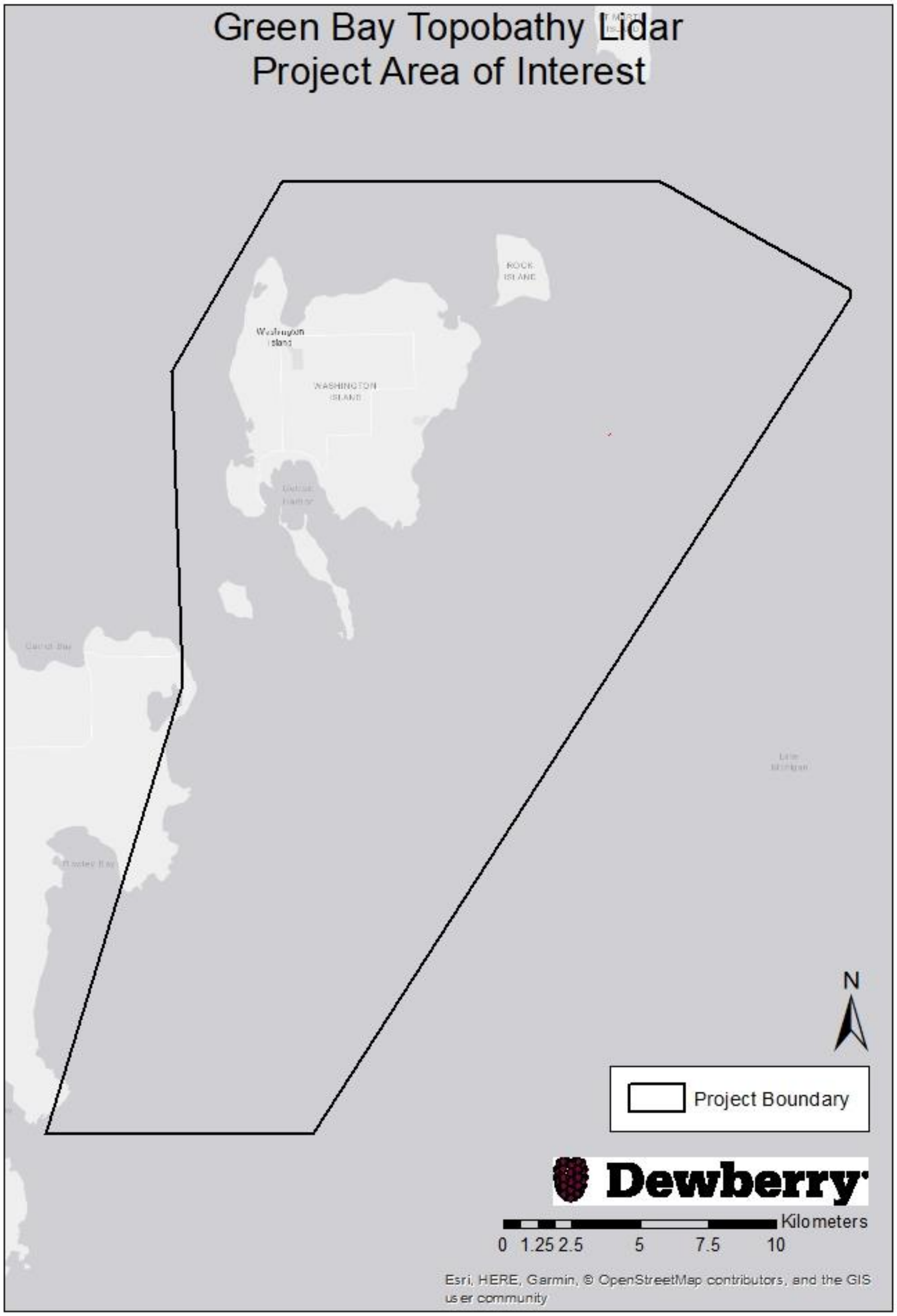

Figure 1. The image shows Green Bay Topobathy Project collection area.

1.3 Date of Survey

The lidar aerial acquisition was conducted from July 19, 2022 through August 16, 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 (NAD 83)

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

Coordinate System: UTM zone 16

Units: Meters

Geiod Model: Geoid18

1.5 Lidar Vertical Accuracy

For the Green Bay Topobathy Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain is **7.2 cm** and the non-vegetated vertical accuracy (NVA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **14.2 cm**.

For the Green Bay Topobathy Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in submerged topography is **13.2 cm** and the bathymetric vertical accuracy (BVA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **25.8 cm**.

For the Green Bay Topobathy Project, the tested vegetated vertical accuracy (VVA) of the classified lidar data computed using the 95^{th} percentile is **18.2 cm**.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and topobathymetric DEM data are found in sections 2, 5, and 6 of this report.

2. LIDAR ACQUISITION CONTROL

Dewberry acquired and calibrated the lidar data for this project. Acquisition was completed on August 16, 2022.

2.1 Lidar Acquisition Static Control

The airborne lidar data was post-processed with Applanix IN-Fusion PP-RTX, a Precise Point Position (PPP) processing solution. Therefore, no static base station control was required.

2.2 Airborn Kinematic Control

Airborne INS-GPS data was processed using the PosPac software suite. Flights were flown with a minimum of 14 satellites in view and with PDOP less than 2.

The Position Error RMS for all missions of the project was under 3.9cm in the down direction, and 1.9cm in the North and East position.

INS-GPS trajectory processing reports for each mission are attached as Appendix A.

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.

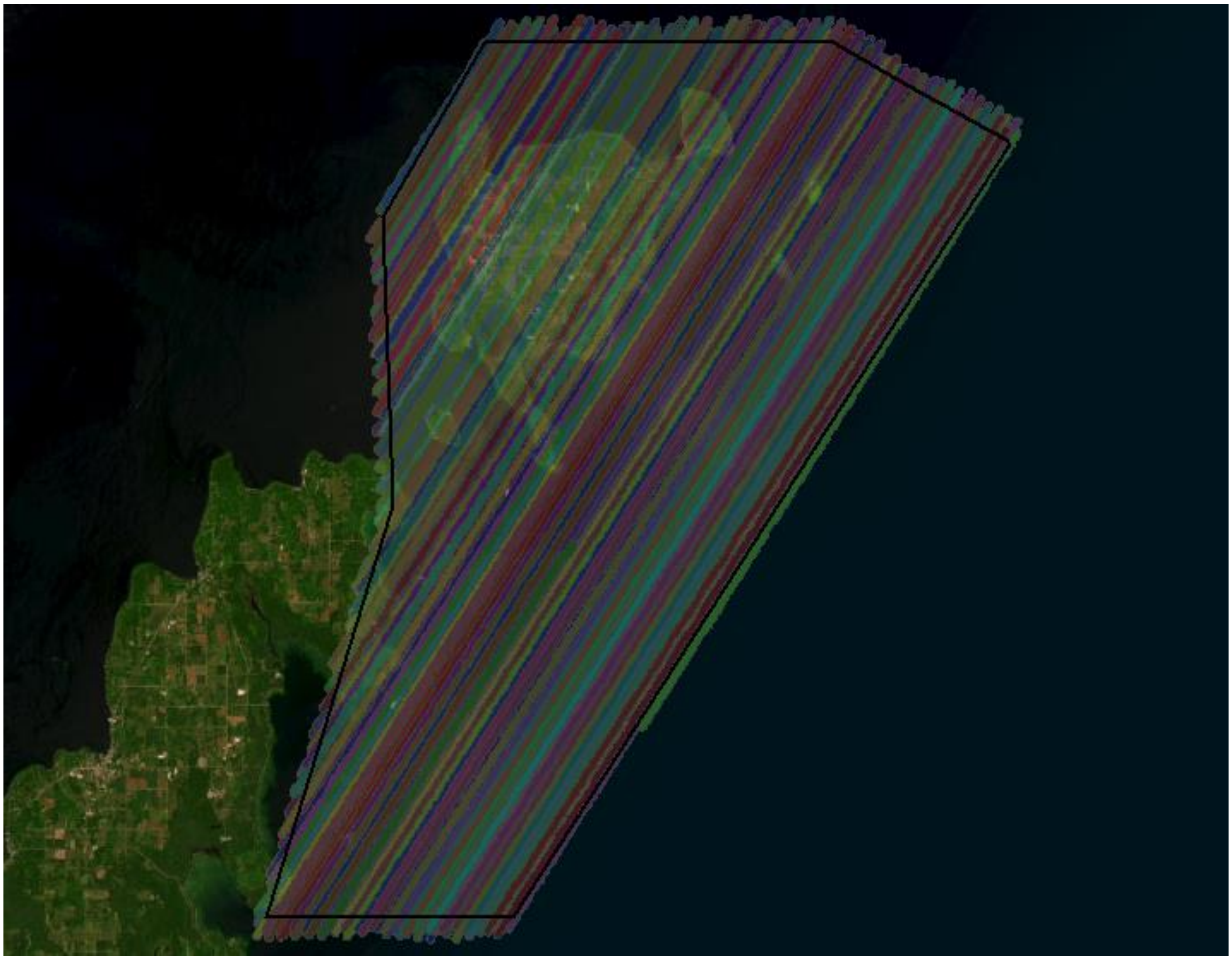

Figure 2. Lidar swath output showing complete coverage.

2.4 Boresight and Relative accuracy

The initial 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. 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.

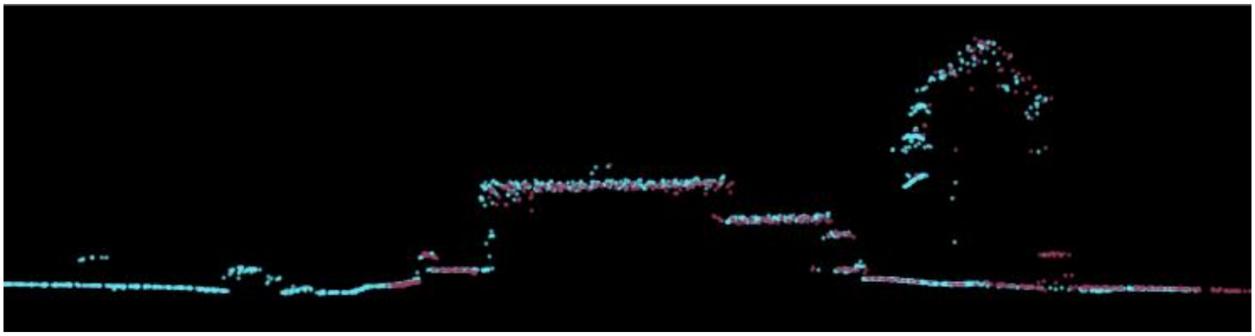

Figure 3. Profile views showing results of roll and pitch adjustments.

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 Green Bay lidar dataset was tested to 0.044 m $RMSE_z$ and 0.087 m vertical accuracy at the 95% confidence level when compared to 20 surveyed control points (Table 1) surveyed by Dewberry. The results of the preliminary vertical accuracy assessment conducted by Dewberry are summarized in Table 2.

The lidar data products calibrated 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. Surveyed GCP points used for preliminary vertical accuracy assessment.

Number	NAD83 UTM zone 16, m		NAVD88 Geoid 18, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
GCP_2	513359.615	5028493.608	144.385	144.390	0.005
GCP_7	511146.723	5027438.001	141.377	141.340	-0.037
GCP_14	505395.554	5026859.502	167.494	167.524	0.030
GCP_20	508690.821	5024851.551	160.854	160.854	0.000
GCP_23	508705.649	5023213.717	167.323	167.257	-0.066
GCP_26	504645.808	5020624.438	143.112	143.109	-0.003
GCP_28	504599.804	5021940.604	144.031	144.060	0.029
GCP_31	505614.653	5022997.882	151.053	151.048	-0.005

Number	NAD83 UTM zone 16, m		NAVD88 Geoid 18, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
GCP_37	509592.532	5020409.433	146.900	146.894	-0.006
GCP_40	501801.290	5015253.438	141.156	141.127	-0.029
GCP_41	501843.641	5014272.530	145.402	145.365	-0.037
GCP_42	502128.825	5013617.416	144.068	143.960	-0.108
GCP_45	501135.898	5011770.804	142.721	142.648	-0.073
GCP_48	503362.019	5016753.604	140.530	140.600	0.070
GCP_50	504068.729	5017659.560	141.591	141.640	0.049
GCP_64	505354.499	5020252.846	140.952	141.004	0.052
GCP_67	501881.527	5006178.955	141.570	141.602	0.032
GCP_69	500402.847	5008972.651	159.574	159.548	-0.026
GCP_72	501169.443	5009357.807	143.861	143.880	0.019
GCP_76	507095.582	5021948.371	159.297	159.280	-0.017

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	20	0.044	0.087	-0.006	0.045	-0.108	0.070

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 22 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 $RMSE_z$ = 5.8 cm, equating to ± 11.3 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 Green Bay Topobathy Project satisfied this criterion. 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	22	0.058	0.113	-0.014	-0.032	0.258	0.057	-0.133	0.091	-0.446

Checkpoint NVA 73 was removed from the raw swath vertical accuracy testing due to its location beneath a structure. Though NVA 73 was located in open terrain, the structure 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 structure was removed from the final ground classification and NVA 73 was usable in the final vertical accuracy testing, the results of which are reported in Section 5 of this report.

Table 4 illustrates the effect of the structure on the apparent positional accuracy of the lidar data by comparing the surveyed elevation of NVA 73 with the elevation of the surface generated from the raw swath data (which includes the power line). Table 5, with its much smaller delta z value, demonstrates that the effect of the structure is removed following classification of the lidar data. Figure 4 shows a 3D model of the lidar point cloud colored by elevation, with the location of the checkpoint beneath the structure marked by a pin.

Table 4. Vertical accuracy information for checkpoint removed from raw swath assessment.

Point ID	NAD83 UTM16N, m		NAVD88 Geoid 18, m		Delta z (sft)
	Easting (x)	Northing (y)	Survey z	Lidar z	
NVA_73	500870.278	5009058.139	149.121	143.889	-5.232

Table 5. Vertical accuracy information for checkpoint in final classified lidar.

Point ID	NAD83 UTM16N, m		NAVD88 Geoid 18, m		Delta z (sft)
	Easting (x)	Northing (y)	Survey z	Lidar z	
NVA 73	500870.278	5009058.139	186.261	186.211	-0.050

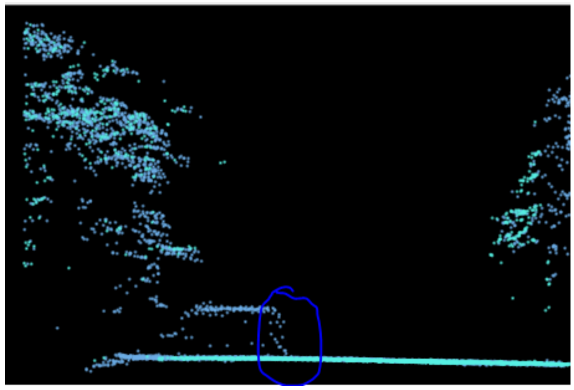

Figure 4. NVA 73 was removed from raw swath vertical accuracy testing because the structure.

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 relative accuracy of overlapping flight lines and final 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 between undifferentiated only returns in non-vegetated areas of overlap between flight lines. 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 colored by intensity.

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 (eg., 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 Green Bay Topobathy Project are shown in Figure 5. Based on visual inspection, no issues with swath-to-swath calibration were noted.

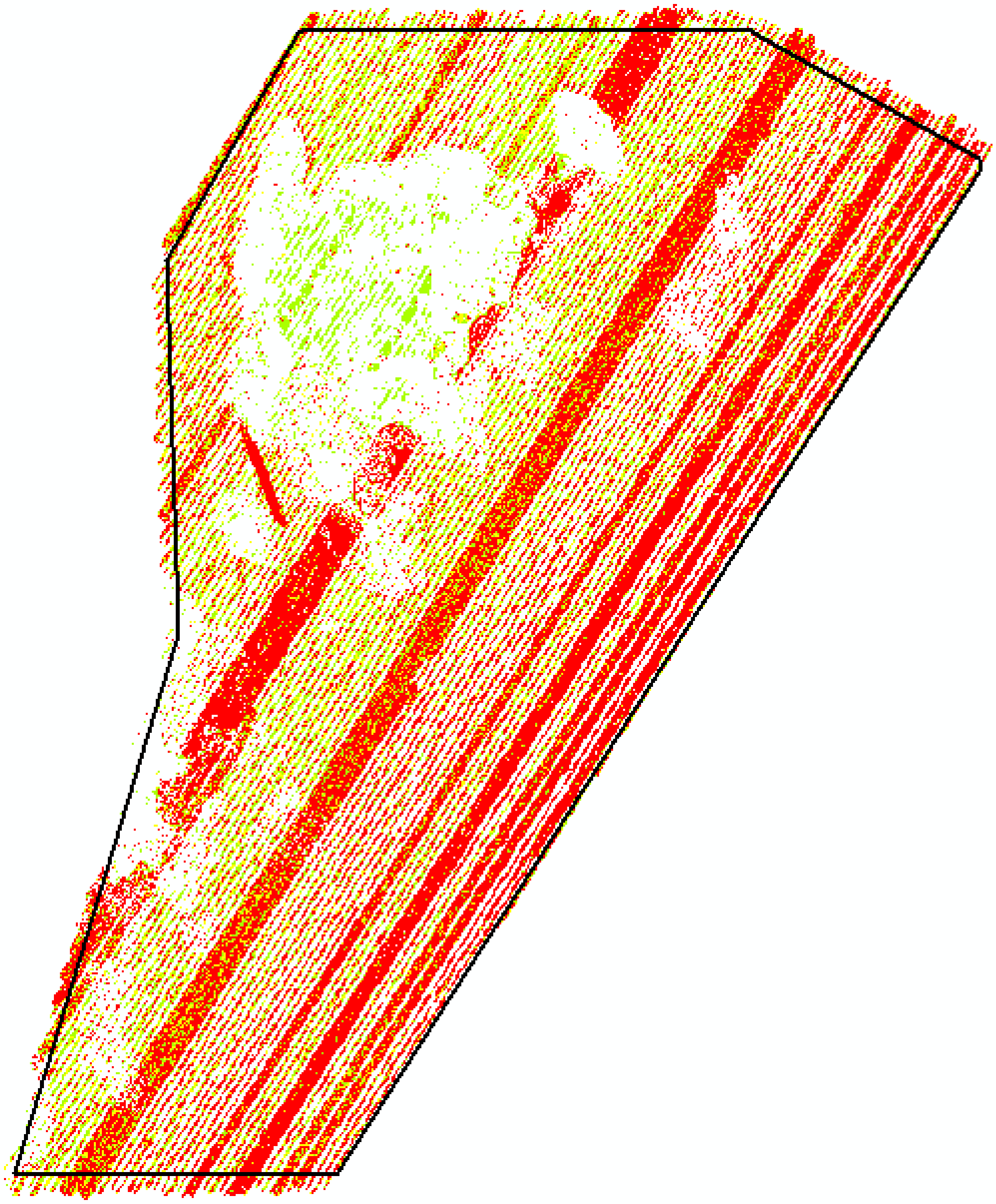

Figure 5. Single return interswath DZ rasters for the Green Bay Topobathy Project.

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 4.5 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 intraswath 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 max elevation difference between all points within a raster cell. 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 intraswath 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 of red pixels following terrain features or land cover zones are typically reflective of variable or unfavorable (eg., vegetated) conditions for within swath measurements, whereas large or continued sections of red pixels in flat, relatively featureless areas can indicate sensor issues. The intraswath rasters for Green Bay Topobathy Project are shown in Figure 6. Based on visual inspection, no issues with hard surface repeatability were noted.

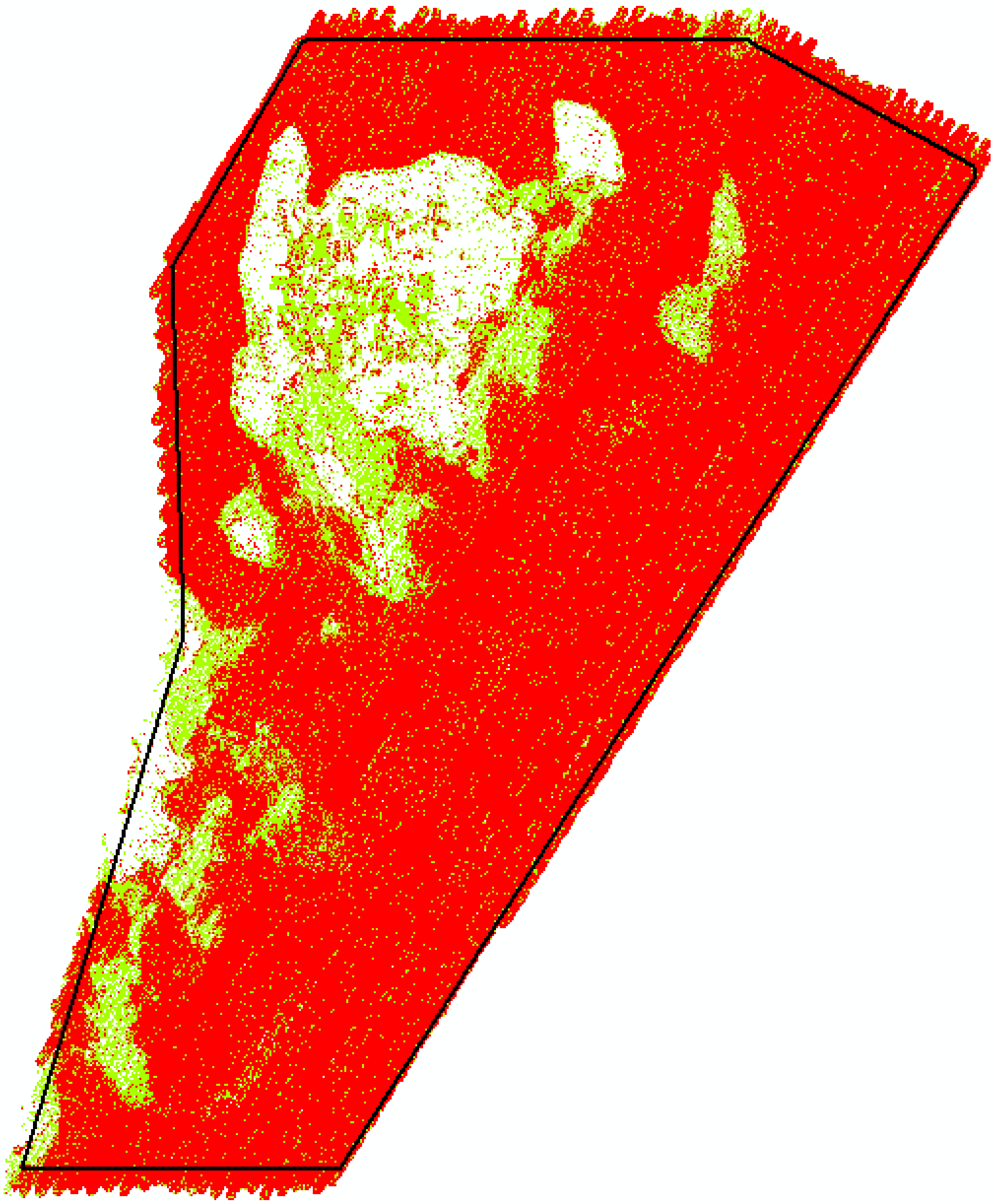

Figure 6. Intraswath rasters for the Green Bay Topobathy Project. Flat, open areas are colored green as they are within 6 cm whereas sloped terrain is colored red because it exceeds 6 cm maximum difference, as expected, due to actual slope/terrain change, water surface, and/or vegetation.

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 Green Bay Topobathy Project; no horizontal alignment issues were identified.

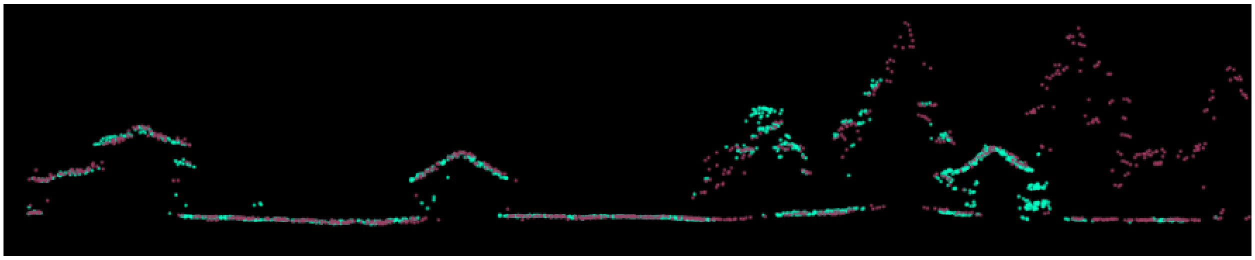

Figure 7. Two separate flight lines are differentiated by color (teal/maroon) to determine whether horizontal misalignments are present. This is a representative example; there is no visible offset between these flight lines.

3.1.5 Point Density

The required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 1 meter, which equates to an Aggregate Nominal Point Density (ANPD) of 1 point 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 0.52 meters (equivalent to an ANPD of 3.6 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. 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, noise, or geometrically unreliable outside the flight line overlap areas.

The final classification schema is detailed in Table 6.

Table 6. 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, or 45. 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	No-bathymetric-bottom-found

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; these points were classified to class 43 and a shapefile of their location was provided.

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 7.

Table 7. Lidar final format requirements

Parameter	Requirement
LAS Version	1.4
Point Data Record Format	6
Coordinate Reference System	NAD83 UTM zone 16, 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
Synthetic and Withheld Points	Synthetic and Withheld flags, properly set including all noise classes also 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 Flightline Extents GDB

Flightline extents are delivered as polygons in a shapefile delineating actual coverage of each swath used in the project deliverables. Dewberry delivered this shapefile 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.

4.3 WDPs

Waveform data packets (WDPs) are a way of storing full lidar waveform data detached from their accompanying individual .las files. This means that each WDP file contains full waveform data for each individual point. Because CARIS Base Editor was used to export the WDPs, they have been generated on a *per flightline* basis. Each WDP file follows this file naming convention:

- **CS11MD20221_P_220810_1930_A_00253**
    - **CS11MD20221 =** Sensor serial number
    - **220810 =** Acquisition date for the particular flightline (August 10, 2022)
    - **1930 =** Starting timestamp of the particular flightline (military time)
    - **00253 =** Unique ID for the paritcular flightline

As such, the date and unique ID within each WDP filename can be matched up with the Flightline Index deliverable for understanding spatial context.

4.4 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 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 coverage is the same as the final bathymetric extents and the pixels align, showing the lidar intensity at each bathymetric DEM grid cell.

4.5 DZ Orthoimages

Dewberry verified inter-swath or between swath relative accuracy of the dataset by generating DZ orthoimages in conjunction with interswath polygons. Color-coding is used to help visualize elevation differences between overlapping swaths. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values.

The swath separation images are symbolized by the following ranges:

- 0-8 cm: **Green**
- 8-16 cm: **Yellow**
- >16 cm: **Red**

Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across one raster pixel) are expected to appear yellow or red in the DZs. Flat, open areas are expected to be green in the DZs. Large or continuous sections of yellow or red pixels following flight line patterns and not the terrain or vegetation can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data.

Dewberry generated DZ orthoimages images using LP360 software. These images were created from the last return of all points except points classified as noise and/or flagged as withheld. Point Insertion was used as the Surface Method and the cell size was set to the deliverable DEM cell size. The three interval bins used are bulleted above and the parameter to “Modulate source differences by Intensity” was set to 50%. The output GeoTIFF rasters are tiled to the project tile grid, clipped to the master DPA, and formatted (including defining the CRS which matches the project CRS) using GDAL software, version 2.4.0.

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 46 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.

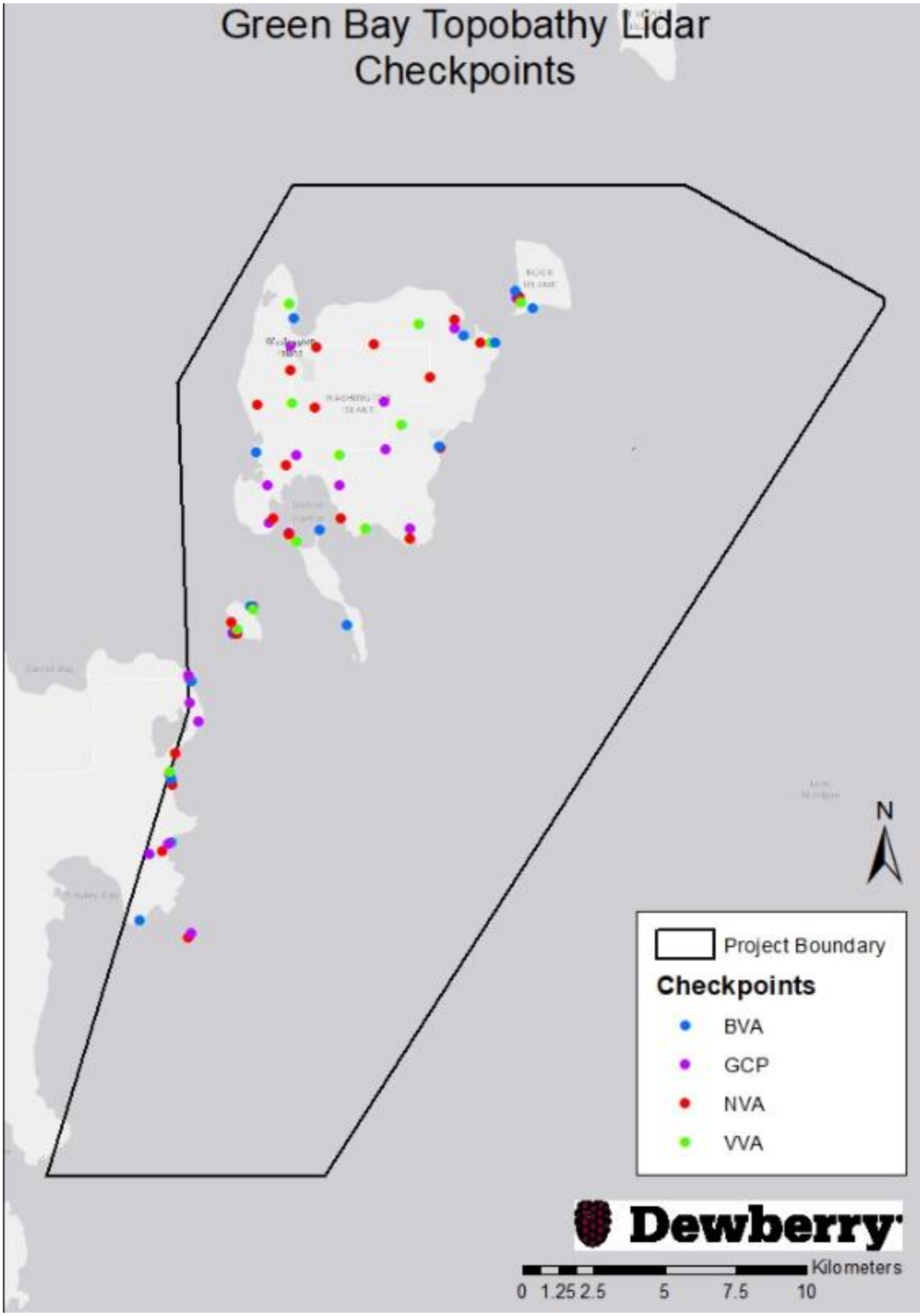

Figure 8. Location of all surveyed checkpoints

Dewberry surveyed 51 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 five bathy checkpoints. Three of these checkpoints (BVA_11, BVA_39, and BVA_61) were removed from the classified lidar vertical accuracy testing due to their location in shifting terrain (i.e. easily moved sandy or mucky bottom). Two checkpoints (BVA_15, and BVA_55) were located on a sloped/pebbled terrain. Per the task order, checkpoints should not be located within 5 meters of a significant change in slope. Breaks in the terrain may cause erroneous vertical accuracy results due to interpolation of the surface. Points on such terrain do not adequately test how well a sensor or a vegetation filtering technique performed. The coordinates of these checkpoints are provided in Table 8.

Table 8. Checkpoints removed from vertical accuracy testing

Point ID	NAD83 UTM 16, m		NAVD88 Geoid 18, m		Delta z, m
	Easting (x)	Northing (y)	Survey z	Lidar z	
BVA_15	505513.078	5027782.767	176.317	176.653	0.336
BVA_11	512580.257	5026950.668	176.535	176.829	0.294
BVA_39	501878.174	5015032.393	176.286	176.547	0.261
BVA_55	503962.553	5017685.607	176.060	176.305	0.245
BVA_61	506378.686	5020349.977	176.361	176.617	0.256

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 Green Bay Topobathy 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 $RMSE_z$ specification is 15.0 cm. For the Green Bay Topobathy Project, bathymetric vertical accuracy specification is 29.4 cm or less based on an $RMSE_z$ of 15.0 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 Green Bay Topobathy 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 9.

Table 9. 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	29.4 cm
VVA	Accuracy in vegetated land cover categories combined at the 95th percentile	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 10 summarizes the tested vertical accuracy of the classified lidar LAS files.

Table 10. Classified lidar vertical accuracy results

Land Cover Type	# of Points	NVA (m)	BVA (m)	VVA (m)
Project Specification		**0.196**	**0.294**	**0.300**
NVA	22	0.142		
BVA	10		0.258	
VVA	14			0.182

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 $RMSE_z$ = 7.2 cm, equating to ± 14.2 cm at 95% confidence level. Actual VVA accuracy was found to be ± 18.2 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 15.0 cm $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 13.2 cm, equating to ± 25.8 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	NAD83 UTM16, m		NAVD88 Geoid 18, m		Delta z, m
	Easting (x)	Northing (y)	Survey z	Lidar z	
VVA_51	503511.268	5016873.281	181.764	181.949	0.185

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	22	0.072	0.003	-0.016	0.312	0.074	-0.133	0.141	-0.681
VVA	14	N/A	0.051	0.021	0.929	0.071	-0.034	0.185	-0.274
BVA	10	0.132	0.122	0.114	0.142	0.053	0.049	0.206	-0.894

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the Green Bay Topobathy 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.

The DEM bare earth surface was sourced 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 object. Void polygons were enforced in the final raster to delineate areas larger than 9 square meters where no valid bathymetric returns were received. The DEM was reviewed for any issues requiring corrections, including 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 46 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 ArcGIS to test the DEM vertical accuracy.

Table 13 summarizes the tested vertical accuracy results from the final DEM dataset.

Table 13. DEM vertical accuracy results

Land Cover Type	# of Points	NVA (m)	BVA (m)	VVA (m)
Project Specification		**0.196**	**0.294**	**0.300**
NVA	22	0.141		
BVA	10		0.281	
VVA	14			0.158

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 $RMSE_z$ = 7.2 cm, equating to ± 14.1 cm at 95% confidence level. Actual VVA accuracy was found to be ± 15.8 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 15 cm $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 14.3 cm, equating to ± 28.1 cm at 95% confidence level.

The VVA 5% outliers are listed in Table 14. Descriptive statistics for all categories are presented in Table 15.

Table 14. VVA 5% outliers

Point ID	UTM zone 16N NAD83, m		NAVD88 Geoid 18, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
VVA_51	503511.268	5016873.281	181.764	181.939	0.175

Table 15. 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	22	0.072	-0.001	-0.023	0.292	0.073	-0.137	0.145	-0.718
VVA	14	N/A	0.054	0.037	0.741	0.064	-0.031	0.175	-0.586
BVA	10	0.143	0.132	0.117	0.247	0.058	0.054	0.214	-1.479

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the Green Bay Topobathy 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, and intensity imagery. All metadata files are FGDC compliant and were verified to be error-free according to the USGS MetaParser utility.