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Great Lakes Topobathy Project

Report Produced for NOAA

Client Contract: 1305M223FNCNP0208

Task Order: 1305M221DNCNP0017

Report Date: November 1, 2024

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Appendix A: Mission GPS and IMU Processing Reports

1. EXECUTIVE SUMMARY

The primary purpose of this project was to develop a consistent and accurate surface elevation dataset derived from high-accuracy Light Detection and Ranging (lidar) technology for the Great Lakes Topobathy Project Area.

Lidar data and derivative products produced in compliance with this task order are based on the "U.S. Geological Survey National Geospatial Program LIDAR Base Specification, Version 1.3". The lidar data were processed and classified according to project specifications. Detailed breaklines and bare-earth Digital Elevation Models (DEMs) were produced for the project area. Data was formatted according to tiles with each tile covering an area of 500 m by 500 m. A total of 8, 983 lidar tiles were produced for the project encompassing an area of approximately 627 sq. miles.

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 completed the ground survey for the project and delivered surveyed checkpoints. Ground control points and checkpoints were surveyed for the project. Ground control points were used in calibration activities and checkpoints were used in independent testing of the vertical accuracy of the lidar-derived surface model.

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

1.2 Project Area

The project area is shown in Figure 1.

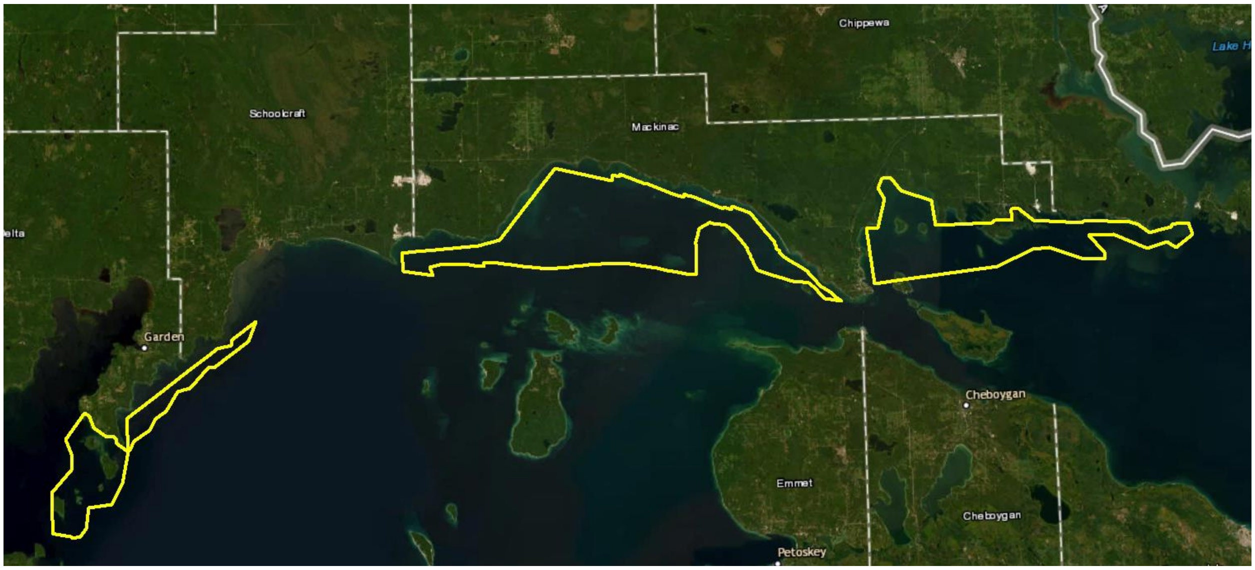


Figure 1. Project AOI.

1.3 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 16N
Units: Meters
Geoid Model: Geoid18

1.4 Project Deliverables

The deliverables for the project are listed below.

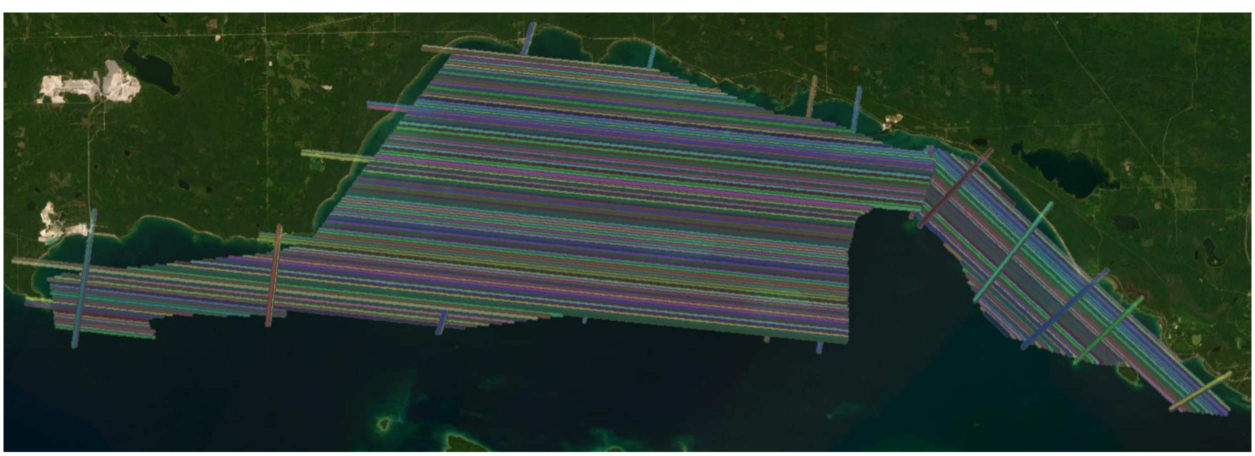
1. Classified Point Cloud (tiled LAS)
2. Bare Earth Surface (Raster DEM – Cloud Optimized GeoTIFF Format)
3. Reflectance Grids(tiled, 8-bit gray scale, GeoTIFF format)
4. DZ Orthoimages (tiled raster, GeoTIFF format)
5. Independent Survey Checkpoint Data (report, photos, coordinates, Esri shapefiles)
6. Calibration Points (report, photos, coordinates, Esri shapefile)
7. Metadata (XML)
8. Project Report
9. Project Extents
10. Flightline Extents SHP
11. Void Polygons

2. LIDAR ACQUISITION CONTROL

Dewberry acquired, processed, and calibrated the lidar data for this project. Acquisition was completed on October 05, 2023.

2.1 Acquisition Extents

Figure 2 shows flightline vectors by lift.



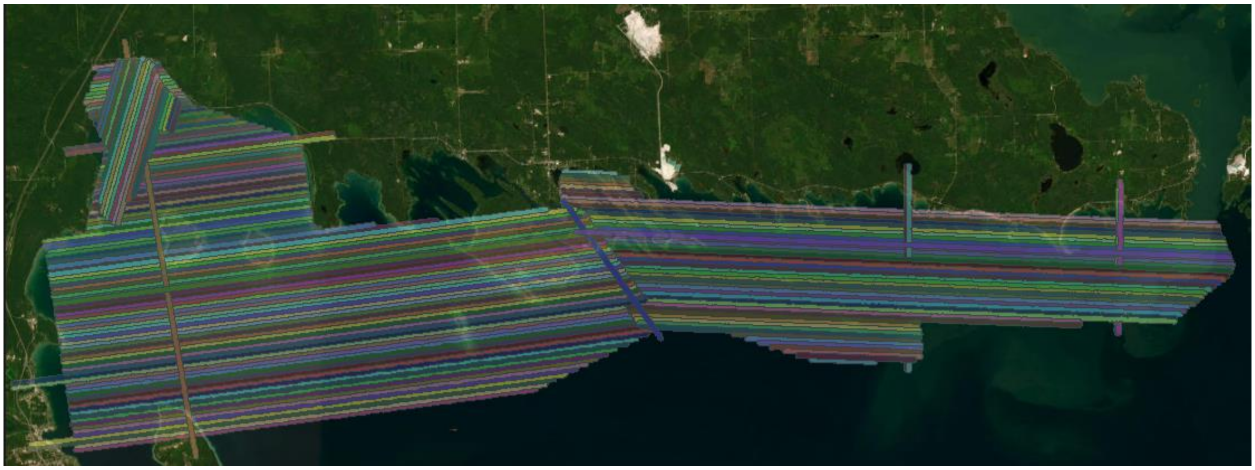


Figure 2. Project swaths

2.2 Acquisition Summary

Dewberry planned 474 passes for the project area as a series of parallel flight lines with cross flightlines for the purposes of quality control. The flight plan included zigzag flight line collection as a result of the inherent IMU drift associated with all IMU systems. In order to reduce any margin for error in the flight plan, Dewberry followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using Teledyne Airborne Mission Manager (AMM) flight design software for direct integration into the aircraft flight navigation system.
- Planned flight lines; flight line numbers; and coverage area.
- Lidar coverage extended by a predetermined margin beyond all project borders to ensure necessary over-edge coverage appropriate for specific task order deliverables.
- Local restrictions related to air space and any controlled areas have been investigated so that required permissions can be obtained in a timely manner with respect to schedule. Additionally, Dewberry filed flight plans as required by local Air Traffic Control (ATC) prior to each mission.

Dewberry monitored weather and atmospheric conditions and conducted lidar missions only when no conditions exist below the sensor that will affect the collection of data. These conditions include leaf-off for hardwoods, no snow, rain, fog, smoke, mist, and low clouds. Low clouds and fog in particular were common, and flights were often delayed until they lifted or burned off.

Dewberry accessed reliable weather sites and indicators (webcams), including the NOAA CoastWatch Great Lakes Node, to establish the highest probability for successful collection in order to position our sensor to maximize successful data acquisition.

Within 72-hours prior to the planned day(s) of acquisition, Dewberry closely monitored the weather, checking all sources for forecasts at least twice daily. As soon as weather conditions were conducive to acquisition, our aircraft mobilized to the project site to begin data collection. Once on site, the acquisition team took responsibility for weather analysis.

Acquisition started on September 14, 2023 and was completed on October 5, 2023. This included all necessary reflights, the majority of were replanned lines to improve bathymetric bottom coverage. One group of lines was at the entrance to Green Bay and a second group of lines in Lake Huron north of Big St. Martin Island.

2.3 Sensor Calibration and Boresight

Prior to project acquisition, Dewberry completed a sensor boresight on September 8-9, 2023 in Kiln, MS and a bathymetric depth calibration near Fort Lauderdale, FL on September 12, 2023. The boresight consisted of multiple opposing lines in an E-W direction as well as multiple opposing lines in a N-S direction. The swaths have a large overlap (>60%) with neighbors. The trajectory (.sbet) was processed using Applanix POSPac and raw swath data (.las) was produced using Caris BaseEditor. The boresight was calibrated and then analyzed. All deemed necessary corrections are then applied to the senor orientation internal files.

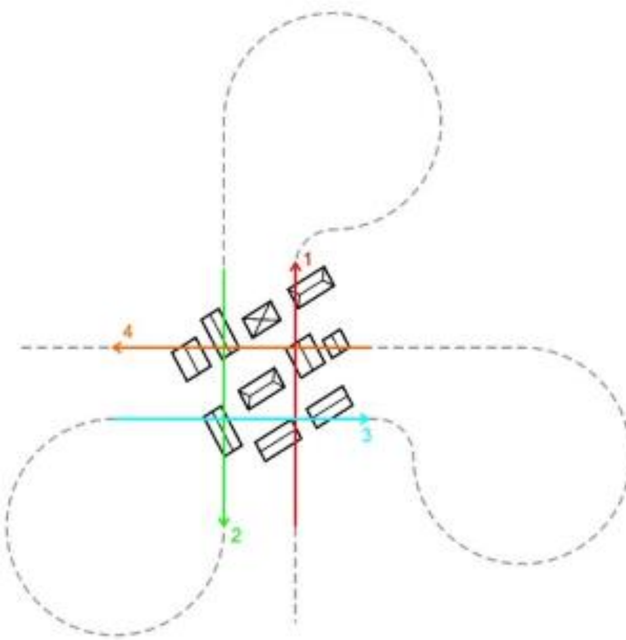


Figure 3. A typical calibration and boresight flight plan where above ground features are acquired from all four cardinal directions, any offsets of the above ground features between overlapping and other directional flight lines are analyzed, and corrections are applied as necessary to ensure proper configuration of the sensor

2.4 Lidar Acquisition and Processing Details

Table 1 outlines lidar acquisition details, including the project spatial reference system, and processing software used for this project.

Table 1. Lidar acquisition details

Parameter	Value
Number of Flight lines	474
Approximate Area	627 sq. miles
Acquisition Dates	September 14, 2023 – October 5, 2023

Horizontal Datum	North American Datum of 1983 (NAD83)
Vertical Datum	North American Vertical Datum of 1988 (NAVD88)
Geoid Model	Geoid18
Coordinate Reference System	UTM Zone 16N and 17N
Horizontal Units	Meters
Vertical Units	Meters
Kinematic Solution Processing Software:	Applanix POSPac MMS
Point Cloud Generation Software	Caris Base Editor
Calibration Software	BayesMap StripAlign

2.5 Lidar System Parameters

Dewberry operated a Cessna 208B (Tail # N119RF) outfitted with a Teledyne CZMIL Supernova lidar system during the collection of the study area. Table 2 details the lidar system parameters used during acquisition for this project.

Table 2: Dewberry lidar system parameters

Item	Parameter
System	Teledyne CZMIL Supernova
Altitude (AGL meters)	400
Approx. Flight Speed (knots)	130
Scanner Pulse Rate (kHz)	140
Scan Frequency (hz)	27
Pulse Duration of the Scanner (nanoseconds)	1.2-2.1
Pulse Width of the Scanner (m)	Proprietary
Swath width (m)	290
Central Wavelength of the Sensor Laser (nanometers)	532
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	Yes
Beam Divergence (milliradians)	5
Nominal Swath Width on the Ground (m)	290
Swath Overlap (%)	30
Total Sensor Scan Angle (degree)	40
Nominal Pulse Spacing (single swath), (m)	.38
Nominal Pulse Density (single swath) (ppsm), (m)	7
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	.38
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	7
Maximum Number of Returns per Pulse	15

2.6 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.

2.7 Airborne Kinematic Control

Airborne GPS data was processed using the POSPac Mobile Mapping Suite (MMS) software. Flights were flown with a minimum of 14 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.

GPS processing reports for each mission are provided in Appendix A: Mission GPS and IMU Processing Reports.

2.8 ABGNSS-Inertial Processing

ABGNSS-Inertial processing was performed using the software identified in Table 3. The reference frame used for this processing does not always match the project spatial reference.

Appendix A contains additional mission GPS and IMU processing covering:

- POSPac graphics and processing
- Graphics of any reference stations used for differential correction
- Graphics of processing interface to show trajectory data and labeled reference stations for each lift (only graphics of trajectory when precise point position is used).
- Graphics of processed plots for each mission/flight/lift to include:
    1. Forward/reverse separation of trajectory
    2. Estimated accuracy of trajectory
    3. Any additional plots used in the analyses of trajectory quality

Table 3. Spatial reference system used for ABGNSS-Inertial processing

Parameter	Value
Horizontal Datum	North American Datum of 1983 (NAD83)
Vertical Datum	North American Vertical Datum of 1988 (NAVD88)
Geoid Model	Geoid18
Coordinate Reference System	UTM Zone 16N
Horizontal Units	Meters
Vertical Units	Meters

2.9 Calibration Process (Project Mission Calibration)

Lidar mission flight trajectories were combined with waveform data within the Teledyne/Optech software CARIS Base Editor. Individual points were extracted from the waveforms using a combination of approaches based on flight, atmospheric, and water conditions for each mission. During waveform processing reflectance normalization was also conducted to better align the reflectance from the shallow channels and deep channel with Shallow Channel 1. This process accounts both for initial normalization as well as depth biasing for each channel. Upon export of the points (.las) each mission calibration were inspected for flight line errors, spatial distribution, data voids, density, or issues with the lidar sensor. If a calibration error greater than specification was observed within the mission, the necessary roll, pitch, and scanner scale corrections were calculated and corrections were applied to each individual swath using Terramatch software. In addition, all GPS, aircraft trajectory, mission information, and ground control files were reviewed and logged into a database. The missions with the new calibration values were regenerated and validated internally once again to ensure quality.

The methodology and assessment for the spatial distribution, density, and sensor anomaly reviews are outlined further in section 3.1.1 the Post Calibration Lidar Review.

2.10 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 refraction correction for this dataset was performed by Dewberry using proprietary software.

2.11 Final Calibration Verification

Dewberry surveyed 19 ground control points (GCPs) in flat, non-vegetated areas to test the accuracy of the calibrated swath data. GCPs were located in open, non-vegetated terrain. To assess the accuracy of calibration, the heights of the ground control points were compared with a surface derived from the calibrated swath lidar. A full list of GCPs used for accuracy testing is included in the GCP Survey Report provided with project deliverables.

Table 4.Summary of calibrated swath vertical accuracy tested with ground control points.

Land Cover Type	# of Points	$RMSE_z$ (m)	NVA (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Ground Control Points (GCPs)	19	0.050	0.099	0.038	0.034	-0.190	0.034	-0.030	0.104	0.118

3. LIDAR PROCESSING & QUALITATIVE ASSESSMENT

Dewberry acquired and calibrated the data for the Great Lakes Topobathy. Acquisition was completed on October 5, 2023.

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, and confirmation of point density and spatial distribution. This initial assessment allowed Dewberry to determine whether the data were suitable for full-scale production.

The methodology and assessment for the absolute and relative accuracy, density, and spatial distribution reviews performed are outlined further in the Post Calibration Lidar Review table.

3.1.1 Post Calibration Lidar Review

The table below identifies requirements verified by Dewberry prior to tiling the swath data, running initial ground macros, and starting manual classification.

Table 5. Post calibration and initial processing data verification steps.

Methodology and Requirement	Description of Deliverables	Additional Comments
Using proprietary software it was determined the non-vegetated vertical accuracy (NVA) of the swath data meet required specifications of 19.6 cm at the 95% confidence level based on RMSEz (10 cm) x 1.96	The swath NVA was tested and passed specifications.	None
Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing density mean statistics output by proprietary tool, the project area was determined to meet the required specification of 1 ppsm or 1 m NPS. A visual review of a 1-square meter density grid is also performed to confirm most 1-square meter cells satisfies the project requirements. Density is also viewed/analyzed by representative 1-square kilometer areas (to account for the irregular spacing of lidar point clouds) to	The average calculated (A)NPD of this project is 19.8 ppsm. Density raster visualization also passed specifications.	None

confirm density passes with no issues.		
The spatial distribution of points must be uniform and free of clustering. This specification is tested by creating a grid with cell sizes equal to the design NPS*2. Proprietary tools are then used to calculate the number of first return points of each swath within each grid cell. At least 90% of the cells must contain 1 lidar point, excluding acceptable void areas such as water or low NIR reflectivity features, i.e. some asphalt and roof composition materials. This project passes spatial distribution requirements, as shown in the image below.	99% of cells (2*NPS cell size) had at least 1 lidar point within the cell.	None
Within swath (Intra-swath or hard surface repeatability) relative accuracy must meet ≤ 6 cm maximum difference. Dewberry verifies the intra-swath or within swath relative accuracy by using proprietary scripting to output intra-swath rasters. Proprietary scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Dewberry performs a visual review of planar surfaces and ensures the data passes specification.	Within swath relative accuracy passed specification.	None
Between swath (Inter-swath or swath overlap) relative accuracy must meet 8 cm RMSDz/16 cm maximum difference. These thresholds are tested in open, flat terrain. Dewberry verifies the inter-swath or between swath relative accuracy by using proprietary	Between swath relative accuracy passed specification, calculated from single return lidar points.	None

scripting to output inter-swath rasters and LP360 generated Swath Separation Images which are both reviewed visually at multiple stages of production to ensure the data passes specification.		
Horizontal Calibration-There should not be horizontal offsets (or vertical offsets) between overlapping swaths that would negatively impact the accuracy of the data or the overall usability of the data. Assessments made on rooftops or other hard planar surfaces where available.	Horizontal calibration met project requirements.	None
Ground Penetration-The missions were planned appropriately to meet project density requirements and achieve as much ground penetration beneath vegetation as possible	Ground penetration beneath vegetation was acceptable.	None
Sensor Anomalies-The sensor should perform as expected without anomalies that negatively impact the usability of the data, including issues such as excessive sensor noise and intensity gain or range-walk issues	No sensor anomalies were present.	None
Edge of Flight line bits-These fields must show a minimum value of 0 and maximum value of 1 for each swath acquired, regardless of which type of sensor is used	Edge of Flight line bits were populated correctly	None
Scan Direction bits-These fields must show a minimum value of 0 and maximum value of 1 for each swath acquired with sensors using oscillating (back-and-forth) mirror scan mechanism. These fields should show a minimum and	Scan Direction bits were populated correctly	None

maximum of 0 for each swath acquired with Riegl sensors as these sensors use rotating mirrors.		
Swaths are in LAS v1.4 formatting	Swaths were in LAS v1.4 as required by the project.	None
All swaths must have File Source IDs assigned (these should equal the Point Source ID or the flight line number)	File Source IDs were correctly assigned	None
GPS timestamps must be in Adjusted GPS time format and Global Encoding field must also indicate Adjusted GPS timestamps	GPS timestamps were Adjusted GPS time and Global Encoding field were correctly set to 17	None
Intensity values must be 16-bit, with values ranging between 0-65,535	Intensity values were 16-bit	None
Point Source IDs must be populated and swath Point Source IDs should match the File Source IDs	Point Source IDs were assigned and match the File Source IDs	None

3.2 Data Classification and Editing

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data were confirmed, Dewberry utilized proprietary and TerraScan software for processing. The acquired 3D laser point clouds were tiled according to the project tile grid using proprietary software. 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 may be geometrically unusable were flagged as withheld 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.

This surface model was generated using four main parameters: building size, iteration angle, iteration distance, and maximum terrain angle. The initial model was based on low points being selected by a "roaming window" with the assumption that these were the ground points. The size of this roaming window was determined by the building size parameter. The low points were triangulated and the remaining points were evaluated and subsequently added to the model if they met the iteration angle and distance constraints. This process was repeated until no additional points were added within iterations. Points that did not relate to classified ground within the maximum terrain angle were not captured by the initial model.

After the initial automated ground routine, each tile was imported into TerraScan and a surface model was created to examine the ground classification. Dewberry analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing. Dewberry analysts employed 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points were removed from the ground classification. Bridge decks were classified to class 1. After the ground classification corrections were completed, the dataset was processed through a refraction extent creation to define the land/water interface and constrained void polygons.

The withheld bit was set on the withheld points previously identified in TerraScan before the ground classification routine was performed. The withheld bit was set on points classified as noise (classes 7 and 18) after manual clean-up. The synthetic bit was set on synthetic points previous identified by CARIS and TerraScan before the ground classification routine was performed. The synthetic bit was set on points classified was synthetic water surface (class 42).

After manual classification, the LAS tiles were peer reviewed and then underwent a final independent QA/QC. 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 software.

3.2.1 Qualitative Review

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, DSMs, and point density rasters. This assessment looked for incorrect classification and other errors sourced in the LAS data. Lidar data are peer reviewed, reviewed by task leads (senior level analysts), and verified by an independent QA/QC team at key points within the lidar workflow.

The following table describes Dewberry's standard editing and review guidelines for specific types of features, land covers, and lidar characteristics.

Table 6. Lidar editing and review guidelines.

Category	Editing Guideline	Additional Comments
No Data Voids	The SOW for the project defines unacceptable data voids as voids greater than 4 x $ANPS^2$, or 1.96 m^2 . Topographic areas should be free of voids unless related to low infrared reflectivity or appropriately filled by an adjacent/overlapping swath. Voids due to aircraft motion (topographic or bathymetric areas) must be reflown. Bathymetric voids may exist due to environmental conditions but best efforts should have been made to fill these voids through reflights.	Please see section 6.1 Void Polygons for information regarding remaining bathymetric voids.

Category	Editing Guideline	Additional Comments
	Remaining bathymetric voids, which could not be filled through reflights, must be geospatially identified and delivered as polygons.	
Topographic Artifacts	Artifacts in the point cloud are typically caused by misclassification of points in vegetation or man-made structures as ground. Low-lying vegetation and buildings are difficult for automated grounding algorithms to differentiate and often must be manually removed from the ground class. Dewberry identified these features during lidar editing and reclassified them to Class 1 (unassigned). Artifacts up to 0.3 m above the true ground surface may have been left as Class 2 because they do not negatively impact the usability of the dataset.	None
Bathymetric Artifacts	At or near laser extinction, bathymetric bottom tends to show diminishing returns and automated grounding can misclassify the water surface or water column as bathymetric bottom due to denser consistency of points. Dewberry identifies these features during lidar editing and reclassifies them to class 1 (unassigned), class 41 (water surface), or class 45 (water column) as appropriate while also looking to bring in any potential valid class 40 (bathymetric bottom).	None
Submerged Object	Submerged objects have been identified and manually classified as class 43 (Submerged Object).	Class 43 submerged objects have been identified and classified appropriately in this AOI.
Culverts and Bridges	It is Dewberry's standard operating procedure to leave culverts in the bare earth surface model and remove bridges from the model. In instances where it is difficult to determine whether the feature was a culvert or bridge, Dewberry errs on the side of culverts, especially if the feature is on a secondary or tertiary road.	None

Category	Editing Guideline	Additional Comments
In-Ground Structures	In-ground structures typically occur on military bases and at facilities designed for munitions testing and storage. When present, Dewberry identifies these structures in the project and includes them in the ground classification.	No in-ground structures present in this dataset
Dirt Mounds	Irregularities in the natural ground, including dirt piles and boulders, are common and may be misinterpreted as artifacts that should be removed. To verify their inclusion in the ground class, Dewberry checked the features for any points above or below the surface that might indicate vegetation or lidar penetration and reviews ancillary layers in these locations as well. Whenever determined to be natural or ground features, Dewberry edits the features to class 2 (ground)	No dirt mounds or other irregularities in the natural ground were present in this dataset
Flight Line Ridges	Flight line ridges occur when there is a difference in elevation between adjacent flight lines or swaths. If ridges are visible in the final DEMs, Dewberry ensures that any ridges remaining after editing and QA/QC are within project relative accuracy specifications.	Ridges may be visually present in the DEM surface but all were reviewed and found to be within project specification of 8cm or less.
Temporal Changes	If temporal differences are present in the dataset, the offsets are identified with a shapefile.	No temporal offsets are present in the data
Low NIR Reflectivity	Some materials, such as asphalt, tars, and other petroleum-based products, have low NIR reflectivity. Large-scale applications of these products, including roadways and roofing, may have diminished to absent lidar returns. USGS LBS allow for this characteristic of lidar but if low NIR reflectivity is causing voids in the final bare earth surface, these locations are identified with a shapefile.	No Low NIR Reflectivity is present in the data
Refraction Extents (Land-Water Interface)	The DEM voids are enforced in bathymetric regions- areas where	None.

Category	Editing Guideline	Additional Comments
	refraction has been applied. Refraction extents are auto-generated from refracted classes and later QC'd for any anomalies. Dewberry identifies missing features (e.g., small inland ponds) and incorrectly captured features (e.g., pools along shorelines) and manually adjusts the refraction extents. Refraction extents will also be manually adjusted to flow through/under manmade objects such as bridges or docks.	
Laser Shadowing	Shadows in the LAS can be caused when solid features like trees or buildings obstruct the lidar pulse, preventing data collection on one or more sides of these features. First return data is typically collected on the side of the feature facing toward the incident angle of transmission (toward the sensor), while the opposite side is not collected because the feature itself blocks the incoming laser pulses. Laser shadowing typically occurs in areas of single swath coverage because data is only collected from one direction. It can be more pronounced at the outer edges of the single coverage area where higher scanning angles correspond to more area obstructed by features. Building shadow in particular can be more pronounced in urban areas where structures are taller. Per specifications, reflights would occur if voids are present due to excessive building shadow. Within dense vegetation, data are edited to the fullest extent possible within the point cloud.	No Laser Shadowing is present in the data

3.2.2 Formatting Review

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 and the final formatting, header information, point data records, and variable length records were verified using proprietary tools. The table below lists the primary lidar header fields that are updated and verified.

Table 7. Classified lidar formatting parameters

Parameter	Project Specification	Pass/Fail
LAS Version	1.4	Pass
Point Data Record Format	6	Pass
Horizontal Coordinate Reference System	NAD83 UTM Zone 16N, meters in WKT format	Pass
Vertical Coordinate Reference System	NAVD88 (Geoid18), meters in WKT format	Pass
Global Encoder Bit	17 for adjusted GPS time	Pass
Time Stamp	Adjusted GPS time (unique timestamps)	Pass
System ID	Sensor used to acquire data	Pass
Multiple Returns	The sensor shall be able to collect multiple returns per pulse and the return numbers are recorded	Pass
Intensity	16-bit intensity values recorded for each pulse	Pass
Classification	Class 0: Created, Never Classified Class 1: Unclassified Class 2: Ground Class 40: Bathymetric Point Class 41: Water Surface Class 42: Derived Water Surface Class 43: Submerged Object Class 44: IHO Object Class 45: No-bottom-found-at	Pass Classes Present: Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 18: High Noise Class 40: Bathymetric Point Class 41: Water Surface Class 42: Derived Water Surface Class 43: Submerged Object Class 45: No-bottom-found-at
Withheld and Synthetic Points	Withheld bits set for geometrically unreliable points and for noise points in classes 7 and 18. Synthetic bit set for synthetically derived points in class 42.	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Recorded for each pulse	Pass

3.2.3 Synthetic Points

Class 42, synthetic water surface points, are those points that are artificially generated by the CARIS processing software for the CZMIL SuperNOVA sensor as a part of the onboard refraction processing step. This dataset contains flagged synthetic points. Lidar Positional Accuracy

4.1 Background

Dewberry quantitatively tested the dataset by testing the vertical accuracy of the lidar. The vertical accuracy is tested by comparing the discrete measurement of the survey checkpoints to that of the interpolated value within the three closest lidar points that constitute the vertices of a three-dimensional triangular face of the TIN. Therefore, the result is that only a small sample of the lidar data is actually tested. However, there is an increased level of confidence with lidar data due to the relative accuracy. This relative accuracy in turn is based on how well one lidar point "fits" in comparison to the next contiguous lidar measurement and is verified as part of the initial processing. If the relative accuracy of a dataset is within specifications and the dataset passes vertical accuracy requirements at the location of survey checkpoints, the vertical accuracy results can be applied to the whole dataset with high confidence due to the passing relative accuracy. For accuracy testing, Dewberry typically uses proprietary software, which utilizes both Esri and lastools software within its workflow.

The Great Lakes Topobathy project AOI is almost completely offshore, significantly limiting the ability to collect surveyed checkpoints and control points within the AOI boundary. After discussion and coordination with NOAA, a modified process was determined to be acceptable, outlined below:

- Dewberry would collect transverse flightlines extending from the actual AOI onto shore see Figure 2.
- The transverse lines extending into topographic areas would cover hard surfaces where topographic control (GCPs) and/or Non-Vegetated Vertical Accuracy (NVA) checkpoints could be located. These transverse lines would also cover shallow bathymetric areas where Bathymetric Control Points (BCPs) and/or Bathymetric Vertical Accuracy (BVA) checkpoints could be collected near the GCPs/NVA checkpoints. See Figure 4 for the location of surveyed points outside of the official AOI boundary.
- Dewberry would minimally process the transverse lines. These lines would be processed enough to use for calibration adjustments (control points) and absolute vertical accuracy assessment (checkpoints) but would not be fully classified.
- Dewberry would first perform all channel-to-channel and then swath-to-swath relative adjustments for all project swaths within the actual AOI boundary.
- The transverse lines would then be tied to the control points in the shallow bathymetric and topographic areas.
- The tied transverse lines would then be compared to the project swaths, mean differences computed, and then mean difference applied as a bias to the entire set of project swaths (already adjusted relative to one another).
- Final positional accuracy (NVA and BVA) would be quantitatively measured by testing the transverse lines, which the project swaths were adjusted to match, against the surveyed checkpoints in the topographic areas and shallow bathymetric areas.
- Lastly, it was agreed that Vegetated Vertical Accuracy (VVA) checkpoints and horizontal accuracy checkpoints would not be collected nor tested for this project.

Dewberry followed the process, outlined above, and the results of the completed vertical accuracy testing for NVA and BVA are provided in the following sections.

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.

4.2 Survey Vertical Accuracy Checkpoints

The Great Lakes Topobathy encompasses approximately 627 square miles within the state of Michigan. The figure below shows the Great Lakes Topobathy project area and the checkpoints that were collected.

Figure 4. Project map checkpoints.

4.3 Vertical Accuracy Test Procedures

NVA (Non-vegetated Vertical Accuracy) 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.

BVA (Bathymetric Vertical Accuracy) 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. Because all of the bathymetric checkpoints for the Great Lakes Topobathy were surveyed at less than 1 m below the water surface, the $RMSE_z$ specification is 15.0 cm. For the Great Lakes Topobathy, bathymetric vertical accuracy specification is 29.4 cm or less based on an $RMSE_z$ of 15.0 cm x 1.9600.

The relevant testing criteria are summarized in Table 8.

Table 8. 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

4.4 Final Swath Vertical Accuracy Assessment

Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to additional processing. Dewberry tested the vertical accuracy of the swath data using the non-vegetated (open terrain and urban) independent survey checkpoints. The vertical accuracy is tested by comparing survey checkpoints in non-vegetated terrain to a triangulated irregular network (TIN) that is 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 techniques to remove vegetation, buildings, and other artifacts from the ground surface. Checkpoints are always compared to interpolated surfaces from the lidar point cloud because it is unlikely that a survey checkpoint will be located at the location of a discrete lidar point. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy. Table 9 below summarizes the swath project accuracy specification, the amount of NVA points tested, and the final tested swath accuracy results.

Table 9. Tested NVA and descriptive statistics from unclassified lidar swaths

100 % of Totals	# of Points	RMSEz (m) NVA	NVA (m) Spec=0.196	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	26	0.069	0.136	0.030	0.017	1.569	0.063	-0.074	0.233	3.013

One checkpoint (NVA 66) was removed from the raw swath vertical accuracy testing due to its location outside the AOI and did not overlap any of the collected lidar data. Four checkpoints (NVA 72, NVA 79, NVA 81, NVA 82) were removed form the swath vertical accuracy due to identified surveyor issue that could not be rectified. Only non-vegetated terrain checkpoints are used to test the unclassified swath data because the unclassified swath data has not been classified to remove vegetation, structures, and other above ground features from the ground classification. Table 10, below, provides the coordinates for this checkpoint and the vertical accuracy results from the unclassified swath data.

Table 10. Checkpoint removed from unclassified swath vertical accuracy testing

Point ID	UTM Zone 16N NAD83, m		NAVD88 Geoid18, m		Delta Z (m)
	Easting X (m)	Northing Y (m)	Survey Z (m)	Lidar Z (m)	
NVA_66	587359.780	5091574.419	182.666	-	
NVA_72	583486.488	5089088.475	180.645	190.717	10.072
NVA_79	537848.263	5068159.075	188.961	189.985	1.024
NVA_81	536238.669	5063393.758	178.871	179.865	0.994
NVA_82	535490.590	5062239.858	179.884	180.932	1.048

4.5 Classified Lidar Vertical Accuracy Results

Table 11 summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar LAS files.

Table 11. Classified lidar vertical accuracy results

Land Cover Type	# of Points	NVA (m)	BVA (m)
Project Specification		**0.196**	**0.294**
NVA	26	0.136	
BVA	6		0.264

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 $RMSE_z$ = 6.9 cm, equating to ± 13.6 cm at 95% confidence level. 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 RMSEz Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be RMSEz = 13.5 cm, equating to ± 26.4 cm at 95% confidence level.

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	26	0.069	0.030	0.018	1.612	0.063	-0.074	0.234	3.187
BVA	20	0.135	-0.042	-0.051	0.015	0.131	-0.275	0.176	-0.950

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the Great Lakes Topobathy satisfies the project's pre-defined vertical accuracy criteria.

4.6 Horizontal Accuracy Test Procedures

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

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

1. Dewberry's team surveyed X, Y, and Z coordinates for discrete checkpoints in accordance with project specifications. Dewberry targeted half of the NVA checkpoints for location on features that would photo-identifiable in the intensity imagery.
2. Following initial processing, Dewberry located the photo-identifiable features in the intensity imagery.
3. Dewberry computed the differences in X and Y values between the surveyed coordinates and the lidar coordinates of the photo-identifiable feature.
4. Horizontal accuracy was assessed based on these data using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. The results are provided in the following section.

4.7 Positional Accuracy Validation

4.7.1 Interswath 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**

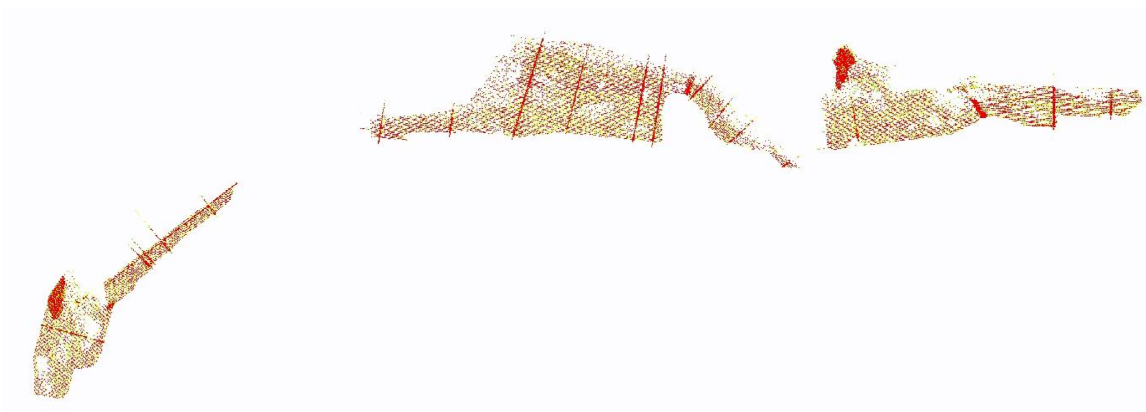


Figure 5. Interswath raster generated using proprietary software and symbolized according to the ranges specified above. Inter-swath relative accuracy passes specifications.

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 6.1 Swath Separation Images (SSIs) and in accordance with U.S. Geological Survey National Geospatial Program LIDAR Base Specification, Version 1.3. 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.

4.7.2 Intraswath 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**

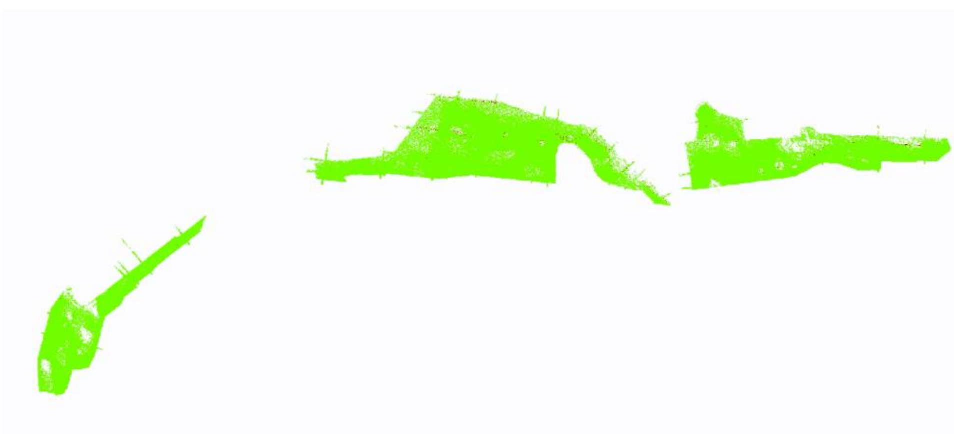


Figure 6 Intra-swath relative accuracy. The top image shows the full project area; areas where the maximum difference is ≤6 cm per pixel within each swath are colored green and areas exceeding 6 cm are colored red.

4. DEM PROCESSING & QUALITATIVE ASSESSMENT

5.1 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.

5.2 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. Upon correction of any outstanding issues, the DEM data was loaded into ESRI's ArcMap for its second review and to verify corrections.

Table 13 below outlines high level steps verified for every DEM dataset.

Table 13. DEM verification steps.

Parameter	Requirement	Pass/Fail
Digital Elevation Model (DEM)	Topobathymetric DEM (1 m) is created from bare-earth lidar ground and bathymetric bottom points and void polygons. DEMs are tiled without overlaps or gaps, show no edge artifact or mismatch, DEM deliverables are .tif format	Pass
DEM Compression	DEMs are not compressed	Pass
DEM NoData	Areas outside survey boundary are coded as NoData. Internal voids are coded as NoData (-999999)	Pass

Bridge Removal	Verify removal of bridges from bare-earth DEMs	Pass
DEM Artifacts	Correct any issues in the lidar classification that were visually expressed in the DEMs. Reprocess the DEMs following lidar corrections.	Pass
DEM Voids	Bathymetric voids greater than 9 sq mi are enforced in the DEM.	Pass
DEM Tiles	Split the DEMs into tiles according to the project tiling scheme	Pass
DEM Formatting	Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression is not applied to the tiled DEMs. GDAL version 2.4.4 used for all DEM formatting.	Pass
DEM Extents	Load all tiled DEMs into ArcMap and verify complete coverage within the (buffered) project boundary and verify that no tiles are corrupt	Pass

5.3 DEM Vertical Accuracy

The same 38 checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by averaging several lidar 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 Esri software to test the DEM vertical accuracy.

Table 14 summarizes the tested vertical accuracy results from the final DEM dataset.

Table 14. DEM vertical accuracy results

Land Cover Type	# of Points	NVA (m)	BVA (m)
Project Specification		**0.196**	**0.588**
NVA	26	0.122	
BVA	12		0.288

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 $RMSE_z$ = 6.2 cm, equating to ± 12.2 cm at 95% confidence level. Actual VVA accuracy was found to be ± 14.4 cm at the 95th percentile. The bathymetric portion of this DEM dataset was tested to meet ASPRS

Positional Accuracy Standards for Digital Geospatial Data (2014) for an 18.5 cm $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 14.7 cm, equating to ± 28.8 cm at 95% confidence level.

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	26	0.062	0.028	0.017	1.963	0.056	-0.059	0.249	5.739
BVA	12	0.147	-0.064	-0.078	0.684	0.138	-0.244	0.230	0.442

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for Great Lakes Topobathy satisfies the project's pre-defined vertical accuracy criteria.

5. DERIVATIVE LIDAR PRODUCTS

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

6.1 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.

6.2 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.

6.3 Intensity Imagery

Intensity orthoimages representing normalized seabed reflectance have been created for the entire project area on a per-tile basis. Each 1-meter grid cell has an associated 8-bit intensity value, 256 color gray scale 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 classified topo-bathymetric LAS and DEMs.

Certain areas of the intensities still presented some visible issues. Dewberry has provided a separate "GreatLakes_RelativeReflectance_Memo.pdf" and a shapefile for each region of the AOI denoting where each issue may be present with the delivery of this dataset.

6.4 Swath Separation Images (SSIs)

Dewberry verified inter-swath or between swath relative accuracy of the dataset by generating swath separation images 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 SSIs. Flat, open areas are expected to be green in the SSIs. 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 swath separation 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 2.4.4.

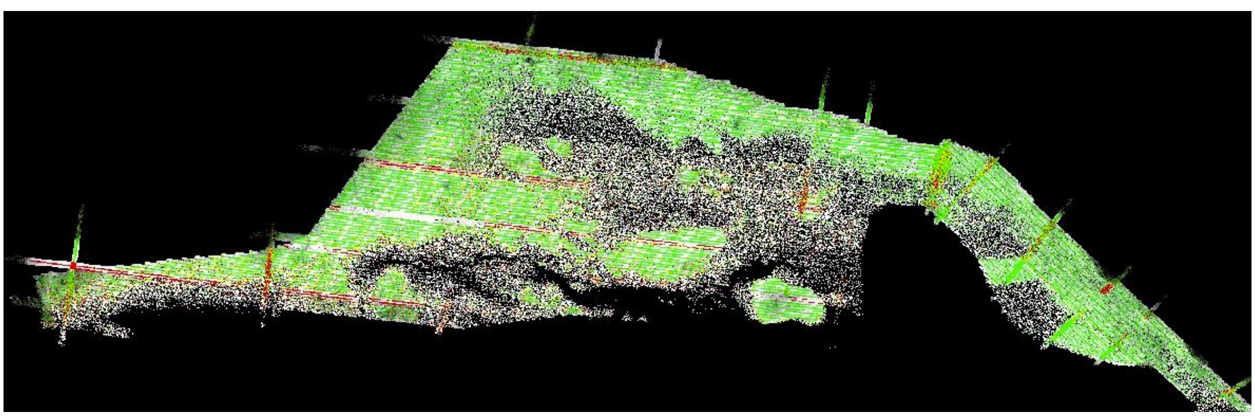


Figure 7. Sample Swath Separation Images (SSIs) generated for Great Lakes Topobathy.

6.1 Maximum Surface Height Rasters (MSHRs)

6.2 Flightline Extents SHP

Flightline extents are delivered as polygons in an Esri SHP, delineating actual coverage of each swath used in the project deliverables. Dewberry delivered this SHP 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 SHP is created from the final, tiled point cloud deliverables to ensure all correct swaths are represented in the flightline SHP. The flightline SHP is then reviewed for complete coverage and correct formatting.