Beaver Islands Archipelago and South Manitou Island Topobathy Report of Survey

Produced for National Oceanic and Atmospheric Administration, Office for Coastal Management

Contract: EA133C-11-CQ-0007

Task Order: Topographic/Bathymetric Data Acquisition on Beaver Islands Archipelago and South Manitou Island in Upper Lake Michigan

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Produced by:
Dewberry
1000 North Ashley Drive, Suite 801
Tampa, FL 33602
813.225.1325

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Executive Summary

Dewberry has been tasked under the NOAA Office of Coastal Management to process topobathymetric lidar data for Beaver Island Archipelago and South Manitou Island in Upper Lake Michigan. Topographic and bathymetric data along the Great Lakes shoreline and nearshore areas are critical to effective planning for coastal storms, mapping fluctuating lake levels, and identifying changes to aquatic vegetation in a changing climate. Beaver Islands Archipelago and Manitou Islands in Lake Michigan have been identified as having critical topographic and bathymetric data gaps by NOAA. This project will fill critical gaps in data coverage.

SURVEY AREA

The Beaver Islands Archipelago and South Manitou topobathymetric lidar survey project area covers approximately 205 square miles. Task 1, which covers the Beaver Islands Archipelago, is approximately 185 square miles, extending out to a 7-meter depth ENC data. Task 2, which covers South Manitou Island, is approximately 20 square miles, extending out to the 7-meter depth contour with a 500 meter buffer using ENC data. There were 3,361 500 m x 500 m lidar tiles delivered for the project area. The project area boundary and overview are shown in Figure 1.

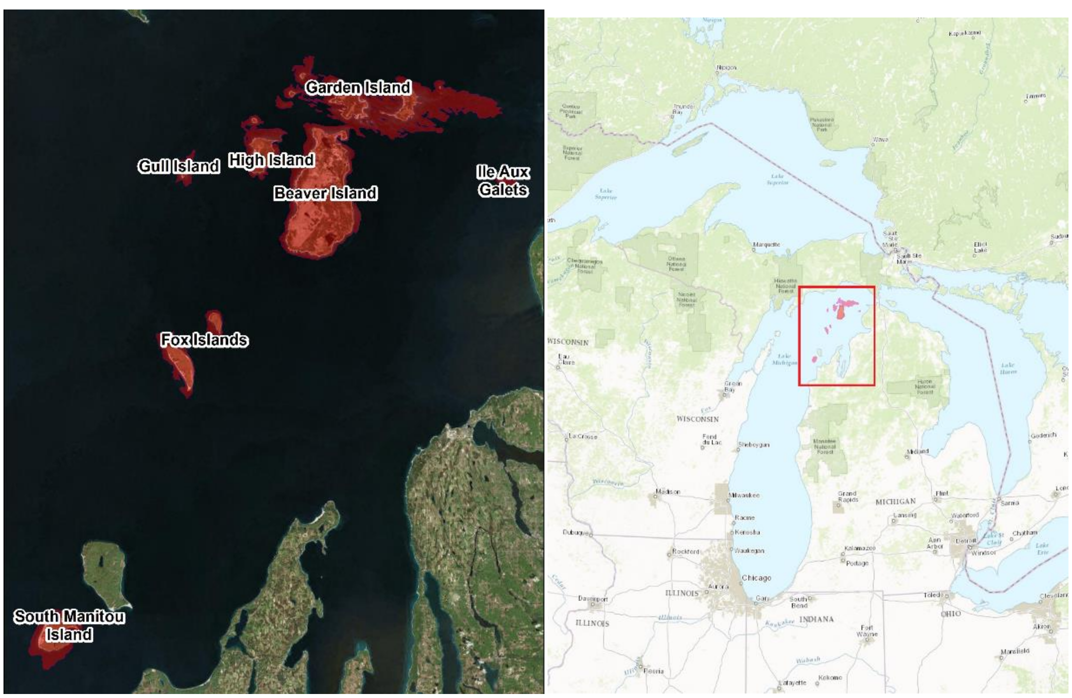


Figure 1-The left image shows Beaver Islands Archipelago and South Manitou Island Topobathy collection area shaded in orange. The right image shows an overview map of where the project is located.

DATE OF SURVEY

The first phase of lidar aerial acquisition was conducted from November 16, 2015 through December 5, 2015. The second phase of lidar aerial acquisition was conducted on June 2, 2016 and June 3, 2016.

PROJECT TEAM

Dewberry was engaged by the National Oceanic Atmospheric Administration's (NOAA) Office of Coastal Management to process topobathy lidar data. Leading Edge Geomatics acquired, calibrated and performed the refraction correction on all topobathy lidar data and provided it to Dewberry. Dewberry classified the lidar data, performed all QAQC including vertical accuracy testing, collected hydrographic breaklines, and created all topobathymetric DEMs and associated DEM products.

DELIVERABLES

The final deliverables for this task order included:

- Tile Grids (Shapefiles)
- Breaklines used to delineate the land-water interface for bathymetric bottom classification (GDB and Shapefiles)
- Final classified lidar tiles (LAS)
- Tiled DEMs with voids enforced (IMG)
- Void layer (shapefile)
- Survey data
- Metadata (XML)
- Final Project report

Lidar Deliverables

The topobathymetric lidar was collected by Leading Edge Geomatics using a Leica Chiroptera II system. The system captures the full waveform in both the 35 kHz bathymetric channel and the 500 kHz topographic channel, making it useful for seamless coastal and land surveying.

Breaklines were collected to delineate the land/water interface. The breaklines were delivered to NOAA in ESRI geodatabase and shapefile formats.

The final topobathymetric lidar tiles, which include the refraction correction and all final editing were delivered to NOAA in 500 m x 500 m LAS tiles. There were 3,361 final topobathymetric tiles, which were delivered in the following spatial reference system:

- Horizontal Datum-NAD83 (2011) epoch: 2010
- Projection-UTM Zone 16N
- Horizontal Units-meters
- Vertical Datum-NAVD88, GEOID12B
- Vertical Units-meters

The final computed vertical accuracy is stated in the accuracy section of this project report. The survey data used to independently test the positional accuracy of the lidar data is also included is this project report as Appendix A.

A final, comprehensive tile grid was also delivered to NOAA. The naming schema follows the schema provided by NOAA. Tiles are named according to easting and northing coordinates of the upper left corner for each tile, e.g. xxxxE_yyyyN.las. A complete listing of all delivered tiles is included in Appendix C.

Metadata, in XML format, were delivered for both of the lidar deliverables—the tiled LAS and the breaklines.

DEM Deliverables

Following classification and QAQC of the point-cloud lidar data, the lidar data were used to generate tiled DEMs from the ground and bathymetric bottom classification. The vertical and horizontal coordinate reference systems are the same as the lidar:

- Horizontal Datum-NAD83 (2011) epoch: 2010
- Projection-UTM Zone 16 North
- Horizontal Units-meters
- Vertical Datum-NAVD88 (Geoid 12B)
- Vertical Units-meters

One set of tiled DEMs, in IMG format with 2 meter cell size, were delivered to NOAA. The DEMs enforced void areas so that areas void of bathymetric bottom data were set to NoData. The DEMs were tiled to the lidar tile grid (500 m x 500 m tiles). There were 3,356 void DEMs delivered to NOAA. There are 5 DEMs that did not contain topographic or bathometric data and are removed from the data set since the DEMs are empty. They are listed in Appendix C under the list of excluded Dems.

A shapefile of the void areas representing bathymetric areas with no bottom returns was delivered for the project. Additionally, a density layer was delivered in IMG format. The density layer reports the number of bathymetric bottom and ground points per 1-meter cell. The density layer was delivered as one raster for the entire project area.

The final DEM vertical accuracy, calculated project-wide after all DEMs were processed, was computed and delivered to NOAA in the accuracy section of this final project report.

Metadata files in XML format were produced for the whole project for both of the DEM deliverables—the tiled DEMs and the void polygons.

OVERVIEW OF CLASSIFICATION

The raw lidar from the bathymetric and topographic sensors were kept in the classes that were outputted by the Leica processing software. This aided in the classification of the ground and bathymetric bottom. The raw swaths delivered to NOAA were kept in this classification schema and is listed below.

Lidar Classification – Raw Topographic Sensor Data	
Class	**Description**
Class 3	Returns rejected due to threshold vales specified in processing settings file
Class 9	First and only return originating from land regions
Class 13	Last of multiple returns
Class 14	Intermediate layer
Class 15	First of multiple returns

Table 1-Lidar Classification Schema of raw LiDAR data of the topographic sensor.

Lidar Classification – Raw Bathymetric Sensor Data	
Class	**Description**
Class 0	Derived Water Surface (synthetic water surface location used in computing refraction)
Class 2	Saturated points from land regions rejected due to low accuracy
Class 3	Returns rejected due to the threshold values specified in the processing settings file
Class 5	Water surface returns confirmed by water surface detection algorithm
Class 6	Returns obtained using the shallow water algorithms
Class 7	Last return originating from sub water surface
Class 8	Returns neglected due to peak shape. Not user affectable.
Class 9	First and only return originating from land regions
Class 10	High criteria Turbid Water Enhancement returns
Class 13	Last of multiple returns
Class 14	Intermediate layer
Class 15	First of multiple returns
Class 17	Returns which are not last return originating from sub water surface
Class 19	Low criteria Turbid Water Enhancement returns

Table 2-Lidar Classification Schema of raw Lidar data of the bathymetric Sensor.

Once the raw topographic and bathymetric sensor data had been combined and tiled out, routines were run to reclassify the data into the classification schema below. This classification schema was used during manual editing and was also the schema used for the final LAS delivered to NOAA as required by the project's scope of work.

LiDAR Classification – Manual Editing and Final Deliverables	
Class	**Description**
Class 0	Created, Never Classified
Class 1	Unclassified (includes buildings and vegetation)
Class 2	Ground
Class 40	Bathymetric Bottom
Class 41	Water Surface
Class 42	Synthetic Water surface
Class 43	Submerged Object, not otherwise specified
Class 44	International Hydrographic Organization (IHO) S-57 object, not otherwise specified
Class 45	No bathymetric bottom found (water column)

Table 3-Final LiDAR Classification Schema

Acquisition and Swath Processing

This project was acquired by Leading Edge Geomatics in two separate phases. The first phase of acquisition was conducted between November 16, 2015 and December 5, 2015, covering Beaver Island, North Fox Island, Gull Island, High Island, Garden Island and Ile Aux Galets. The second phase of acquisition was conducted on June 2, 2016 and June 3, 2016, covering South Manitou Island, South Fox Island and several smaller areas that needed to be reacquired on Beaver Island due to data gaps.

Final swath deliverables for Gull Island, High Island, North Fox Island, Garden Island and Ile Aux Galets were sent to NOAA on February 29, 2016. Final swath deliverables for South Manitou Island, South Fox Island and Beaver Island were sent to NOAA on July 29, 2016.

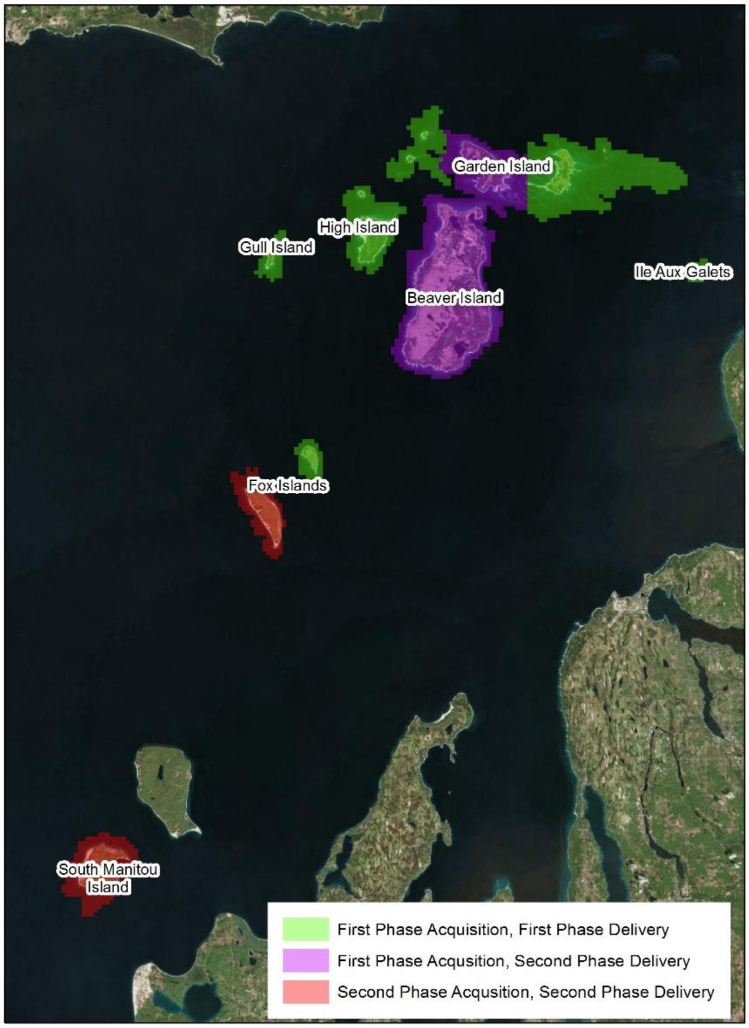


Figure 2-Acquisition and Swath Delivery Phases.

CALIBRATION AND REFRACTION CORRECTION

The full acquisition and swath processing, including calibration procedures, is described in the complete acquisition report located in Appendix B. The refraction correction was done after lidar aerial acquisition and was completed using the Leica processing software.

INITIAL SWATH ACCURACY AND CALIBRATION CHECKS

After receiving the data from Leading Edge Geomatics, Dewberry performed initial checks on the data to ensure there were no remaining calibration or other issues present in the data. These validations include vertical accuracy of the swath data, inter-swath (between swath) relative accuracy validation, intra-swath (within a single swath) relative accuracy validation, verification of horizontal alignment between swaths, and confirmation of point density and spatial distribution. This initial assessment allows Dewberry to determine if the data are suitable for full-scale production. Addressing issues at this stage allows the data to be corrected while imposing the least disruption possible on the overall production workflow and overall schedule.

Swath Vertical Accuracy Assessment

Dewberry performed the initial swath vertical accuracy assessment using non-vegetated 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.

Project specifications require a NVA of 19.6 cm based on the $RMSE_z$ (10 cm) x 1.96. The dataset for the Beaver Islands Archipelago and South Manitou Island Topobathy Project satisfies this criteria. This raw lidar swath data set 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 $RMSE_z$ = 8 cm equating to +/- 15.6 cm at the 95% confidence level. This meets and exceeds the project's QL2 Lidar Base Specification of 19.6 cm at the 95% confidence level.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.10 m	NVA- Non-vegetated Vertical Accuracy ((RMSEz x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)
NVA	21	0.080	0.156	0.001	-0.001	-0.100	0.082	-0.161	0.125

Table 4- Initial Swath Accuracy Results.

Inter-Swath (Between Swath) Relative Accuracy

Dewberry verified inter-swath or between swath relative accuracy of the dataset by creating Delta-Z (DZ) orthos. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet inter-swath relative accuracy of 8 cm RMSDz or less with maximum differences less than 16 cm. These measurements are to be taken in non-vegetated and flat open terrain using single or only returns from all classes. Measurements are calculated in the DZ orthos on 1-meter pixels or cell sizes. Areas in the dataset where overlapping flight lines are within 8 cm of each other within each pixel are colored green, areas in the dataset where overlapping flight lines have elevation differences in each pixel between 8 cm -16 cm are colored yellow, and areas in the dataset where overlapping flight lines have elevation differences in each pixel greater than 16 cm are colored red. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values. 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 orthos. Flat, open areas are expected to be green in the DZ orthos. Large or continuous sections of yellow or red pixels can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data, especially when these yellow/red sections follow the flight lines and not the terrain or areas of vegetation. The DZ orthos for the Beaver Islands Archipelago and South Manitou Island Topobathy Project are shown in the figure below; this project meets inter-swath relative accuracy specifications.

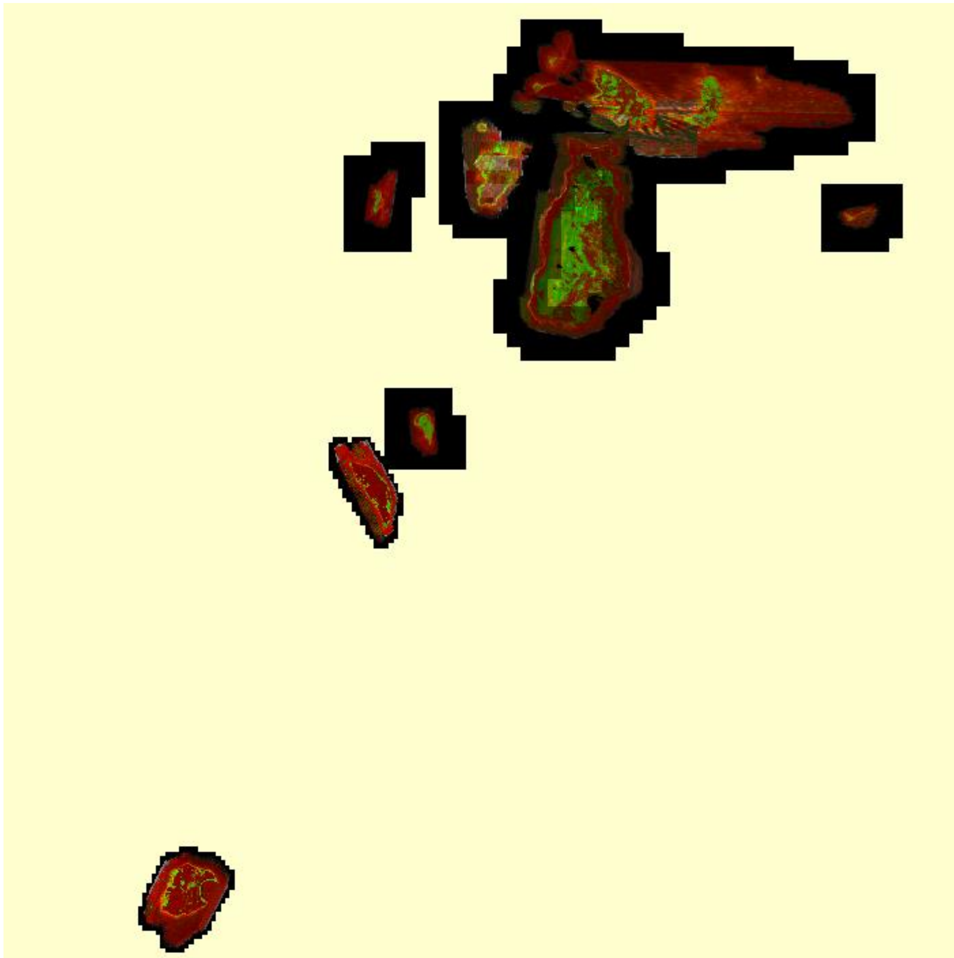


Figure 3-DZ Orthos. Offsets between flightlines of 0-8 cm are green, 8-16 cm are yellow, and above 16 cm are red. Larger offsets in vegetated and bathymetric areas are expected as different returns from water column and vegetation can occur between different flightlines.

Intra-Swath (Within a Single Swath) Relative Accuracy

Dewberry verifies the intra-swath or within swath relative accuracy by using Quick Terrain Modeler (QTM) scripting and visual reviews. QTM scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Dewberry analysts then identify planar surfaces acceptable for repeatability testing and analysts review the QTM results in those areas. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet intra-swath relative accuracy of 6 cm maximum difference or less. The image below shows an example of the intra-swath relative accuracy; this project meets intra-swath relative accuracy specifications.

Figure 4–Intra-swath relative accuracy. This image shows a portion of the dataset; areas where the maximum difference is ≤6 cm per pixel within each swath are colored green. This open flat area is acceptable for repeatability testing. Intra-swath relative accuracy passes specifications.

Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, a random sample of cross-sections was taken along cultural features such as buildings and roads. The image below shows an example of the horizontal alignment between swaths for the Beaver Islands Archipelago and South Manitou Island Topobathy Project; no horizontal alignment issues were identified.

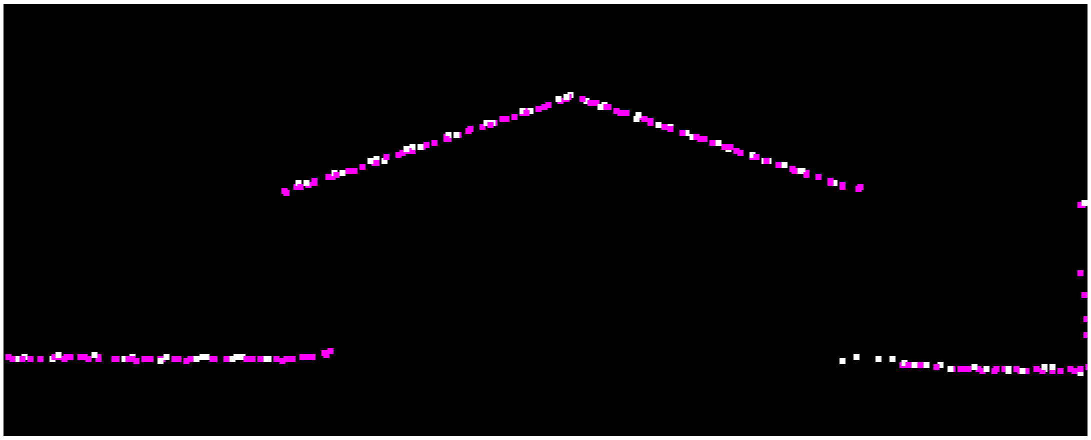


Figure 5-Cross-section of lidar points along a building colored by flightline. There are two flightlines in this cross-section, the pink flightline and the white flightline. This cross-section shows there are no visible offsets between the flightlines.

Point Density and Spatial Distribution

For topographic areas, the required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.71 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 2 points per square meter or greater. For bathymetric areas, the required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 1.41 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 0.5 points per square meter or greater. Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing statistics, the project area was determined to have an ANPS of 0.32 meters or an ANPD of 9.73 points per square meter which satisfies the project requirements. An image of the point density is shown below; this project satisfies density requirements.

Figure 6-Density image shows areas meeting the 2 points per square meter requirement colored purple and areas with at least 1 point per square meter are colored green.

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. QTM scripting is 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.

Figure 7– Spatial Distribution. All tiles containing at least one lidar point are colored green.

Lidar Processing, Editing, and QA/QC

Once the swath data passed all initial validations, Dewberry tiled the data and began full-scale production. This included breakline creation to define the land/water interface, automated and manual editing of the lidar tiles, QA/QC, and final formatting of the LAS files.

BREAKLINE CREATION AND QA/QC

Breaklines representing the land/water interface must be created so that bathymetric bottom and ground points can be classified properly in the lidar. The processing software for the Leica Chiroptera II system does a basic classification on the lidar, differentiating between land and bathymetric areas. The points classified as bathymetric areas by the sensor processing software were aggregated into polygons using ArcGIS. These polygons were then compared to downloaded RGB imagery to make adjustments where needed. The final land/water interface delineation was used in the lidar classification of ground and bathymetric points.

Figure 8- Tile 0200E_6400N. The breakline representing the land/water interface is shown outlined in blue along with RGB imagery.

TERRASCAN PROCESSING

Once complete tiles were created with lidar from both the topographic and bathymetric data, macros were run on the tiles in TerraScan to create the initial automated ground and bathy bottom classifications, using the final project classification schema.

MANUAL EDITING USING TERRASCAN

After running the automated TerraScan macros, the tiles were ready for manual editing. Surface models in TerraModeler were created from both bathy bottom (class 40) and ground (class 2) classes. Multiple 'correction' or 'supplemental' macros were run on tiles or portions of tiles to address systematic or prevalent issues, including some of the issues mentioned below.

Special attention was given along shorelines or the land/water interface as no hard edges or seams should exist between ground and bathy bottom.

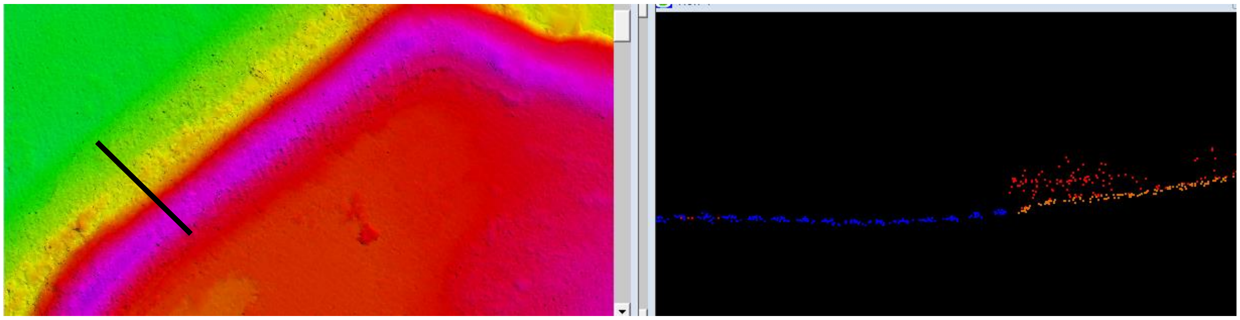


Figure 9-The land water interface should be seamless with no hard edges or seamlines. The topobathy surface model is shown on the left with a profile location overlaid. The profile is shown in the right image where bathy bottom points are blue, ground points are orange, and unclassified points are red.

Areas of rapids or swift moving water may also need to be removed from the bathy bottom class as these may be surface or water column points and not bathy bottom points due to the water movement and stirring of sediment (increased turbidity). When possible, color orthos were used to help determine water clarity and likelihood of full penetration to the submerged bottom.

Generally, editors looked for consistency in data, especially continuous topography (connecting the dots method to ensure channel geometry is reasonable).

Special attention was given in deeper areas where there may not be any true bathy bottom points, but the automated algorithm classified lower water column points as bathy bottom. When evaluating points to determine if they are low water column points or true bathy bottom, the following rules were used as guidelines to maintain accuracy and consistency:

1. Gradient consistency-if the points are part of consistent gradients or consistent channel geometry, they are more likely to be bathy bottom rather than low water column noise. Conversely, points that would cause abrupt changes or inconsistency in the overall gradient or channel geometry are less likely to be bathy bottom points, especially if the abrupt change would result in shallower (higher) bathy bottom points above lower bathy bottom points with a high confidence.

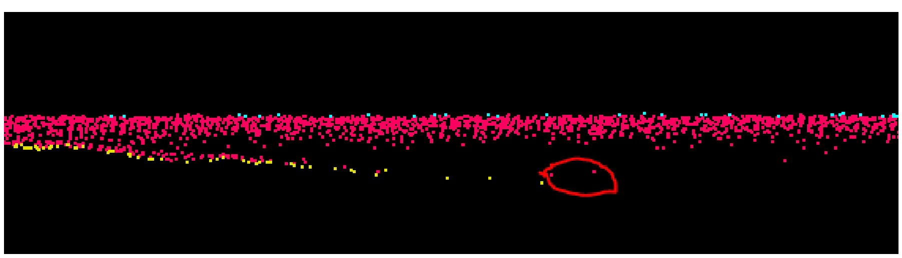


Figure 10-Bathy Bottom points (yellow) are shown with water column (pink) and water surface points (turquoise) in this profile. The two water column points circled in red would cause inconsistent and upward changes in the topobathy model if these points were classified to bathy bottom. These points should remain classified as water column.

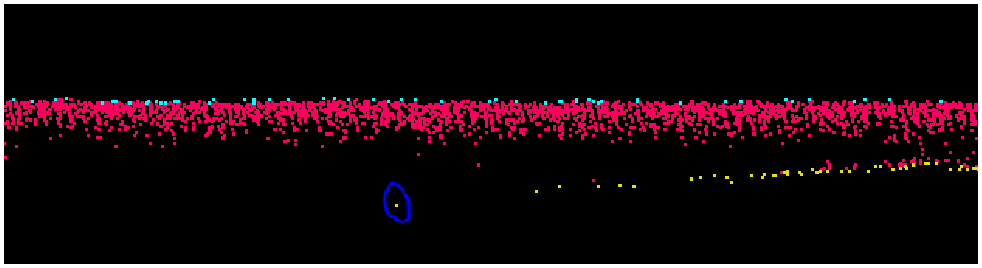


Figure 11-Bathy Bottom points (yellow) are shown with water column (pink) and water surface points (turquoise) in this profile. The bathy bottom point circled in blue is isolated, but maintains a consistent gradient with other bathy bottom points to the east. This point should remain classified as bathy bottom.

2. Manmade object consistency-manmade objects, such as marinas and artificial or modified channels, are more likely to have been created consistently and at similar depths when multiple channels or inlets are in close proximity to each other. In these locations, if one channel appears much shallower than other manmade channels, the points classified as bathy bottom are more likely to be low water column points.

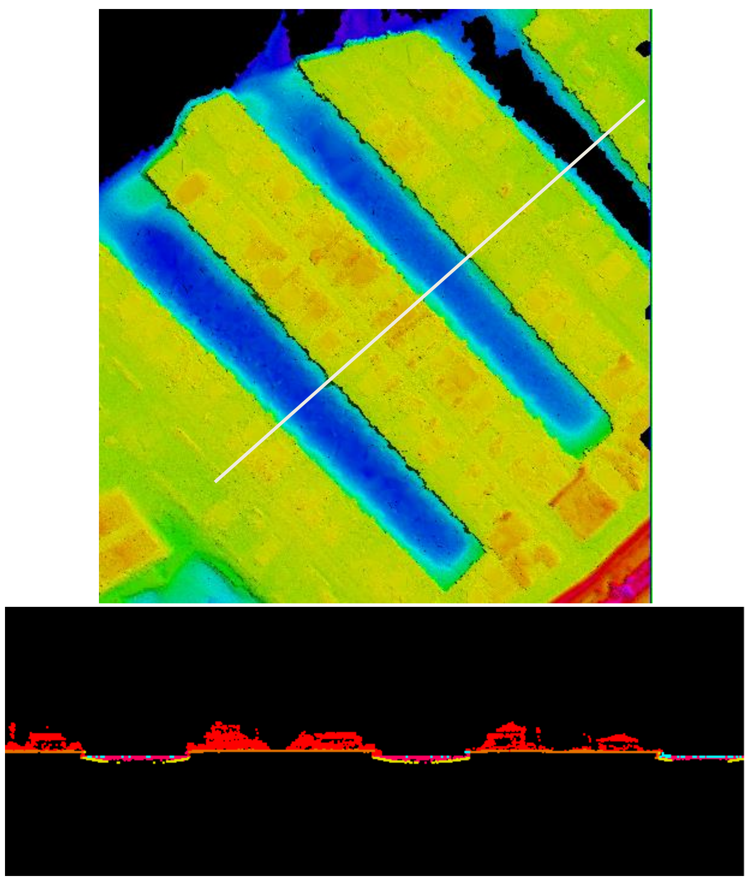


Figure 12-The topobathy surface model is shown on the top with a profile location overlaid. The profile is shown in the bottom image where bathy bottom points are yellow, ground points are orange, water column points are pink, water surface points are turquoise, and unclassified points are red. These three marina inlets are man-made and likely at very similar depths, as shown in the overview profile. In locations similar to this, points significantly deeper (lower) or shallower

(higher) are likely not legitimate bathy bottom, but are more likely to be noise or water column, respectively.

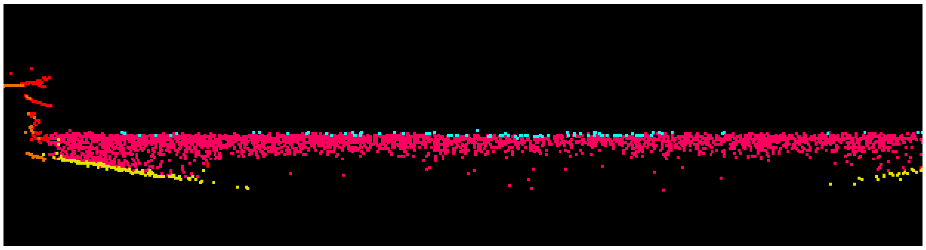


Figure 13- This profile is a close-up of one of the marina inlets shown in Figure 12. Bathy bottom points are yellow, ground points are orange, water column points are pink, water surface points are turquoise, and unclassified points are red. These marina inlets are man-made and likely at very similar depths. The low water column points are not classified as possible bathy bottom because that classification would cause this inlet to be much shallower than its neighboring inlets in close proximity.

3. Small gap verification-If bathy bottom was obtained for the vast majority of a channel, but small random gaps or voids in the bathy bottom exist after the initial grounding where it is unclear if existing points are bathy bottom or low water column, these small gaps should usually be filled by classifying the points in question to bathy bottom. It is unlikely such small portions of the channel are that much deeper where no bathy bottom was obtained when the lidar penetrated to the bathy bottom in the rest of the channel. However, if the gaps/voids are larger or consistently form over specific areas or locations, then these areas are more likely to represent deeper areas where the lidar may not have penetrated to the submerged bottom. In these areas. Classify the points as low water column.

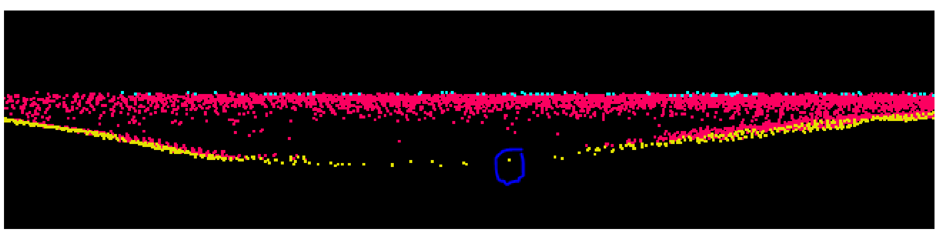


Figure 14-Bathy Bottom points (yellow) are shown with water column (pink) and water surface points (turquoise) in this profile. The bathy bottom point circled in blue was classified as bathy noise by the initial grounding macro, resulting in a small void. This point was re-classified as bathy bottom to the fill the small gap because this point is at the same depth as surrounding points, maintains a consistent gradient, and is more likely to be submerged bottom rather than low water column noise. Based on the surrounding data, this point most likely represents bathy bottom.

Submerged Objects

No submerged objects were identified during editing and review of the lidar data, therefore no points were classified to class 43 or class 44.

Temporal Changes

Changes in the bathymetric bottom surface can result from differences between collection periods due to factors such as currents moving sediment. However, Dewberry did not identify any significant temporal changes in this project.

QA/QC

After manual edits, tiles are peer reviewed. All data then undergoes QA/QC performed by analysts not involved in the production and manual classification. Keeping the editing and QA/QC separate results in a more independent QA/QC.

Manual Review

During QA/QC, reviewers check for consistent and correct classification. Reviewers verified all guidelines outlined in the Manual Editing section above have been adhered too. . Dewberry used QT Modeler and TerraScan for this review. QT Modeler allows the user to create and load multiple surface models (created from both ground-class 2-and submerged topography-class 40) and to rotate the models for better analysis. Review of the full point cloud classification as well as areas identified in QT Modeler for additional review was accomplished in TerraScan.

Create Void Polygons

Void polygons were created as part of the QA/QC. The void polygons identify areas of sparse to no bathy bottom points. The void polygons were loaded when reviewing the data to ensure correct and full classification of bathy bottom. All void areas 3m x 3m or larger were identified with a void polygon.

While Dewberry has used the aggregate point method in the past to create void polygons, isolated points may be included as part of the void polygons with this method. To ensure that every single bathy bottom point, regardless of its isolation, would be used in the final DEMs and excluded from void polygons, Dewberry used Global Mapper to create the void polygons for the data. Global Mapper created a pixel for every single bathymetric bottom and ground LiDAR point.

To create void polygons using the Global Mapper method, all ground and bathy bottom points were loaded into Global Mapper. If using both ground and bathy bottom LAS points resulted in large DEMs that are hard to work with, then only the bathy bottom points were loaded. The NoData cells were then converted to polygons in ArcMap. The void polygons representing topographic areas were then removed or clipped from the dataset later in the process.

LAS Formatting

After the final QA/QC is performed and all corrections have been applied to the dataset, all lidar files are updated to the final format requirements and the final formatting, header information, point data records, and variable length records are verified using Dewberry proprietary tools. The table below lists some of the main lidar header fields that are updated and verified.

Classified LiDAR Formatting		
Parameter	**Requirement**	**Pass/Fail**
LAS Version	1.4	Pass
Point Data Format	Format 6	Pass
Coordinate Reference System	NAD83 (2011) UTM Zone 16, meters and NAVD88 (Geoid 12B), meters	Pass
Global Encoder Bit	Should be set to 17 for Adjusted GPS Time	Pass
Time Stamp	Adjusted GPS Time (unique timestamps that are not GPS week)	Pass
System ID	Should be set to the processing system/software and is set to NIIRS10 for GeoCue software	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 are recorded for each pulse	Pass
Classification	Required Classes include: Class 0: Created, Never Classified Class 1: Unclassified Class 2: Ground Class 40: Bathymetric Bottom Class 41: Water Surface Class 43: Submerged Object, not otherwise specified Class 44: International Hydrographic Organization (IHO) S-57 object, not otherwise specified Class 45: No bathymetric bottom found (water column)	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates are recorded for each pulse	Pass
Flight line IDs	Set to the unique ID for each flight line	Pass

Table 5-Final lidar formatting

LIDAR POSITIONAL ACCURACY

Dewberry quantitatively tested the dataset by testing the vertical accuracy of the lidar. The vertical accuracy is tested by comparing the discreet 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 end 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.

The survey checkpoints used to test this topobathymetric dataset are listed in the survey report included as Appendix A. The surveyor was only able to obtain survey checkpoints on Beaver Island.

Vertical Accuracy Test Procedures

NVA (Non-vegetated Vertical Accuracy) is determined with check points located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas, where there is a very high probability that the lidar sensor will have detected the bare-earth ground surface and where random errors are expected to follow a normal error distribution. The NVA determines how well the calibrated lidar sensor performed. 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. For the Beaver Islands Archipelago and South Manitou Island Topobathy project, vertical accuracy must be 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

VVA (Vegetated Vertical Accuracy) is determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas, where 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 Beaver Islands Archipelago and South Manitou Island Topobathy Project VVA standard is 29.4 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; these are always the largest outliers that may depart from a normal error distribution. Here, $Accuracy_z$ differs from VVA because $Accuracy_z$ assumes elevation errors follow a normal error distribution where RMSE procedures are valid, whereas VVA assumes lidar errors may not follow a normal error distribution in vegetated categories, making the RMSE process invalid.

Vertical Accuracy Results

The table below summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified LAS files.

Lidar Vertical Accuracy Results			
Land Cover Category	# of Points	NVA – Non-vegetated Vertical Accuracy (RMSE$_z$ x 1.9600) Spec=0.196 m	VVA – Vegetated Vertical Accuracy (95th Percentile) Spec=0.294 m
NVA	21	0.158	
VVA	12		0.227

Table 6-Final Lidar Vertical Accuracy Results

This lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be RMSE$_z$ =8.1 cm, equating to +/- 15.8 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 22.7 cm at the 95th percentile.

Table 7 lists the 5% outliers that are larger than the VVA 95th percentile.

Lidar 5% Outliers						
Point ID	NAD83 UTM Zone 16N		NAVD88 (Geoid 12B)		Delta Z	AbsDelta Z
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-LiDAR (m)		
VVA-3	612379.788	5064055.494	197.350	197.600	0.250	0.250

Table 7-Lidar 5% Outliers

Table 8 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	21	0.081	0.005	0.009	-0.233	0.082	-1.011	-0.161	0.125
VVA	12	N/A	0.077	0.089	-0.264	0.113	-0.687	-0.120	0.250

Table 8 – Overall Descriptive Statistics

Based on the vertical accuracy testing conducted by Dewberry, this topobathymetric project meets the pre-defined vertical accuracy criteria.

DEM Processing and QA/QC

The final topobathy DEMs are IMG format with 2 meter pixel cell size, tiled and named according to project specifications, and contain pyramids. Void polygons were enforced in the DEMs so that bathymetric areas where no bathymetry was collected are NoData in the DEMs.

FINAL VOID POLYGONS

Final void polygons, after all lidar edits and corrections, were created for use in the topobathymetric DEM production. If absolutely no modifications were required after the QA/QC, then the void polygons created as part of that process could be used. However, if any classification changes to the lidar were performed, then a final set of void polygons were created to ensure these polygons are consistent with the final lidar data.

Once the final void polygons had been created, these polygons were imported into the terrain GDB for use during topobathymetric DEM creation.

DEM GENERATION

After the final void polygons are created and imported into the terrain GDB, a multipoint is created of all lidar bathymentric bottom and ground points. After the multipoint was created, a terrain was created using the multipoint. The void polygons are used in the terrain as "soft erase" features. This ensures that bathymetric areas where there are no bathymetric bottom points will be set as NoData in the DEM. After the terrain has been created, the Arc tool Terrain to Raster was used to create the final topobathy DEM raster.

DEM QUALITATIVE REVIEW

The final topobathy DEM was reviewed in Global Mapper at a 1:3000 scale. A review with the void polygons visible and another review without the void polygons visible was done. Special attention was given along the land/water interface to ensure there were no hard edges along the interface. Any remaining lidar issues and DEM artifacts were flagged by the reviewer and corrected by the editing team as necessary.

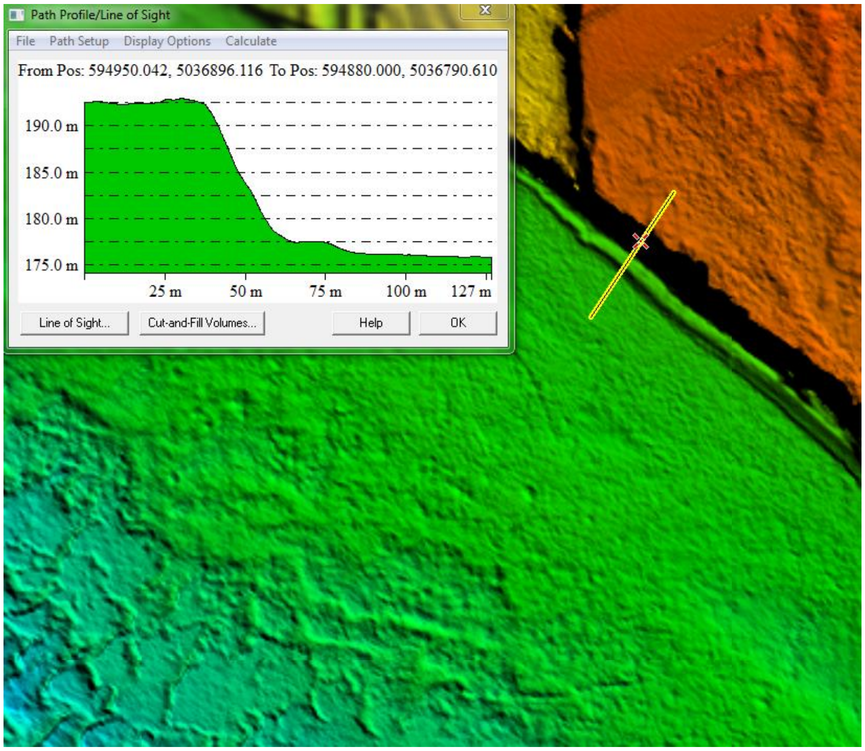


Figure 15-DEM tile 9500E_3700N. An example of the land-water interface is shown. No hard edges along the interface were identified during DEM QA/QC.

DEM POSITIONAL ACCURACY

The same checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products as well. 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 source LAS, which does not average several lidar points together but may interpolate (linearly) between two or three points to derive an elevation value. The vertical accuracy of the DEM is tested by extracting the elevation of the pixel that contains the x/y coordinates of the checkpoint and comparing these DEM elevations to the surveyed elevations.

The survey checkpoints used to test this topobathymetric dataset are listed in the survey report included as Appendix A. The surveyor was only able to obtain survey checkpoints on Beaver Island.

Vertical Accuracy Results

The table below summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the DEMs.

DEM Vertical Accuracy Results			
Land Cover Category	# of Points	NVA – Non-vegetated Vertical Accuracy (RMSE$_z$ x 1.9600) Spec=0.196 m	VVA – Vegetated Vertical Accuracy (95th Percentile) Spec=0.294 m
NVA	21	0.156	
VVA	12		0.244

Table 9-Final DEM Vertical Accuracy Results

This DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be RMSE$_z$ =8.0 cm, equating to +/- 15.6 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 24.4 cm at the 95th percentile.

Table 10 lists the 5% outliers that are larger than the VVA 95th percentile.

DEM 5% Outliers						
Point ID	NAD83 UTM Zone 16N		NAVD88 (Geoid 12B)		Delta Z	AbsDelta Z
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-DEM (m)		
VVA-3	612379.788	5064055.494	197.350	197.618	0.268	0.268

Table 10-DEM 5% Outliers

Table 11 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	21	0.080	0.003	-0.015	-0.037	0.081	-1.221	-0.151	0.134
VVA	12	N/A	0.085	0.095	-0.411	0.115	0.258	-0.141	0.268

Table 11 — Overall DEM Descriptive Statistics

Based on the vertical accuracy testing conducted by Dewberry, the DEMs for this topobathymetric project meet the pre-defined vertical accuracy criteria.

Metadata

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

Appendix A: Survey Report

Check Point Survey Report

"TOPOGRAPHIC/BATHYMETRIC UPPER LAKE MICHIGAN"

NOAA Contract: EA133C-11-CQ-007
Task Order Number: T-0038

Prepared for:

National Oceanic & Atmospheric Administration (NOAA)

Prepared By:

Dewberry Consultants LLC

10003 Derekwood Lane, Suite 204
Lanham, Maryland, 20706
Phone (301)364-1855 Fax (301)731-0188

1. INTRODUCTION

1.1 *Project Summary*

Dewberry Consultants LLC is under contract to the National Oceanic & Atmospheric Administration (NOAA) to provide 33 Check Points in the State of Michigan. Under the above referenced NOAA Task Order, Dewberry is tasked to complete the quality assurance of LiDAR products. As part of this work Dewberry staff will complete Check Point surveys that will be used to evaluate vertical and horizontal accuracy. The ground survey was conducted December 9-10, 2015.

Existing NGS Control Points were located and surveyed to check the accuracy of the RTK/GPS survey equipment with the results shown in Section 2.4 of this Report.

As an internal QA/QC procedure and to verify that the Check Points meet the 95% confidence level approximately 50% of the points were re-observed and are shown in Section 5 of this report.

Final horizontal coordinates are referenced to UTM Zone 16 North, NAD83 (2011) in meters. Final Vertical elevations are referenced to NAVD88 in meters using Geoid model 2012B (Geoid12B).

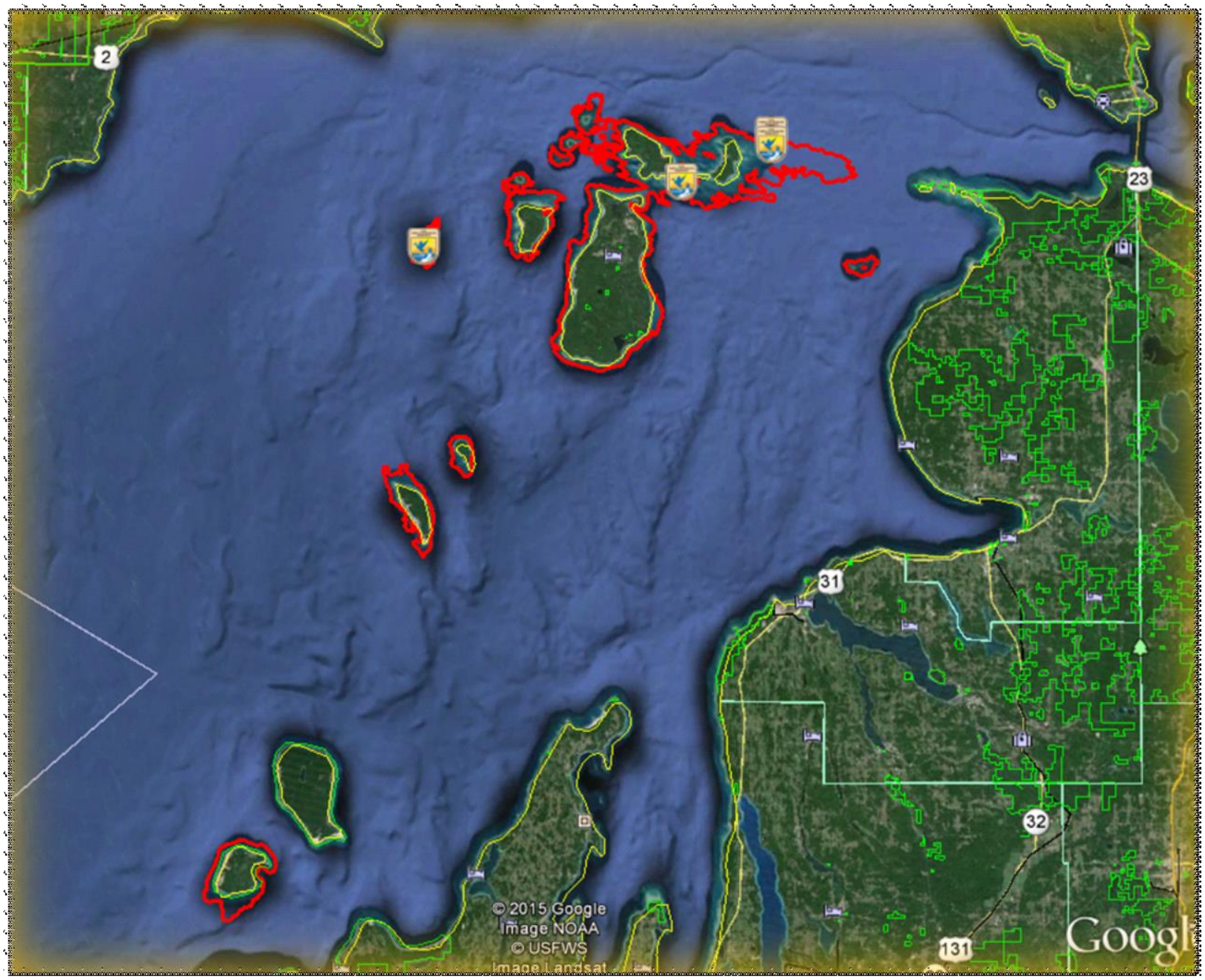
1.2 *Points of Contact*

Questions regarding the technical aspects of this report should be addressed to:

Dewberry Consultants LLC

Gary D. Simpson, L.S.
Senior Associate
10003 Derekwood Lane
Suite 204
Lanham, Maryland 20706
(301) 364-1855 direct
(301) 731-0188 fax

1.3 *Project Area*



Upper Lake Michigan

PROJECT DETAILS

2.1 *Survey Equipment*

In performing the GPS observations Trimble R-10 GNSS receiver/antenna attached to a two meter fixed height pole with a Trimble TSC3 Data Collector to collect GPS raw data were used to perform the field surveys.

2.2 *Survey Point Detail*

The 33 LiDAR Check Points were well distributed throughout the project area.

A sketch was made for each location and a nail was set at the point where possible or at an identifiable point. The Check Point locations are detailed on the "Check Point Documentation Report" sheets attached to this report.

2.3 *Network Design*

The GPS survey performed by Dewberry Consultants LLC office located in Lanham, MD was tied to a Real Time Network (RTN) managed by the Michigan Department of Transportation. The network is a series of "real-time" continuously operating, high precision GPS reference stations. All of the reference stations have been linked together using Trimble GPSNet software, creating a Virtual Reference Station System (VRS).

The Trimble NetR5 Reference Station is a multi-channel, multi-frequency GNSS (Global Navigation Satellite System) receiver designed for use as a stand-alone reference station or as part of a GNSS infrastructure solution. Trimble R-Track technology in the NetR5 receiver supports the modernized GPS L2C and L5 signals as well as GLONASS L1/L2 signals.

2.4 *Field Survey Procedures and Analysis*

Dewberry field surveyors used Trimble R-10 GNSS receivers, which is a geodetic quality dual frequency GPS receiver, to collect data at each surveyed location.

All locations were occupied once with approximately 50% of the locations being re-observed. All re-observations matched the initially derived station positions within the allowable tolerance of ± 5cm or within the 95% confidence level. Each occupation which utilized the VRS network was occupied for approximately three (3) minutes in duration and measured to 180 epochs.

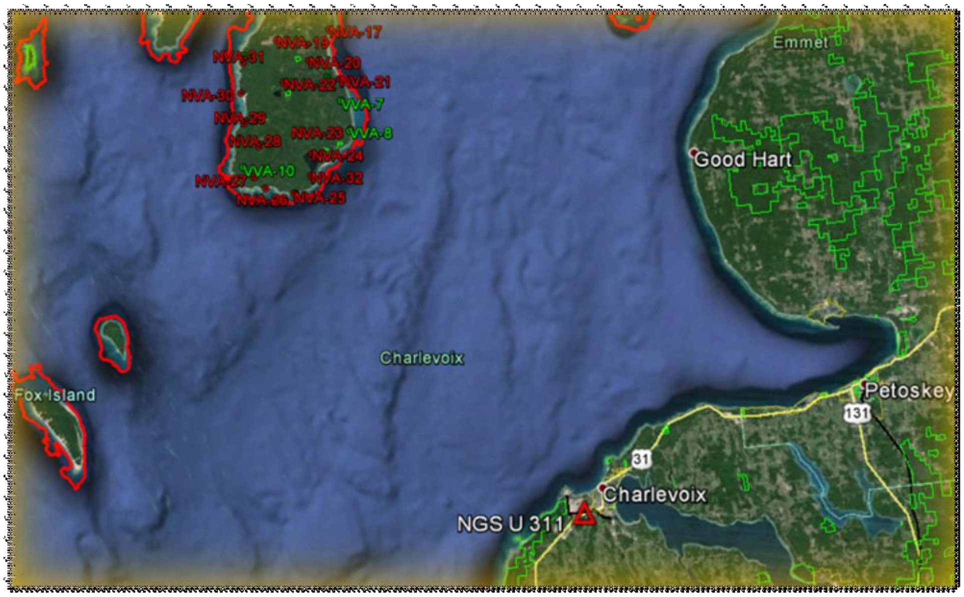
Each occupation which utilized OPUS (if used) was occupied between 20 and 30 minutes.

Field GPS observations are detailed on the "Check Point Documentation Reports" submitted as part of this report.

One (1) existing NGS monuments listed in the NSRS database were located as an additional QA/QC method to check the accuracy of the VRS network as well as being the primary project control monuments designated as QK0470. The results are as follows:

	As Surveyed (F)			Published (F)			Differences (F)		
NGS PT. ID	Northing(M)	Easting(M)	Elev.(M)	Northing(M)	Easting(M)	Elev. (M)	Δ N	Δ E	Δ Elev.
NGS U 311	5017812.212	634707.274	206.608	5017812.210	634707.278	206.600	0.002	0.004	0.008

The above results indicate that the VRS network is providing positional values within the 5cm parameters for this survey.



NGS Monuments

2.5 *Adjustment*

The survey data was collected using Virtual Reference Stations (VRS) methodology within a Virtual Reference System (VRS).

The system is designed to provide a true Network RTK performance, the RTKNet software enables high-accuracy positioning in real time across a geographic region. The RTKNet software package uses real-time data streams from the KEYNET system user and generates correction models for high-accuracy RTK GPS corrections throughout the network. Therefore, corrections were applied to the points as they were being collected, thus negating the need for a post process adjustment.

2.6 *Data Processing Procedures*

After field data is collected the information is downloaded from the data collectors into the office software. The Software program used is called TBC or Trimble Business Center.

Downloaded data is run through the TBC program to obtain the following reports; points report, point comparison report and a point detail report. The reports are reviewed for point accuracy and precision.

After review of the point data an “ASCII” or “txt” file which is the industry standard is created. Point files are loaded into our CADD program (Carlson Survey 2014) to make a visual check of the point data (Pt. #, Coordinates, Elev. and Description). The data can now be imported into the final product.

3. *FINAL COORDINATES*

Upper Lake Michigan FY 2015 LiDAR POINTS			
POINT #	**NORTHING (M)**	**EASTING (M)**	**ELEV. (M)**
NVA			
NVA-12	**5068299.06**	**611558.675**	**179.404**
NVA-13	**5066323.232**	**611894.895**	**179.551**
NVA-14	**5067060.729**	**614601.81**	**186.617**
NVA-15	**5066555.377**	**615974.903**	**178.461**
NVA-16	**5063885.211**	**615595.612**	**199.735**
NVA-17	**5061370.268**	**616725.858**	**184.272**
NVA-18	**5063816.788**	**611747.974**	**197.169**
NVA-19	**5060931.357**	**612077.82**	**203.157**

NVA-20	5058899.246	614715.602	202.091
NVA-21	5057104.784	617236.586	178.768
NVA-22	5057245.665	612342.706	214.532
NVA-23	5052695.318	617754.581	180.694
NVA-24	5050899.322	615135.309	187.188
NVA-25	5047587.711	612308.74	181.487
NVA-26	5048283.956	609895.682	178.593
NVA-27	5049218.515	608973.424	216.985
NVA-28	5051930.267	609664.607	218.643
NVA-29	5054058.011	608516.355	182.731
NVA-30	5057074.848	608532.08	180.277
NVA-31	5059316.328	608964.332	181.925
NVA-32	5048995.251	613894.375	188.081
VVA			
VVA-1	5067501.616	612710.51	185.529
VVA-2	5067259.659	615369.253	179.215
VVA-3	5064055.494	612379.788	197.35
VVA-4	5060265.704	614691.382	202.035
VVA-5	5059886.821	609028.5	180.309
VVA-6	5057313.807	616110.587	187.314
VVA-7	5057287.647	615185.586	199.828
VVA-8	5052300.409	617665.646	180.189
VVA-9	5054499.276	609917.69	219.511
VVA-10	5048337.817	609725.684	179.69
VVA-11	5047718.108	612629.837	180.401
VVA-12	5064900.568	615019.155	196.935

4. *GPS OBSERVATIONS*

POINT ID	OBSERV. DATE	JULIAN DATE	TIME OF DAY	RE-OBSERV. DATE	RE-OBSERV. TIME
NVA					
NVA-12	12/9/2015	343	15:10	12/9/2015	18:01
NVA-13	12/9/2015	343	15:20	12/9/2015	18:12
NVA-14	12/9/2015	343	14:40	12/9/2015	18:18
NVA-15	12/10/2015	344	5:30	12/10/2015	15:13
NVA-16	12/10/2015	344	14:50	N/A	N/A
NVA-17	12/10/2015	344	6:30	12/10/2015	13:48
NVA-18	12/9/2015	343	15:55	12/9/2015	18:28
NVA-19	12/9/2015	343	16:13	12/9/2015	18:47

NVA-20	12/10/2015	344	6:45	N/A	N/A
NVA-21	12/10/2015	344	12:25	12/10/2015	14:10
NVA-22	12/9/2015	343	16:30	12/9/2015	18:59
NVA-23	12/10/2015	344	12:05	N/A	N/A
NVA-24	12/10/2015	344	11:30	N/A	N/A
NVA-25	12/10/2015	344	10:15	N/A	N/A
NVA-26	12/10/2015	344	9:40	N/A	N/A
NVA-27	12/10/2015	344	9:30	N/A	N/A
NVA-28	12/9/2015	343	17:30	12/10/2015	14:36
NVA-29	12/9/2015	343	17:10	N/A	N/A
NVA-30	12/10/2015	344	7:48	N/A	N/A
NVA-31	12/10/2015	344	7:15	N/A	N/A
NVA-32	12/10/2015	344	11:05	N/A	N/A
VVA					
VVA-1	12/9/2015	343	14:55	12/9/2015	18:06
VVA-2	12/10/2015	344	6:15	N/A	N/A
VVA-3	12/9/2015	343	15:45	12/9/2015	18:35
VVA-4	12/10/2015	344	6:55	12/10/2015	13:55
VVA-5	12/10/2015	344	7:25	N/A	N/A
VVA-6	12/10/2015	344	12:35	12/10/2015	14:16
VVA-7	12/10/2015	344	13:15	12/10/2015	14:25
VVA-8	12/10/2015	344	11:50	N/A	N/A
VVA-9	12/9/2015	343	16:55	12/9/2015	19:22
VVA-10	12/10/2015	344	10:05	N/A	N/A
VVA-11	12/10/2015	344	10:49	N/A	N/A
VVA-12	12/10/2015	344	13:35	12/10/2015	15:03

5. *POINT COMPARISON*

LiDAR QA/QC				
POINT ID	POINT CK	DELTA NORTH (M)	DELTA EAST (M)	VERT. DIFF (M)
NVA QA				
NVA-12	NVA-12CK	0.020	0.003	0.010
NVA-13	NVA-13CK	0.016	0.010	0.001
NVA-14	NVA-14CK	0.004	0.000	0.017
NVA-15	NVA-15CK	0.000	0.004	0.000
NVA-17	NVA-17CK	0.016	0.000	0.002
NVA-18	NVA-18CK	0.008	0.001	0.001
NVA-19	NVA-19CK	0.004	0.004	0.015

NVA-21	**NVA-21CK**	**0.000**	**0.001**	**0.001**
NVA-22	**NVA-22CK**	**0.003**	**0.005**	**0.007**
NVA-28	**NVA-28CK**	**0.002**	**0.004**	**0.003**
VVA QA				
VVA-1	**VVA-1CK**	**0.021**	**0.000**	**0.023**
VVA-3	**VVA-3CK**	**0.015**	**0.011**	**0.048**
VVA-4	**VVA-4CK**	**0.016**	**0.003**	**0.010**
VVA-6	**VVA-6CK**	**0.004**	**0.002**	**0.010**
VVA-7	**VVA-7CK**	**0.008**	**0.002**	**0.026**
VVA-9	**VVA-9CK**	**0.005**	**0.003**	**0.000**
VVA-12	**VVA-12CK**	**0.007**	**0.001**	**0.012**

Appendix B: Acquisition Report

Upper Lake Michigan, MI Topobathy Acquisition and Calibration Report

Report Date: 27/7/2016

SUBMITTED BY:

Dewberry
1000 North Ashley Drive Suite 801
Tampa, FL 33602
813.225.1325

SUBMITTED TO:
NOAA Office of Coastal Management
2234 South Hobson Avenue
Charleston, SC 29405
843.740.11334

Overview

Dewberry elected to subcontract the LiDAR Acquisition and Calibration activities to Leading Edge Geomatics (LEG). Leading Edge Geomatics was responsible for providing LiDAR acquisition, calibration and delivery of LiDAR data files to Dewberry.

Dewberry received the final calibrated swath data from Leading Edge Geomatics beginning on June 16, 2016.

PROJECT AREA

The project area addressed by this report is the Beaver Islands Archipelago, covering an area of approximately 480 km2 (185 sq. miles) out to the 7-meter depth contour with a 500 m using ENC data. Manitou Island, covering an area of approximately 51 km^2 (20 sq. miles) out to the 7 meter depth was also collected.

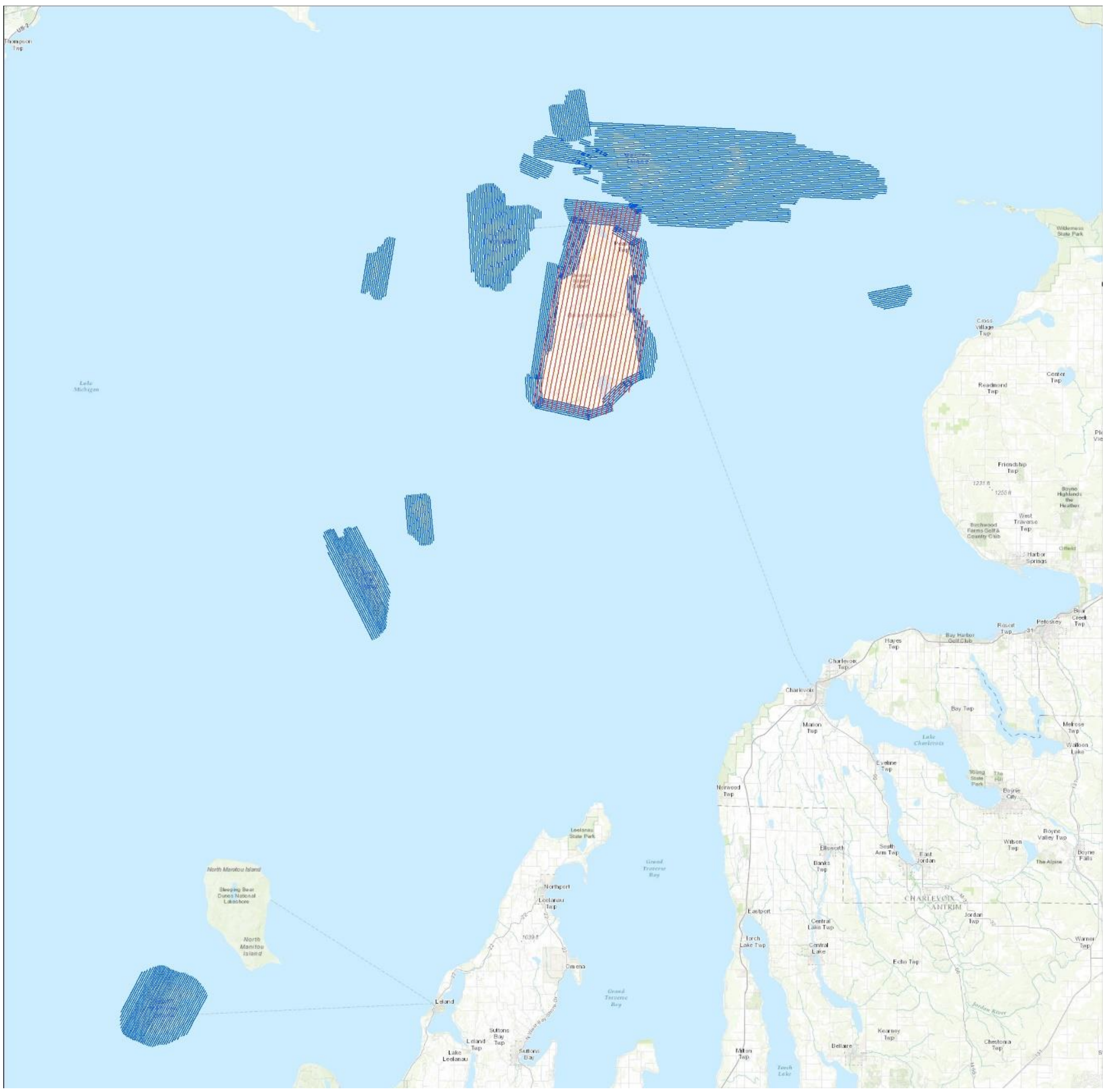


Figure 1 – Area of Interest

ACQUISITION DATES

The LiDAR survey was conducted between November 16, 2015 and June 4, 2016. Flying was suspended in December 2015 due to weather and completed in June 2016.

DATUM REFERENCE

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

Horizontal Datum: The horizontal datum for the project is North American Datum of 1983 (NAD 83 CORS2011)
Vertical Datum: The Vertical datum for the project is North American Vertical Datum of 1988 (NAVD88)
Coordinate System: UTM 16.
Units: Horizontal units are in meters, Vertical units are in meters.
Geoid Model: None. The data was delivered to Dewberry in Ellipsoidal.

LiDAR Acquisition Details

Leading Edge Geomatics planned a total of 404 passes for bathy and 22 for topographic only to complete the entire project area. 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, Leading Edge Geomatics followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using Track Air 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 had been investigated so that required permissions can be obtained in a timely manner with respect to schedule. Additionally, Leading Edge Geomatics will file our flight plans as required by local Air Traffic Control (ATC) prior to each mission.

Leading Edge Geomatics monitored weather, turbidity 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, snow, rain, fog, smoke, mist and low clouds. LiDAR systems are active sensors, not requiring light, thus missions may be conducted during night hours when weather restrictions do not prevent collection. Leading Edge Geomatics accesses reliable weather sites and indicators (webcams) 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, Leading Edge Geomatics 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.

Leading Edge Geomatics LiDAR sensors are calibrated at a designated site located in downtown Fredericton, New Brunswick and are periodically checked and adjusted to minimize corrections at project sites. Both systems were calibrated before departing for the project area.

LIDAR SYSTEM PARAMETERS

Leading Edge Geomatics operated a Piper Navajo (Tail # C-GKCN) with a Leica/AHAB Chiroptera II LiDAR system during the collection of the entire project. Table 1 illustrates Leading Edge Geomatics system parameters for LiDAR acquisition on this project.

Item	Parameter	
System	AHAB CHiroptera II (Bathy)	AHAB CHiroptera II (Topo)
Altitude (AGL meters)	400	400
Approx. Flight Speed (knots)	120	120
Scanner Pulse Rate (kHz)	35	140
Scan Frequency (RPM)	2358	4715
Pulse Duration of the Scanner (nanoseconds)	0.5	5
Pulse Width of the Scanner (m)	UNK	UNK
Swath width (m)	291	291
Central Wavelength of the Sensor Laser (nanometers)	1030 and 515	1064
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	No	No
Beam Divergence (milliradians)	4.5	0.5
Nominal Swath Width on the Ground (m)	291	291
Swath Overlap (%)	50	50
Total Sensor Scan Angle (degree)	40	40
Computed Down Track spacing (m) per beam	0.87	0.35
Computed Cross Track Spacing (m) per beam	0.87	0.43

Item	Parameter	
Nominal Pulse Spacing (single swath), (m)	0.87	0.35
Nominal Pulse Density (single swath) (ppsm), (m)	1.34	6.61
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.43	0.152
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	2.6	13.2
Maximum Number of Returns per Pulse	infinite	infinite

Table 1: Leading Edge Geomatics LiDAR System Parameters

ACQUISITION STATUS REPORT AND FLIGHTLINES

Upon notification to proceed, the flight crew loaded the flight plans and validated the flight parameters. The Acquisition Manager contacted air traffic control and coordinated flight pattern requirements. LiDAR acquisition began immediately upon notification that control base stations were in place. During flight operations, the flight crew monitored weather and atmospheric conditions. LiDAR missions were flown only when no condition existed below the sensor that would affect the collection of data. The pilot constantly monitored the aircraft course, position, pitch, roll, and yaw of the aircraft. The sensor operator monitored the sensor, the status of PDOPs, and performed the first Q/C review during acquisition. The flight crew constantly reviewed weather, water conditions and cloud locations. Any flight lines impacted by unfavorable conditions were marked as invalid and re-flown immediately or at an optimal time.

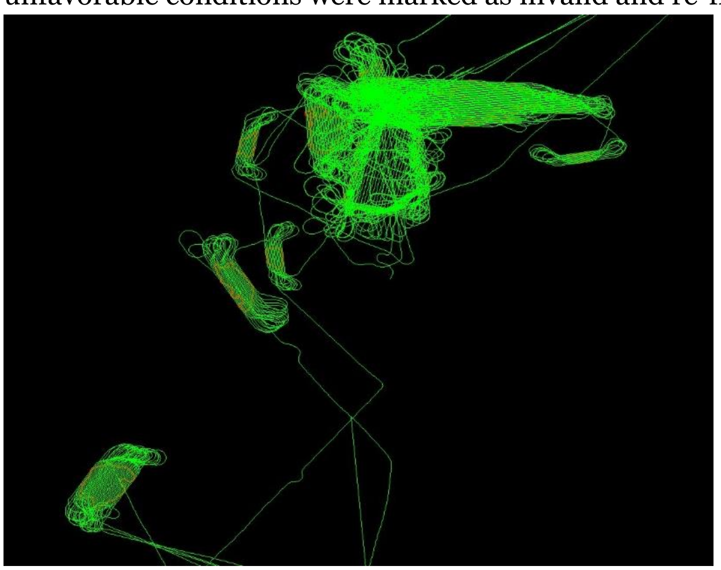


Figure 2 shows the combined trajectory of the flight lines.

LIDAR CONTROL

Five base stations were set by LEG for the collection. All stations were adjusted to CORS (2011). The coordinates of all used base stations are provided in the table below.

Name	Source	Degrees	Minutes	Seconds	Degrees	Minutes	Seconds	Ellipsoidal
LEG2		45	45	34.93334	-85	34	1.73833	141.6638
LEG3		45	34	51.08278	-85	32	2.52398	141.5158
BASE1		45	41	34.07144	85	33	43.1686	167.357
BASE2		45	9	6.67265	85	37	34.37559	181.259
BASE3		44	53	53.72122	86	1	46.3602	145.403

Table 2 – Base Stations used to control LiDAR acquisition

AIRBORNE GPS KINEMATIC

Airborne GPS data was processed using the Inertial Explorer from Waypoint. Flights were flown with a minimum of 6 satellites in view (12.5° above the horizon) and with a PDOP of better than 4.

For all flights, the GPS data can be classified as excellent, with GPS residuals of 3cm average or better but no larger than 10cm being recorded.

GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

The initial step of calibration is to verify availability and status of all needed GPS and Laser data against field notes and compile any data if not complete.

Subsequently the mission points are output using AHAB's LiDAR Survey Studio (LSS) application. System calibration was conducted prior to the aircraft departing for the project and the initial calibration values are used to position the point cloud. If a calibration error greater than specification is observed within the mission, the roll, pitch and yaw corrections that need to be applied are calculated. The missions with the new calibration values are regenerated and validated internally once again to ensure quality. Bathy data is processed on site to ensure that all data is useable and that appropriate bottom returns are being acquired.

Data collected by the LiDAR unit is reviewed for completeness, acceptable density and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database.

On a project level, a supplementary coverage check is carried out to ensure no data voids unreported by Field Operations are present.

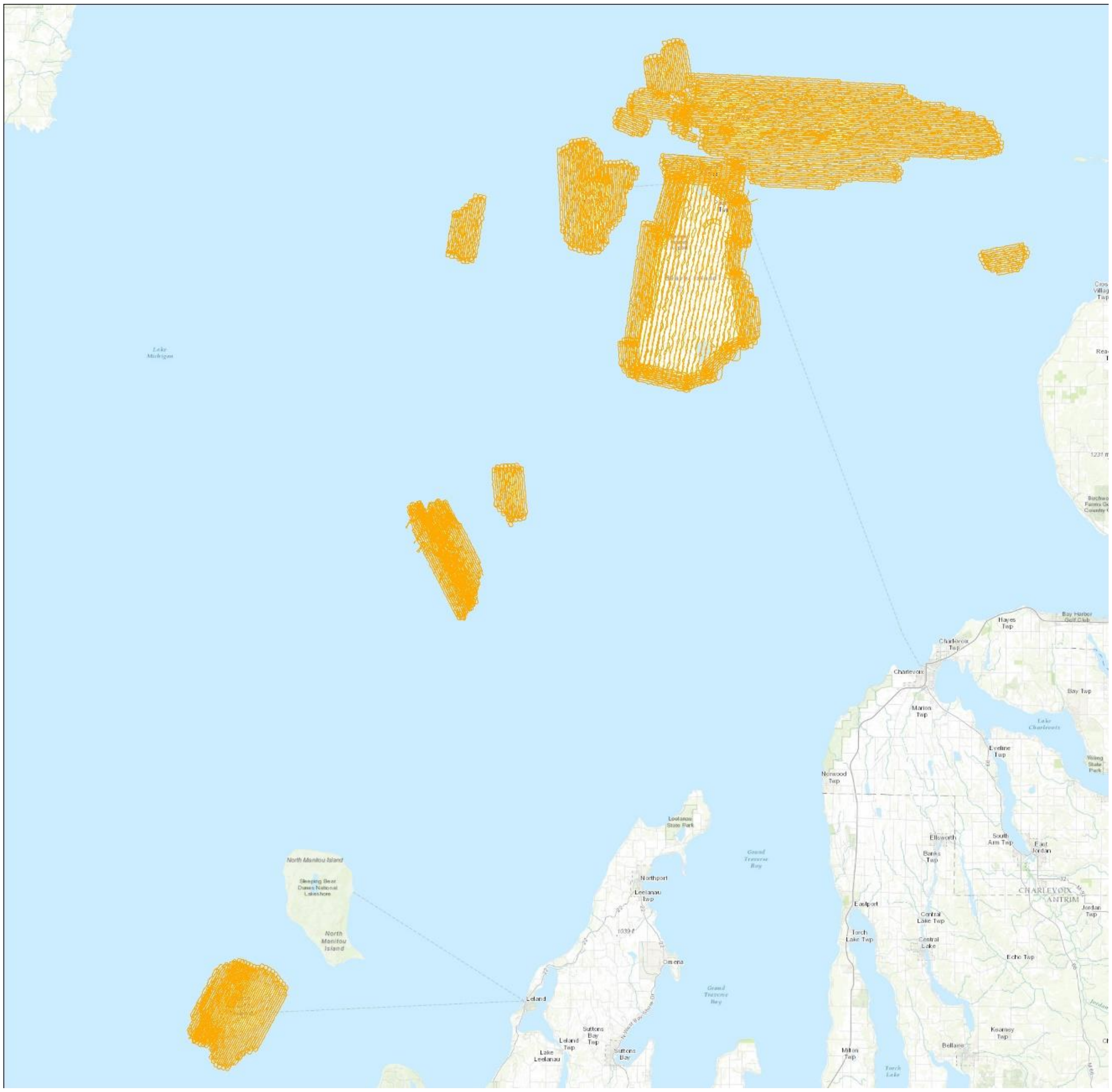


Figure 3 – LiDAR Swath output showing complete coverage.

BORESIGHT AND RELATIVE ACCURACY

The initial points for each mission calibration are 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 yaw are optimized during the calibration process until the relative accuracy is met.

Relative accuracy and internal quality are checked using at least 3 regularly spaced QC blocks in which points from all lines are loaded and inspected. Vertical differences between ground surfaces of each line are displayed. Color scale is adjusted so that errors greater than the specifications are flagged. Cross sections are visually inspected across each block to validate point to point, flight line to flight line and mission to mission agreement.

For this project the specifications used are as follow:

Absolute accuracy <=25 cm RMSEZ or within swath overlap (between adjacent swaths).

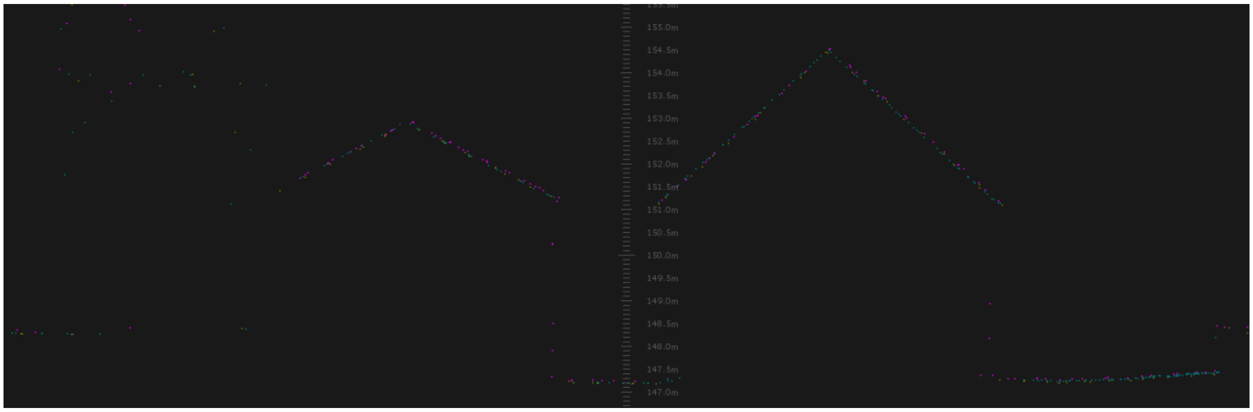


Figure 5 – Profile views cross section of multiple swaths.

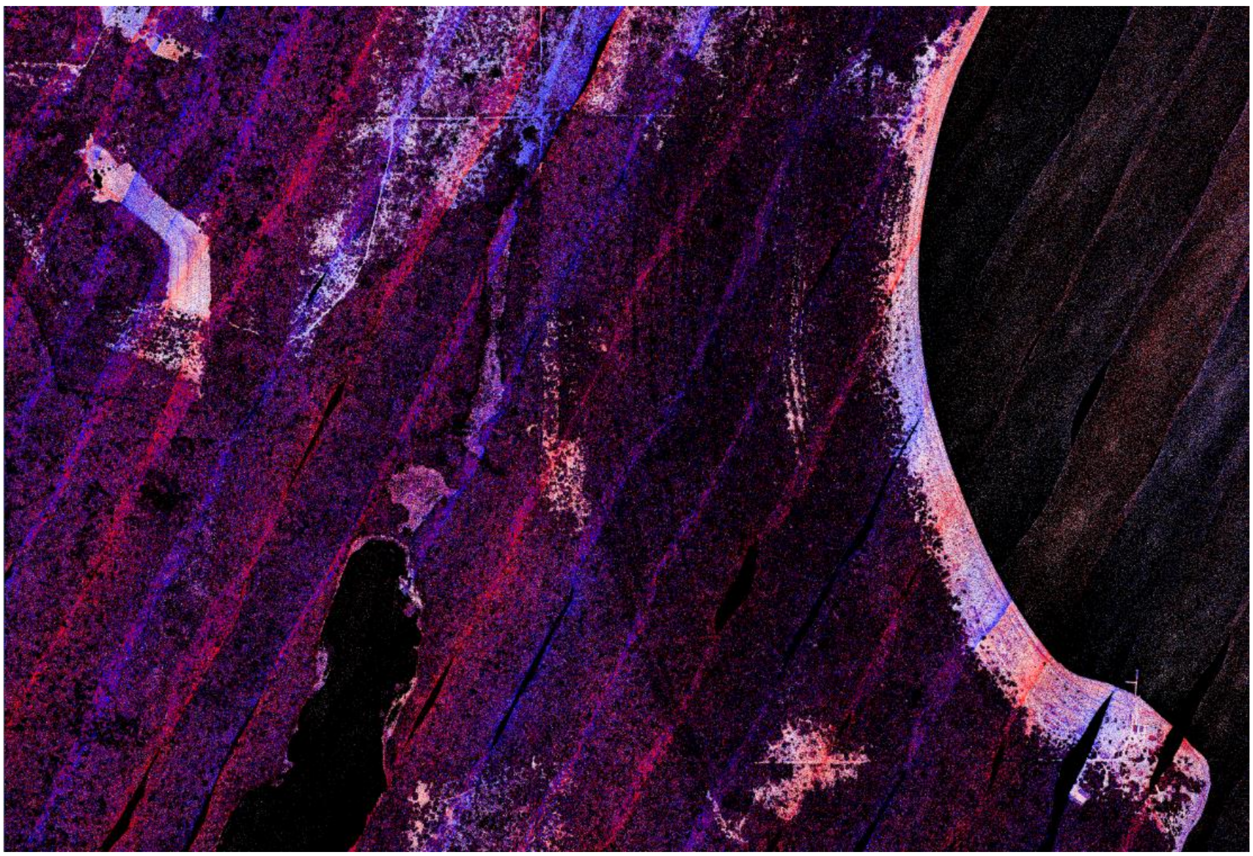


Figure 6 – QC block colored by distance to ensure accuracy at swath edges (8cm range).

A different set of QC blocks are generated for final review after all transformations have been applied.

PRELIMINARY VERTICAL ACCURACY ASSESSMENT

A preliminary $RMSE_z$ error check is performed by Leading Edge Geomatics at this stage of the project life cycle in the raw LiDAR dataset against GPS static data and compared to $RMSE_z$ project specifications. The LiDAR data is examined in open, flat areas away from breaks. Ground control points were collected by rapid static survey and compared against the LiDAR ground points and statistics are generated.

Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met project accuracy requirements (vertical accuracy <=25cm RMSEz) or better in open, non-vegetated terrain) when compared to static GPS checkpoints. Below is a summary for the test:

The calibrated Beaver Island LiDAR dataset was tested to 0.246 m (0.807 ft) vertical accuracy at 95% confidence level based on consolidated $RMSE_z$ (0.12m x 1.9600) when compared to 21 rapid static check points.

The following are the final statistics for the GPS static checkpoints used by Leading Edge Geomatics to internally verify vertical accuracy.

Average dz	0.1170 m
Root mean square	0.1260 m
Std deviation	0.0472 m

Overall the calibrated LiDAR data products collected by Leading Edge Geomatics meet or exceed the requirements set out in the Statement of Work. The quality control requirements of Leading Edge Geomatics quality management program were adhered to throughout the acquisition stage for this project to ensure product quality.

Appendix C: Complete List of Delivered Tiles

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7000E_8250N	7100E_8850N	7300E_8600N	8650E_3550N
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7000E_8500N	7150E_8250N	7300E_8850N	8700E_3150N
7000E_8550N	7150E_8300N	7300E_8900N	8700E_3200N
7000E_8600N	7150E_8350N	7350E_8600N	8700E_3250N
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9950E_7000N

List of Excluded DEMs

0550E_5150N
0650E_5550N
0650E_5600N
1850E_6100N
1850E_6200N