



NOAA
Coast Survey

H14138

North Thunder Bay
National Marine Sanctuary

OPR-X395-KR-25
Thunder Bay
Michigan

Responsible Party

DOC/NOAA/NOS/OCS -- Office of Coast Survey

Contact Information

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Field Unit

NV5

Survey Dates

July 18, 2025 - July 26, 2025

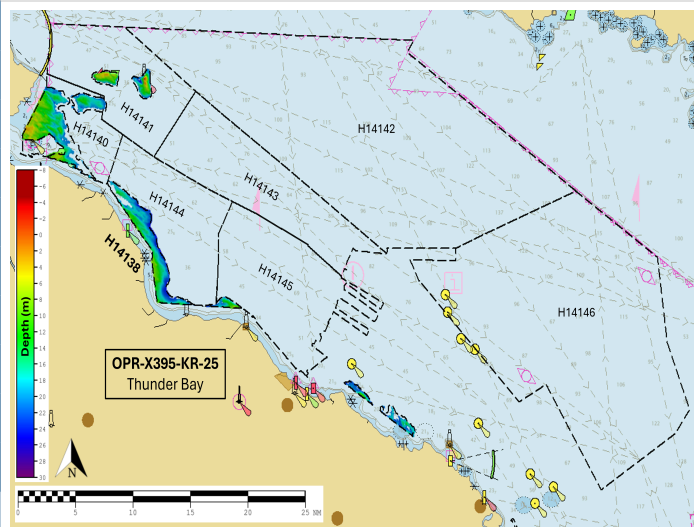
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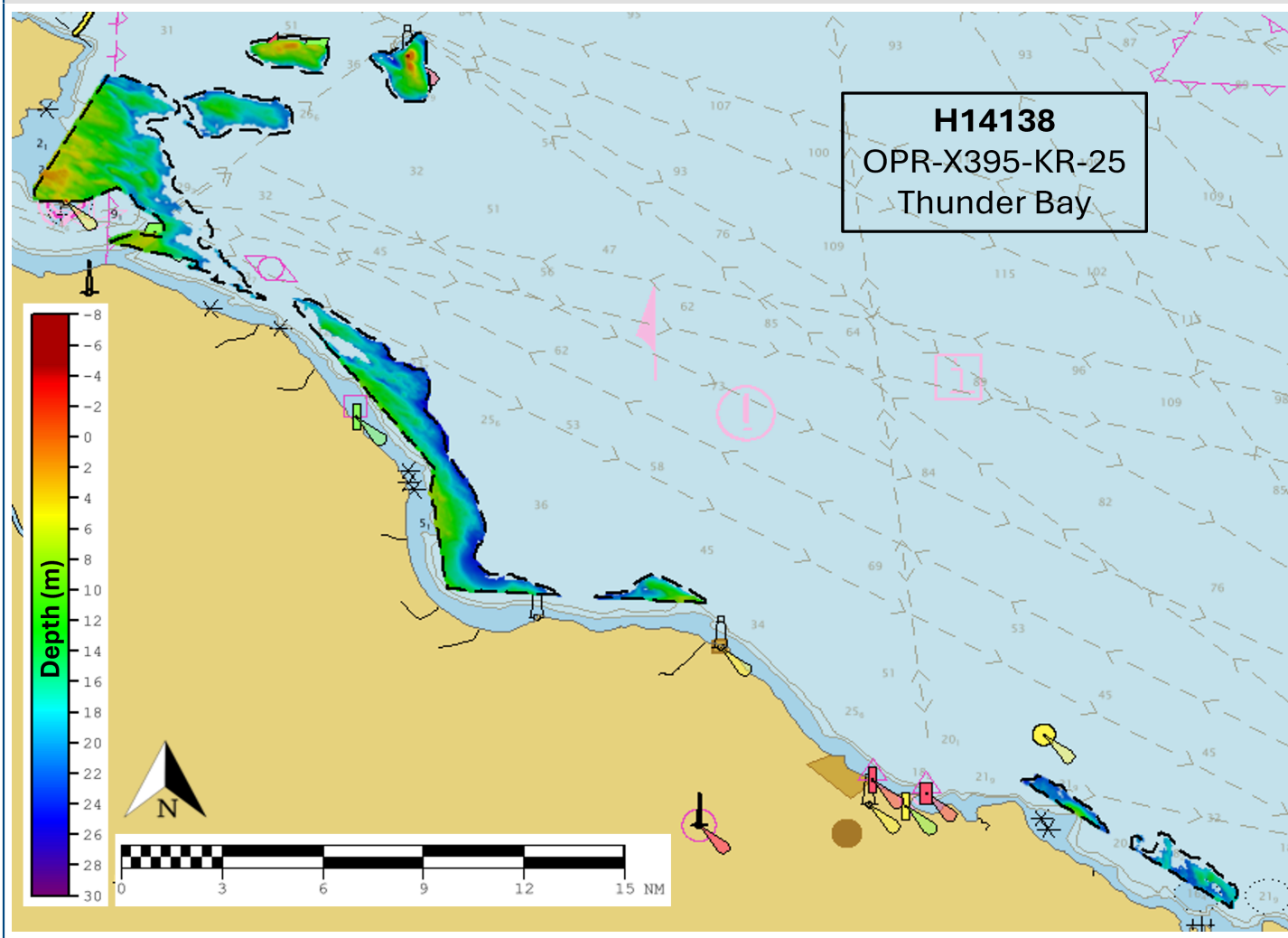
Approver

Nicholas Damm, CH

Overview



Survey Area



Platform and Sonar Equipment

Cessna Caravan (N216RF)

Unknown Unknown

Unknown Unknown

Bathymetry Grid

H14138_LI_1m_LWD_1of1.bag

Sounding Technique: **Lidar**

	Features Detected:	No	Fixed	Variable
North American Datum 1983 (2011)	Least Depth Detected:	No		
Projected UTM 17, Unit: meters	Full Seafloor Coverage:	Yes	Feature Detection Size: N/A	N/A
Low Water Datum IGLD-1985	Bathymetric Coverage:	Yes	Uncertainty Horizontal: 5m	5%
Unit: meters	Interpolated:	No	Uncertainty Vertical: 0.5m	1%

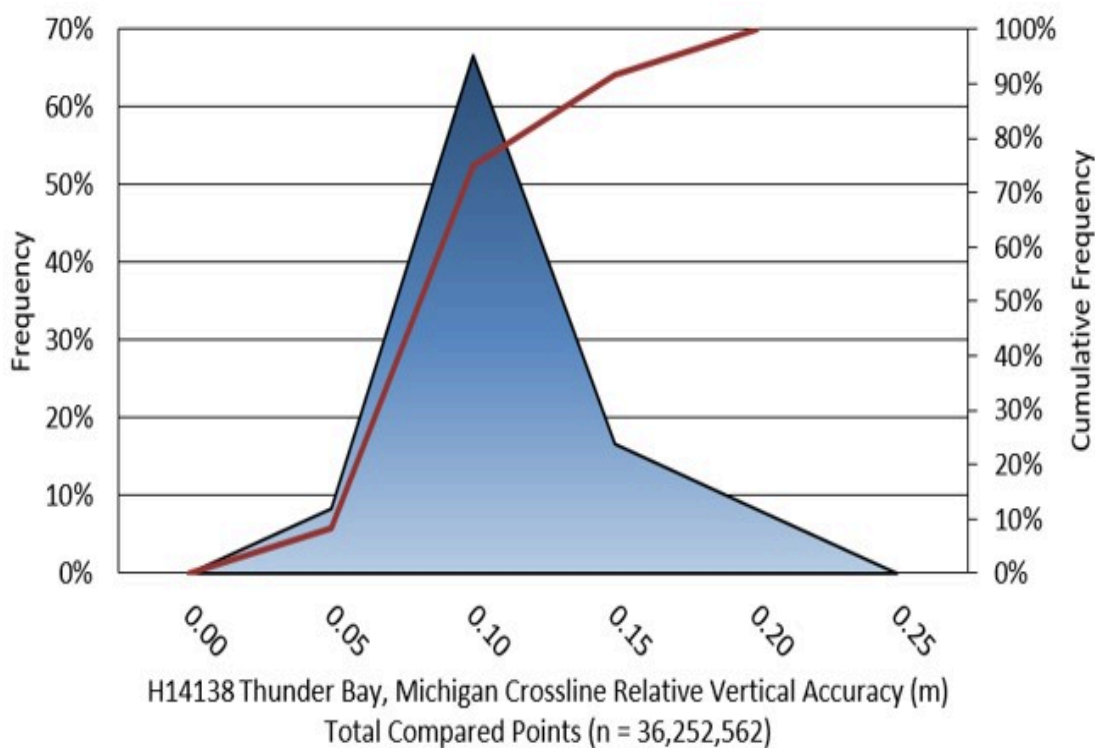
Quality Control Procedure

Crosslines

Crosslines were collected perpendicular to the shore within the project area at intervals less than 30 kilometers. Each mainscheme flightline within the dataset was compared to overlapping crosslines on a per-scanner basis to characterize the relative vertical accuracy across the dataset. The average (mean) relative vertical accuracy for the data overlapping the crosslines is listed in the image below.

Parameter	Relative Accuracy
Sample	24 surfaces
Average	0.048 m
Median	0.071 m
RMSE	0.090 m
Standard Deviation (1 σ)	0.037 m
1.96 σ	0.072 m

Relative accuracy results from crossline analysis for H14138



Frequency plot for relative vertical accuracy between cross-flightlines for H14138

Junction Overlap

As a means of data quality control, overlapping data was acquired with adjoining surveys as assigned in the Project Instructions. The Compare Grids tool in Pydro Explorer 24 was used to generate a depth difference surface as well as a fraction of allowable error surface, which computes the portion of the required Total Vertical Uncertainty budget consumed by the survey-to-survey depth differences per surface node.

Additionally, the tool produces graphs for statistical results of the comparison. The output surfaces were carefully evaluated in CARIS with a detailed visual inspection. The statistical graphs were reviewed for compliance with allowable error standards defined in the Project Instructions (PI) and the 2025 Hydrographic Surveys Specifications and Deliverables (HSSD) and indicated passing results. Any noncompliance issues, if present, are discussed in the Report of Survey section.

Statistical Analysis

Prior to initiating the project lidar data collection, NV5 conducted a calibration flight with the aircraft and Leica Chiroptera-5 and HawkEye-5 topobathymetric lidar sensors specifically utilized for the Thunder Bay lidar acquisition over a well-controlled area with varied planar surfaces as recommended by the system manufacturer. This data supported geometric corrections and boresight analysis to properly position and orient the sensor system within the aircraft. This process, performed in Leica's Lidar Survey Studio (LSS), is essential for interswath agreement and effective swath adjustments applied during the post-processing phase. Additional details and statistical results of the calibration can be found in the Boresight and Calibration Report provided in the Metadata QC Folder.

Statistical analysis of the lidar data collected for this survey followed components of NOAA Remote Survey Division (RSD) guidelines which specifies American Society for Photogrammetry and Remote Sensing (ASPRS) Positional Accuracy Standards for Digital Geospatial Data (Edition 1, Version 1 (2014)) as well as NOAA Office of Coast Survey (OCS) hydrographic standard assessments and reporting practices. Analysis

included ground survey point (GSP) assessment, line-to-line relative vertical accuracy analysis, horizontal accuracy evaluation, and point density analysis. All results are described in greater detail below and were provided in the "Additional Information" section of the Report of Survey. Software used for lidar statistical analysis following NOAA RSD guidelines and practices is listed in the table below. The statistical analysis for NOAA OCS standard hydrographic reporting practices, utilized NOAA's Pydro tool suite as well as CARIS Base Editor.

GSPs were collected using real time kinematic (RTK) and post-processed kinematic (PPK) survey techniques. For RTK, a roving receiver received corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. Alternatively with PPK surveys, roving receivers recorded data while stationary for at least five seconds, calculating the position using at least three one-second epochs. Corrections were then computed during post-processing using Trimble Business Center (TBC) software instead of real-time to achieve comparable accuracy. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of less than 3.0 with at least six satellites in view of the stationary and roving receivers. See the Control Point Establishment section for the specific GNSS equipment utilized for GSP collection.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. Highly reflective surface areas such as center line stripes or lane markings on roads were avoided when taking GSP measurements due to increased noise seen in laser returns over such surfaces. Due to the lack of land cover within the project extent, all project GSPs exist outside of the contracted boundary. However, the Thunder Bay GSPs were collected within crosslines areas on land connecting to the open-water lidar missions. Distribution of GSPs depended on crossline locations, ground access constraints, and monument locations and may not be equally distributed throughout the surveyed area. See the Ground Survey Data folder in the Metadata QC folder for a map and the associated files.

Collected GSP types consisted of non-vegetated accuracy checkpoints, bathymetric (submerged) accuracy checkpoints (BAPs), and ground control points (GCPs). ASPRS Positional Accuracy Standards for Digital Geospatial Data (Edition 1, Version 1 (2014)) Non-Vegetated Vertical Accuracy (NVA) reporting was used for lidar absolute accuracy assessment for the non-vegetated accuracy checkpoints and bathymetric accuracy (BAP) checkpoints. NVA reporting compares known ground checkpoint data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the ground classified lidar point cloud as well as the derived gridded bare earth digital elevation model (DEM). NV5 assessed this using TerraSolid's TerraModeler software. NVA is a measure of the accuracy of lidar point data in open unobstructed and non-vegetated bare surface areas where the lidar system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval ($1.96 * RMSE$). The mean and standard deviation (sigma) of divergence of the ground surface model from ground checkpoint coordinates are also considered during accuracy assessment. These statistics assume the error for x, y, and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics to better evaluate the magnitude and distribution of the estimated error. BAPs are typically not collected in depths greater than 1 meter. Though the ground control points (GCPs) were utilized in post processing to aid in the lidar point cloud calibration, absolute accuracy was also calculated and reported for the GCPs utilizing the above method as they provide a good assessment of the dataset as well.

A relative vertical accuracy assessment evaluates the internal consistency of a dataset without regard to absolute coordinates given the ability to place an object in the same location given multiple flight

lines, GNSS conditions, and aircraft attitudes. The average magnitude of vertical difference between repeated surfaces in sampled areas of flight line overlap for the H14138 survey area was calculated using TerraSolid's TerraMatch software. NV5 also verified that the relative vertical accuracy was within project specifications with Delta-Z (DZ) rasters created using NV5's proprietary software Lidar Product Creator (LPC). When a lidar dataset is well calibrated, the swath-to-swath vertical divergence is low (<0.10 m).

A horizontal accuracy check was also conducted. This check is derived from Global Navigation Satellite System (GNSS) positional error estimates, flying altitude, and Inertial Measurement Unit (IMU) derived attitude (angular orientation) errors. NovAtel's Inertial Explorer software was used to resolve kinematic corrections for aircraft position data using kinematic aircraft Global Positioning System (GPS) from Continuously Operating Reference Stations (CORS) utilizing the Online Positioning User Service (OPUS) for precise positioning and develop a smoothed best estimate of trajectory (SBET) files that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey. NV5 then used proprietary software LAS Monkey to summarize the GNSS and IMU errors from lidar trajectory files. From these values, the RMSEr value is determined and then multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95% of the time (ACCr).

Lidar point density analysis included calculations for nominal first return density, ground and bathymetric bottom classified return density, and bathymetric bottom only classified return density based off of 1 meter resolution density rasters output using TerraSolid's TerraModeler. First return density describes the density of pulses that return at least one or more echoes to the system emitted from a given laser channel. The first return density was calculated for the overall combined first returns for the project as well as independently for NIR and green channels. Some types of surfaces (e.g., breaks in terrain, water, and steep slopes) may have returned fewer pulses than originally emitted by the sensor. The density of ground and bathymetric bottom classified lidar returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity influence the density of ground classified surface returns. Density of mapped bathymetric bottom classified returns is influenced by turbidity, depth, and bottom surface reflectivity. In turbid areas, fewer pulses may have penetrated the water surface, resulting in lower bathymetric bottom classified point density. The lidar point density statistics were calculated per 100 meter x100 meter sampled cell then averaged for the full survey area. All areas within the survey boundary, including zones of full laser extinction, were included in the first return density and the ground and bathymetric bottom classified point density reporting, which contributed to lower overall averages. For the bathymetric bottom-only classified point density, 100 meter x 100 meter sampled cells lacking bathymetric bottom classified returns were not considered in the calculation, meaning this density value only is only in respect to the area of the 100 meter x100 meter sampled cells with successfully mapped bathymetric bottom classified returns within the project boundary area.

A ground and bathymetric bottom point density raster was provided in the Source Grids folder for reference and additional back-end review. The density raster was produced as a gridded 1-meter resolution geotiff (.tif) file format raster with integer values. The bathymetric bottom void shapefile was used to clip the ground and bathymetric bottom point density raster extent similar to that of the bare earth model raster.

The statistical analysis and reporting performed in accordance with NOAA OCS standard hydrographic reporting practices were completed using a combination of CARIS, custom scripts, and QC Tools 4 within Pydro Explorer 24.

The finalized BAG raster submitted for this survey contains a bare earth digital elevation model (DEM) raster created using a triangulated irregular network (TIN) surface built from class 2 topographic ground,

class 40 bathymetric bottom, and class 43 submerged feature classified points in accordance with the PI alteration described below and further explained in the Holiday Identification section. The vertical uncertainty band contained in the final submitted BAG was created with vertical uncertainty values calculated from NOAA's cBLUE software using class 2 topographic ground, class 40 bathymetric bottom, and class 43 submerged feature classified points and compiled by custom NV5 scripts.

Vertical uncertainty values within the finalized BAG were assessed visually in CARIS Base Editor to identify grid nodes exceeding allowable total vertical uncertainty (TVU) thresholds specified in the PI and the 2025 HSSD for the applicable depth ranges. Graphs output from QC Tools 4 on the finalized BAGs were reviewed for compliance with PI and 2025 HSSD specifications. The Quality Metric for vertical uncertainty required by the PI for this survey is General 1. The metric reported in the Metadata section above is the achieved metric as evaluated by the modeled TVU attributed to each node of the BAG assessed using QC Tools 4 Grid Stats utility (results are provided in the Metadata QC folder). The required vertical uncertainty quality metric was consistently utilized for data quality assessment and flier reviews. Additionally, javascript object notation (JSON) metadata files created from cBLUE containing TVU statistics were provided in the Metadata QC folder. Please note the delivered JSON file organization is described in the Uncertainty Source section of the report.

Horizontal uncertainty values were assessed from a standalone QAQC raster created from cBLUE outputs, which is provided in the Source Grids folder. This raster was assessed visually in CARIS Base Editor to identify grid nodes of total horizontal uncertainty (THU) exceeding allowable thresholds specified in the PI and the 2025 HSSD for the applicable depth ranges. The Quality Metric for horizontal uncertainty required by the PI for this survey is General 1. The metric reported in the Metadata section above is the achieved metric determined through the evaluation of this horizontal uncertainty raster.

Density evaluation, conducted in a manner consistent with HSSD hydrographic reporting standards, was performed using a standalone QAQC density raster. This raster performs a hit count within a one meter square area for the classes used to generate the Bare Earth DEM and is provided in the Source Grids folder. A custom script was subsequently employed to evaluate nodes within the density raster containing five or more soundings, as the raster could not be processed using QC Tools. Additional discussion regarding lidar point density is provided later in this report.

Resultant graphs from QC Tools 4 are provided in the Metadata QC folder. Any non-compliance issues related to grid resolution, density, or uncertainty, if present, are discussed in the Report of Survey section.

Statistical Software	Version
Trimble Business Center (TBC)	2025.10
NovAtel's Inertial Explorer	9.0
Leica's Lidar Studio Suite (LSS)	3.4
Trimble's Applanix POSPac	9.4
TerraSolid's TerraMatch	25.003
TerraSolid's TerraModeler	25.001
TerraSolid's TerraScan	25.007
NOAA's Pydro software suite	24
Teledyne's CARIS BASE editor	5.5.25
NV5's Proprietary software LAS Monkey	2.6.11
NOAA's cBLUE	4.1

Software used for statistical analysis for standard lidar reporting practices

Directed Editing

To maximize data quality, sensor selection is critical. The Leica Chiroptera-5 (CH5) NIR and shallow green lidar sensor was chosen due to its ability to perform well in areas with dynamic wave action, which can be useful in collecting shallow coastal and shoreline data. These systems detect obstructions, such as vegetation and anthropogenic features. This means they can provide additional information from multiple positions that more closely resemble the actual features and can allow for further analyses compared to traditional imagery. The CH5 lidar sensor was dually mounted in a Cessna Caravan with a Leica HawkEye-5 (HE5) 40kHz deep green bathymetric sensor. HawkEye deep green lasers have the same wavelength as Chiroptera shallow green lasers (515 nm) but are optimized for deeper bathymetric environments and provide better resolution and depth penetration. Both the CH5 and HE5 have an oblique front-back palmer scanner which produces a scanner pattern with a degree of incidence ranging from $\pm 14^\circ$ (front and back) to $\pm 20^\circ$ (sides), providing a 40° field of view providing multiple look angles on a single pass and helping to eliminate shadowing effects. This can be of particular use for bathymetric features such as sides of narrow water channels and smaller objects or features on the seafloor. These Leica lidar systems support correction for water refraction in post-processing.

Upon completion of the Thunder Bay lidar data acquisition, kinematic corrections were resolved for aircraft position and orientation using NovAtel's Inertial Explorer software. A SBET file was developed to combine sensor head positions calculated during the pre-project calibration and boresight flight (aforementioned in the Statistical Accuracy report section) with the positions and attitudes from IMU and gyro-stabilized mount data recorded throughout the Thunder Bay lidar survey.

Using Leica's LSS software, laser point positions were calculated per flightline by associating SBET position and orientation information to each lidar point return timestamp and applying the misalignment corrections calculated from the pre-project calibration and boresight flight data. A subsequent raw lidar point cloud was output in *.las (ASPRS version 1.4, point record format 6) file format, then imported into optimally

sized blocks for further processing. Erroneous noise points were filtered and initial topographic ground point classifications were applied using TerraSolid's TerraScan software. Manual and automated swath position adjustments were performed to correct for system attitude parameters (pitch, roll, heading), mirror flex, and GNSS/IMU drift using BayesMap's StripAlign software. The resulting final line-to-line relative accuracy was assessed using TerraSolid's TerraMatch and verified through reviewing Delta-Z (DZ) rasters created with NV5's proprietary software Las Product Creator (LPC) tools as discussed in the Statistical Analysis section of the report.

Light refracts when entering water, changing speed and direction described by Snell's Law. Refraction must be accounted for and corrected for the bathymetric (or submerged) green channel point returns. A refraction correction was applied as part of the raw lidar data extraction process in Leica's LSS software.

Leica's LSS software automatically generates synthetic water surface points for both the CH5 and HE5 datasets based on information derived from the CH5 sensor's NIR channel returns. High absorption of NIR wavelengths in water causes extremely limited NIR laser pulse penetration into water bodies resulting in NIR channel returns at the water's surface which accurately model variable water surfaces including those with wave action or tidal changes. Because the NIR and green laser channels from the CH5 sensor are coaligned, NIR channel water surface returns are also representative of the associated green channel pulses. The use of synthetic points in the point cloud makes it clear where the refraction correction surfaces were placed ensuring complete coverage of submerged points.

To calculate the proper refraction corrections for all submerged returns, an appropriate index of refraction was selected for the survey area based on water salinity and temperature. Water surface models (WSMs) were developed for each flightline swath and scan direction per sensor to account for all temporal changes of the water's surface during the survey collection. Using the WSMs, LSS software applied a refraction correction to each submerged point by intersecting the trajectory of the green laser pulses with their respective WSM, determining how much time the laser pulse spent traveling through water and the angle that it entered. After the resulting data was reviewed to ensure accurate positioning, custom classification algorithms were applied followed by manual classification editing using TerraSolid software packages and NV5's proprietary LAS Monkey software to meet the PI specified ASPRS classification scheme (table below).

During manual classification editing, the team stepped through individual tiles in efforts to identify potential submerged or charted features meeting HSSD specifications within the survey area. The team reviewed the bare earth DEM for features that were incongruous with the surrounding morphology to help inform areas to better inspect in the point cloud. Features that were captured in multiple flightlines or had a unique intensity profile compared to surrounding terrain and were given more preference. These identified points were given the class 43 submerged feature classification, which were then utilized to identify multibeam investigation areas and in the development of the Lidar Contacts File and the Final Feature File.

To confirm the classification of lidar points used in the final bathymetric surfaces, the QC Tools Flier Finder tool was used to identify grid nodes flagged as potential fliers for further review. The tool was run using standard preset parameters and was also manually adjusted using forced flier heights to support targeted data editing. These checks were performed using early iterations of the DEM, and edits to spurious nodes identified during this process were addressed in the point cloud prior to final surface generation. The Flier Finder tool identifies surface anomalies based on defined criteria and may also flag valid surface aspects that meet the same criteria. Outputs generated from the QC Tools Flier Finder process are provided in the Metadata QC folder and were reviewed thoroughly. Given the context of this survey, the isolated node flag

was not utilized due to extinction areas containing scattered nodes. Any non compliance issues identified during this review, if present, are discussed in the Report of Survey section.

All submerged green channel intensity values in the final classified lidar point cloud were normalized for depth. This process is detailed in the Image Coverage section of the report.

As discussed in the Statistical Analysis section of the report, the absolute vertical accuracy, and horizontal accuracy of the final lidar point cloud was assessed.

All raster product deliverables were created from the final classified lidar point cloud.

Classification Number	Classification Name	Classification Description
1	Unclassified	Processed, but unclassified
2	Ground	Topographic ground
7 Withheld	Low Noise	Noise (low manually identified)
18 Withheld	High Noise	Noise (high manually identified)
20	Ignored Ground	Ground point in Breakline Proximity
21	Snow	Snow
40	Bathymetric Bottom	Bathymetric bottom point (e.g., seafloor or riverbed; also known as submerged topography)
41	Water Surface	Water's surface (sea/river/lake surface from topographic-bathymetric lidar)
42- Synthetic	Derived Water Surface	Synthetic water surface location used in computing refraction correction
43	Submerged Feature	Submerged object, not otherwise specified (e.g., wreck, rock, submerged piling)
44	Reserved	IHO S-57 object, not otherwise specified
45	Water Column	Refracted returns not determined to be water surface or bathymetric bottom
46	Submerged Aquatic Vegetation	Benthic vegetation in submerged, refracted areas
47 Withheld	Submerged Noise	Submerged noise points resulting from system errors and anomalies; not representative of real objects
48	Submerged Temporal Exclusion	Denotes bathymetric bottom temporal changes from varying lifts, not utilized in the bathymetric point class
1-Withheld	Edge Clip	Unclassified points flagged as withheld. These are primarily "edge" points from the higher scan angle being removed
1-Overlap Withheld	Unrefracted Green Laser Returns	Unrefracted green laser data

ASPRS LAS classification standards applied to the Thunder Bay dataset

Holiday Identification

Bathymetric lidar DEMs present a challenge with respect to interpolation in areas with no bathymetric bottom classified point returns (bathymetric voids). Traditionally, bare earth DEMs created using a TIN surface have interpolation across areas lacking ground or bathymetric bottom classified returns from valid mapped point returns, with the assumption that the interpolation is close to reality. In bathymetric modeling, these assumptions can be prone to error because the resulting void areas could be at greater depths due to topobathymetric lidar sensor mapping limitations, rather than similar elevations from neighboring bathymetric bottom returns. Therefore, a shapefile delineating bathymetric voids was created to limit the extent of triangulation (interpolation in the TIN) in the delivered bare earth topobathymetric elevation model to avoid potentially false interpolation across areas without mapped bathymetry.

A threshold of 9 square meters was determined to restrict interpolation in areas lacking bathymetric bottom returns. Bathymetric void polygons were developed by calculating the maximum edge lengths of delineated triangles in the TIN surface model built from bathymetric bottom and submerged object classified returns. The maximum edge length that a 9 square meter equilateral triangle can have is 4.56 meters. Any TIN

triangles with edge lengths greater than 4.56 meters were delineated into the bathymetric void shapefile and were used to clip out (exclude) interpolation areas from the bare earth DEM. Any TIN triangles with maximum edge lengths less than 4.56 meters were not delineated as a bathymetric void and remain as interpolation in the bare earth DEM. This approach was reviewed and approved in coordination with the COR (see PI Alteration section). Remaining areas of interpolation can be identified by comparing the bare earth DEM to the ground and bathymetric bottom classified return density raster and locating elevations associated with zero value density nodes. Because this gridding methodology was fully documented, approved, and does not exceed the HSSD holiday threshold, the “Data Interpolation” entry in the Metadata section above is set to No. Overall, these interpolations techniques and parameters are consistent with standard practices used across NOAA RSD bathymetric lidar projects.

The PIs specify that the lidar acquisition extend to the survey limits or to laser extinction, whichever occurs first. Due to lidar sensor limitations, bathymetric bottom classified lidar surfaces naturally contain voids in areas influenced by certain environmental conditions such as turbidity and water clarity or at depths near laser extinction. These bathymetric bottom voids are expected for this type of survey and are not considered deficiencies under the PIs and discussions with the COR for lidar-only survey areas. The Full Seafloor Coverage field in the Metadata section is set to Yes because all bathymetric lidar voids were explicitly captured and attributed within the delivered bathymetric void shapefile, meeting the requirements defined in the PIs. This bathymetric voids shapefile is provided in the Metadata QC folder.

In areas where the lidar survey overlapped designated multibeam sheets (H14140, H14141, H14144, H14145), multibeam echosounder data were collected to complement lidar coverage. For holiday assessment, the lidar and multibeam rasters were combined to represent the fully mapped seafloor. QC Tools 4 Holiday Finder was then applied to the combined rasters for each applicable sheet to verify that the integrated dataset satisfied the full coverage and holiday thresholds as defined in the PIs and HSSD.

Survey Adequacy

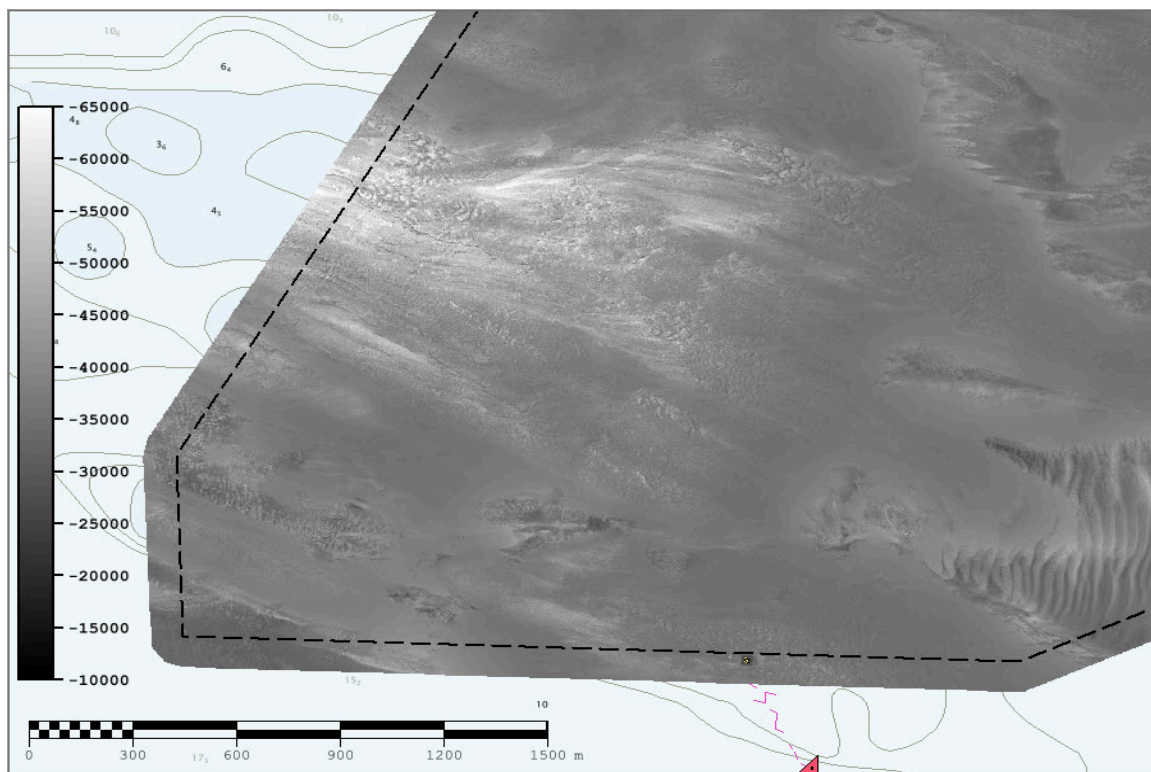
All survey data may be used to update or supersede prior data within the survey limits, with consideration given to bathymetric lidar specific considerations documented in the associated survey metadata and survey evaluation data products.

Imagery Coverage

Each lidar echo return signal has a recorded amplitude associated for each point and is stored in a LAS format file as an intensity record. Laser return intensity is generally a unitless measure of discrete return signal strength, stored as a 16-bit integer value (0 to 65,535). Intensity values roughly correspond to the reflectivity of the surface, which is a function of surface material composition. Stronger returns, indicating higher reflectivity, correspond to higher magnitude intensity values, while weaker returns, indicative of lower reflectivity, correspond to lower magnitude intensity values. The magnitude of intensity values can vary across similar surfaces due to variability in atmospheric, water clarity, range, submerged depth, and the laser angle of incidence on an object. This can result in line-to-line inconsistencies and streaking in intensity image rasters which can reduce the utility of these data for analytics. For bathymetric (submerged) returns, laser energy attenuates exponentially with depth, with the rate of decay dependent on water properties such as turbidity and composition. By comparing point returns from consistent substrate types across overlapping flightlines and varying depth ranges, attenuation correction coefficients were developed and applied to normalize seabed (submerged green laser point return) intensity values for depth. The final green channel bathymetric intensity values are therefore corrected for depth related signal loss. Although these corrections significantly improve consistency, localized differences in water column properties may still

produce some variance in intensity values across the survey area, which may be seen in the final intensity image rasters. The corrected, normalized intensity values for submerged returns were also applied to the final processed LAS files.

NV5 produced a 2-band intensity raster to meet the PI requirement to generate a normalized seabed reflectance intensity raster, serving as the lidar equivalent to multibeam backscatter and acoustic intensity product. Band 1 was created using the average intensity value from all returns within a pixel cell of class 40 bathymetric bottom and class 43 submerged object classified point green laser returns which were normalized for laser attenuation due to depth. Band 2 was created using the average intensity value from the first returns within a pixel cell of class 1 unclassified and class 2 topographic ground classified point NIR laser returns. Band 2 (NIR) intensity values were not normalized for depth as they pertain to above water surface returns. As mentioned above, the intensity values roughly correspond to the reflectivity of the surface, which is a function of surface material composition. Stronger returns, indicating higher reflectivity, correspond to higher magnitude intensity values, while weaker returns, indicative of lower reflectivity, correspond to lower magnitude intensity values.



H14138 Lidar Intensity Mosaic Band 1 (submerged points)

Data Interpolation

Data interpolation was not performed for this survey

Backscatter

Calibration Method

N/A

Dynamic Range

No echosounder was utilized for this survey area.

The Leica Chiroptera-5 (CH5) NIR and shallow green channel lidar system paired with the Leica HawkEye deep green channel lidar system was well suited to this project area and project needs, ensuring continuous mapping across the full range of required survey depths.

Acquisition Configuration

No echosounder was utilized for this survey area.

The lidar survey was accomplished using Leica Chiroptera 5 and HawkEye-5 (CH5/HE5) lidar systems mounted in a Cessna Caravan. The figure below summarizes the settings used to yield an average nominal pulse density of 3 pulses per square meter for green channel returns and 4 pulses per square meter for NIR channel returns within the survey area.

Parameter	Leica Chiroptera-5 NIR Channel	Leica Chiroptera-5 Shallow Green Channel	Leica HawkEye-5 Deep Green Channel
Acquisition Dates	7/18/2025 - 7/26/2025	7/18/2025 - 7/26/2025	7/18/2025 - 7/26/2025
Aircraft Used	Cessna Caravan	Cessna Caravan	Cessna Caravan
Resolution/Density	Average 4 pulses/m ²	Average 3 pulses/m ²	Average 3 pulses/m ²
Nominal Pulse Spacing	0.50 m	0.57 m	0.57 m
Survey Altitude (AGL)	400 m	400 m	400 m
Survey speed	145 knots	145 knots	145 knots
Field of View	40°	40°	40°
Mirror Scan Rate	4200 RPM	3430 RPM	1833 RPM
Target Pulse Rate	250 kHz	50 kHz	10 kHz
Pulse Length	2.5 ns	2.5 ns	2.5 ns
Laser Pulse Footprint Diameter	20 cm	190 cm	300 cm
Laser Wavelength	1064 nm	515 nm	515 nm
Pulse Mode	Continuous Multipulse	Continuous Multipulse	Continuous Multipulse
Beam Divergence	0.50 mrad	4.75 mrad	7.50 mrad
Swath Width	291m	291 m	291 m
Swath Overlap	60%	60%	60%
Intensity	16-bit	16-bit	16-bit

Lidar specifications and aerial survey settings for H14138

Environmental Variable(s)

No echosounder was utilized for this survey area.

Environmental variables that can affect lidar ground surface density returns include terrain character, land cover, and ground surface reflectivity. Ground surface areas with breaks in terrain, water, and steep slopes may return fewer pulses than originally emitted by the sensor. Fewer pulses may penetrate through vegetated areas such as tree canopy or thick brush resulting in lower ground density. Similarly, the density of bathymetric bottom returns is influenced by several environmental factors.

NV5's acquisition team considered several environmental conditions during the planning stage of the project to target the best possible windows for capturing bathymetric bottom surfaces. Factors such as satellite constellation availability and weather windows were considered during the planning stage. Any

weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access, potential air space restrictions, channel flow rates, turbidity, and water clarity were reviewed.

Bathymetric bottom returns can be limited by depth, water clarity, and submerged surface reflectivity. Poor water clarity causes a high rate of green laser scattering throughout the water column, and high turbidity can prevent water surface penetration, resulting in diminished returns. Additionally, the bathymetric bottom surface must be reflective enough to return the remaining laser energy back to the sensor at a detectable level.

The CH5 shallow green channel was designed for shallower, near-shore bathymetry and allows for a depth penetration of 3.2/k at 15% seabed reflectance. This translates to about 1.8 times Secchi depth under optimal conditions. This means bathymetric data deeper than 1.8 times the Secchi depth at the time of the lidar acquisition from the CH5 shallow green laser is not to be expected. The HE5 system however, is designed specifically for deeper waters but does not map shallower areas of bathymetry well. The HE5 deep green channel allows for a depth penetration of 4/k at 15% seabed reflectance which equates to about 3 times the Secchi depth under optimal conditions. When paired together, the CH5 and HE5 systems provide bathymetric surface mapping over a range of depths across a survey area.

Acquisition Output

No echosounder was utilized for this survey area.

Both CH5 and HE5 lidar systems acquire full waveform data for every pulse. The recorded waveform enables range measurements for all discernible targets for a given pulse. All discernible lidar returns were processed for the output dataset.

Control Point Establishment

Horizontal (*Operation Date: Jul 18, 2025 - Aug 06, 2025*)

Position

Base stations were utilized for real time kinematic (RTK) and post processed kinematic (PPK) survey techniques. NV5 utilized 3 permanent real-time network (RTN) base stations from Hexagon SmartNet and Michigan Department of Transportation (MIDOT) networks and established 2 new monuments for this project (table below). New monuments were set using 6" mag hub nails with orange survey washers. NV5's professional land surveyor, Byron Howell (MI PLS #101567), oversaw and certified the ground survey. These base station setup locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. See the Metadata QC folder for the map of ground survey point locations as well as the provided ground survey point shapefile.

NV5 utilized static GNSS data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS data was triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Monument ID	Latitude	Longitude	Ellipsoid (meters)	σ_X	σ_Y	σ_Z	Owner	Type
MIAP	45° 06' 00.56392"	-83° 27' 18.79359"	166.447	Online	Online	Online	SMART NET	RTN
MIRC	45° 25' 28.48779"	-83° 49' 07.75715"	153.359	Online	Online	Online	MIDOT	RTN
MIAL	45° 03' 46.72858"	-83° 25' 42.86742"	145.751	Online	Online	Online	MIDOT	RTN
THUNDERBAY _01	45° 33' 06.71394"	-84° 07' 45.75048"	143.525	0.000	0.001	0.020	NV5	Nail
THUNDERBAY _02	45° 39' 06.31324"	-84° 20' 33.63743"	170.323	0.002	0.002	0.007	NV5	Nail

Base station positions for the Thunder Bay acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Receiver Model	Antenna	OPUS Antenna ID	Serial Numbers	Use
Trimble R750	Zephyr Model 3 GNSS	TRM115000.10	7253	Static
Trimble R12	Integrated Antenna	TRMR12	0269	Rover

GNSS Equipment used for Ground Survey

Uncertainty

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks. This standard provides guidelines for classification of monument quality at the 95%

confidence interval as a basis for comparing the quality of one control network to another. The network rating for this project is shown in the table below.

Please note the RMS values from the OPUS solutions on the base stations installed for this project are in the above table.

Direction	Rating
1.96 * St Dev _{NE} :	0.020 m
1.96 * St Dev _z :	0.050 m

Federal Geographic Data Committee monument rating for network accuracy

Application to Data

Ground survey collection, including monumentation and GSPs, was conducted to support the airborne lidar acquisition. Ground survey data were also used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on the final lidar dataset.

Vertical (Operation Date: Jul 18, 2025 - Aug 06, 2025)

Position

Please reference Horizontal Position Section above.

Uncertainty

Please reference Horizontal Uncertainty Section above.

Application to Data

Please reference Application to Data Section above.

Report of Survey

Uncertainty Source

Total propagated uncertainty (TPU) is the combination of the calculated horizontal and vertical uncertainty which aims to quantify errors associated with any given measurement. With regard to the H14138 lidar survey, NV5 used NOAA’s cBLUE v4.1 software for calculating uncertainty values for the lidar point

classified returns that were utilized in creating the bare earth DEM (class 2 topographic ground, class 40 bathymetric bottom, and class 43 submerged object). cBLUE software calculates uncertainty in two parts; first, aerial uncertainty computations are calculated considering the beam divergence of the utilized lasers and sensor trajectory parameters such as sensor IMU position and orientation at the time of each laser pulse for all points. A subsequent subaqueous uncertainty computation then occurs using Monte Carlo ray tracing simulations derived from water surface conditions due to wind speed, and water clarity and turbidity conditions at the time of the lidar survey only for user-specified point classifications. In order to maintain accurate uncertainty calculations due to varying environmental conditions between flight missions, NV5 divided the lidar point cloud inputs to be processed with cBLUE by sensor channel (NIR, shallow green, and deep green) by mission date. Class 2 topographic ground returns received aerial uncertainty computations; class 40 bathymetric bottom and class 43 submerged object returns received both aerial and subaqueous uncertainty computations. cBLUE v4.1 offers optional vertical and horizontal uncertainty input components in order to account for any additional uncertainty not considered in the cBLUE automated calculations. For the H14138 lidar survey an additional vertical uncertainty component of 0.08 m to account for the vertical data transformation from GRS80 ellipsoidal heights to IGLD85 LWD elevations was added in the sum of squares calculation for the final TVU values. The resulting estimates of uncertainty are combined to produce total propagated horizontal and vertical uncertainty values at 95% confidence.

cBLUE software outputs JSON metadata files and LAS files appended with TPU data stored in the extra bytes. NV5 used LasTools and custom scripts to create resulting TVU and THU rasters. Initial uncertainty rasters were gridded and created by using the maximum respective uncertainty point value within a 1 meter pixel area. As discussed in the Holiday Identification section, the final vertical uncertainty and horizontal uncertainty rasters were produced to match the bare earth resolution and pixel coverage across areas of NoData using nearest neighbor assignment. The final TVU was utilized in creating the 2-band BAG raster (band 1 contains the bare earth elevation values; band 2 corresponds with the TVU values).

The THU raster is provide in the Source Grids folder and cBLUE JSON files were provided in the Metadata QC folder. Please note, the lidar data input into cBLUE software was delineated into 500 meter by 500 meter tiles and were divided by sensor channel (NIR, shallow green, and deep green) by acquisition missions date. The provided JSON metadata files are sub-divided and organized in the same manner as a result.

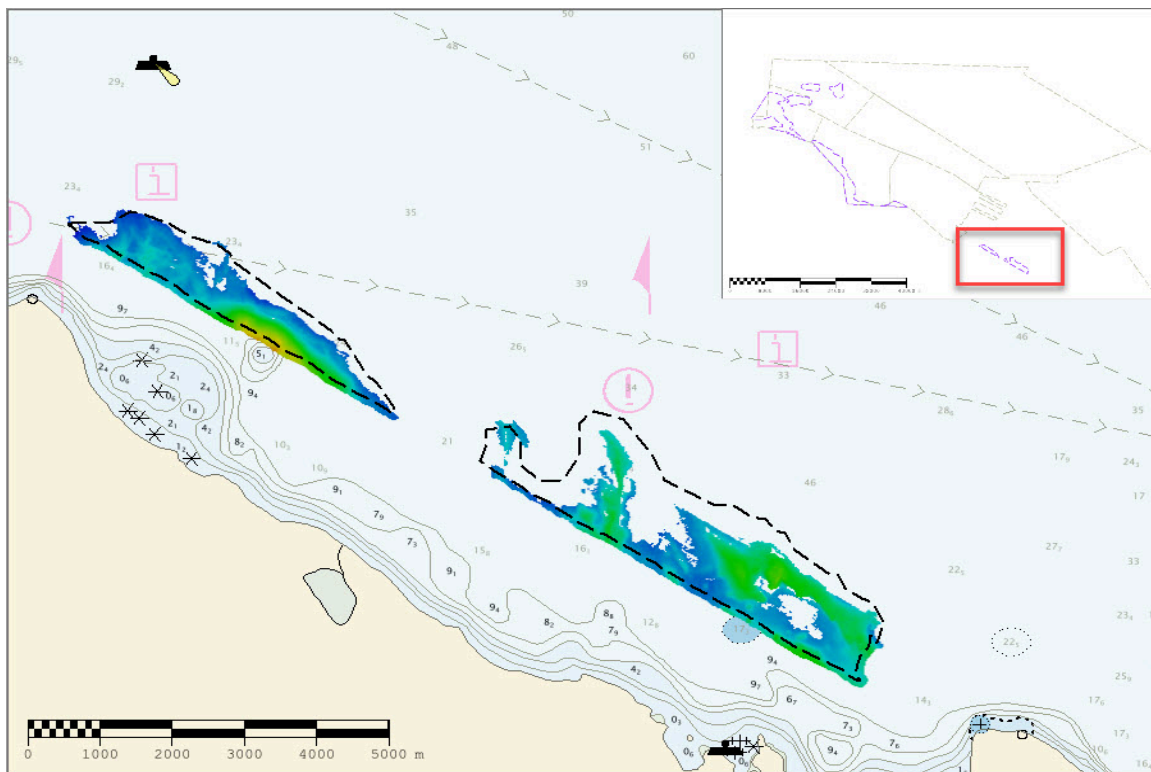
Uncertainty was achieved to General 1 standards.

Error Source

Density - Density analysis, evaluated against the HSSD requirement of achieving at least five soundings per node for 95% of all grid nodes, was not met for this survey. The procedures used to generate and assess the ground and bathymetric bottom point density raster are described in the Statistical Analysis section above. This shortfall was discussed with the COR and is attributable to inherent limitations of bathymetric lidar sensors particularly at the greater depths included within the lidar survey extent and the agreed upon survey scheme. The ground and bathymetric bottom point density raster provided in the Source Grids folder is included for reference and additional back end review. For this project, only ~40% of grid nodes met the greater than or equal to 5 points per node threshold. As coordinated with the government, this reflects a broader industry discussion regarding the applicability of bathymetric lidar to General 1 standards and the need for continued evaluation of density expectations for this sensor type. The current specifications also assume CUBE based density calculations, and alternative approaches may be warranted for assessing density for bathymetric lidar. Importantly, the planned density proposed during

project estimation was achieved. Additional details on that density assessment are provided in the ASPRS density analysis in the Additional Information section below.

Data Gaps- Holidays and data gaps in this survey occur due to the nature of bathymetric lidar sensor limitations and the sensor defined survey areas (sheet limits) used for this project. Methods for identifying and evaluating these gaps are described in the Holiday Identification section earlier in this report. A bathymetric void shapefile has been provided in the Metadata QC folder to satisfy the PI requirement to highlight areas within the lidar sheet limit not meeting General 1 standards, as coordinated with the COR. If these void areas fell within the overlapping multibeam sheet limits, multibeam infill for lidar holidays (bathymetric voids) was conducted, consistent with the COR approved project approach. In these overlapping areas between sheet limits, the lidar and multibeam bathymetric coverage were evaluated together to ensure full bathymetric coverage was achieved. An example of an area that was not approved for multibeam infill because it falls outside of the multibeam sheet limits for this project is below.



H14138 area where MBES Infill was not required because it falls outside the OPR-X395-KR-25 MBES Survey Areas. Future MBES infill can be planned based off the bathymetric void shapefile provided.

Features - In accordance with the PI and in coordination with the COR, reasonable efforts were made to use multibeam to investigate potential features identified during lidar processing, within the inherent limitations of bathymetric lidar. In addition, multibeam disprovals were conducted for charted features within the H14138 sheet limits, as approved by the COR. Results from these multibeam investigations and disprovals are reported in the data products and files associated with the overlapping MBES survey areas. These data are submitted with the corresponding MBES sheet limits as separate survey products, consistent with the project survey scheme.

Because feature detection was outside the formal survey requirements and lidar has inherent constraints for feature identification, the Feature Detection Size in the Metadata section above is set to N/A. Lidar contacts assessed with high confidence as anthropogenic in origin were investigated with multibeam, as

approved by the COR. Two feature related files are provided for this survey: the Lidar Contacts file (per COR concurrence) and the Final Feature File. These products are included to add value and support downstream analysis of the dataset. The Lidar Contacts file documents the vector file provided to the COR in the field, including recommendations for lidar identified contacts and also includes the results of subsequent feature investigations. Where applicable, imagery from MBES investigations is included in the Lidar Contacts file to support analysis of this dataset. Charted features documented in the Final Feature Files include remarks and recommendations appropriate to this project survey scheme.

Please refer to the overlapping MBES surveys (H14140, H14141, H14144, H14145) for additional information on reported new features and disproved features within the H14138 survey limits.

Above Water ATONs (Poe Reef Light and Spectacle Reef Light) - Topographic ground classified points, class 2, were included in the final BAG and DEM products in addition to the bathymetric bottom, class 40, and submerged object, class 43, classified points. The methodology for including class 2 points in the final DEM products is described in the PI alteration section. The best available estimate of the water edge at the time of the H14138 lidar survey is provided as a two dimensional planimetric shapefile in the Metadata QC folder. Within H14138, two platforms with associated lights exist for charted ATONs. The associated data were classified in a manner consistent with NOAA RSD survey practices. The platforms were classified as class 2 topographic ground, as water cannot flow beneath them. The vertical bulkhead walls of the platforms and the lighthouse structures were classified as class 1 unclassified. However, to remain consistent with multibeam hydrographic practices, since these platforms are associated with charted ATONs, the platforms were removed from the Final BAGs using raster extraction techniques. The platforms are retained in all other raster products located in the Source Grids folder to better align with RSD methodologies. The only exception is the Finalized CSAR, which directly mirrors the BAG. The Parent CSAR may be used if the end user wishes to retain the ATON platforms within the data products.

Localized Nodes with Elevated Uncertainty in BAG and THU Rasters - Within the finalized BAG surface and THU raster, a very small number of nodes contain irregularly elevated uncertainty values. These values appear to be caused by an unknown processing issue within cBLUE and do not correlate with poor data quality or any observed degradation in the underlying lidar measurements. NV5 currently has an active support case open with cBLUE to further investigate this behavior.

Unlike multibeam and similar hydrographic processing workflows, cBLUE assigns uncertainty values to lidar points after full classification of the lidar point cloud. Removing the affected points would require reverting to an earlier stage of processing and is not considered a recommended solution, as the points retain value, lidar data has relatively low density, and these points do not appear to be associated with data quality issues. Despite the presence of these nodes, the finalized surface meets the General 1 requirements specified in the HSSD and PI, with greater than 95% of the uncertainty values reported at grid nodes not exceeding the maximum allowable TVU. Documentation supporting this compliance is provided in the Grid Stats folder within the Metadata QC, including the associated graph for the finalized BAG.

For reference, a vector file identifying the localized nodes with elevated uncertainty in the Final BAG is provided in the Metadata QC folder. This file is an output from the QC Tools BAG Checks and may be used to locate and review the affected nodes.

Lidar Processing Extents in Final Grids- A buffer was applied around the provided survey (sheet limits) to define the extent of data that underwent the full lidar processing workflow. This is included in the Project Extent folder within Metadata QC. While this approach differs from typical NOAA hydrographic practices, it

is standard for lidar based surveys. It should be noted that the bathymetric void shapefile extends beyond the sheet limits to this buffered extent. Sheet limits in the PRF are the defining areas for this survey, not the buffered project (processing) extent. Lastly, to note, to add value to the feature products for this survey and project, several lidar contacts identified outside the buffer were investigated with multibeam and are documented in the Lidar Contacts file and relevant Final Feature Files.

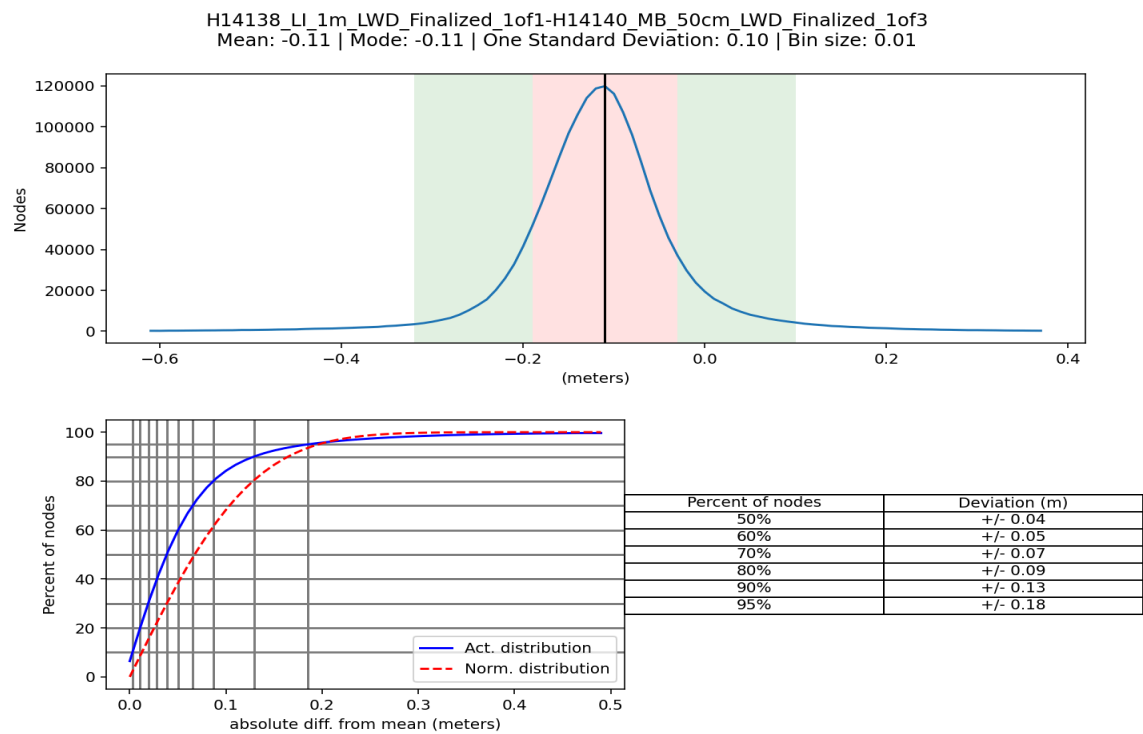
CSARs and BAGs - The CSAR file and additional Source Grid rasters are provided to add value for the end user, as the creation of OCS compliant products via lidar represents a unique workflow. Should the end user elect to regenerate BAGs, the ultimate workflow consisted of converting TIFF to CSAR, followed by conversion of CSAR to BAG files. As noted above, the only difference between the Parent and Finalized CSAR is the removal of the two platforms.

The CSAR files are provided to accelerate end user review within CARIS, as CSARs offer significantly improved raster rendering performance when panning and scrolling compared to BAGs. CARIS was not utilized for any point cloud manipulation as part of this process; its use was limited strictly to raster manipulation.

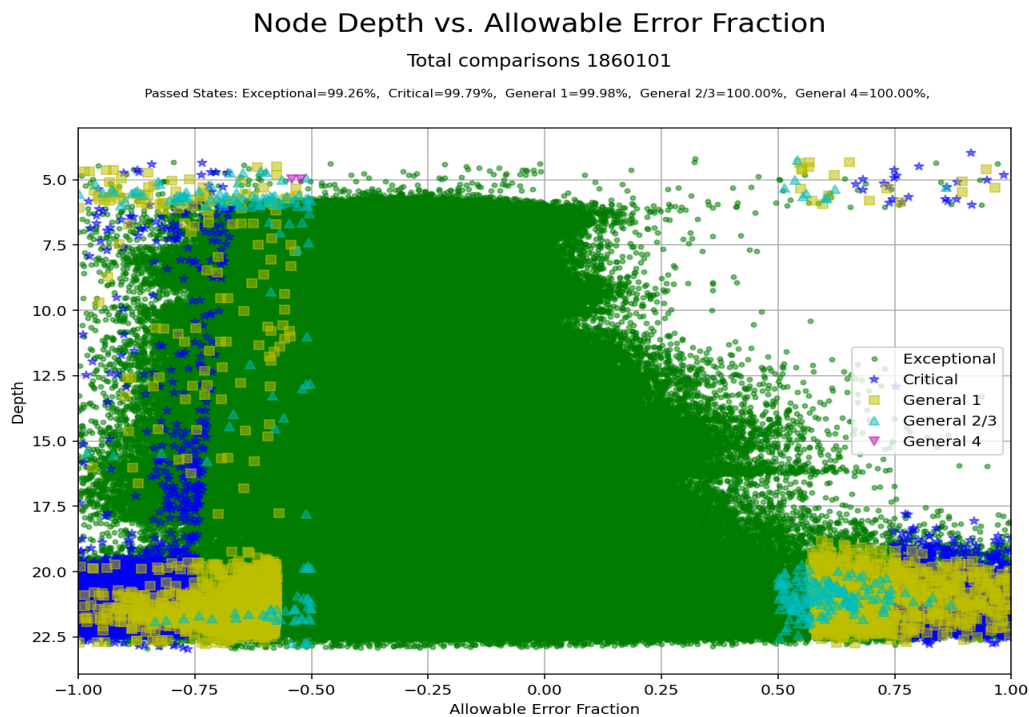
To correctly attribute the uncertainty band from the CSAR, the Uncertainty_Negative band should be exported and assigned as the Uncertainty band in the raster output, as CARIS will invert the uncertainty values if this step is not followed.

Junction Analysis

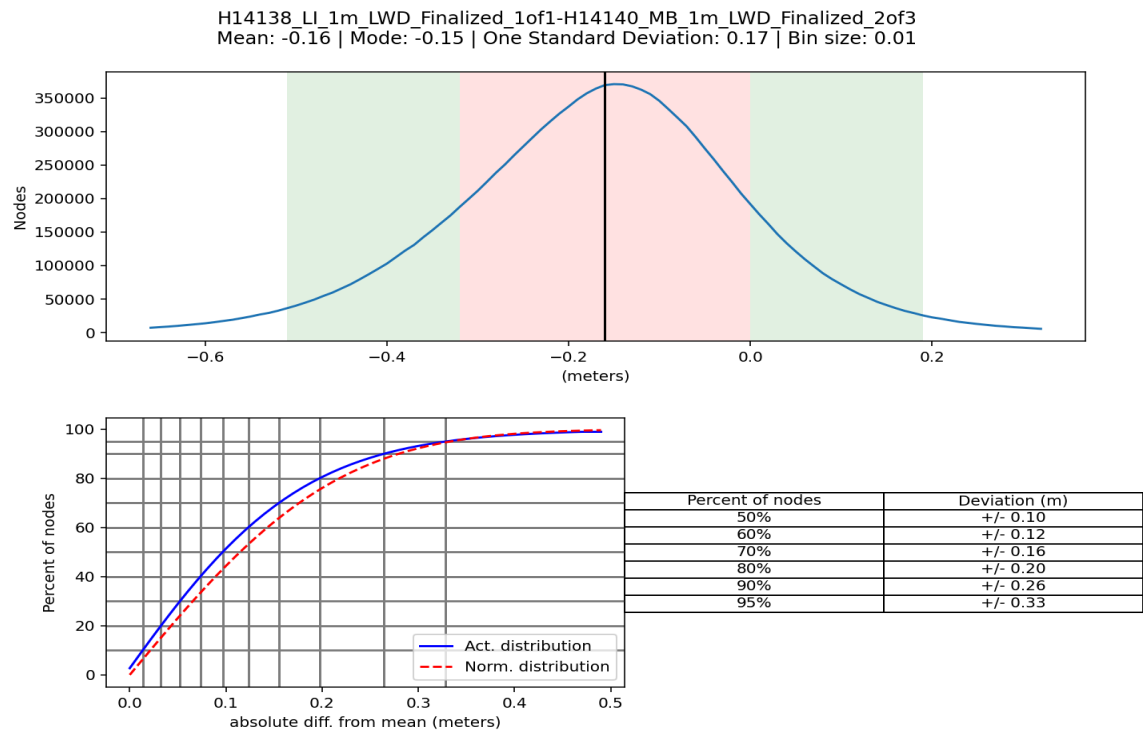
H14138 junctions with survey H14140. A junction analysis was performed as described in the Quality Control Procedures section above. The associated statistical graphs were reviewed for compliance with allowable error standards defined in the Project Instructions (PI) and the 2025 HSSD, and indicated passing results. Resultant images are provided below. Please refer to the Metadata QC folder for all additional junction analysis and their associated statistical graphs.



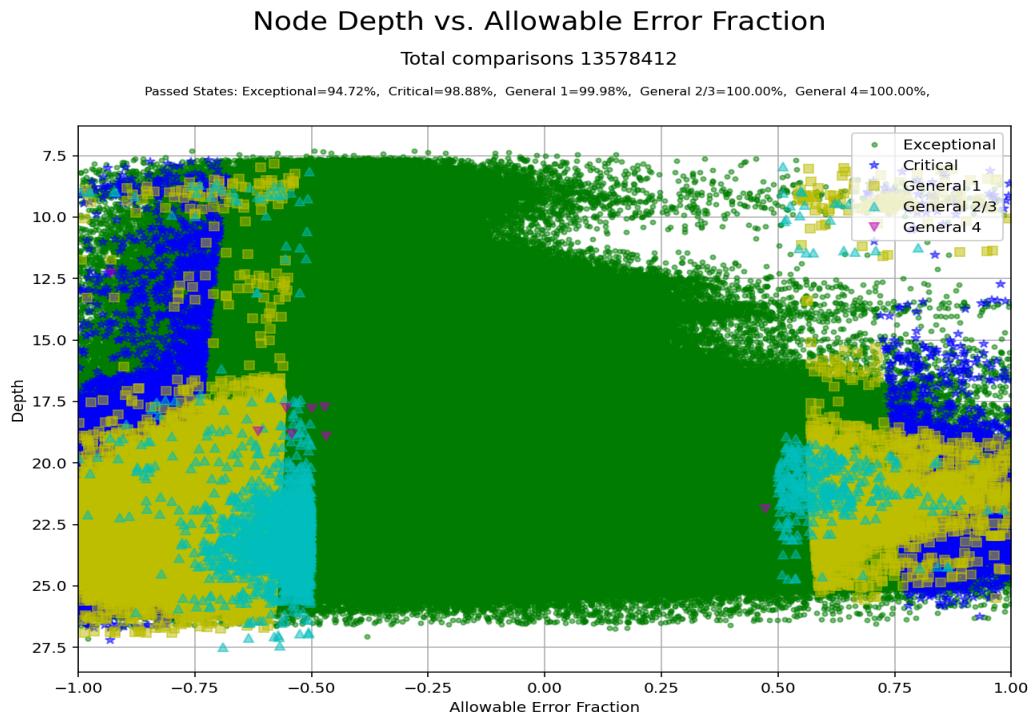
Statistical results of junction analysis between H14138 1 m LI surface and H14140 0.50 m MBES CUBE surface



Node Depth vs. Fraction of Allowable Error distribution plot indicating adherence with Quality Metrics



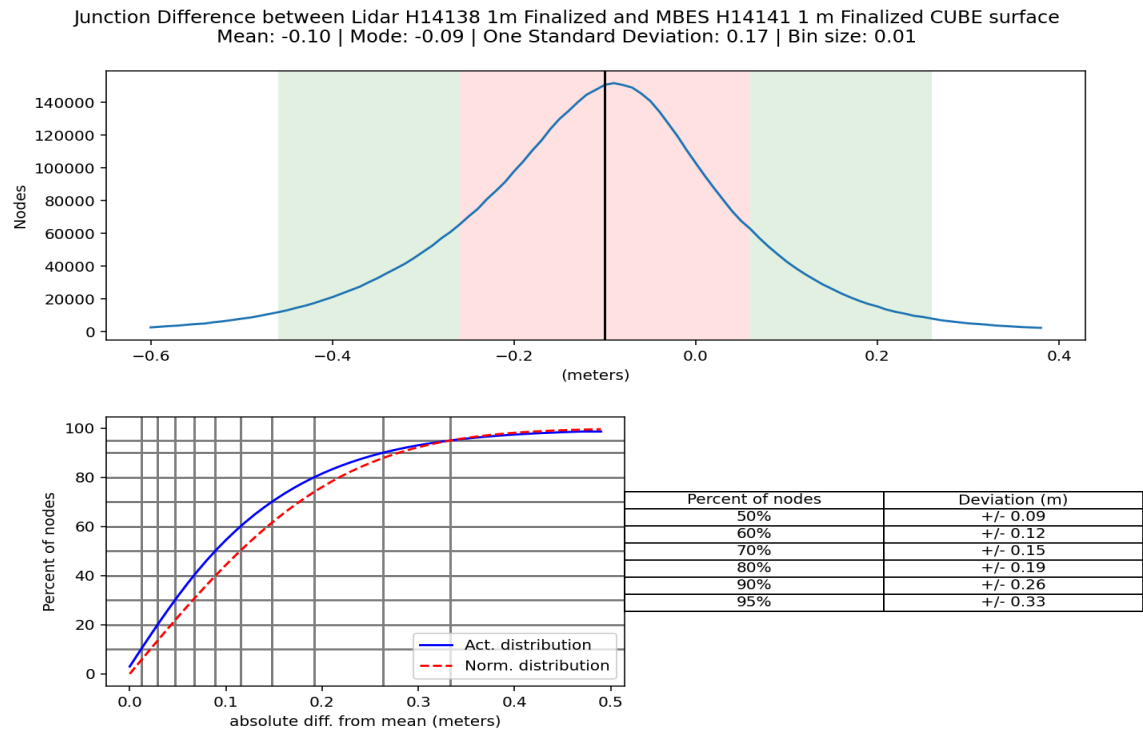
Statistical results of junction analysis between H14138 1 m LI surface and H14140 1 m MBES CUBE surface



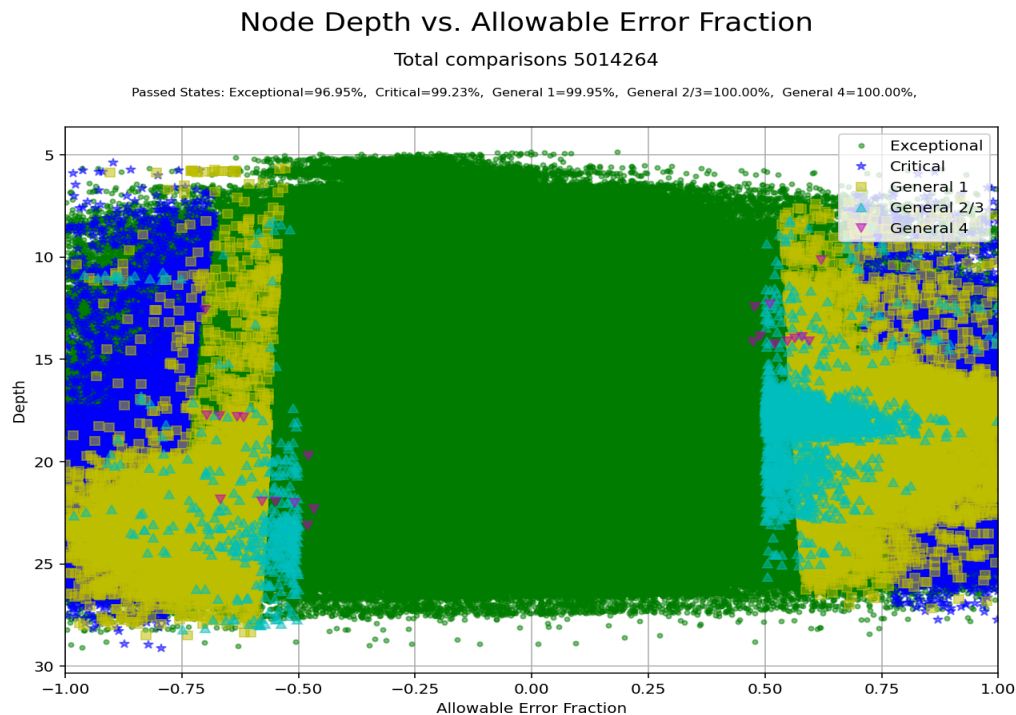
Node Depth vs. Fraction of Allowable Error distribution plot indicating adherence with Quality Metrics

H14138 junctions with survey H14141. A junction analysis was performed as described in the Quality Control Procedures section above. The associated statistical graphs were reviewed for compliance with allowable error standards defined in the Project Instructions (PI) and the 2025 HSSD, and indicated passing

results. Resultant images are provided below. Please refer to the Metadata QC folder for all additional junction analysis and their associated statistical graphs.



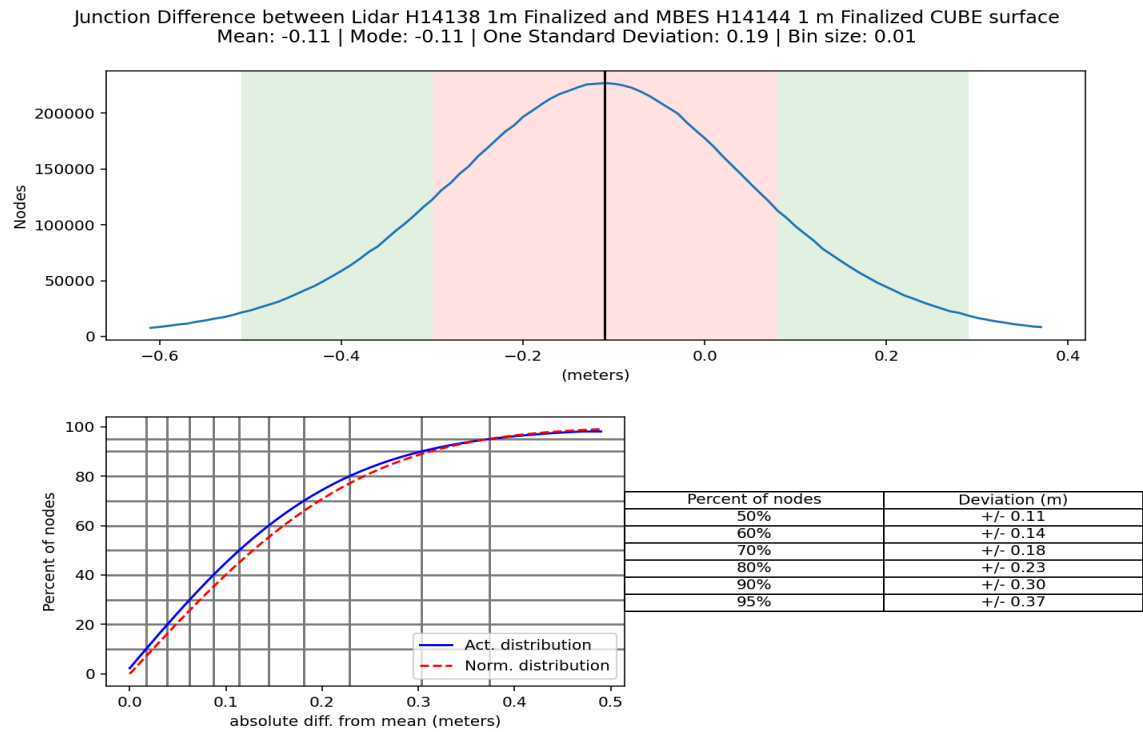
Statistical results of junction analysis between H14138 1 m LI surface and H14141 1 m MBES CUBE surface



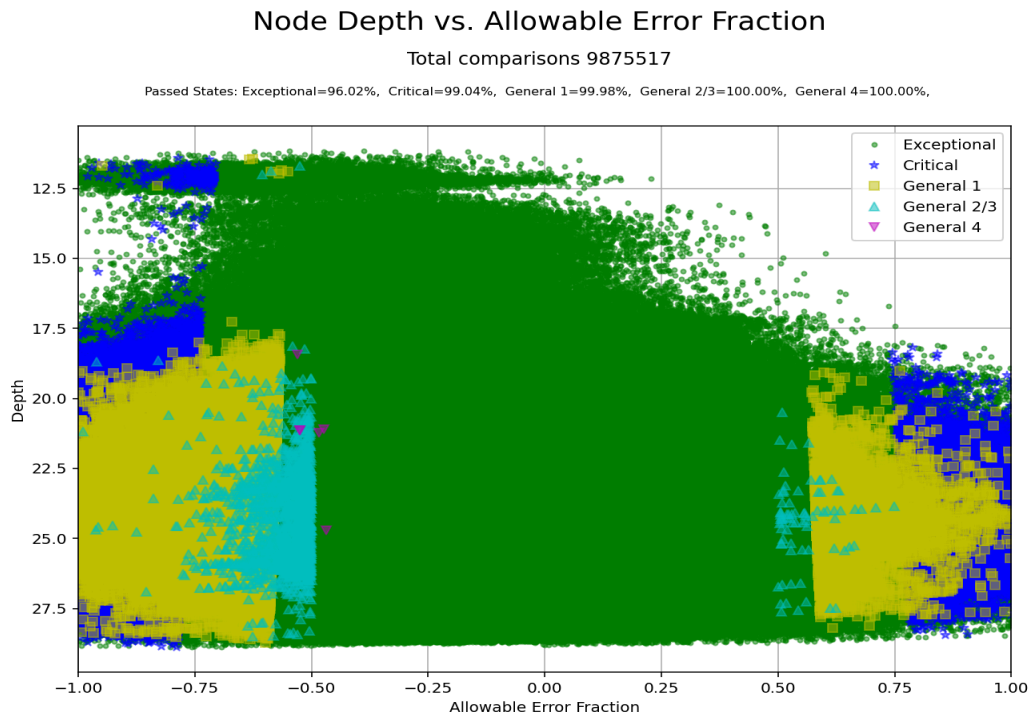
Node Depth vs. Fraction of Allowable Error distribution plot indicating adherence with Quality Metrics

H14138 junctions with survey H14144. A junction analysis was performed as described in the Quality Control Procedures section above. The associated statistical graphs were reviewed for compliance with

allowable error standards defined in the Project Instructions (PI) and the 2025 HSSD, and indicated passing results. Resultant images are provided below. Please refer to the Metadata QC folder for all additional junction analysis and their associated statistical graphs.

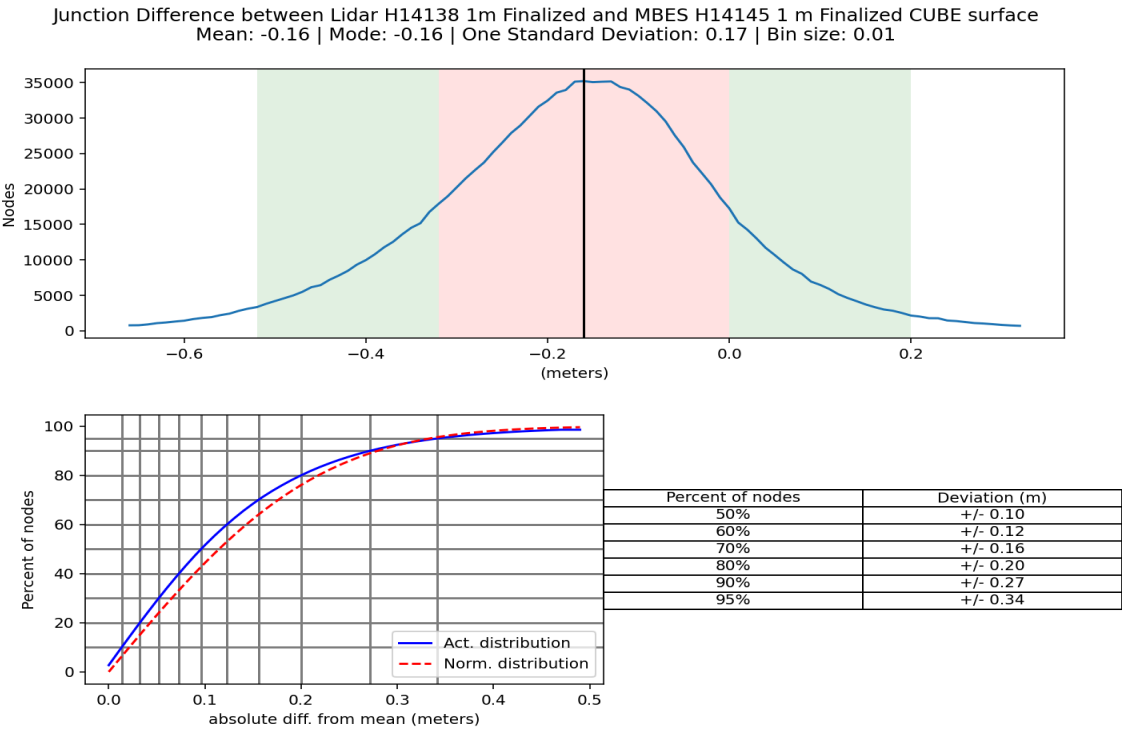


Statistical results of junction analysis between H14138 1 m LI surface and H14144 1 m MBES CUBE surface



Node Depth vs. Fraction of Allowable Error distribution plot indicating adherence with Quality Metrics

H14138 junctions with survey H14145. A junction analysis was performed as described in the Quality Control Procedures section above. The associated statistical graphs were reviewed for compliance with allowable error standards defined in the Project Instructions (PI) and the 2025 HSSD, and indicated passing results. Resultant images are provided below. Please refer to the Metadata QC folder for all additional junction analysis and their associated statistical graphs.

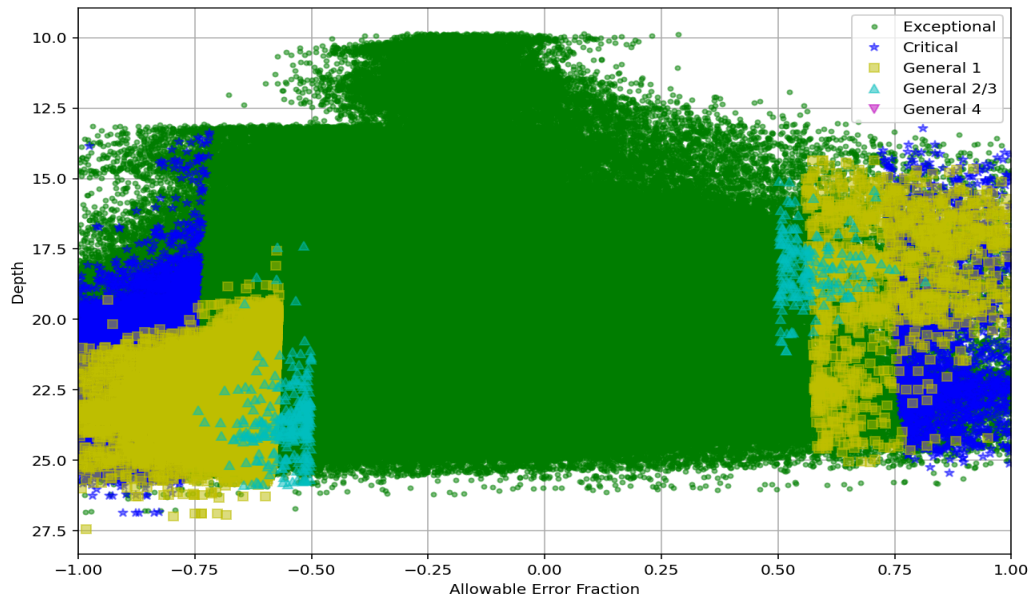


Statistical results of junction analysis between H14138 1 m LI surface and H14145 1 m MBES CUBE surface

Node Depth vs. Allowable Error Fraction

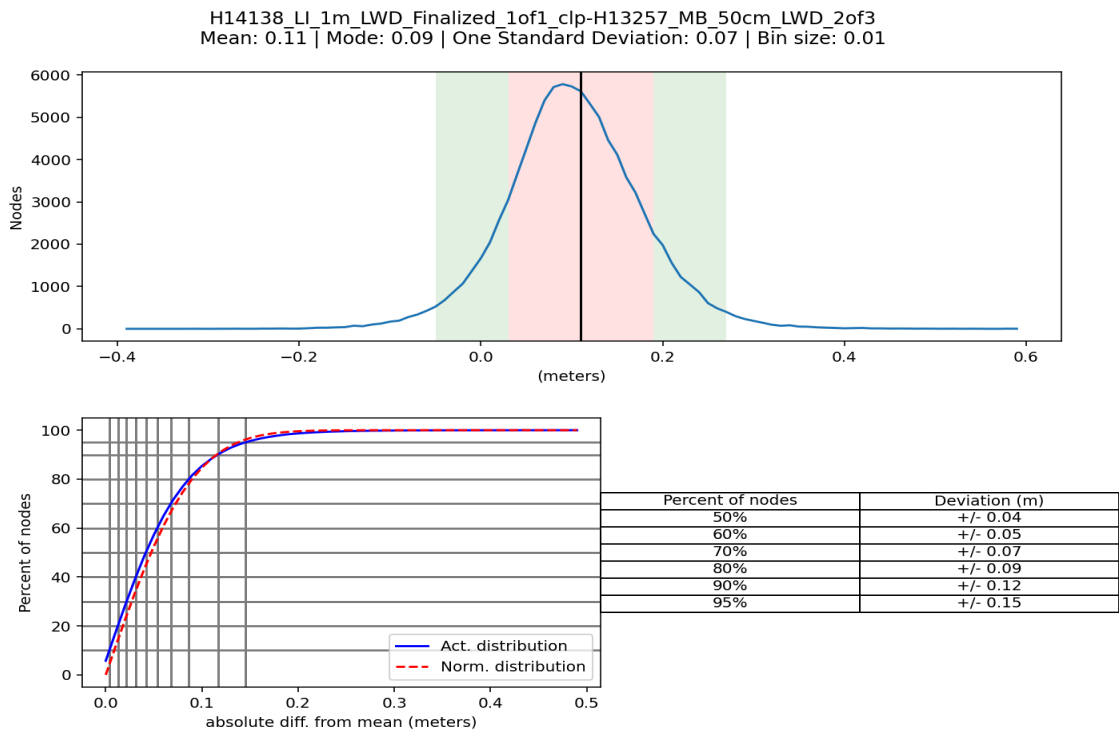
Total comparisons 1294722

Passed States: Exceptional=94.35%, Critical=98.69%, General 1=99.96%, General 2/3=100.00%, General 4=100.00%,

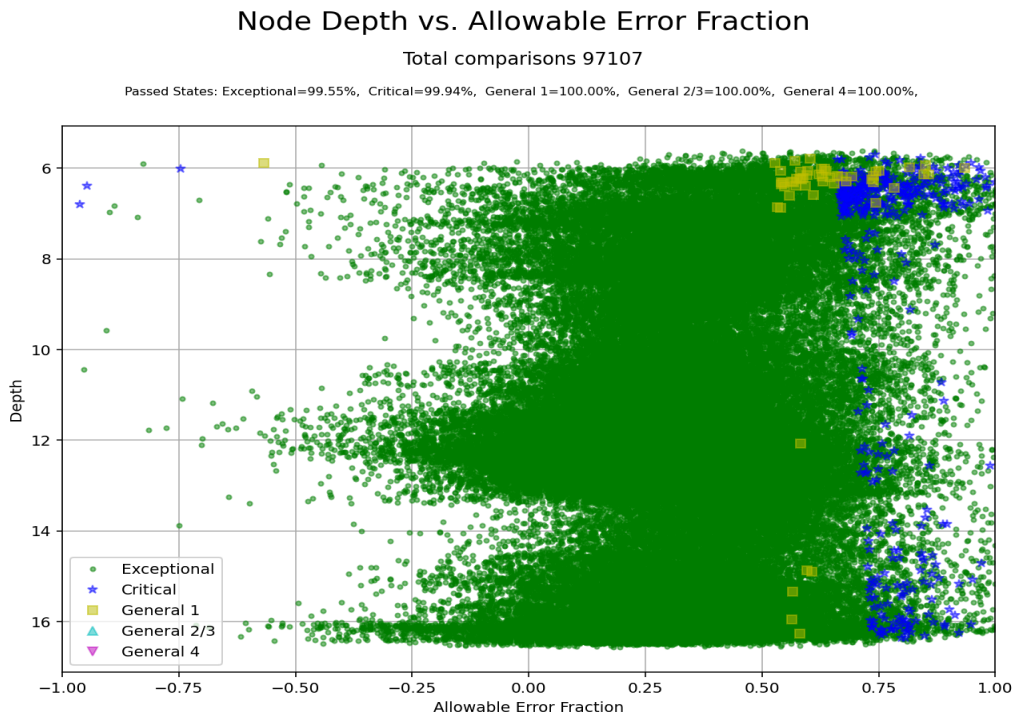


Node Depth vs. Fraction of Allowable Error distribution plot indicating adherence with Quality Metrics

H14138 junctions with survey H13527. A junction analysis was performed as described in the Quality Control Procedures section above. The associated statistical graphs were reviewed for compliance with allowable error standards defined in the Project Instructions (PI) and the 2025 HSSD, and indicated passing results. Resultant images are provided below. Please refer to the Metadata QC folder for all additional junction analysis and their associated statistical graphs.



Statistical results of junction analysis between H14138 1 m LI surface and H13527 0.50 m MBES CUBE surface



Node Depth vs. Fraction of Allowable Error distribution plot indicating adherence with Quality Metrics

Additional Information

Lidar Non-Vegetated Vertical Accuracy Analysis (NOAA RSD/2014 ASPRS Standard Reporting Practice):

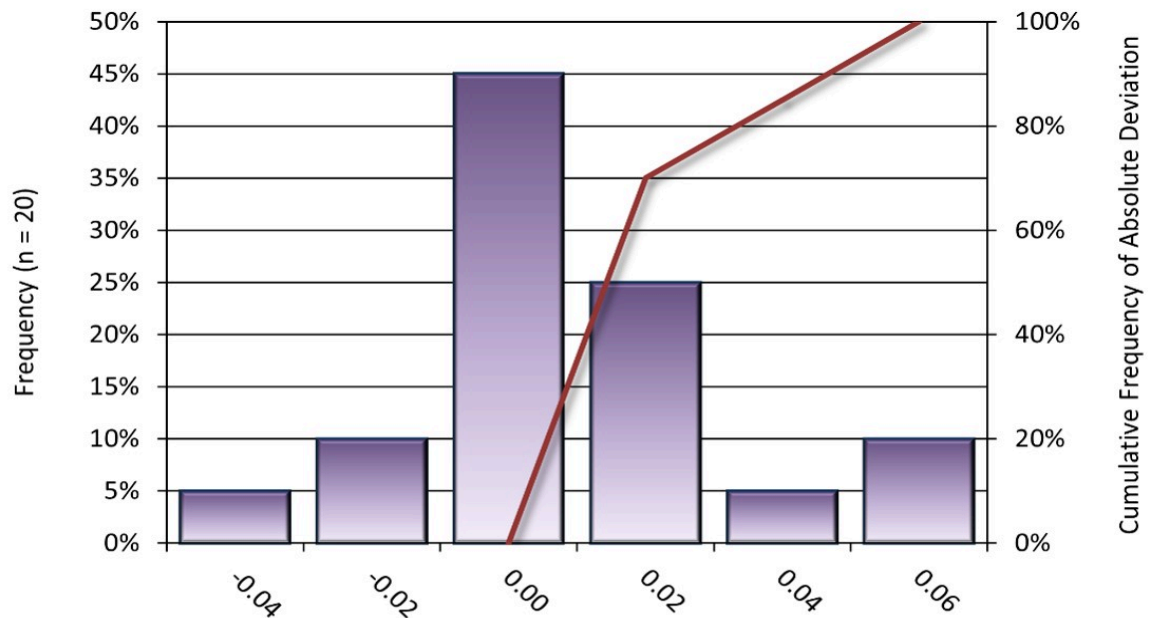
For H14138, 20 ground checkpoints were withheld from the calibration and post processing of the lidar point cloud, with a resulting non-vegetated vertical accuracy (NVA) of 0.046 meters as compared to the

classified LAS, and 0.051 meters against the bare earth DEM, with 95% confidence. Frequency histograms for the NVA for H14138 are depicted in the figures below.

NV5 also assessed absolute accuracy using 280 ground control points. Although these points were used in the calibration and post-processing of the lidar point cloud, they still provide a good indication of the overall accuracy of the lidar dataset and therefore have been provided in the figures below.

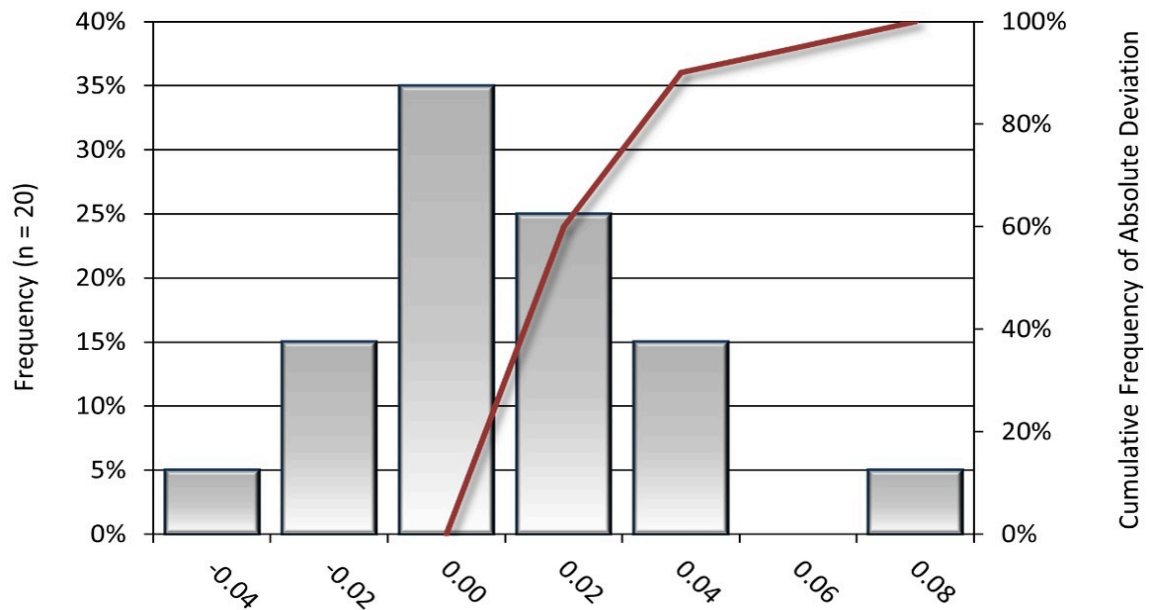
Area	Parameter	Sample	95% Confidence (1.96*RMSE)	Average	Median	RMSE	Standard Deviation (1 σ)
H14138	NVA, as compared to classified LAS	20 points	0.046 m	-0.001 m	-0.002 m	0.023 m	0.024 m
H14138	NVA, as compared to bare earth DEM	20 points	0.051 m	0.000 m	-0.002 m	0.026 m	0.026 m
H14138	Ground Control Points	280 points	0.053 m	-0.001 m	-0.001 m	0.027 m	0.027 m

NVA, as compared to Classified LAS



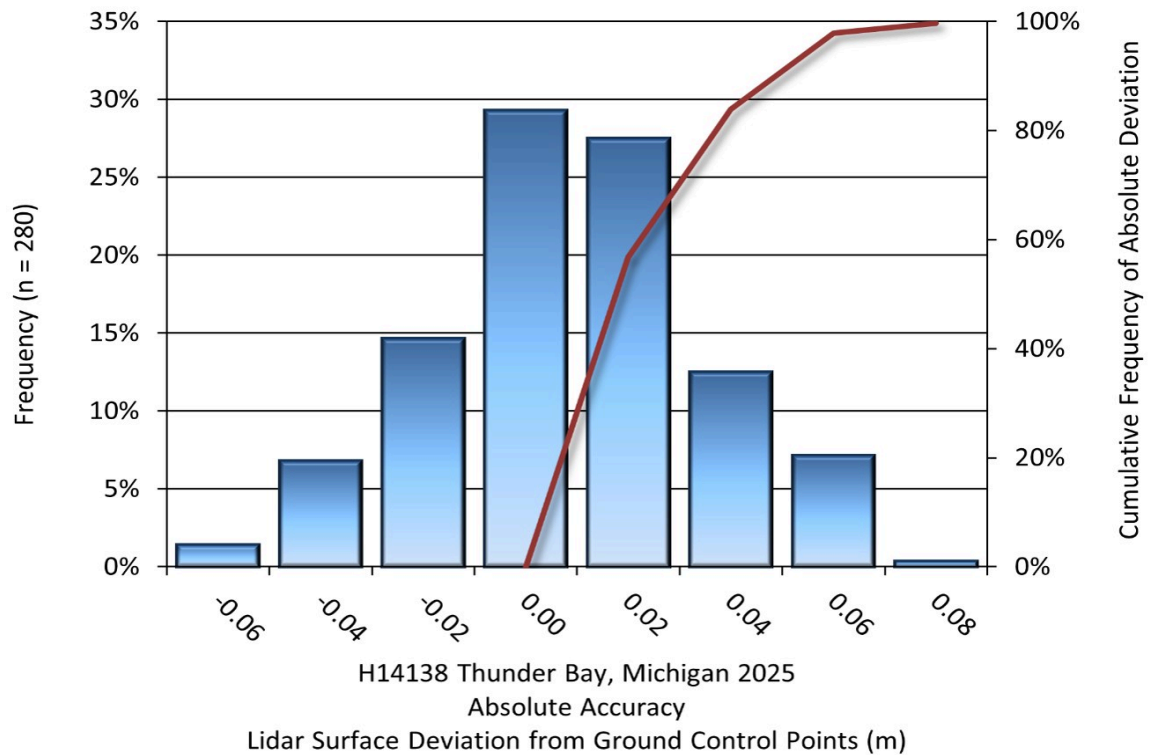
H14138 Thunder Bay, Michigan 2025
Non-Vegetated Vertical Accuracy (NVA)
Lidar Surface Deviation from Ground Check Points (m)

Frequency histogram for classified LAS deviation for the NVA for H14138



H14138 Thunder Bay, Michigan 2025
Non-Vegetated Vertical Accuracy (NVA)
Digital Elevation Model Deviation from Ground Check Points (m)

Frequency histogram for lidar bare earth DEM deviation for the NVA for H14138

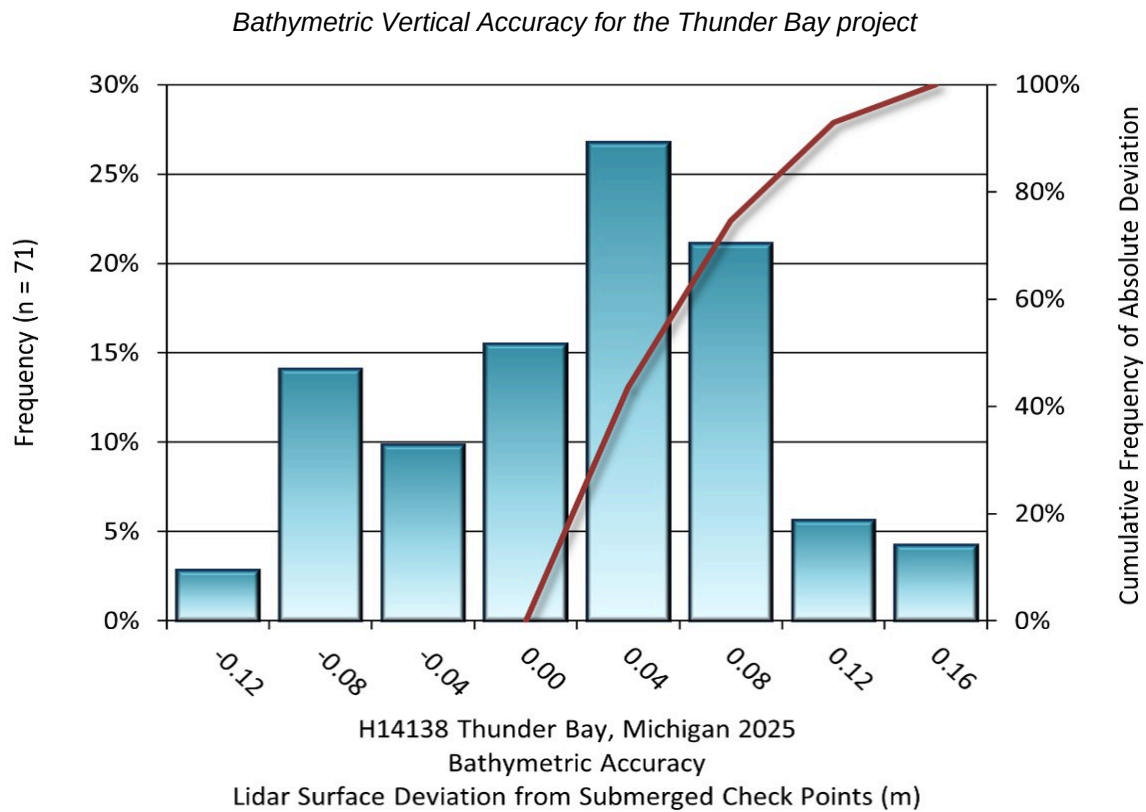


Frequency histogram for lidar surface deviation from all ground control point values (even those used in calibration) for H14138

Lidar Bathymetric Vertical Accuracies (NOAA RSD/2014 ASPRS Standard Reporting Practice):

Bathymetric (submerged) checkpoints were collected and compared against the classified LAS to assess the submerged surface vertical accuracy. The Bathymetric Vertical Accuracy for H14138 was found to be RMSE = 0.068 m with 71 submerged points.

Area	Sample	95% Confidence (1.96* RMSE)	Average	Median	RMSE	Standard Deviation (1σ)
H14138	71 points	0.133 m	0.004 m	0.008 m	0.068 m	0.068 m

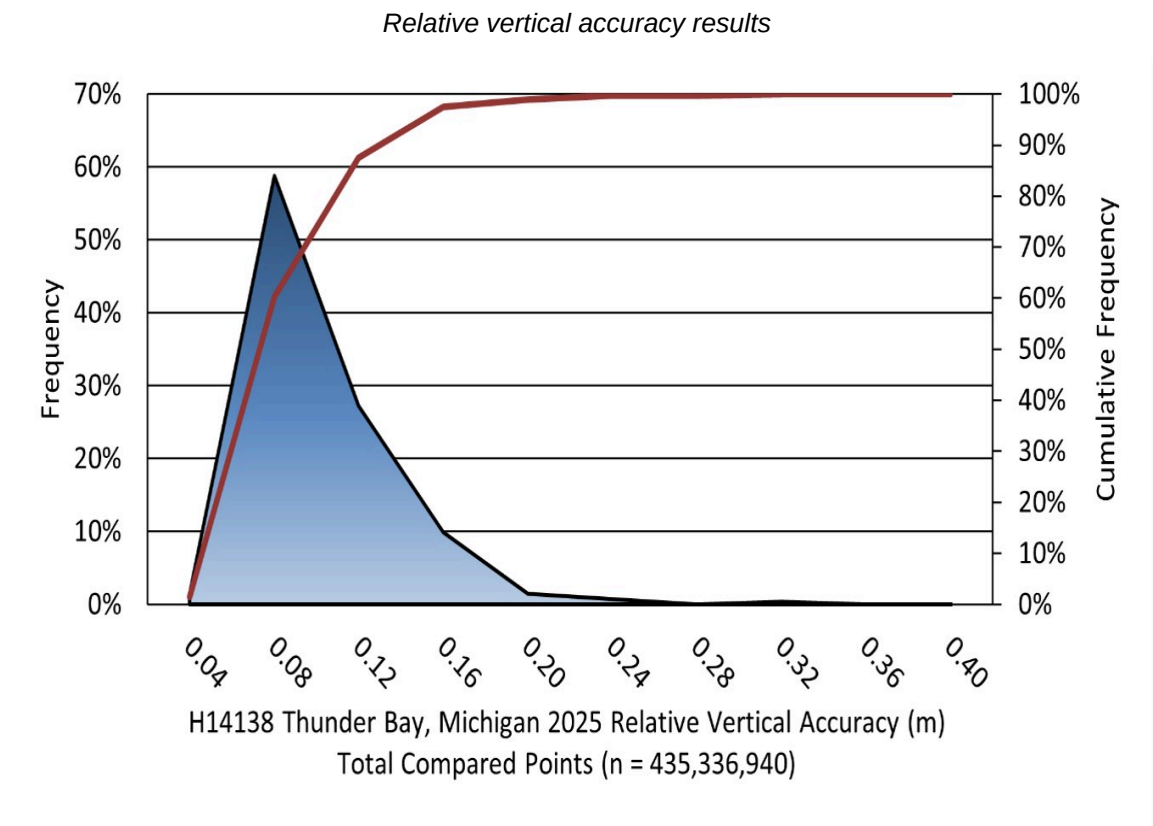


Frequency histogram for lidar surface deviation from submerged check point values for H14138

Lidar Relative Vertical Accuracy (NOAA RSD/2014 ASPRS Standard Reporting Practice):

Relative vertical accuracy for the lidar survey areas was determined by calculating the line-to-line divergence between overlapping flightlines. The average (mean) line to line relative vertical accuracy for the H14138 Thunder Bay lidar survey area was 0.054 meters (table and figure below).

Area	Sample	Average	Median	RMSE	Standard Deviation (1σ)	1.96σ
H14138	272 flight line surfaces	0.054 m	0.073 m	0.087 m	0.034 m	0.066 m



Frequency plot for relative vertical accuracy between flight lines for H14138

Horizontal Accuracy Check using the IMU and GNSS Positional Error (NOAA RSD/2014 ASPRS Standard Reporting Practice/FGDC NSSDA):

IMU and GNSS positional error were computed separately using the Chiroptera-5 trajectories and the HawkEye-5 trajectories for H14138, but were all found to be the same. Based on the following parameters, a flying altitude of 400 meters, a maximum combined roll/pitch IMU error of 0.002 decimal degrees and a maximum GNSS positional error of 0.005 meters, this project was produced to meet a 0.025 m RMSE_r Horizontal Positional Accuracy Class and 0.044 m ACC_r (the accuracy value according to NSSDA at 95% confidence) (table below).

Parameter	Horizontal Accuracy
RMSE _r	0.025 m
ACC _r	0.044 m

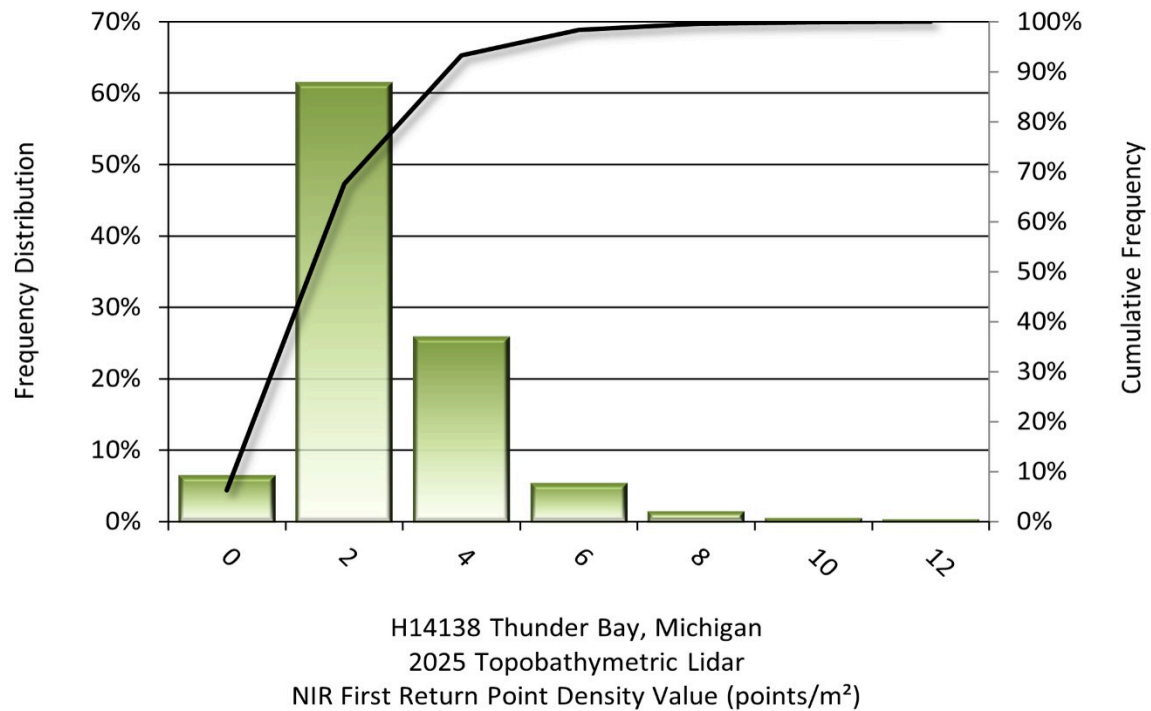
Horizontal accuracy using IMU and GNSS data

Density Analysis for Lidar Quality Assessment (NOAA RSD/2014 ASPRS Standard Reporting Practice):

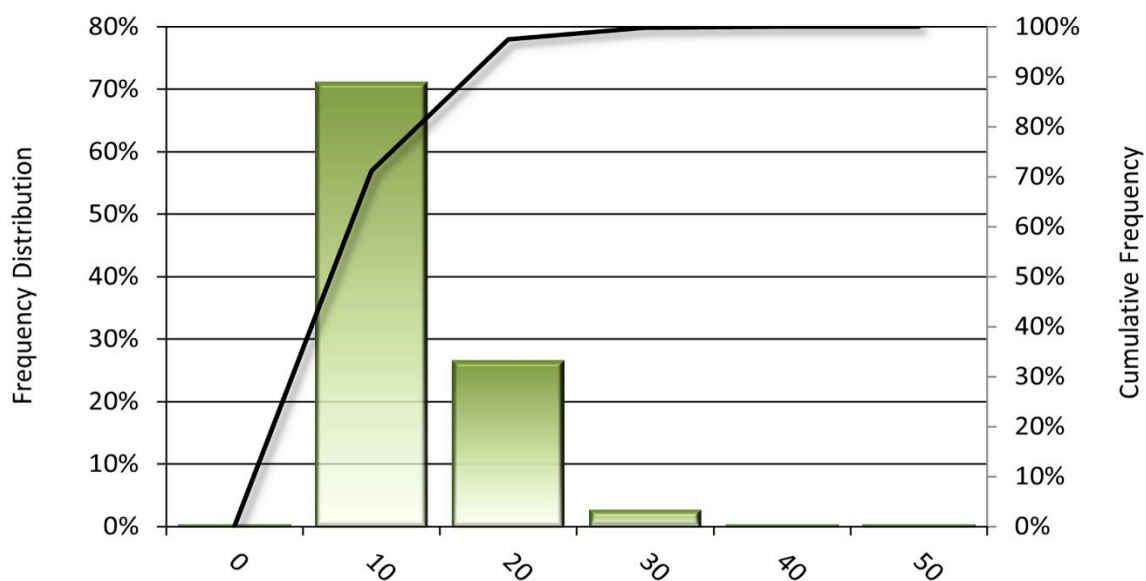
The densities for NIR channel first returns, green channel first returns, all-combined first returns, ground and bathymetric bottom classified returns, and bathymetric bottom-only classified returns were determined for the Thunder Bay H14138 project area as described in the Statistical Analysis section of the report. The density statistics were calculated per 100 meter x 100 meter sampled cells. These values and the statistical distributions per 100 m x 100 m cell can be found in the table and figures below.

Area	NIR First Returns	Green First Returns	Combined First Returns	Ground and Bathymetric Bottom Classified Returns	Bathymetric Bottom Classified Returns
H14138	1.57 points/m ²	8.83 points/m ²	9.78 points/m ²	3.87 points/m ²	4.66 points/m ²

Average lidar point densities for H14138

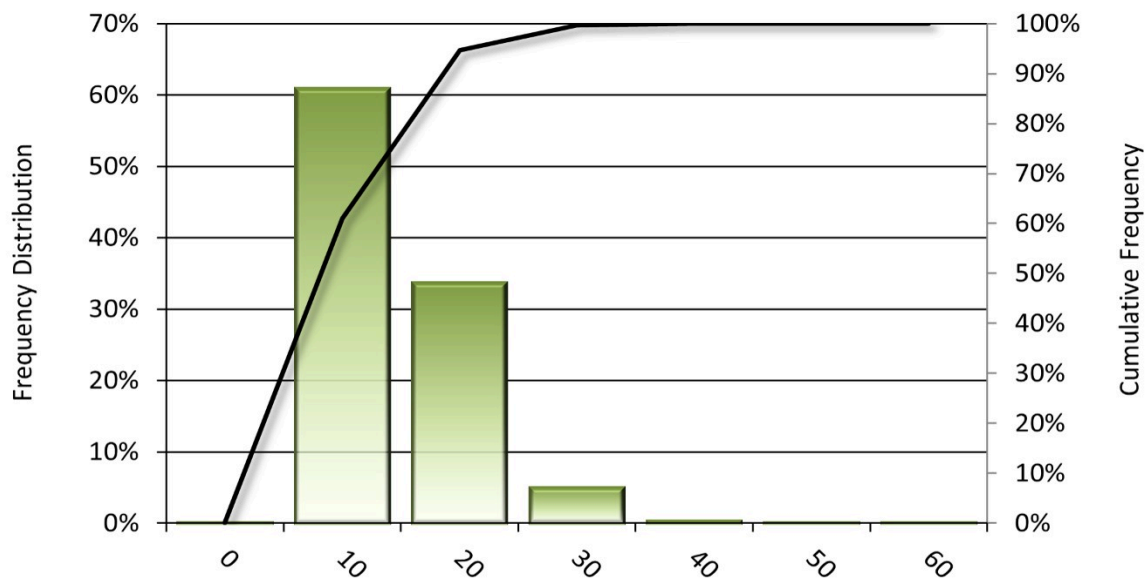


Frequency distribution of first return densities per 100 x 100 m cell for the NIR sensor for H14138



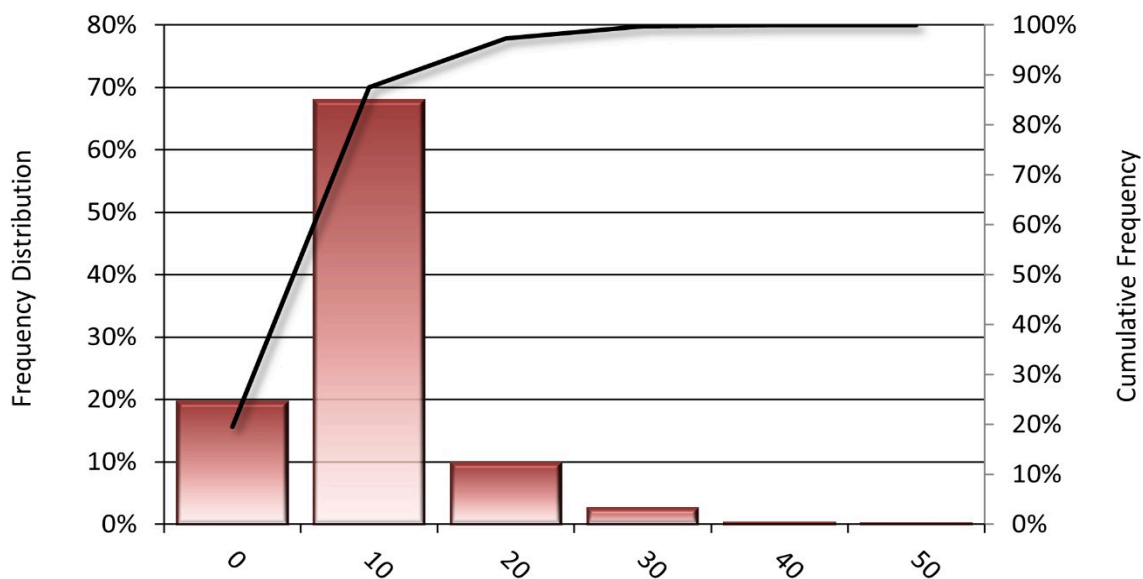
H14138 Thunder Bay, Michigan
2025 Topobathymetric Lidar
Green First Return Point Density Value (points/m²)

Frequency distribution of first return densities per 100 x 100 m cell for the green sensor for H14138



H14138 Thunder Bay, Michigan
2025 Topobathymetric Lidar
Combined First Return Point Density Value (points/m²)

Frequency distribution of first return densities per 100 x 100 m cell for all the sensors for H14138

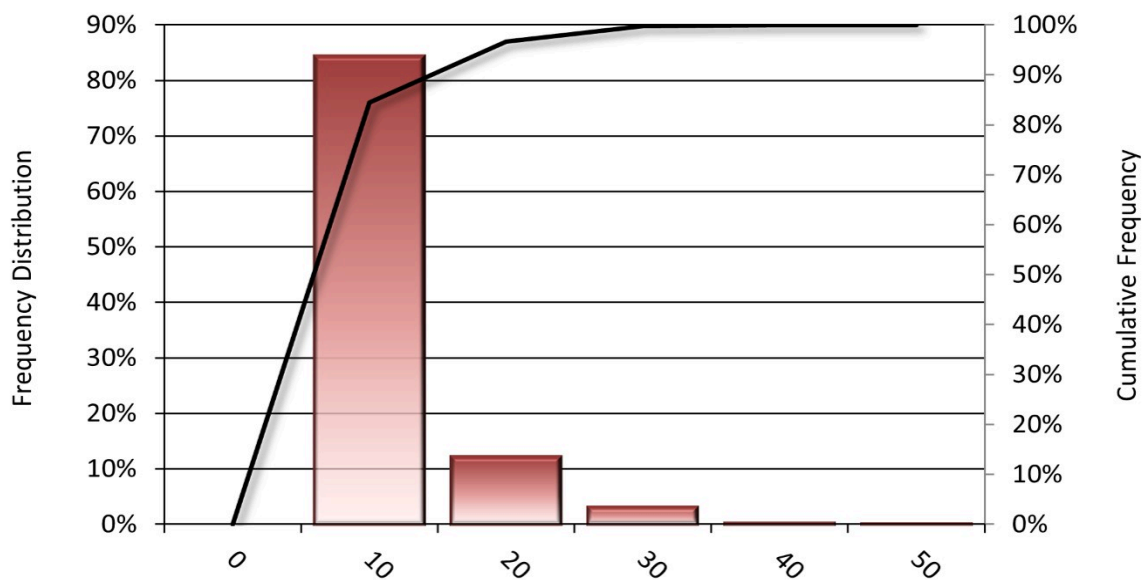


H14138 Thunder Bay, Michigan

2025 Topobathymetric Lidar

Ground and Bathymetric Bottom Classified Return Point Density Value (points/m²)

Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell for all the sensors for H14138



H14138 Thunder Bay, Michigan

2025 Topobathymetric Lidar

Bathymetric Bottom Classified Return Point Density Value (points/m²)

Frequency distribution of only bathymetric bottom classified return densities per 100 x 100 m cell for all the sensors for H14138

For the purposes of planning future MBES work in the survey area, it is recommended that the delivered Lidar Contacts file, Final Feature File, and Bathymetric Void Shapefile be used in conjunction with the other provided survey assessment products. Full bathymetric coverage was achieved within the overlapping

survey limits of H14138 and H14140, H14141, H14144, and H14145 through the combined use of MBES and Lidar data for the respective sheets.

The area described in the Error Source section above, located southeast of the H14145 sheet limits, did not receive MBES infill, as this work was not planned within the scope of the project. This area may be further evaluated using the Bathymetric Void Shapefile if additional investigation or infill is desired for future surveys.

PI Alteration

For Notes 1 and 2 in the PIs, the reference to survey H14139 was a typo. These notes about multibeam infill were intended to apply to the North AOI, H14138. The COR acknowledged this discrepancy and on 08/27/2025 provided an updated excerpt of Notes 1 and 2 confirming the correct survey identifier.

The use of the TIN raster gridding method with restricted maximum triangle edge length parameters for the final products was discussed extensively with the government through multiple meetings and an ongoing email chain related to the proposed multibeam infill for H14138. Restrictive TIN parameters were recommended by NV5 on 08/27/2025 and agreed upon by the COR for use in this survey. This is a common practice for NOAA RSD work.

The density raster approach for assessing compliance with the General 1 standard was discussed with the government early on in the field, several possible calculation methods were considered. On 08/29/2025, it was agreed to calculate density per node by counting all valid bare earth DEM point returns using class 2 topographic ground, class 40 bathymetric bottom, and class 43 submerged object from both CH5 and HE5 sensors within a one square meter pixel area. During the 09/05/2025 meeting regarding multibeam infill for H14138, it was determined that density based infill would not be required given the results of the preliminary lidar density assessment, as documented in the 09/11/2025 synopsis and subsequently with the final infill approval. Later, on 12/19/2025, during final deliverable discussions, the methods for creating the final density raster product were reviewed again, and it was acknowledged that the lidar dataset would not meet the density specifications. It was mutually agreed that providing the ground and bathymetric bottom classified point density raster for evaluation purposes was sufficient for these lidar only survey areas and any end product quality determinations.

During a meeting on 12/19/2025 and subsequent emails following the meeting, all lidar deliverable products and file structures provided were discussed/portrayed with the COR and applicable parties. This included all products: raw data, rasters and mosaics, feature files (contacts and final feature file) as well as required reporting. NV5 followed the exact conclusions from this meeting with the only major exception being with that Class 2 (topographic ground) inclusion in the final BAG and associated products. This was because we were able to calculate uncertainty values for Class 2 topographic ground classified point returns which had been uncertain at the time of the initial conversation. Class 2 topographic ground was relevant to product deliverables for added data insights and discussed in email on 02/06/2026. A PowerPoint which highlighted the lidar-only survey products was provided to the COR and was approved. This agreed upon deliverable outline PowerPoint is also provided in the delivered Metadata QC folder.

Holidays and data gaps in this survey are inherent to bathymetric lidar surveys due to the functional limitations of the lidar sensors utilized for this project. To meet the PI requirement to identify areas not achieving General 1 standards, a bathymetric void shapefile was created and accepted for this purpose (first discussed on 08/27/2025). Multibeam infill for lidar holidays was performed only in locations where lidar and multibeam survey boundaries overlapped, as confirmed via a clarification email on 08/18/2025.

The final infill plan including holiday infill decisions and associated methods was reviewed, discussed, and approved by the COR on 10/06/2025 to close field efforts.

Submerged feature considerations with lidar were discussed extensively throughout both the acquisition and post-processing phases of the survey. For H14138, files supporting multibeam feature investigations and feature disprovals were provided to the COR for review on 09/17/2025. A final determination was reached on some lingering aspects on 10/06/2025 that concluded no further investigation or disapproval was required for the fish stakes or a disapproval needed on the charted submarine cable. All approved plans for addressing charted and newly identified lidar features were followed exactly. The results of these plans are discussed and documented in the H14138 Lidar Contacts file and Final Feature File. On 12/19/2025, the intended purpose and final form of the Lidar Contacts file and Final Feature File for both lidar only surveys were reviewed and the methodologies were agreed upon with the COR and applicable parties. Additionally, there was discussion/acknowledgment of the lidar sensors' limitations with feature detection and the resulting outcome of comparing lidar identified features with the multibeam investigations.

For all lidar and multibeam surveys for this project (multibeam included), on 11/20/2025, the Project Manager was contacted to confirm this requirement in the PI that mentioned the Chart Comparison. NOAA HSD OPS advised that it was no longer needed.

It should be noted that this project required extensive coordination with the COR and other government stakeholders, including numerous meetings and detailed email exchanges regarding the bathymetric lidar workflow and its application for charting. While this section summarizes only the key PI related decisions, additional context from these discussions can be provided upon request. All bathymetric lidar survey plans, produced deliverables, associated methodologies, and subsequent multibeam infill plans for H14138 were fully reviewed, discussed, and approved by the COR.

Supplementals

- Trained Marine Mammal Observers list (*Nov 13, 2025*)
Viewed US Navy training video per 2025 HSSD 13.5
- Coast Pilot Report (*Jan 14, 2026*)
- Final Survey Outline (*Nov 10, 2025*)
- NCEI Sound Speed Data (*Oct 24, 2025*)

Approval Statement

As Chief of Party, field operations for this survey were conducted under my overall supervision and coordination, with frequent review of progress, data quality, and adequacy of deliverables. I have reviewed and approved all data and metadata. Field operations and data integration were carried out in close coordination with the NV5 lidar team, who were actively engaged throughout the project. This team regularly supports NOAA Remote Sensing Division operations and is familiar with NOAA requirements, workflows, and Office of Coast Survey standards. Their collaboration contributed to effective integration and quality assurance of the lidar derived products utilized for this survey. The survey meets or exceeds requirements as set forth in the Project Instructions, NOS Hydrographic Surveys Specifications, and discussions with NOAA HSD OPS throughout this project, with the noted deficiencies/limitations associated with the proposed sensor utilized for this survey. The survey is complete and no additional work is required, with the exception of any deficiencies noted in the Report of Survey.

Approver Name	Approver Title	Approver Certification
Nicholas Damm, CH	Chief of Party	Nicholas Damm Digitally signed by Nicholas Damm Date: 2026.04.24 11:06:02 -04'00'

Full Equipment List						
Equipment Type	Manufacturer and System	Model Number	Serial Number	Calibration Date	Frequency	Accuracy Check Date
Cessna Caravan (N216RF)						
Positioning and Attitude System	Not Specified Not Specified	Novatel LCI-100c	1425, 1455	2025-07-10	NA	NA
Positioning and Attitude System	Not Specified Not Specified	Trimble AV39	N/A	2025-07-10	NA	NA
Positioning and Attitude System	Not Specified Not Specified	Leica PAV100 Gyrostabilized Mount	18808	2025-07-10	NA	NA
Laser	Unknown Unknown	Leica Chiroptera 5 (CH5)	7859	2025-07-10	NA	2025-07-10
Laser	Unknown Unknown	Leica Hawkeye 5 (HE5)	7820	2025-07-10	NA	2025-07-10
Sound Speed System	Not Specified Not Specified	N/A	N/A	2025-07-18	N/A	