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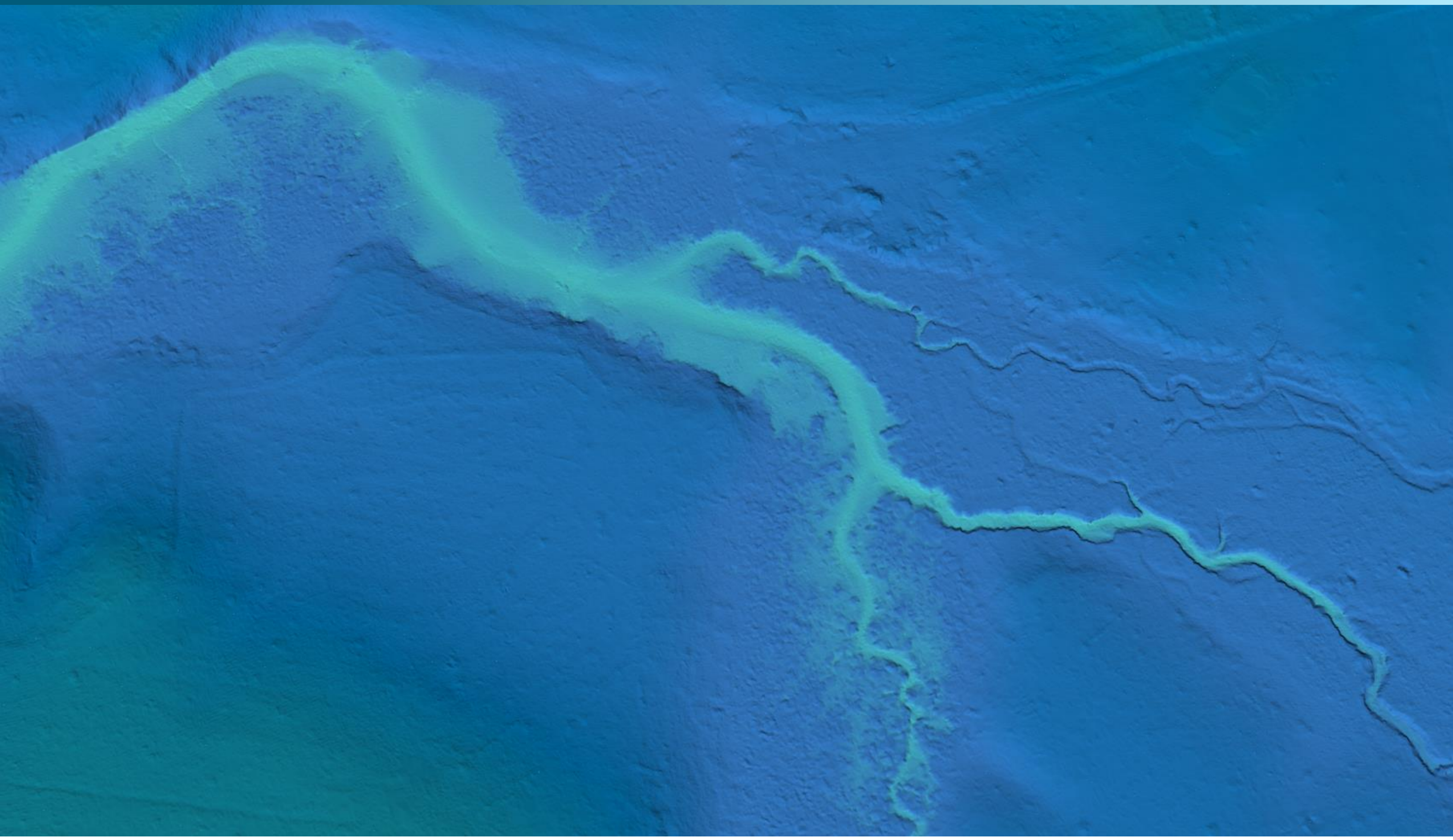

Chesapeake Bay, Maryland

Topobathymetric Lidar: MD-1902-1903-TB

Technical Data Report NOAA Contract: EA-133C-14-CQ-0007, Task Order 1305M219FNCNL0226

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Cover Photo: A view looking over the bathymetric surface within the MD-1902 area of interest. The image was created using bathymetric ground return derived gridded surfaces colored by elevation.

Project Summary

This photo taken by NV5 acquisition staff shows a scenic view of the Chesapeake Bay site in Maryland.

In July 2019, NV5 Geospatial (NV5) was contracted by the National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) Remote Sensing Division (RSD) and Coastal Mapping Program (CMP), to collect topobathymetric Light Detection and Ranging (Lidar) data in the fall of 2019 for two distinct sites at the north eastern reach of Chesapeake Bay in Maryland (Contract No. EA-133C-14-CQ-0007). Data were collected to aid NOAA in enabling accurate and consistent measurement of the national shoreline to support additional mapping, nautical charting, geodesy services, marine debris surveys, marine resource management assessments and other applications.

The topobathymetric lidar dataset was processed, and delivered as two separate deliveries, MD-1902 and MD-1903. This report provides a comprehensive summary of the delivered topobathymetric lidar data and deliverables. Documented herein are contract specifications, data acquisition procedures, processing methods, and accuracy results. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to NOAA is shown in Table 2, and the project extents are shown in Figure 1 and Figure 2.

Table 1: Acquisition dates, acreage, and data types collected on the Chesapeake Bay MD-1902 and MD-1903 sites

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Chesapeake Bay 1902, Maryland	61,621	64,296	11/09/2019 - 11/11/2019	Topobathymetric Lidar
Chesapeake Bay 1903, Maryland	64,661	67,588	11/14/2019 - 11/16/2019	Topobathymetric Lidar

Survey Area

The NOAA Chesapeake Bay Topobathymetric Lidar project area was contracted to cover two unique sites, approximately 207 square miles in the state of Maryland.The MD-1902 survey area extends from Severna Park to Londontowne and Mayo encompassing Annapolis, the Severn River, South River, and Rhode River. The MD-1903 survey area stretches from West River to Dares Beach covering Holland Point, North Beach, Chesapeake Beach and Herring Bay. NV5 Geospatial conducted all lidar acquisition of the project area between November 9th, 2019 and November 16th, 2019.

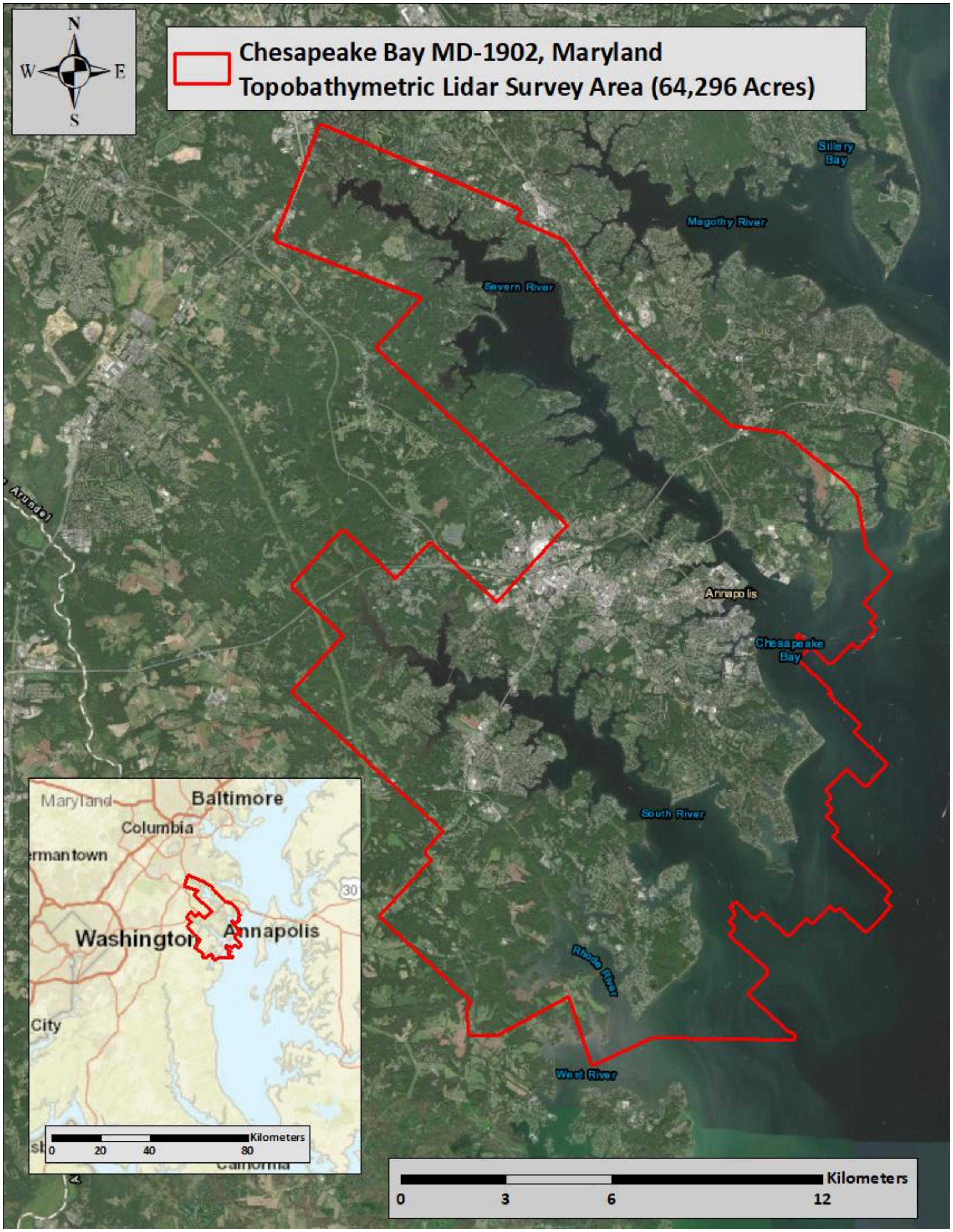


Figure 1: Location map of the Chesapeake Bay MD-1902 site in Maryland

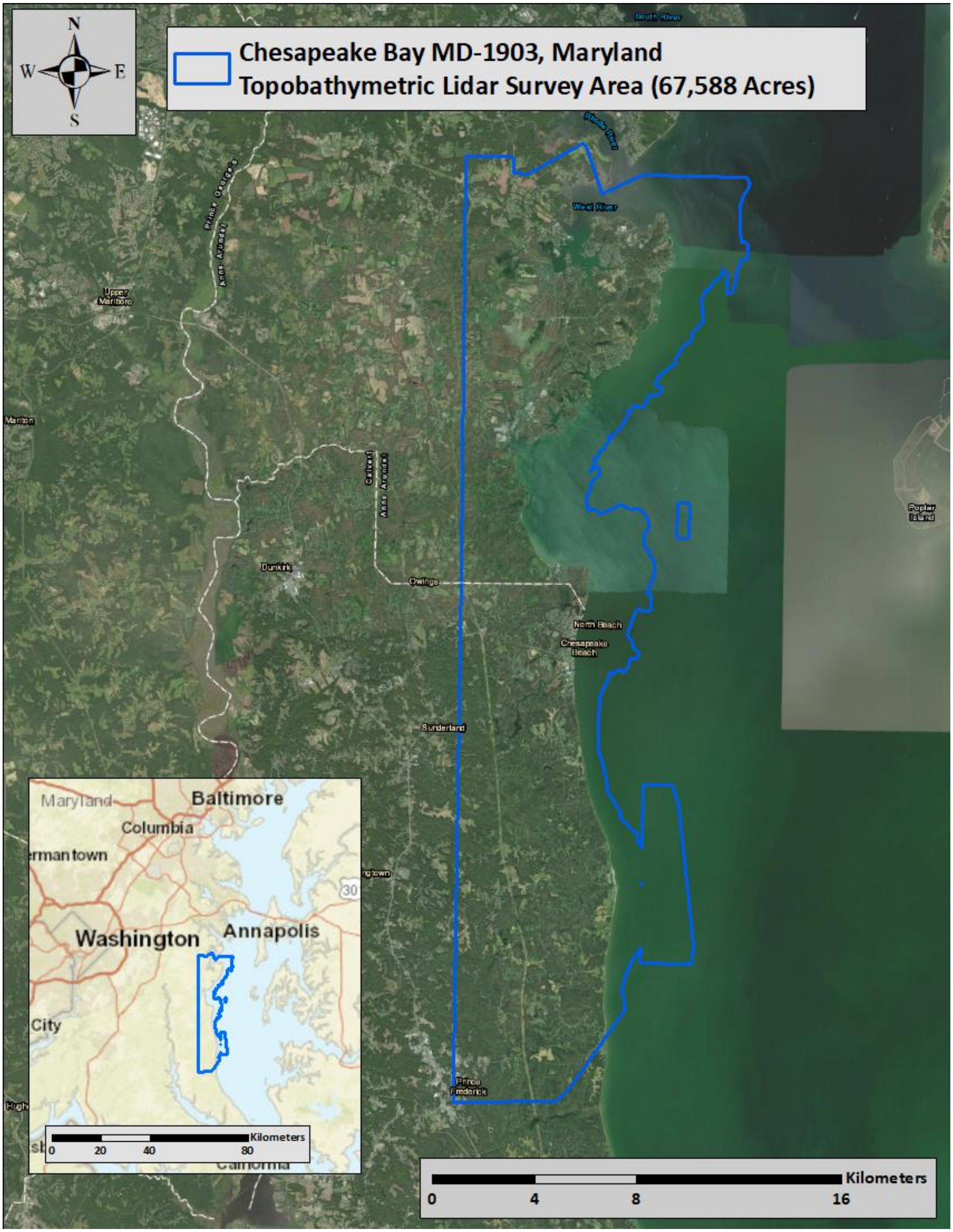


Figure 2: Location map of the Chesapeake Bay MD-1903 site in Maryland

Deliverable Products

Table 2: Products delivered to NOAA for the Chesapeake Bay sites

NOAA Chesapeake Bay MD-1902 & MD-1903 Lidar Products	
Classified LAS Projection: UTM Zone 18 North **Horizontal Datum: NAD83 (2011)** **Vertical Datum: GRS 80 (Ellipsoidal Height)** **Units: Meters**	**DEM Projection: UTM Zone 18 North** **Horizontal Datum: NAD83 (2011)** **Vertical Datum: NAVD88 (Geoid12B)** **Units: Meters**
Points	LAS v 1.4, Point Format 6 • All Classified Returns, with Depth Bias Correction for Intensity
Rasters	1.0 Meter GeoTIFFs (*.tif) • Void Clipped Topobathymetric Bare Earth Digital Elevation Models (DEMs) • Topobathymetric Standard Deviation Models • Green Sensor DZ Orthos • NIR Sensor DZ Orthos
Vectors	Shapefiles (*.shp) • Project Boundary • Lidar Tile Index • DEM Tile Index • Bathymetric Void Shape • Flightline Index • Flightline Date Coverage Polygon ASCII Text Format (*.txt) • Lidar Trajectory files
Reports	• Ground Survey Report • Lidar Calibration Boresight Report • FGDC Compliant Metadata

Lidar Deliverables

Final topobathymetric Lidar deliverables for the Chesapeake Bay project areas were the final classified and tiled Lidar returns delivered in ellipsoidal heights, DZ ortho raster models, Standard Deviation raster models, topobathymetric bare earth DEMs, and supplemental shapefiles including bathymetric void polygons , flightline swaths, and mission coverage polygons. NV5 also provided several intermittent deliverables to NOAA in order to ensure project quality, consistency, and transparency in processing throughout the project. These additional intermittent deliverables included Quick-look Lidar coverage maps in GeoTIFF format to display bathymetric Lidar collection results. NOAA reviewed all QuickLook reports and approved each area for data processing or flagged each area to re-fly. SBETs were provided for each Lidar collection mission to ensure that NOAA is provided with all raw topobathymetric data.

Final topobathymetric lidar data was provided in 500 x 500 meter tiles, divided in two delivery blocks. All associated shapefiles delineating tile grids were provided to NOAA with each delivery block, and as a final comprehensive tile index for the Chesapeake Bay lidar project areas. Final lidar DZ Orthos were created in order to evaluate the line to line relative accuracy of the lidar data, and were delivered to NOAA in GeoTIFF format as well. Finally, FGDC compliant project metadata in .xml format were delivered with all final lidar data and derived deliverables.

DEM Deliverables

After the final lidar data were accepted by NOAA, NV5 Geospatial processed the final classified orthometric point cloud into the contracted DEM deliverables First, data were converted from ellipsoid heights to orthometric heights prior to DEM generation so that all final tiled DEMs include orthometric heights from Vertical Datum NAVD88, Geoid 12B, meters.

The provided sets of tiled DEMs are enforced to the bathymetric void polygon so that areas lacking bathymetric bottom returns are set to "no data" to avoid false triangulation (interpolation from TIN'ing) across areas in the water with no bathymetric returns. All DEMs were delivered in GeoTIFF (*.tif) format with a 1 meter cell size, tiled in a 5,000 x 5,000 meter grid. Void polygons used in DEM generation were provided in addition to a confidence layer. The confidence layer reports the standard deviation (in meters) of all ground and bathymetric bottom return points within each 1 meter cell, provided in GeoTIFF (*.tif) format with a 1 meter pixel resolution, tiled in 500 x 500 meter grid.

ACQUISITION

NV5's ground acquisition equipment set up in the Chesapeake Bay Topobathymetric Lidar study area.

Planning

In preparation for data collection, NV5 reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Chesapeake Bay Lidar study area and to meet the USGS Lidar Base Specification 2.1 QL1 standards of ≥8 points/m^2 as required for the topographic Lidar, while simultaneously acquiring bathymetric lidar to meet the National Coastal Map standards at ≥2 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications. All Lidar data were acquired using a Chiroptera 4X (CH4X) sensor.

Factors such as satellite constellation availability and weather windows must be 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.

Airborne Lidar Survey

The lidar survey was accomplished using a Leica Chiroptera 4X (CH4X) laser system mounted in a Cessna 208 Caravan. The green wavelength (ʎ=532 nm) laser is capable of collecting high resolution topography data, as well as penetrating the water surface with minimal spectral absorption by water. The Leica Chiroptera 4X (CH4X) contains an integrated NIR laser (ʎ=1064 nm) that adds additional topography data. The recorded waveform enables range measurements for all discernible targets for a given pulse. The typical number of returns digitized from a single pulse range from 1 to 15 for the Chesapeake Bay project areas. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the lidar sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset. Table 3 summarizes the settings used to yield an average topographic pulse density of ≥8 points/m^2 and an average bathymetric pulse density of ≥2 points/m^2 over the Chesapeake Bay project areas.

Table 3: Lidar specifications and survey settings

Lidar Survey Settings & Specifications		
Acquisition Dates	November 9, 2019 – November 11, 2019, November 14, 2019 – November 16, 2019	
Aircraft Used	Cessna 208 Caravan	
Sensor	Leica	
Laser	Chiroptera 4X (NIR)	Chiroptera 4X (Shallow green)
Maximum Returns	15	15
Resolution/Density	To Exceed 8 pulses /m^2	To Exceed 2 pulses /m^2
Nominal Pulse Spacing	0.35 m	0.71 m
Survey Altitude (AGL)	400 m	400 m
Survey speed	140 knots	140 knots
Field of View	40°	40°
Mirror Scan Rate	70 Hz	70 Hz
Target Pulse Rate	300 kHz	35 kHz
Pulse Length	2.5 ns	2.5 ns
Laser Pulse Footprint Diameter	20 cm	160 cm
Central Wavelength	1064 nm	532 nm
Pulse Mode	Continuous multipulse	Continuous multipulse
Beam Divergence	0.5 mrad	4.0 mrad
Swath Width	291 m	291 m
Swath Overlap	34%	34%
Intensity	16-bit	16-bit
Accuracy	$RMSE_Z \leq 15$ cm	$RMSE_Z \leq 15$ cm

All areas were surveyed with an opposing flight line side-lap of ≥34% (≥68% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the Lidar data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

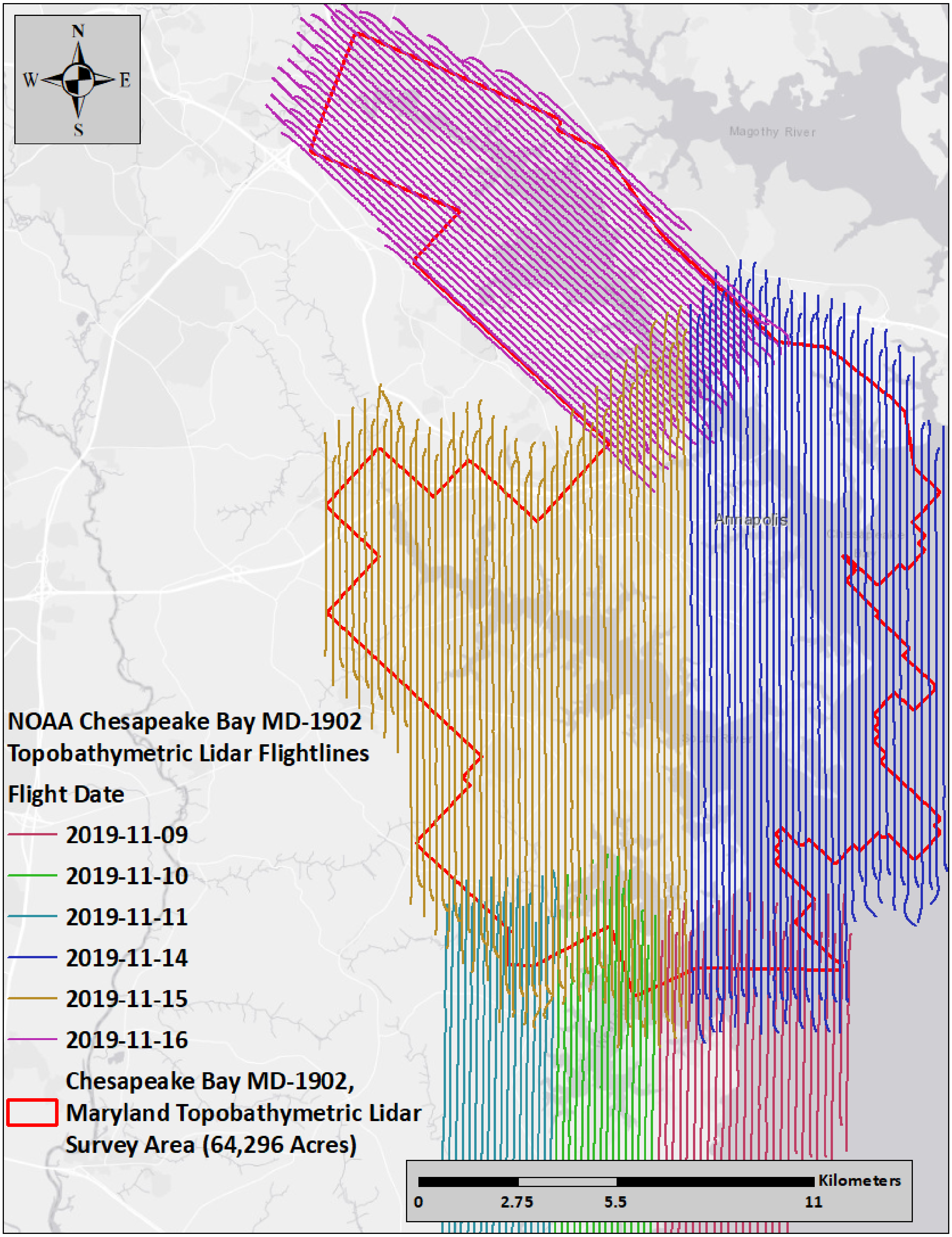


Figure 3: Flightline map for the Chesapeake Bay MD-1902 survey area

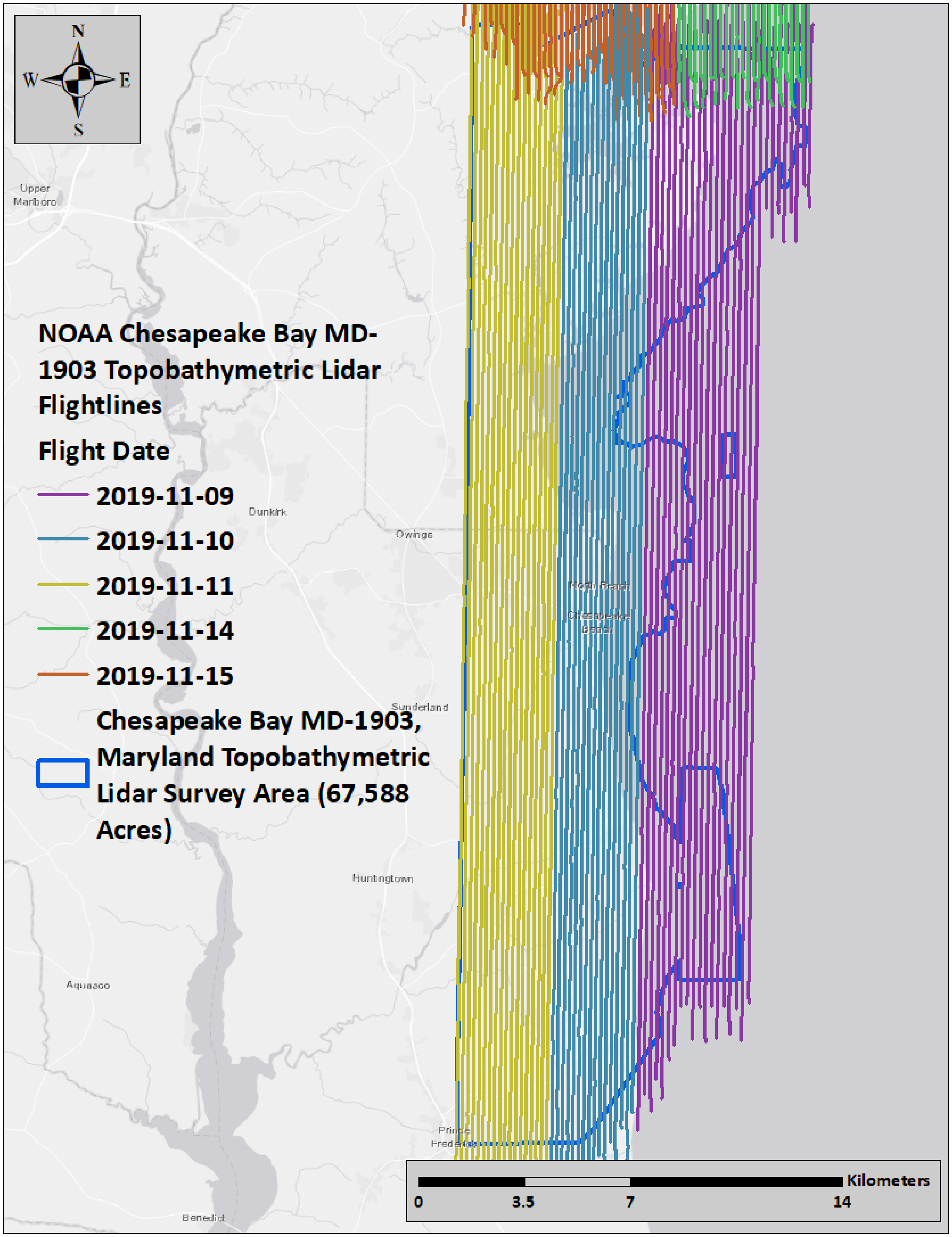


Figure 4: Flightline map for the Chesapeake Bay MD-1903 survey area

Ground Survey

Ground control surveys, including base station occupation, aerial targets and ground survey point (GSPs) collection, were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data.

Base Stations

Base Stations were used for collection of ground survey points using real time kinematic (RTK), and total station (TS) survey techniques.

NV5 utilized five permanent GNSS Real-Time Network (RTN) GNSS Base Stations for the Chesapeake Bay Lidar project. Three base stations were from the Keynet VRS network and two from the Smartnet VRS network. The position, precision, and network of each base station have been provided in Table 4. Record positions were held for all base stations. NV5's professional land surveyor, Mark Meade (MDPLS#5256592) oversaw and certified the ground survey.

Table 4: Monument positions for the Chesapeake Bay acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Network	Latitude	Longitude	Ellipsoid (meters)
DEW1	Keynet	38° 59' 16.79825"	-76° 41' 37.22571"	6.977
DEW4	Keynet	38° 46' 50.06257"	-76° 33' 14.26005"	-17.749
HB13	Keynet	38° 17' 38.63553"	-76° 35' 57.79389"	7.411
LOYF	Smartnet	38° 58' 28.07429"	-76° 31' 19.88530"	-14.498
LOYK	Smartnet	39° 07' 53.75859"	-76° 47' 25.53170"	35.287

NV5 utilized static Global Navigation Satellite System (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[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS/.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK) survey techniques. For RTK surveys, a roving receiver receives 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. RTK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See Table 5 for NV5 ground survey equipment information.

Forested check points are collected using total stations in order to measure positions under dense canopy. Total station backsight and setup points are established using GNSS survey techniques.

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. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 5 and Figure 6).

Table 5: NV5 ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R8 Model 2	Integrated Antenna	TRM-R8-GNSS	Rover
Nikon NPL-322+ 5” P Total Station		n/a	VVA

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 6, see Lidar Accuracy Assessments, page 25).

Table 6: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrubland	SHRUB		Maintained or low growth herbaceous grasslands	VVA
Tall Grass	TALL_GRASS		Herbaceous grasslands in advanced stages of growth	VVA
Mixed Forest	MX_FOR		Forested areas with a mix of coniferous and deciduous species	VVA
Bare Earth	BARE, BE		Areas of bare earth surface	NVA
Urban	URBAN, UA		Areas dominated by urban development, including parks	NVA

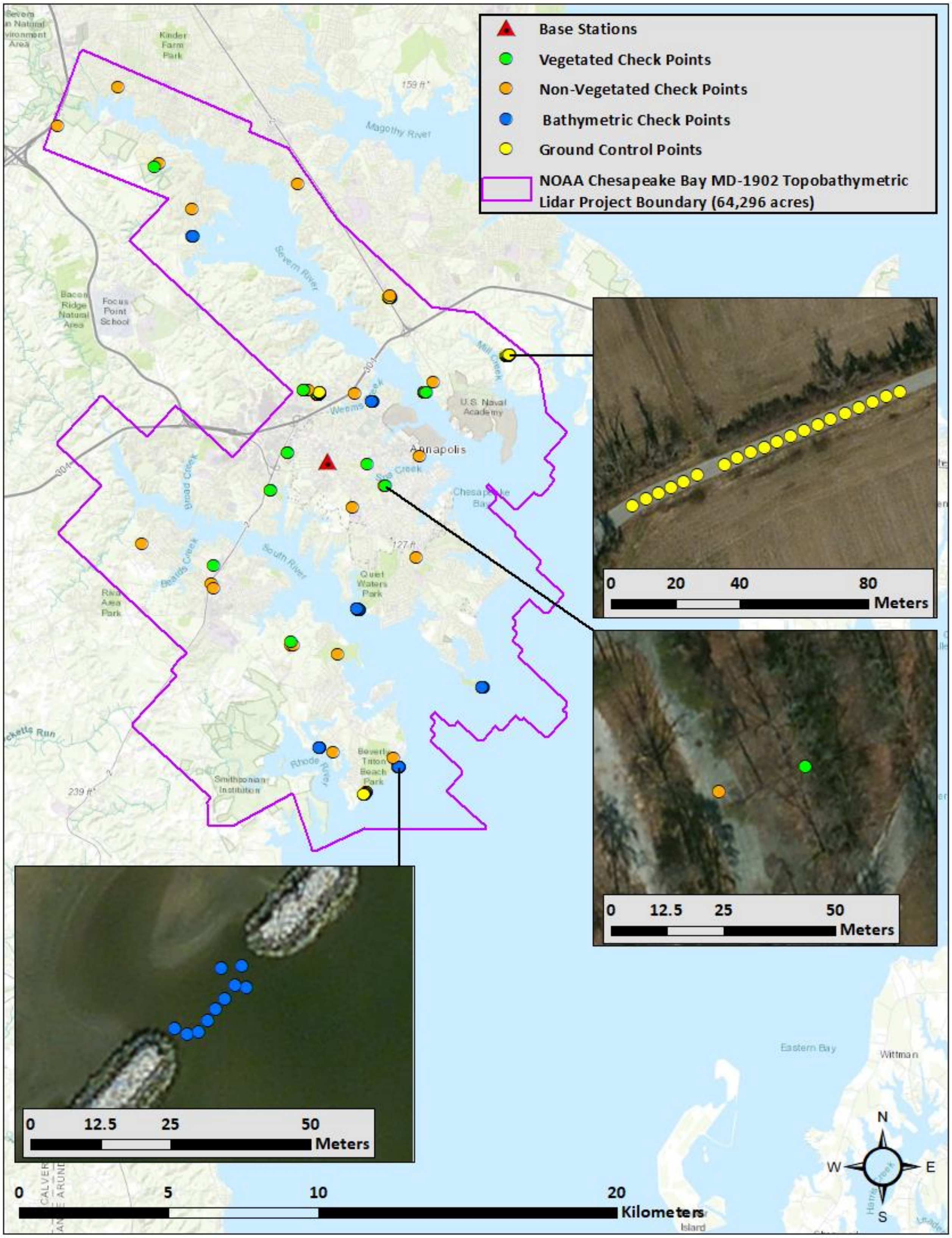


Figure 5: MD-1902 ground survey location map

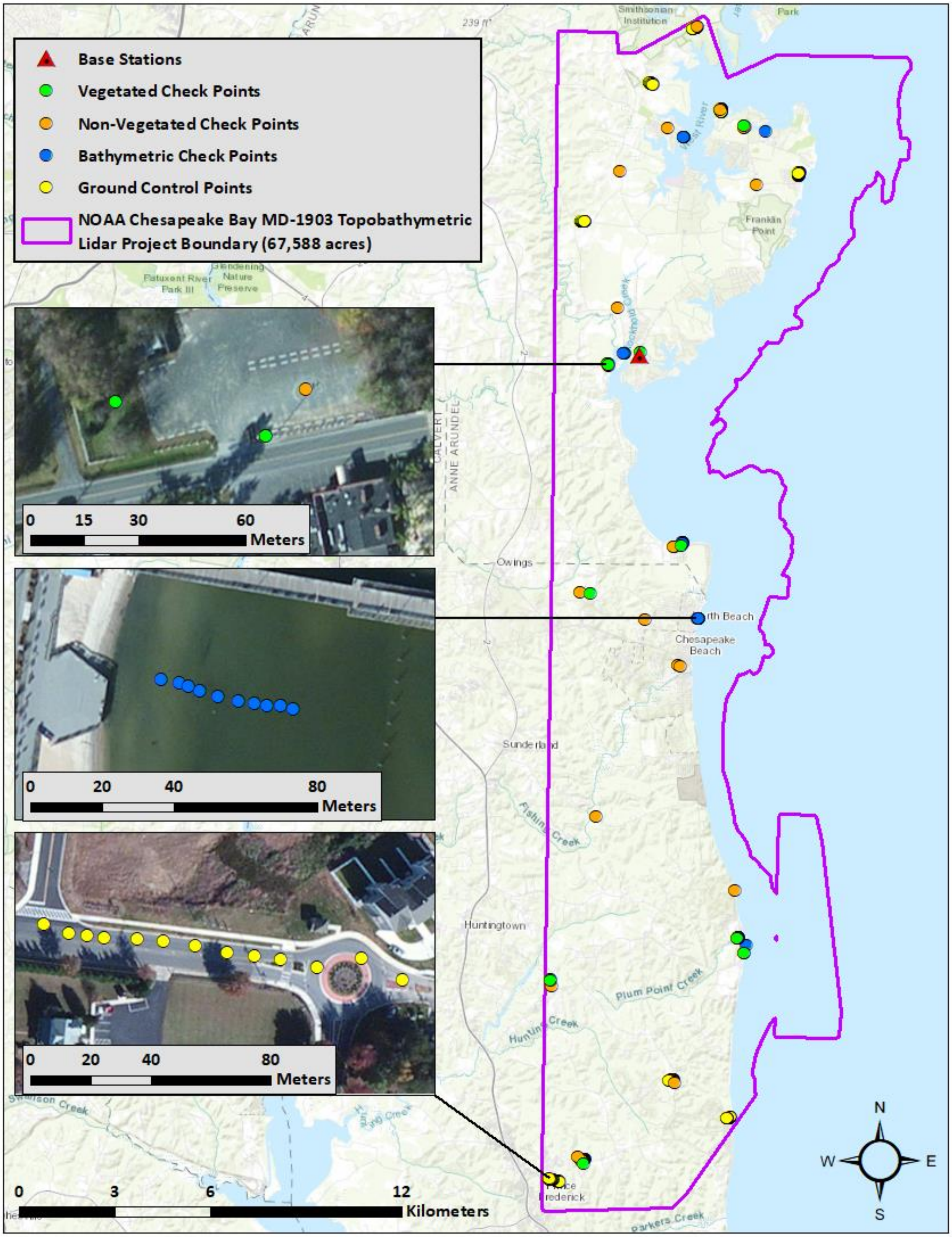
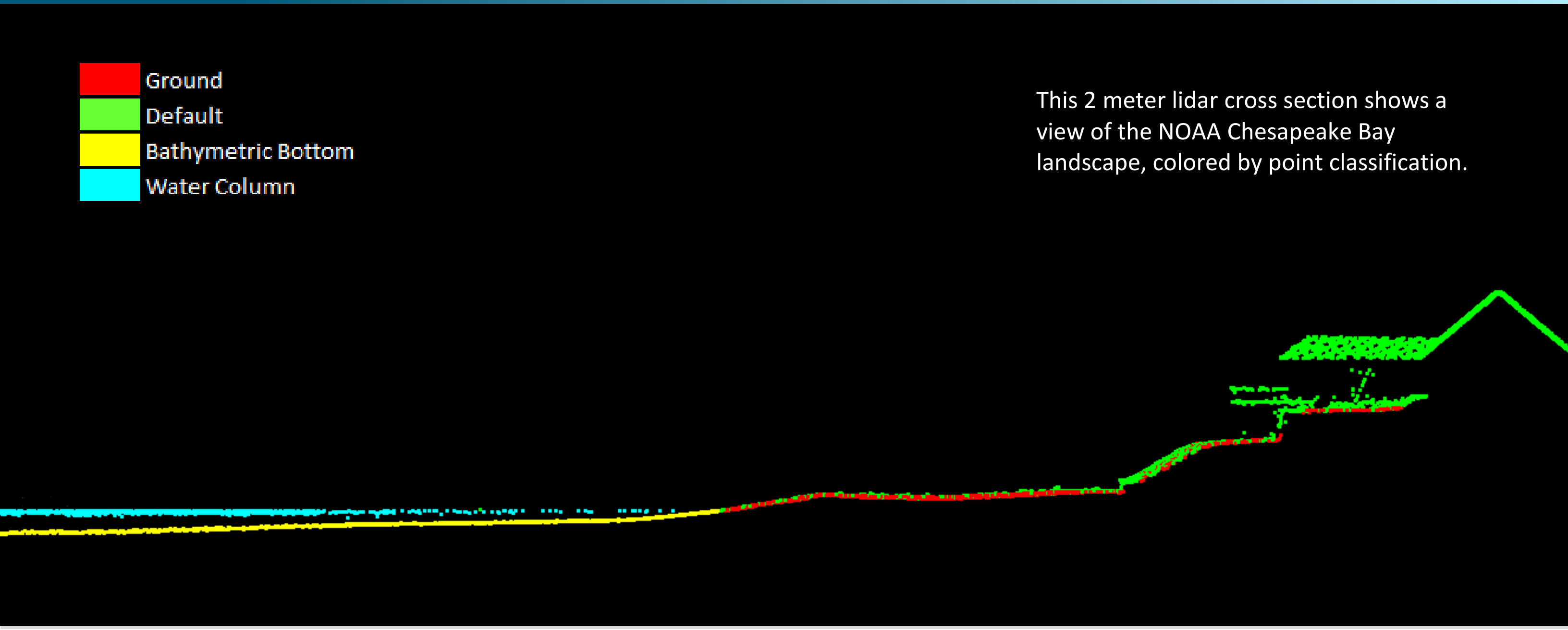


Figure 6: MD-1903 ground survey location map



Topobathymetric Lidar Data

Upon completion of data acquisition, NV5 processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and lidar point classification (Table 7).

Bathymetric Refraction

Following final SBET creation for the Leica Chiroptera 4X, NV5 Geospatial used Leica Lidar Survey Studio (LSS) to calculate laser point positioning by associating SBET positions to each laser point return time, scan angle, and intensity. Leica LSS was used to derive a synthetic water surface to create a water surface model. Light travels at different speeds in air versus water and its direction of travel or angle is changed or refracted when entering the water column. The refraction tool corrects for this difference by adjusting the depth (distance traveled) and horizontal positioning (change of angle/direction) of the lidar data. All lidar data below the water surface model were classified as water column to correct for refraction. LSS then outputs the Lidar point cloud as classified LAS 1.4 files.

Table 7: ASPRS LAS classification standards applied to the Chesapeake Bay dataset

Classification Number	Classification Name	Classification Description
1	Unclassified	Processed, but unclassified
2	Ground	Bare-earth ground
7	Noise	Noise (low or high; manually identified)
40	Bathymetric Bottom	Bathymetric 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
43	Submerged Feature	Submerged object, not otherwise specified (e.g., wreck, rock, submerged piling)
44	S-57 Object	International Hydrographic Organization (IHO) S-57 object, not otherwise specified
45	Water Column	Refracted returns not determined to be water surface or bathymetric bottom
46	Overlap Bathymetric Bottom	Denotes bathymetric bottom temporal changes from varying lifts, not utilized in the bathymetric point class
71	Adjacent Lift Unclassified	Adjacent lift Unclassified associated with areas of overlap bathy bottom where temporal bathymetric differences are present
72	Adjacent Lift Ground	Adjacent lift Ground associated with areas of overlap bathy bottom where temporal bathymetric differences are present
81	Adjacent Lift Water Surface	Adjacent lift Water Surface associated with areas of overlap bathy bottom where temporal bathymetric differences are present
85	Adjacent Lift Water Column	Adjacent lift Water Column associated with areas of overlap bathy bottom where temporal bathymetric differences are present
1-Overlap	Edge Clip	Unclassified points flagged as withheld. These are primarily "edge" points from the higher scan angle being removed
1-Withheld	Withheld	Green sensor returns within topographic areas
42-Synthetic	Derived Water Surface	Synthetic water surface location used in computing refraction at water surface
139	Withheld Tail Clip	These are points from the start/end of lines overlapping in adjoining lifts where flight data is not consistent or necessary to create coverage

Original SOW classification scheme	Delivered in LAS files
Additional classification codes	Delivered in LAS files
Original SOW classification code not used	Not delivered in LAS files
Deleted points	Not delivered in LAS files

Table 8: Lidar processing workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.3 SP3
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Apply refraction correction to all sub water surface returns.	Leica Lidar Survey Studio (LSS)
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19.005
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.19.002
Classify resulting data to ground and other client designated ASPRS classifications (Table 7). Assess statistical absolute accuracy via direct comparisons of ground classified points and the derived Bare Earth DEM to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.002
Convert data to orthometric elevations by applying a geoid correction for DEM creation. Generate bare earth models as triangulated surfaces. Export all surface models in GeoTIFF (.tif) format at a 1 meter pixel resolution.	TerraScan v.19 ArcMap v. 10.5.1 LasProjector v.1.3 (NV5) LPD v 3.0.28 (NV5)
Export intensity images layered under DZ Orthos as GeoTIFFs at a 1 meter pixel resolution.	ArcMap v.10.5.1 Las Product Creator v.3.5 (NV5)
Export standard deviation of ground, bathymetric bottom, and submerged objects in GeoTIFF (.tif) format at a 1 meter pixel resolution	LAS Tools

Lidar Derived Products

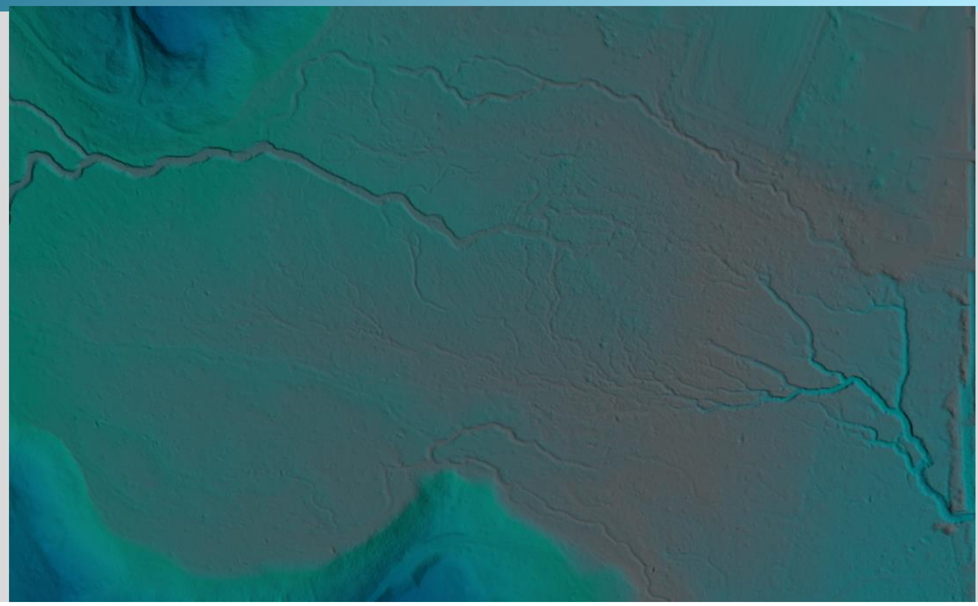
Because hydrographic laser scanners penetrate the water surface to map submerged topography, this affects how the data should be processed and presented in derived products from the lidar point cloud. The following discusses certain derived products that vary from the traditional (NIR) specification and delivery format.

Topobathymetric DEMs

Bathymetric bottom returns can be limited by depth, water clarity, and bottom surface reflectivity. Water clarity and turbidity affects the depth penetration capability of the green wavelength laser with returning laser energy diminishing by scattering throughout the water column. Additionally, the bottom surface must be reflective enough to return remaining laser energy back to the sensor at a detectable level. Although the predicted depth penetration range of the Leica Chiroptera 4x (CH4X) is 2.7 secchi depths on brightly reflective surfaces, it is typical to have no bathymetric bottom returns in turbid or non-reflective areas.

As a result, creating digital elevation models (DEMs) presents a challenge with respect to interpolation of areas with no returns. Traditional DEMs are “unclipped”, meaning areas lacking ground returns are interpolated from neighboring ground returns, with the assumption that the interpolation is close to reality. In bathymetric modeling, these assumptions are prone to error because a lack of bathymetric returns can indicate a change in elevation that the laser can no longer map due to increased depths. The resulting void areas may suggest greater depths, rather than similar elevations from neighboring bathymetric bottom returns. Therefore, a bathymetric void polygon was created to delineate areas outside of successfully mapped bathymetry. This shapefile was used to control the extent of the delivered clipped topobathymetric model and to avoid false triangulation across areas in the water with no returns. Insufficiently mapped areas were identified by triangulating bathymetric bottom points with an edge length maximum of 4.56 meters. This ensured areas with no bathymetric returns (> 9 m_2), were identified as bathymetric data voids.

A view looking over the bathymetric surface within the MD-1902 area of interest. The image was created using bathymetric ground return derived gridded surfaces colored by elevation.



Bathymetric Lidar

An underlying principle for collecting hydrographic lidar data is to survey near-shore areas that can be difficult to collect with other methods, such as multi-beam sonar, particularly over large areas. In order to determine the capability and effectiveness of the bathymetric Lidar, certain parameters were considered; such as bathymetric return density and spatial accuracy.

Lidar Point Density

First Return Point Density

The acquisition parameters were designed to acquire an average first-return density of 2 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser.

First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The average first-return density of the Chesapeake Bay MD-1902 project area was 16.00 points/m^2 and 15.24 points/m^2 for the Chesapeake Bay MD-1903 project area (Table 9). The statistical and spatial distributions of all first return densities per 100 m x 100 m cell are portrayed in Figure 7 and Figure 9.

Bathymetric and Ground Classified Point Densities

The density of ground classified lidar returns and bathymetric bottom returns were also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may have penetrated the canopy, resulting in lower ground density. Similarly, the density of bathymetric bottom returns was influenced by turbidity, depth, and bottom surface reflectivity. In turbid areas, fewer pulses may have penetrated the water surface, resulting in lower bathymetric density.

The ground and bathymetric bottom classified density of lidar data for the Chesapeake Bay MD-1902 project area was 6.40 points/m^2(Table 9). The statistical and spatial distributions ground classified and bathymetric bottom return densities per 100 m x 100 m cell are portrayed in Figure 8. The ground and bathymetric bottom classified density of lidar data for the Chesapeake Bay MD-1903 project area was 6.04 points/m^2 (Table 9). The statistical and spatial distributions ground classified and bathymetric bottom return densities per 100 m x 100 m cell are portrayed in Figure 10.

Table 9: Average Lidar point densities

Project Area	Density Type	Point Density
MD-1902	**First Returns**	16.00 points/m^2
	Ground and Bathymetric Bottom Classified Returns	6.40 points/m^2
MD-1903	**First Returns**	15.24 points/m^2
	Ground and Bathymetric Bottom Classified Returns	6.04 points/m^2

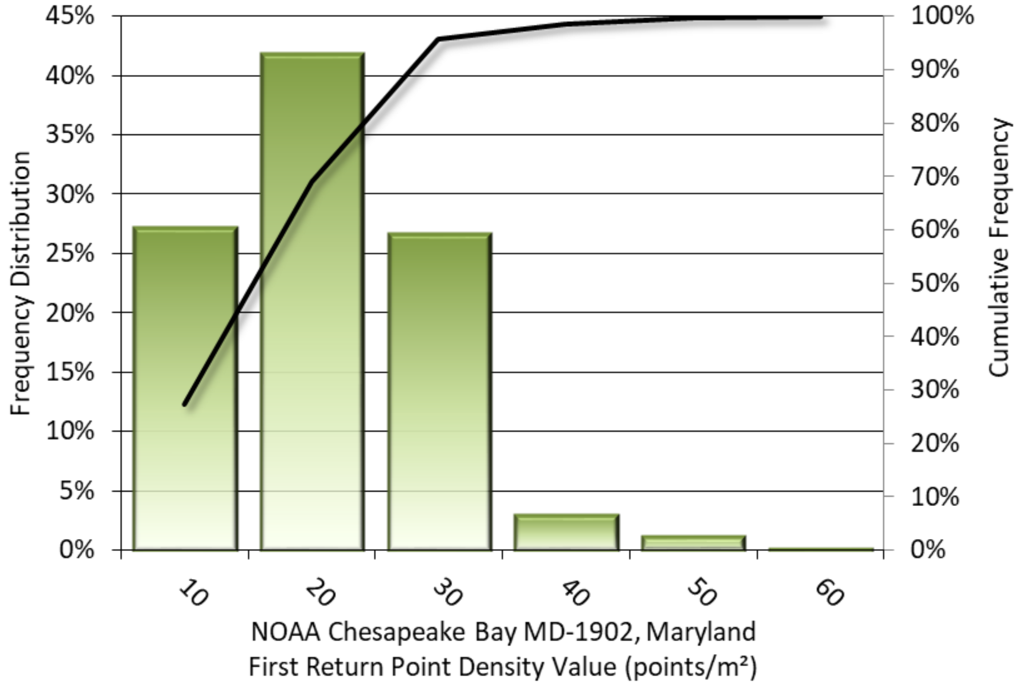


Figure 7: Frequency distribution of first return densities per 100 x 100 m cell

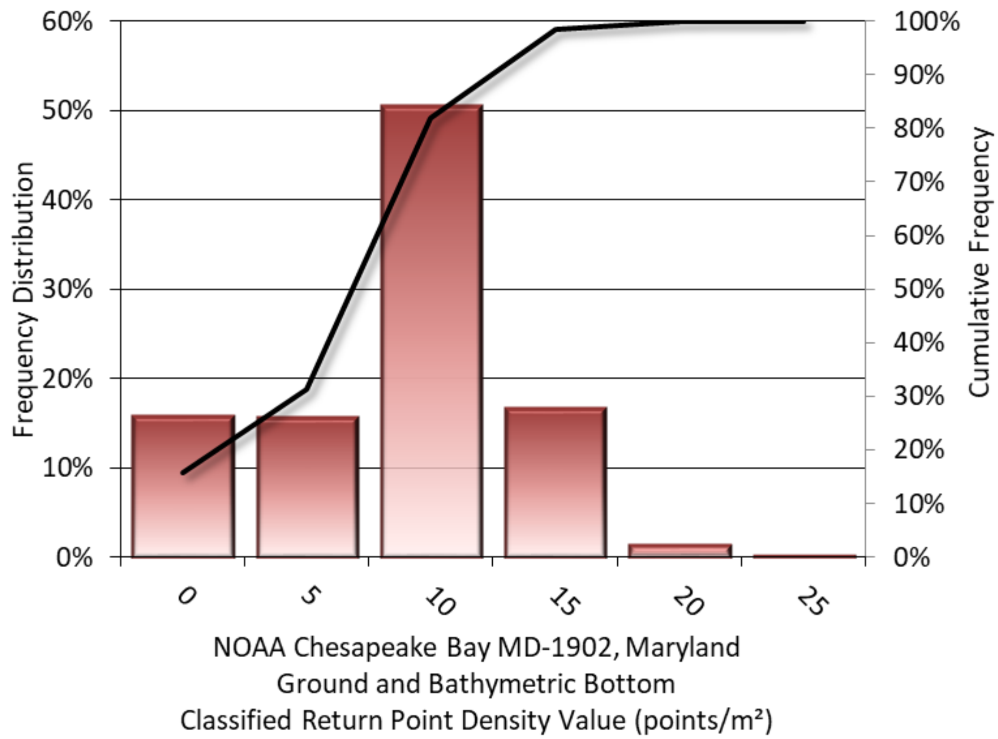


Figure 8: Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell

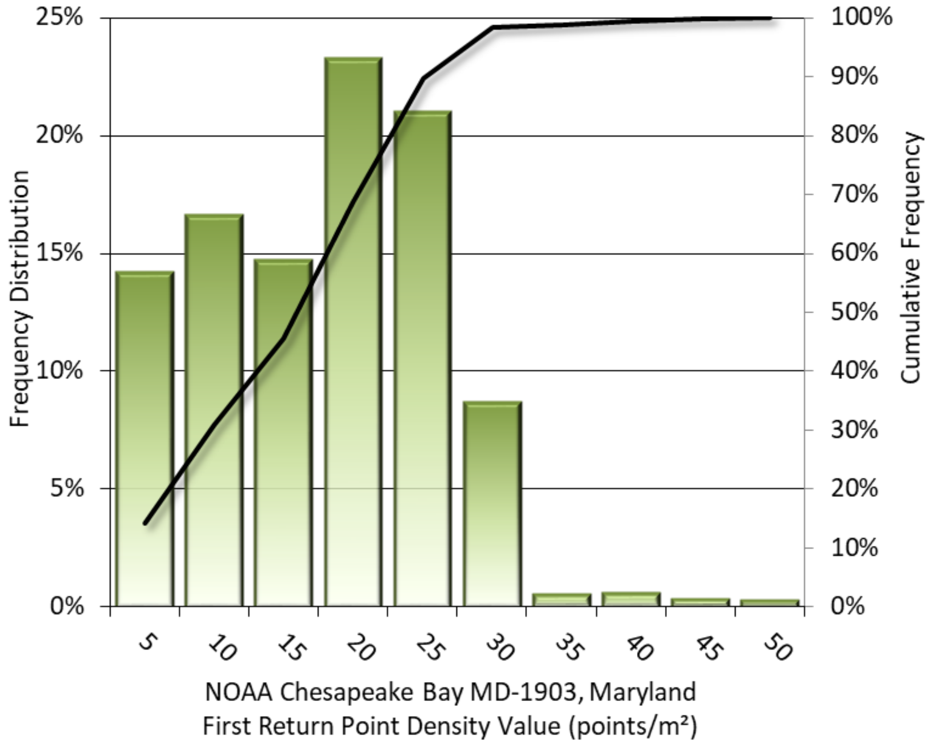


Figure 9:Frequency distribution of first return densities per 100 x 100 m cell

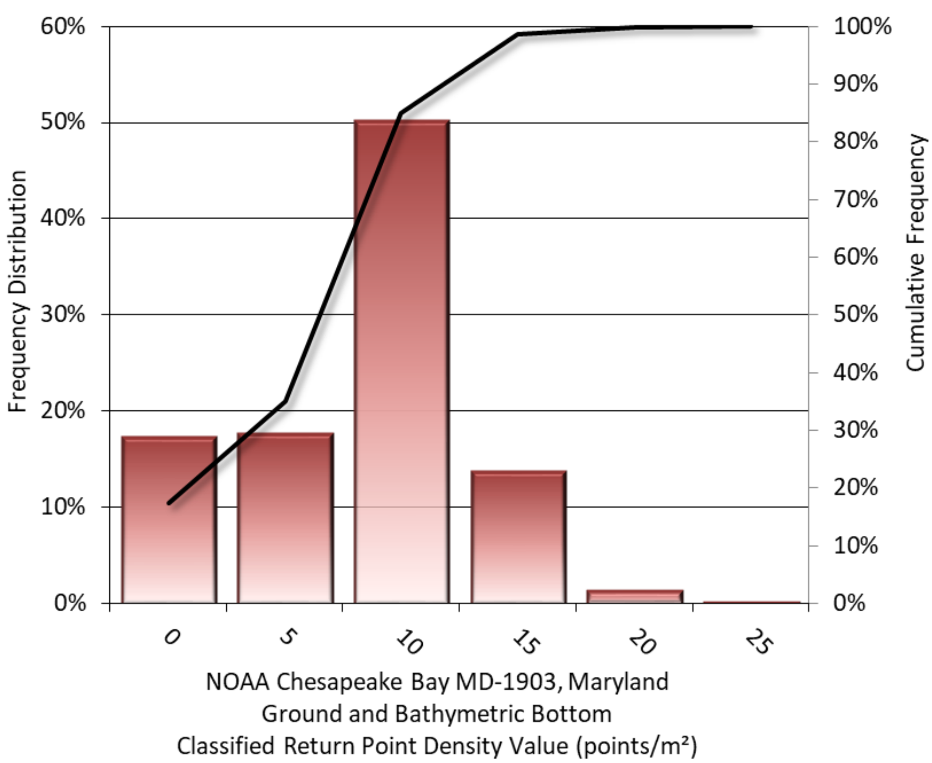


Figure 10: Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell

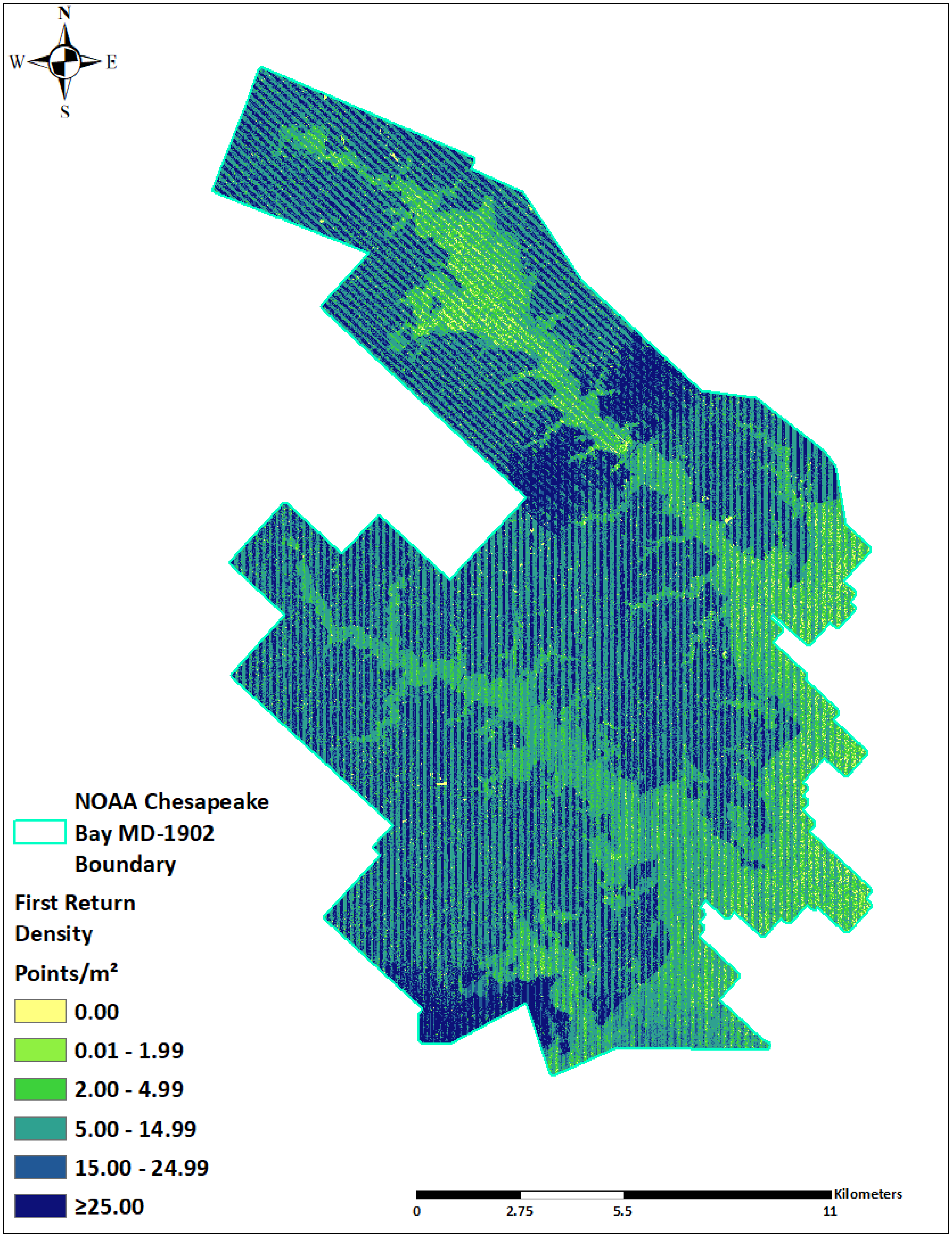


Figure 11: First return density map for the NOAA Chesapeake Bay MD-1902 topobathymetric lidar area

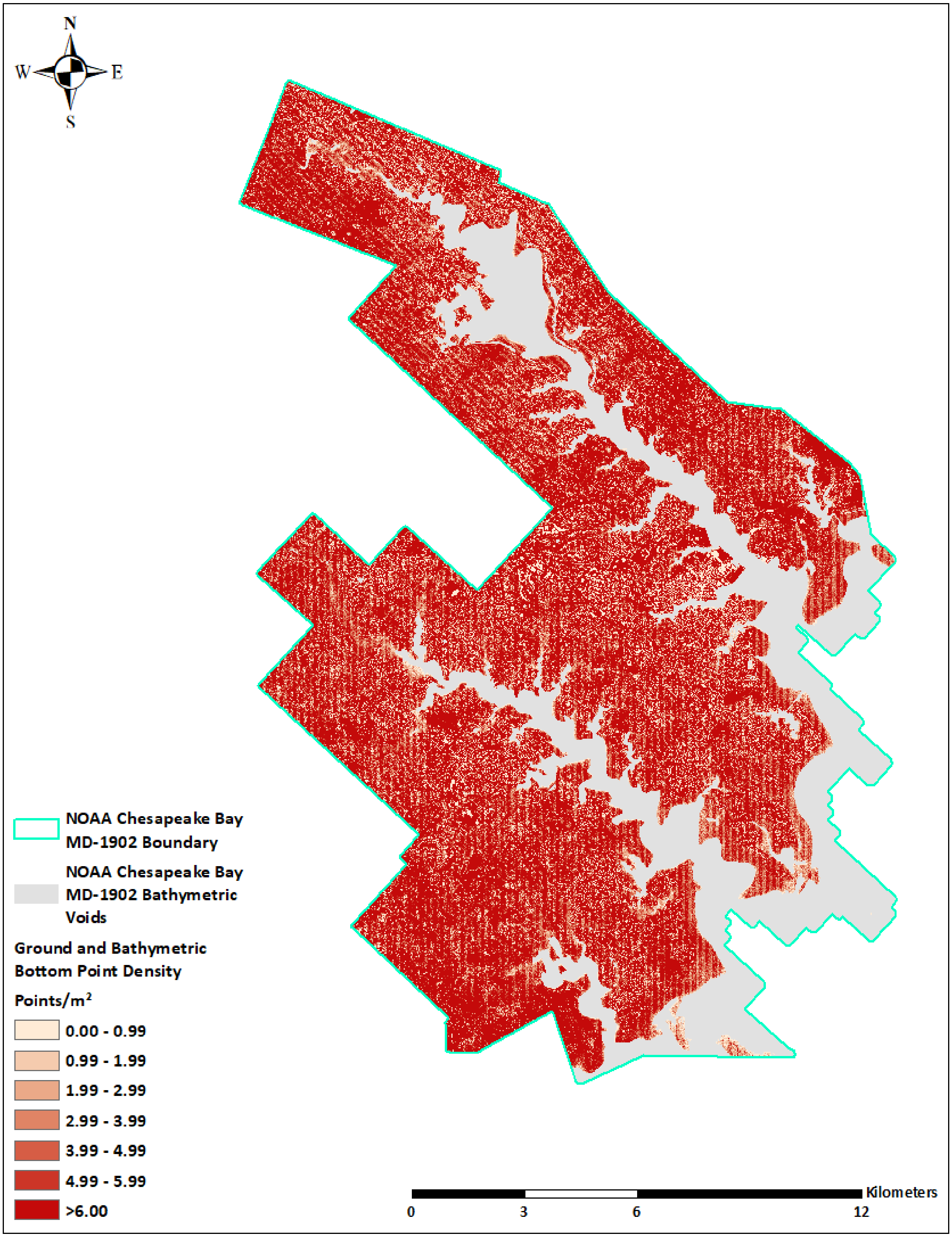


Figure 12: Ground and bathymetric bottom classified density map for NOAA Chesapeake Bay MD-1902 topobathymetric lidar

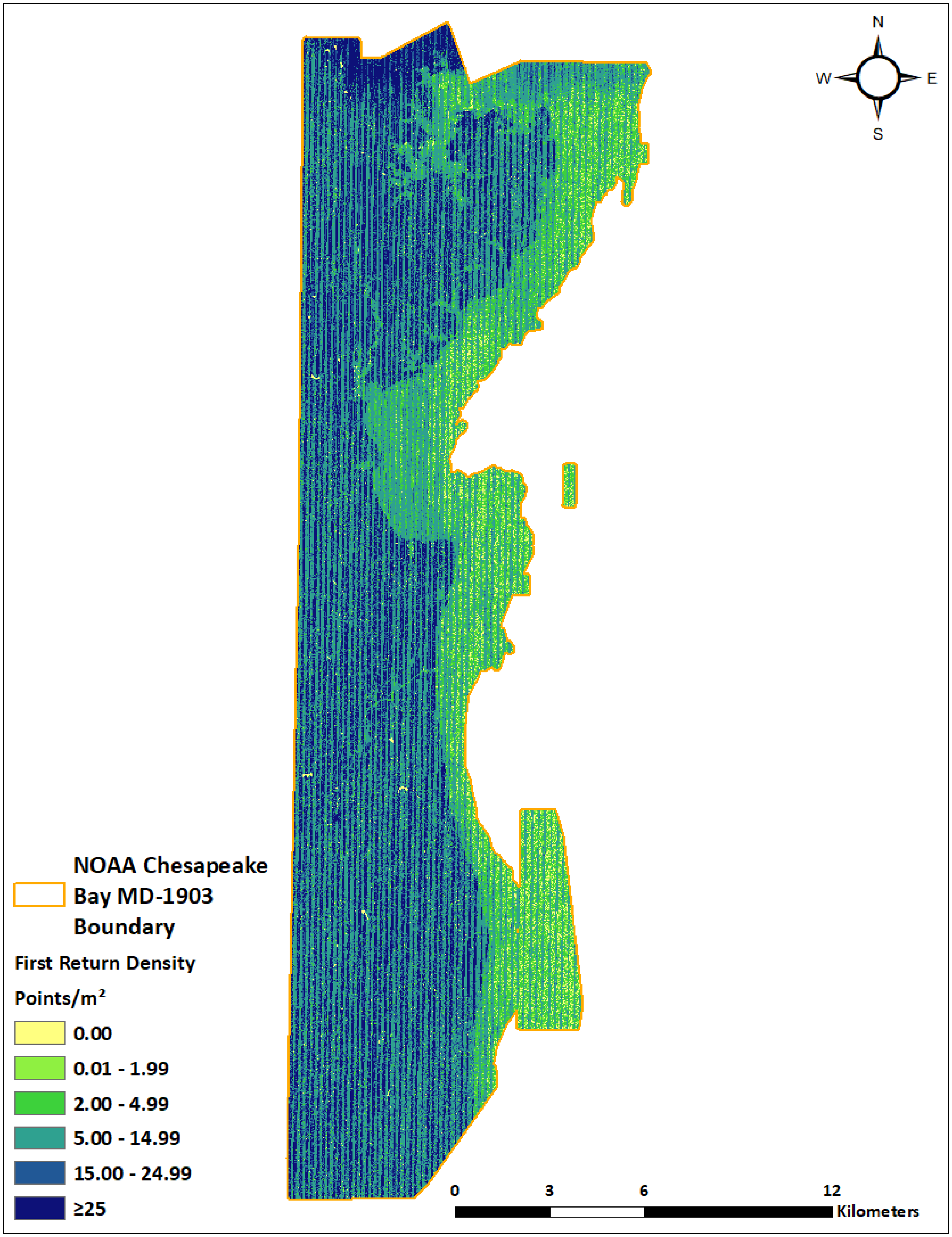


Figure 13: First return density map for the NOAA Chesapeake Bay MD-1903 topobathymetric lidar area

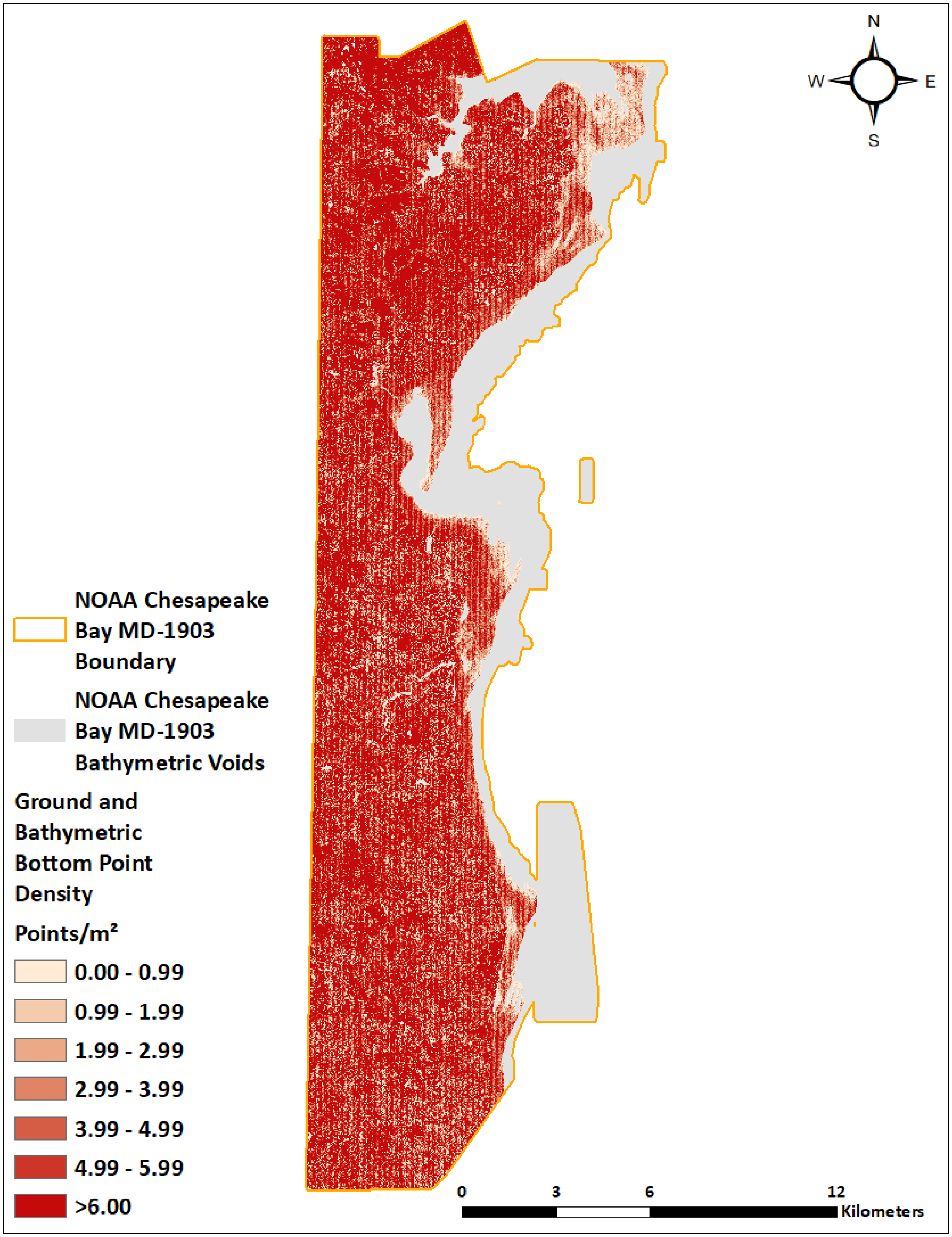


Figure 14: Ground and bathymetric bottom classified density map for NOAA Chesapeake Bay MD-1903 topobathymetric lidar

Lidar Accuracy Assessments

The accuracy of the lidar data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the classified lidar point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of lidar point data in open 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), as shown in Table 10 & Table 11.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground check point 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. For the Chesapeake Bay MD-1902 survey, 25 ground check points were withheld from the calibration and post-processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.064 meters, as compared to the classified LAS and 0.070 meters against the bare earth DEM, with 95% confidence (Figure 15, Figure 16). For the Chesapeake Bay MD-1903 survey, 23 ground check points were withheld from the calibration and post-processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.073 meters, as compared to the classified LAS and 0.081 meters against the bare earth DEM, with 95% confidence (Figure 18, Figure 19).

NV5 also assessed absolute accuracy using 104 ground control points for MD-1902 and 229 ground control points for MD-1903. 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 Table 10 and Table 11 as well as Figure 17 and Figure 20.

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[2] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 10: Absolute accuracy results for the Chesapeake Bay MD-1902 Lidar Survey

MD-1902 Absolute Vertical Accuracy			
	NVA, as compared to Classified LAS	NVA, as compared to Bare Earth DEM	Ground Control Points
Sample	25 points	25 points	104 points
95% Confidence (1.96*RMSE)	0.064 m	0.070 m	0.075 m
Average	-0.009 m	-0.008 m	0.006 m
Median	-0.008 m	0.002 m	0.007 m
RMSE	0.033 m	0.036 m	0.038 m
Standard Deviation (1σ)	0.032 m	0.035 m	0.038 m

Table 11: Absolute accuracy results for the Chesapeake Bay MD-1903 Lidar Survey

MD-1903 Absolute Vertical Accuracy			
	NVA, as compared to Classified LAS	NVA, as compared to Bare Earth DEM	Ground Control Points
Sample	23 points	23 points	229 points
95% Confidence (1.96*RMSE)	0.073 m	0.081 m	0.058 m
Average	-0.004 m	-0.007 m	-0.005 m
Median	-0.004 m	-0.010 m	-0.008 m
RMSE	0.037 m	0.041 m	0.030 m
Standard Deviation (1σ)	0.038 m	0.042 m	0.029 m

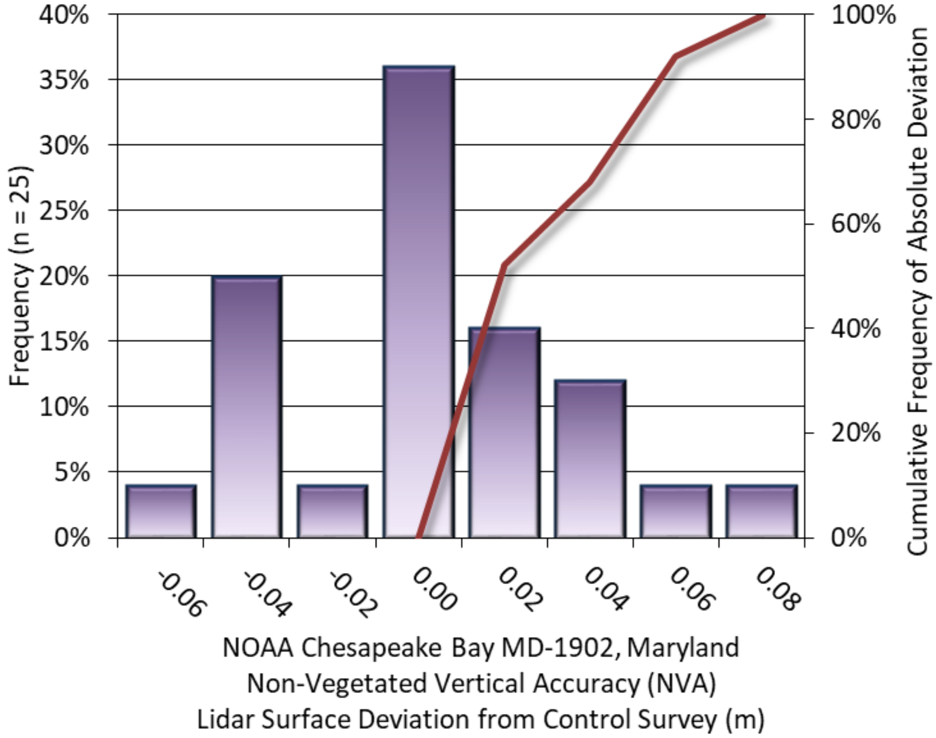

Figure 15: MD-1902 Frequency histogram for classified LAS deviation from ground check point values

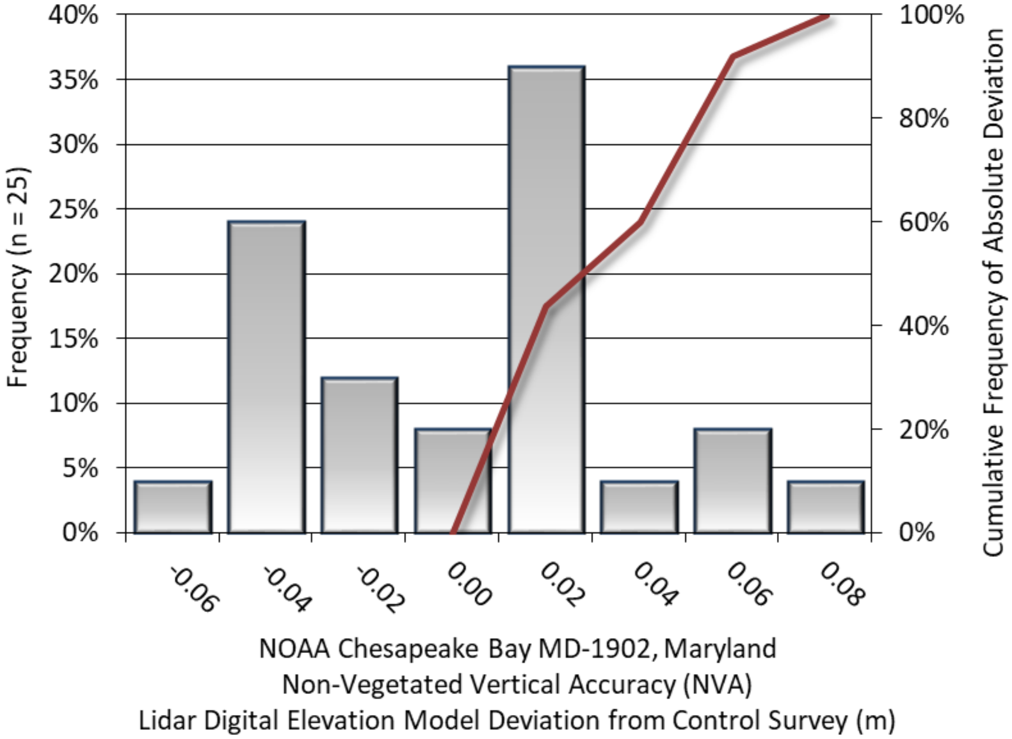

Figure 16: MD-1902 Frequency histogram for lidar bare earth DEM deviation from ground check point values

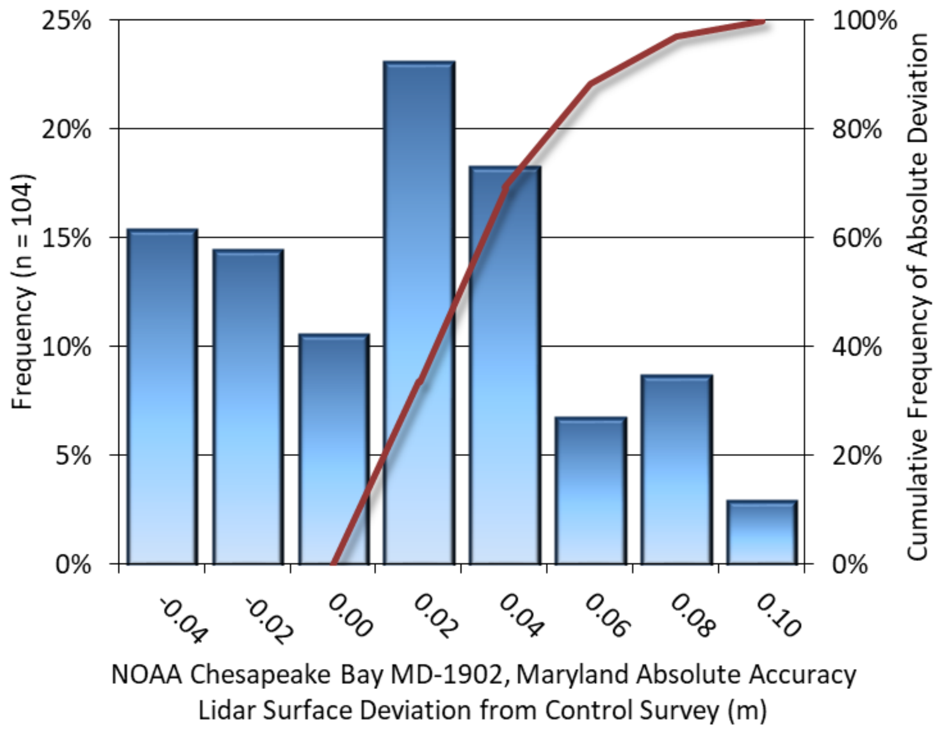

Figure 17: MD-1902 Frequency histogram for lidar surface deviation ground control point values

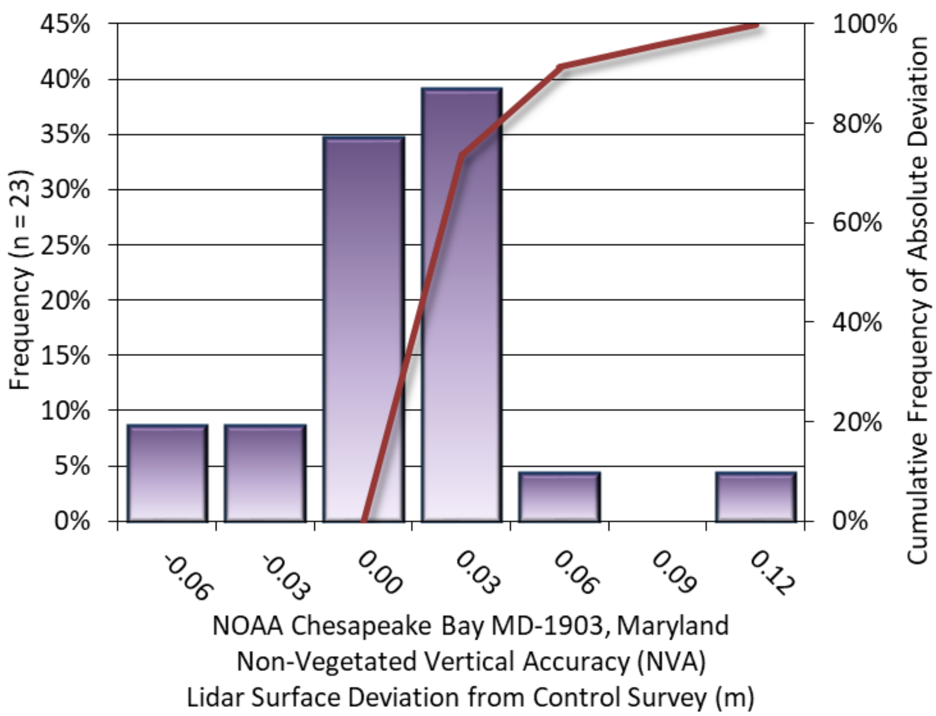

Figure 18: MD-1903 Frequency histogram for classified LAS deviation from ground check point values

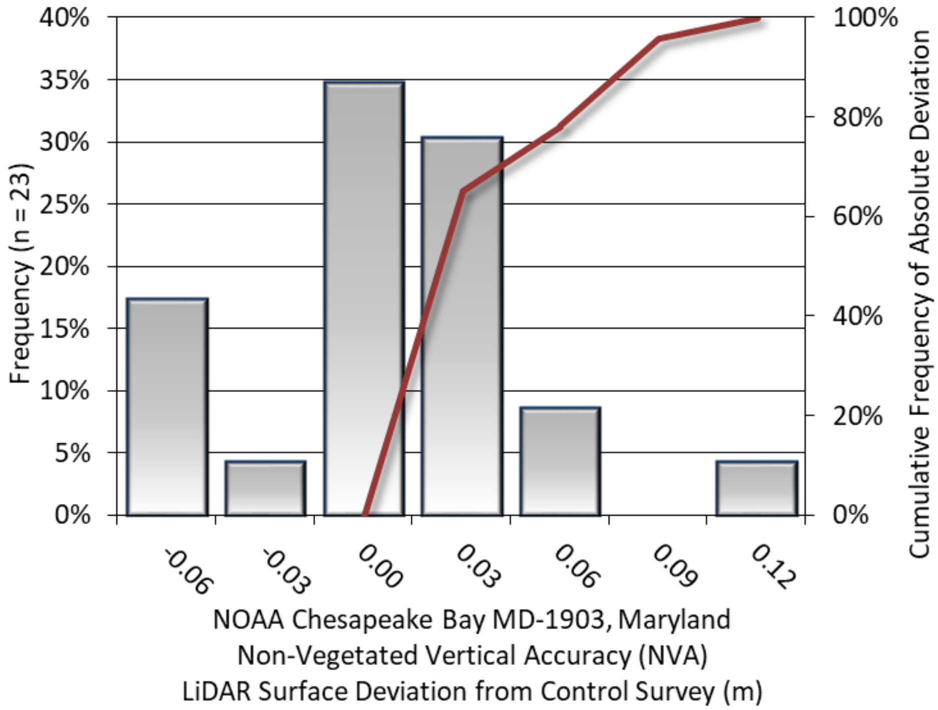

Figure 19: MD-1903 Frequency histogram for lidar bare earth DEM deviation from ground check point values

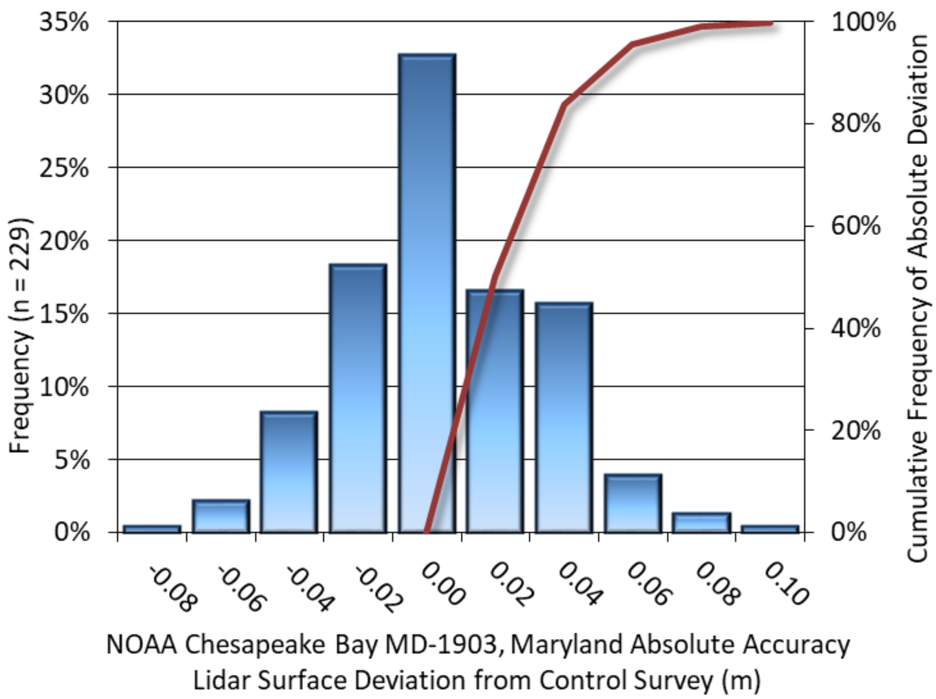

Figure 20: MD-1903 Frequency histogram for lidar surface deviation ground control point values

Lidar Bathymetric Vertical Accuracies

Bathymetric (submerged) check points were also collected to assess the submerged surface vertical accuracy. Assessment of 89 submerged bathymetric check points for the Chesapeake Bay MD-1902 survey in resulted in a vertical accuracy of 0.111 meters as compared to the classified LAS and 0.136 meters as compared to the bare earth DEM, evaluated at 95% confidence interval (Table 12, Figure 21 & Figure 22). Assessment of 43 submerged bathymetric check points for the Chesapeake Bay MD-1903 survey in resulted in a vertical accuracy of 0.157 meters as compared to the classified LAS and 0.158 meters as compared to the bare earth DEM, evaluated at 95% confidence interval (Table 13, Figure 23 & Figure 24).

Table 12: MD-1902 Bathymetric Vertical Accuracy for the Chesapeake Bay Project

MD-1902 Bathymetric Vertical Accuracy (BVA)		
	Submerged Bathymetric Check Points Compared to the Classified LAS	Submerged Bathymetric Check Points compared to the Bare Earth DEM
Sample	89 points	89 points
95% Confidence (1.96*RMSE)	0.111 m	0.136 m
Average Dz	0.012 m	0.019 m
Median	0.025 m	0.011 m
RMSE	0.057 m	0.069 m
Standard Deviation (1σ)	0.056 m	0.067 m

Table 13: MD-1903 Bathymetric Vertical Accuracy for the Chesapeake Bay Project

MD-1903 Bathymetric Vertical Accuracy (BVA)		
	Submerged Bathymetric Check Points Compared to the Classified LAS	Submerged Bathymetric Check Points compared to the Bare Earth DEM
Sample	43 points	43 points
95% Confidence (1.96*RMSE)	0.157 m	0.158 m
Average Dz	0.000 m	0.000 m
Median	-0.006 m	-0.008 m
RMSE	0.080 m	0.081 m
Standard Deviation (1σ)	0.081 m	0.081 m

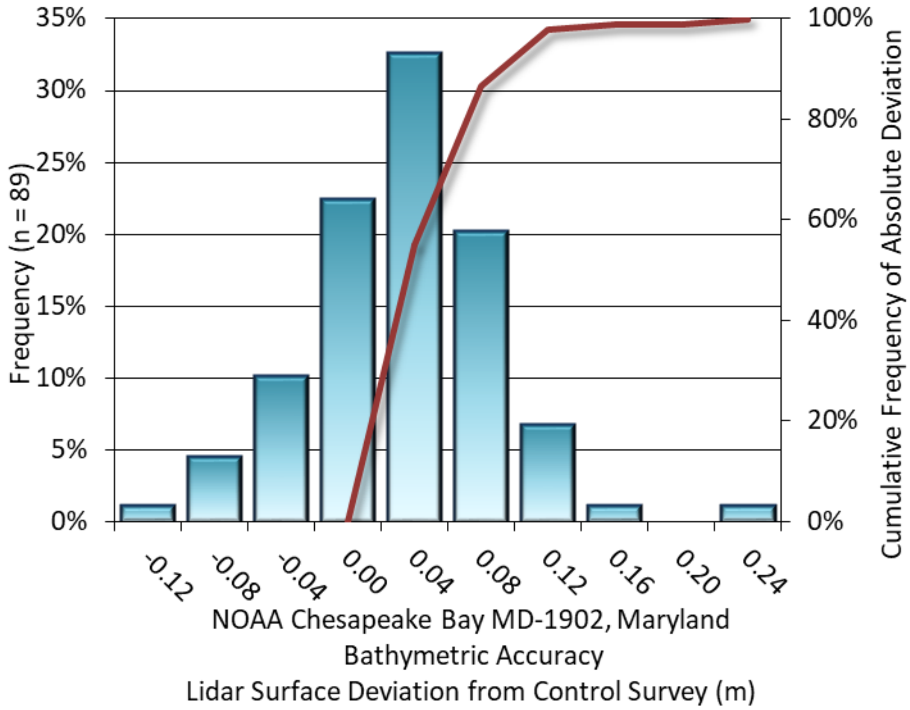

Figure 21: MD-1902 Frequency histogram for lidar surface deviation from submerged check point values

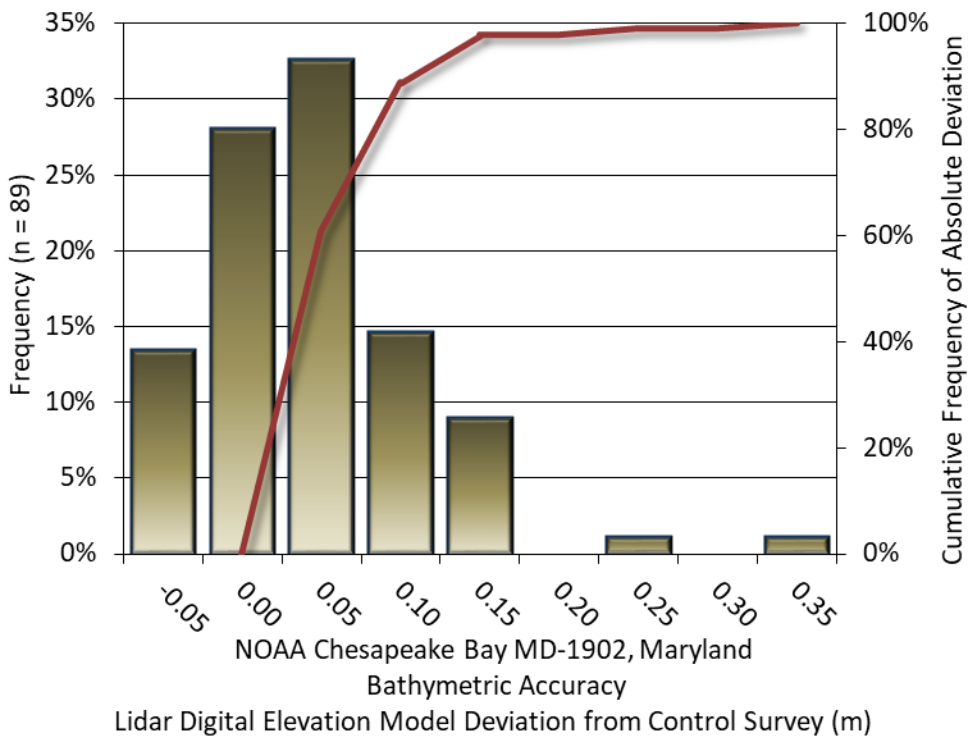

Figure 22: MD-1902 Frequency histogram for lidar bare earth DEM deviation from ground check point values

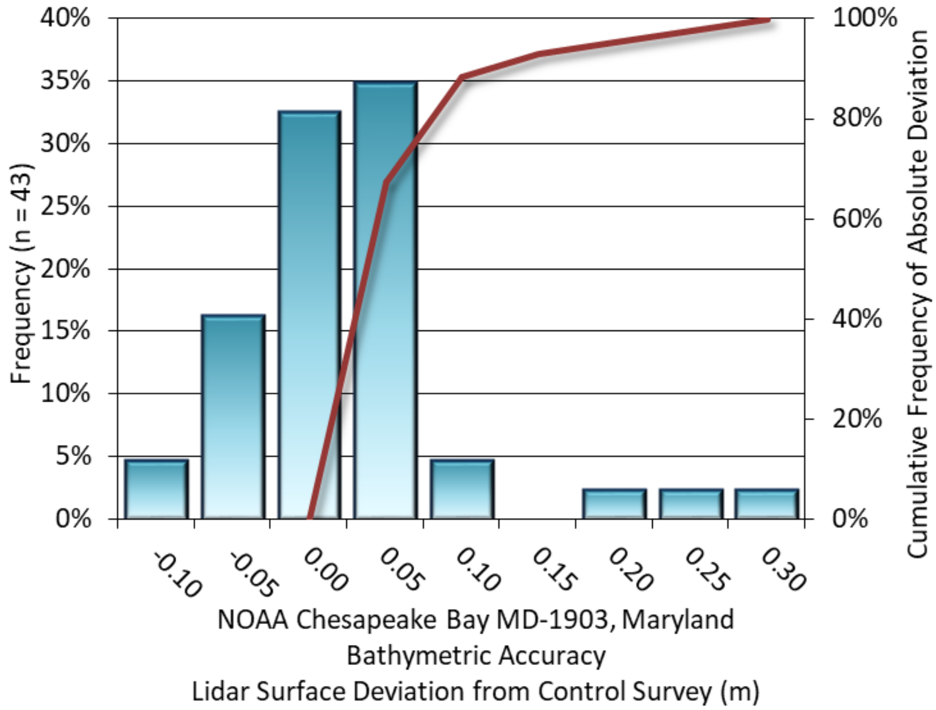

Figure 23: MD-1903 Frequency histogram for lidar surface deviation from submerged check point values

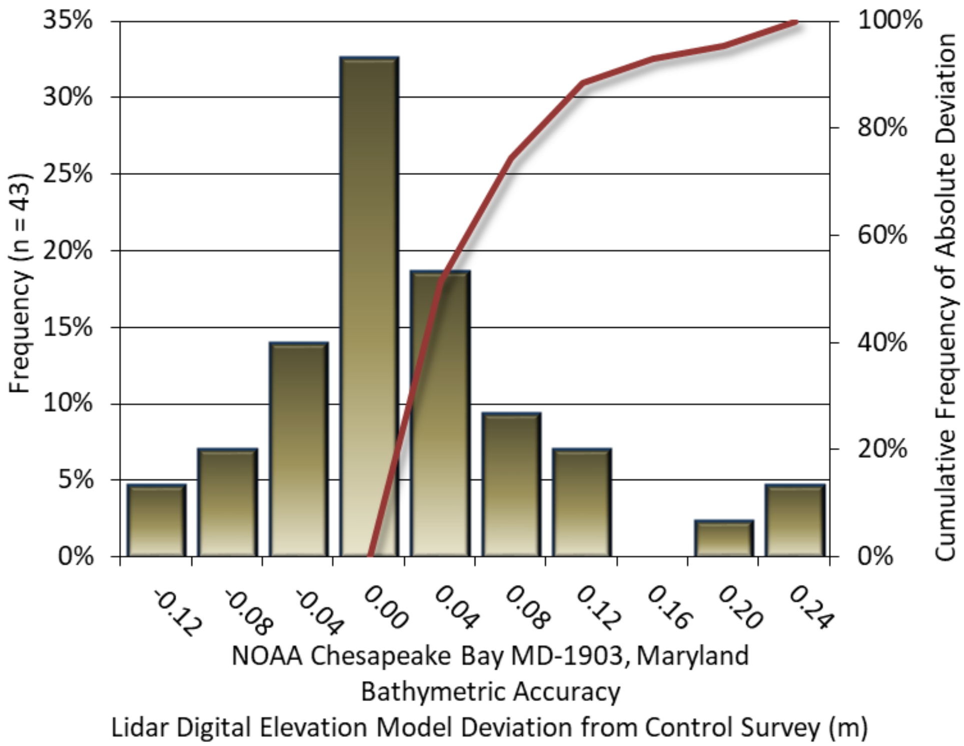

Figure 24: : MD-1903 Frequency histogram for lidar bare earth DEM deviation from ground check point values

Lidar Vegetated Vertical Accuracies

NV5 also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified lidar points. VVA is evaluated at the 95th percentile (Table 14 & Table 15, Figure 25 & Figure 26).

Table 14: MD-1902 Vegetated Vertical Accuracy for the Chesapeake Bay Project

MD-1902 Vegetated Vertical Accuracy (VVA)	
Sample	9 points
Average Dz	0.119 m
Median	-0.023 m
RMSE	-0.012 m
Standard Deviation (1σ)	0.059 m
95th Percentile	0.058 m

Table 15: MD-1903 Vegetated Vertical Accuracy for the Chesapeake Bay Project

MD-1903 Vegetated Vertical Accuracy (VVA)	
Sample	11 points
Average Dz	0.159 m
Median	0.037 m
RMSE	0.034 m
Standard Deviation (1σ)	0.090 m
95th Percentile	0.086 m

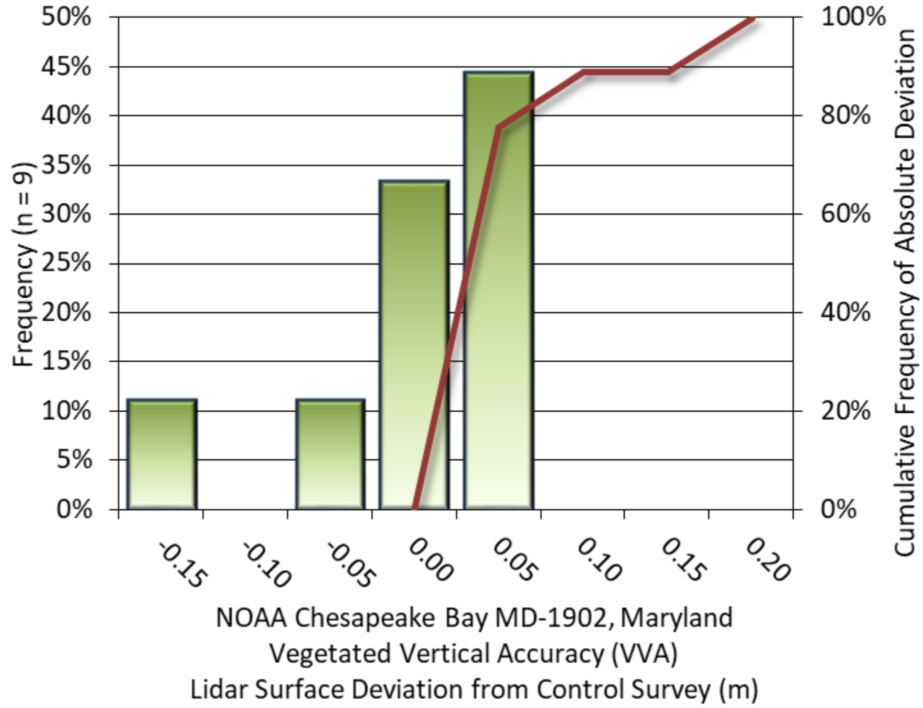

Figure 25: MD-1902 Frequency histogram for lidar surface deviation from all land cover class point values (VVA)

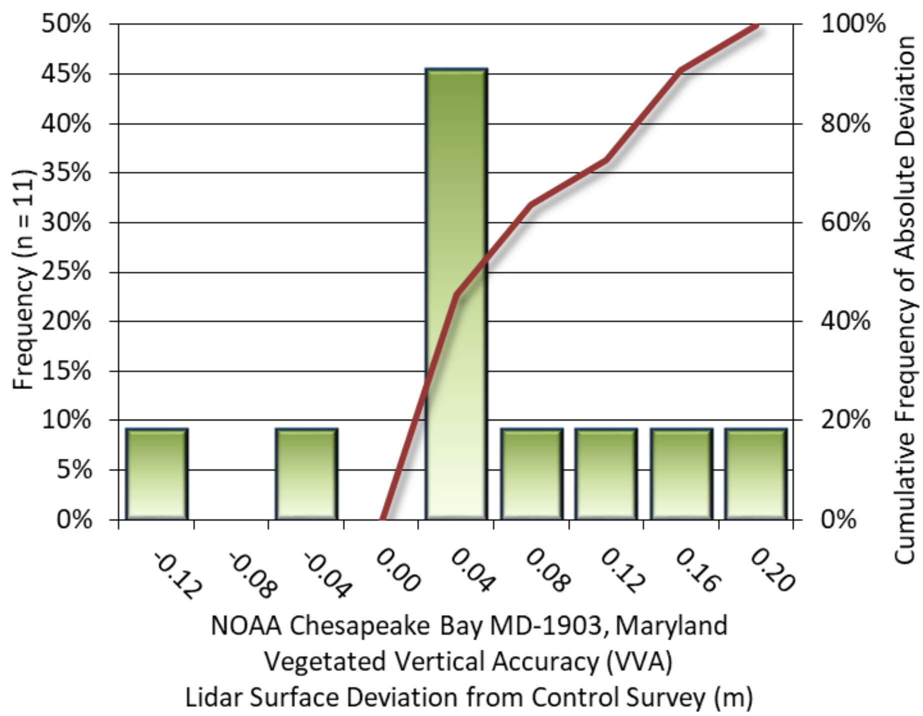

Figure 26: MD-1903 Frequency histogram for lidar surface deviation from all land cover class point values (VVA)

Lidar Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Chesapeake Bay MD-1902 Lidar survey was 0.016 meters (Table 16, Figure 27). The average (mean) line to line relative vertical accuracy for the Chesapeake Bay MD-1903 Lidar survey was 0.018 meters (Table 17, Figure 28).

Table 16: Relative accuracy results for the Chesapeake Bay MD-1902 lidar survey

MD-1902 Relative Accuracy	
Sample	358 flight line surfaces
Average	0.016 m
Median	0.020 m
RMSE	0.022 m
Standard Deviation (1σ)	0.007 m
1.96σ	0.014 m

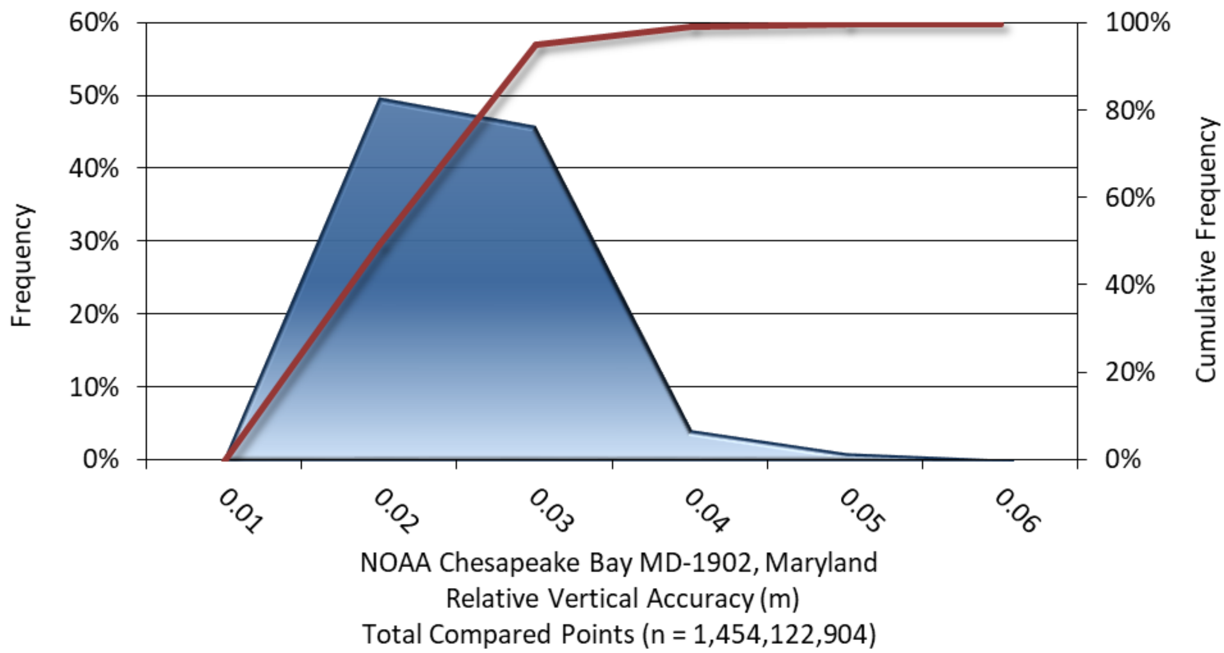

Figure 27: Frequency plot for relative vertical accuracy between flight lines

Table 17: Relative accuracy results for the Chesapeake Bay MD-1903 lidar survey

MD-1903 Relative Accuracy	
Sample	195 flight line surfaces
Average	0.018 m
Median	0.021 m
RMSE	0.022 m
Standard Deviation (1σ)	0.007 m
1.96σ	0.014 m

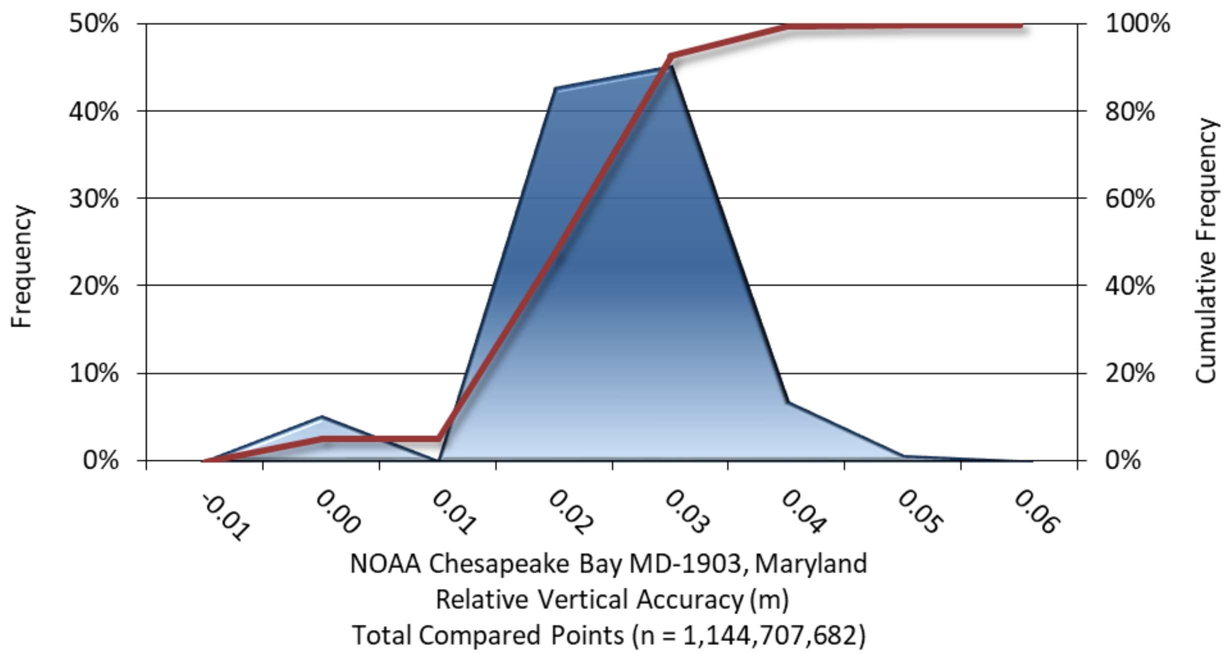

Figure 28: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is 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 percent of the time. Based on a flying altitude of 400 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.005 meters,the combined Chesapeak Bay MD-1902 & MD-1903 projects were produced to meet 0.110 m horizontal accuracy at the 95% confidence level.

Table 18: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.064 m
ACC_r	0.110 m

NV5 Geospatial, Inc. provided lidar services for the Chesapeake Bay project as described in this report.

I, Steven Miller, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Aug 4, 2021

Steven Miller
Project Manager
NV5 Geospatial, Inc.

I, Mark Meade, PLS, being duly registered as a Professional Land Surveyor in and by the state of Maryland, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between November 9th and 16th, 2019.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

Mark Meade, PLS
NV5 Geospatial, Inc.
Corvallis, OR 97330

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (FVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of lidar data is described as the mean and standard deviation (sigma σ) of divergence of lidar point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the lidar system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the lidar points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of lidar resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native Lidar Density: The number of pulses emitted by the lidar system, commonly expressed as pulses per square meter.

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data was tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Lidar accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 17^{o}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.

NOAA_CB_1902_1903_Topobathymetric_Lidar_Report_mm_signed

Final Audit Report 2021-08-04

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Status:	Signed
Transaction ID:	CBJCHBCAABAALZRpOLGHAFdBsCtv4yZlhdwXyfHb40L4

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