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March 31, 2021

NOAA Chesapeake Bay Option 3, West 1

Lidar & Shoreline Mapping: VA-1901-TB-C

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

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Cover Photo: A view looking west over Hog Island just south of Maryus, Virginia shows the topobathymetric surface of the intertidal zone, and was created from the lidar bare earth model colored by elevation, overlaid with above-ground lidar returns colored using digital imagery.

PROJECT SUMMARY

This photo taken by NV5 Geospatial acquisition staff shows a scenic view of the NOAA Chesapeake Bay Option 3 project area in Virginia.

Introduction

In November 2018, NV5 Geospatial (powered by Quantum Spatial), was contracted by the National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) Remote Sensing Division (RSD) Coastal Mapping Program (CMP), to collect topobathymetric Light Detection and Ranging (Lidar) data and digital imagery from February through April of 2019, for the NOAA Chesapeake Bay Option 3 site along the coast of Maryland (Contract No. EA-133C-14-CQ-0007). The NOAA Chesapeake Bay Option 3 project covers approximately 358 square miles along the eastern shoreline of the Chesapeake Bay. Data were collected to aid NOAA in assessing the topobathymetric surface of the near-shore and intertidal zones of the study area to support mapping and updating the national shoreline.

NV5 Geospatial provided all lidar and Digital Imagery in one delivery package. This report provides a comprehensive summary of the delivered topobathymetric lidar, digital imagery dataset, and shoreline compilation products. 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 extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected for the NOAA Chesapeake Bay Option 3 project

Project Site	Contracted Acres	Square Miles	Acquisition Dates	Data Type
NOAA Chesapeake Bay Option 3, Virginia	229,353	358	02/17/2019 - 04/12/2019	Topobathymetric Lidar
			04/01/2019	4 Band Digital Imagery (RGB-NIR)

Survey Area

The Chesapeake Bay Option 3 project area was contracted to cover approximately 358 square miles in the state of Virginia, along the western shoreline of the Chesapeake Bay. NV5 Geospatial conducted all lidar acquisition of the project area between February 17th, 2019 and April 12th, 2019. All digital imagery acquisition was conducted on April 1st, 2019 by NV5 Geospatial's imagery subcontractor, Keystone Aerial (Figure 1).

Project Team

NV5 Geospatial served as the prime contractor for the Chesapeake Bay Option 1 project and completed all lidar acquisition and processing including lidar extraction, calibration and refraction, and editing. NV5 Geospatial generated all Digital Elevation Models (DEM), raster layers, and lidar-derived void polygons from processed lidar data. Additionally, NV5 Geospatial collected all independent checkpoints to be used in assessing vertical accuracy.

A subcontractor to NV5 Geospatial, Keystone Aerial, acquired all digital imagery; however, all imagery processing and supplemental ground survey collection to support the imagery production was completed by NV5 Geospatial's Lexington office.

Figure 1: Location map of the NOAA Chesapeake Bay Option 3 site in Virginia

Deliverable Products

Table 2: Products delivered to NOAA for the NOAA Chesapeake Bay Option 3, Virginia project

NOAA Chesapeake Bay Option 3, Virginia Topobathymetric Lidar Products	
Classified LAS Projection: UTM Zone 18 North **Horizontal Datum: NAD83 (2011)** **Vertical Datum: GRS80 Ellipsoidal Heights** **Units: Meters**	**DEM Projection: UTM Zone 18 North** **Horizontal Datum: NAD83 (2011)** **Vertical Datum: NAVD88 (Geoid12B)** **Units: Meters**
Lidar	LAS v 1.4, Point Format 6 • All Classified Returns
Raster Models	1 Meter GeoTIFF Files (*.tif) • Bathymetric Void Clipped Topobathymetric Bare Earth Digital Elevation Model (DEM) • Topobathymetric Standard Deviation Model • DZ Orthos
Digital Imagery	• 6 inch Tiled Orthomosaic GeoTiffs (*.tif) • Raw Image Frames with Socet Set SUP files and camera calibrations.
Vectors	Shapefiles (*.shp) • Delivery Boundary • Lidar Tile Index • DEM Tile Index • Bathymetric Void Shape • Flightline Shapefile • Flight Date Coverage Polygon

NOAA Chesapeake Bay Option 3, Virginia Topobathymetric Lidar Products	
Reports	• Ground Survey Report *(NOAA Chesapeake Bay Option3 Ground Survey Report.docx)* • Check Point Location Photos (*NOAA CB-Op3 Form 76-53.zip*) • Lidar QC Report (*NOAA_Chesapeake_Bay_VA1901_Option_3_West_1_Cover_Letter.docx*) • Final Compiled Report of Survey • FGDC Compliant Metadata • Airborne Collection Log and Lift Extents/Coverage • Airborne Navigation and Kinematic GPS Reports • Aerotriangulation Report (*VA1901_Chesapeake_Bay_Option3_West1_Aerotriangulation_Report.doc*) • Airborne Positioning and Orientation Reports • Boresight Calibration Report • Camera Calibration Reports • EED • Photographic Flight Reports & Flightline Maps • Tabulation of Aerial Photography

Lidar Deliverables

Final topobathymetric lidar deliverables for the Chesapeake Bay Option 3, Virginia project area were the final classified and tiled lidar returns, DZ ortho raster models, Standard Deviation raster models, topobathymetric bare earth DEMs, and supplemental shapefiles including bathymetric void polygons and flightline swaths. NV5 Geospatial 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. RiProcess projects were also provided along with SBETs for each lidar collection mission to ensure that NOAA is provided with all raw topobathymetric data.

Final topobathymetric data was provided in 500 x 500-meter tiles, delivered by AOI (Figure 1). All associated shapefiles delineating tile grids were provided to NOAA in Blocks, and as a final comprehensive tile index for the Option 3 project area. 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, 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 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.

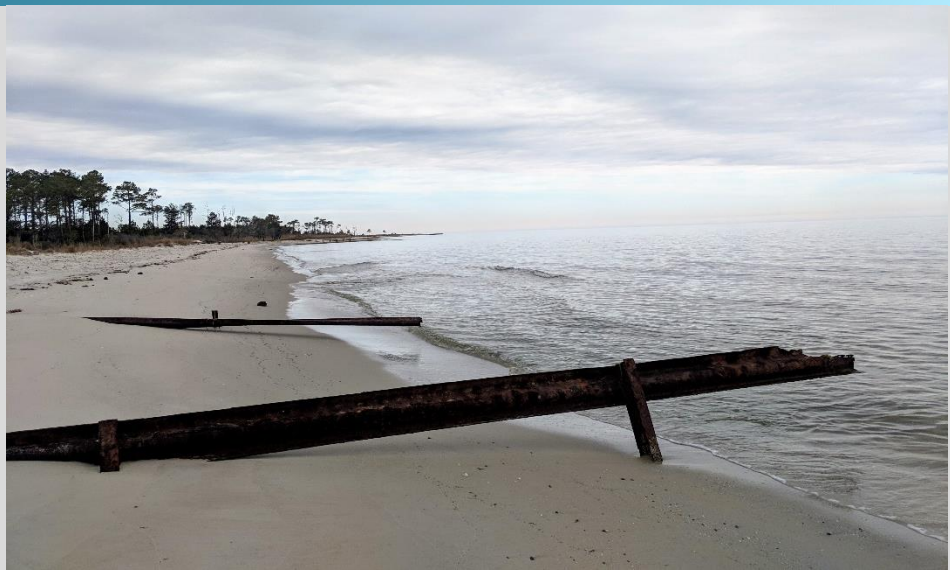
NV5 Geospatial provided NOAA with Digital Elevation Models (DEMs) with void polygons enforced so that areas lacking bathymetric bottom returns are set to “no data.” Void polygons used in DEM generation were also provided to indicate all areas greater than 9 square meters without bathymetric returns. All DEMs were delivered in GeoTIFF format with a 1 meter cell size, tiled in a 5,000 x 5,000 meter grid.

Imagery Deliverables

NV5 Geospatial provided NOAA with all acquired image frames to be viewed in both stereo as well as mosaic format. All appropriate imagery orientation and calibration information was provided along with image frames, including Socet Set SUP files and a center point shapefile. Metadata were delivered in .xml format for both stereo imagery and orthomosaics.

The collected 4-band (RGB/NIR) digital imagery was processed with 3000 x 3000 meter tile delineation, and mosaicked in GeoTIFF format. In total, 319 final orthomosaics were provided in the deliverable coordinate system: Projection: UTM Zone 18 North, Horizontal Datum: NAD83 (2011) epoch 2010.00, meters. For detailed processing information, please reference documentation provided with the imagery delivery, which includes: Aerotriangulation Report, Airborne Positioning and Orientation Report, Boresight Calibration Report, Camera Calibration Reports, EED, Flightline Maps, Ground Control Report, Photographic Flight Reports, and Tabulation of Aerial Photography.

This photo shows a scenic view of the Virginia shoreline in the Chesapeake Bay Option 3 project area.



Sensor Selection: the Riegl VQ-880-G Series

The Riegl VQ-880-G series were selected as the hydrographic airborne laser scanners for the NOAA Chesapeake Bay Option 3 project based on fulfillment of several considerations deemed necessary for effective mapping of the project site. A higher combined pulse rate (up to 550 kHz), higher scanning speed, small laser footprint, and wide field of view allow for seamless collection of high-resolution data of both topographic and bathymetric surfaces. A short laser pulse length allows for discrimination of underwater surface expression in shallow water. Sensor specifications and settings for the NOAA Chesapeake Bay Option 3 acquisition are displayed in Table 3.

Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the NOAA Chesapeake Bay Option 3 lidar study area at the target point density of ≥2.0 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.

Figure 2: Hach Turbidity Meter

NV5 Geospatial's acquisition team considered several environmental conditions during the planning stage in order to target the best possible windows for capturing bathymetric bottom returns. Water clarity was monitored on a daily basis using handheld Hach

turbidity meters operated by NV5 Geospatial ground operations professionals (Figure 3), in addition to two Turbidity Stations managed by the Chesapeake Bay Interpretive Buoy System (CBIBS[1]): York Spit and Stingray Point.

Flights over shoreline areas were planned during optimal conditions with low wind and wave conditions whenever possible, and within 20% of the Mean Range of tide around Mean Lower Low Water (MLLW) as contractually specified. NV5 Geospatial acquisition teams carefully monitored NOAA tide stations at Sewells Point, Virginia (8638610), Chesapeake Channel, Virginia (8638901) and Yorktown USCG Training Center, Virginia (8637689) to ensure acquisition requirements were met or exceeded.[2] Utilized stations are indicated with a blue star in Figure 3 below. NV5 Geospatial acquisition managers oversaw all logistical considerations including private property access and coordination of NOTAMs prior to flights.

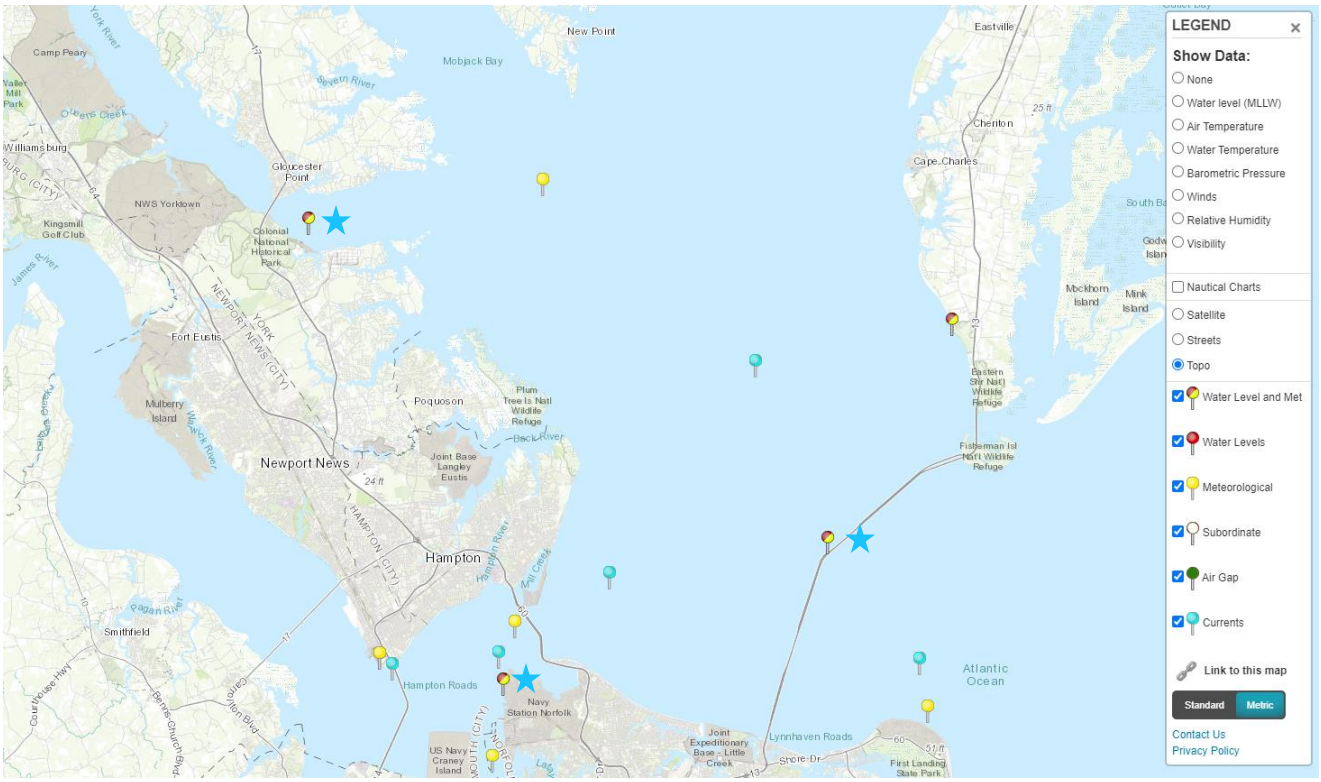


Figure 3: NOAA Tide Station Map

[1] Chesapeake Bay Interpretive Buoy System: https://buoybay.noaa.gov/

[2] NOAA Tides and Currents: https://tidesandcurrents.noaa.gov/map/

Airborne Lidar Survey

The lidar survey was accomplished using a Riegl VQ-880-GH green laser system mounted in a Cessna Caravan. The Riegl VQ-880-GH uses a green wavelength (ʎ=532 nm) laser that is capable of collecting high resolution vegetation and topography data, as well as penetrating the water surface with minimal spectral absorption by water. The Riegl VQ-880-GH also contains an integrated NIR laser (ʎ=1064 nm) that aids in water surface modeling for refraction purposes. The recorded waveform enables range measurements for all discernible targets for a given pulse. 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 first return pulse density of ≥2 pulses/m^2 over the NOAA Chesapeake Bay Option 3 project area.

Table 3: Lidar specifications and survey settings

Lidar Survey Settings & Specifications		
Acquisition Dates	02/17/2019 - 04/14/2019	02/17/2019 - 04/14/2019
Aircraft Used	Cessna Caravan	Cessna Caravan
Sensor	Riegl	Riegl
Laser	VQ-880-GH	VQ-880-GH-IR
Maximum Returns	15 (LAS 1.4 Format)	15 (LAS 1.4 Format)
Resolution/Density	To exceed 2 pulses/m^2	To exceed 2 pulses/m^2
Nominal Pulse Spacing	0.70 m	0.70 m
Survey Altitude (AGL)	400 m	400 m
Survey speed	140 knots	140 knots
Field of View	40°	40°
Mirror Scan Rate	80 revolutions per second	Uniform Point Spacing
Target Pulse Rate	245 kHz	245 kHz
Pulse Length	1.5 ns	3 ns
Laser Pulse Footprint Diameter	28 cm	8 cm
Central Wavelength	532 nm	1064 nm
Pulse Mode	MTA (multiple times around)	MTA (multiple times around)
Beam Divergence	0.7 mrad	0.2 mrad
Swath Width	291 m	291 m
Swath Overlap	30%	30%
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 ≥30% (≥60% 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.

Airborne Collection Logs & Coverage Reports

NV5 Geospatial provided daily airborne collection logs to NOAA throughout the acquisition process in the form of a daily blog and acquisition tracker update on NV5 Geospatial's tracking platform InSITE. Information included in each report detail the collection date, tide window and conditions, lines collected, coverage, and operator notes.

Ground Control

Ground control surveys 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

NV5 Geospatial utilized eight permanent Real-Time Network (RTN) stations for the NOAA Chesapeake Bay Option 3 project. Four base stations were from the KeyNetGPS RTN and four were from the HxGN SmartNet RTN. The position, precision, and network of each base station have been provided in Table 21. Network record positions were held as indicated, when found to be in alignment with the NSRS.

NV5 Geospatial triangulated static Global Navigation Satellite System (GNSS) data (1 Hz recording frequency) from each base station with nearby National Geodetic Survey (NGS) Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[3]) Projects[4] to ensure alignment with the National Spatial Reference System (NSRS), updating record positions as necessary. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Table 4: Permanent Real-Time Network (RTN) stations utilized for the NOAA Chesapeake Bay Option 3 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00. Precision values shown are for the 68% (1-sigma) confidence interval. Units are in meters.

Station ID	Latitude	Longitude	Ellips.	σ X	σ Y	σ Z	Network	Held?
DP04	37° 30' 49.53128"	-76° 37' 48.86347"	4.225	0.002	0.002	0.013	KeyNet	No
HB15	37° 11' 57.19198"	-75° 58' 45.73318"	-23.982	0.002	0.002	0.002	KeyNet	Yes
JRE1	36° 58' 35.09218"	-76° 59' 34.10477"	-1.472	0.002	0.002	0.006	KeyNet	Yes
LOYX	37° 16' 35.03057"	-76° 41' 43.81957"	2.198	0.002	0.002	0.004	SmartNet	Yes

[3] OPUS is a free service provided by NGS to process corrected monument positions aligned with NSRS. http://www.ngs.noaa.gov/OPUS.

[4] OPUS Projects is a free upgrade to standard OPUS that enables network processing of static data. https://www.ngs.noaa.gov/OPUS-Projects/

Station ID	Latitude	Longitude	Ellips.	σ X	σ Y	σ Z	Network	Held?
LOYZ	36° 51' 48.91944"	-76° 34' 24.80885"	-19.502	0.002	0.002	0.002	SmartNet	Yes
VACC	37° 15' 59.89409"	-76° 01' 22.32026"	-29.962	0.002	0.002	0.007	SmartNet	Yes
VAKI	37° 42' 39.58516"	-76° 22' 50.91365"	-1.883	0.002	0.002	0.004	SmartNet	No
WLP2	36° 45' 59.76765"	-76° 15' 30.56728"	-13.247	0.002	0.002	0.007	KeyNet	No

OPUS Project keys applicable to this project are 6ZT27M6K and 53UKRE6C; credentials are available by request. The five NGS CORS utilized during OPUS Project processing are listed in Table 22.

Table 5: NGS CORS utilized with OPUS Project. Published NAD83(2011) coordinates were held and can be retrieved from http://www.ngs.noaa.gov/CORS/.

CORS used in OPUS Project							
ANP5	BACO	CORB	DEMI	DRV5	DRV6	GODZ	HNPT
LOY2	LOY8	LOYF	LOYO	LOYW	LOYX	LOYZ	LS02
LS03	NCEL	NCGA	SCWT	UMBC	WDC6	YAGP	YORK

Network Accuracy

Base station coordinates 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.[5] 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 monument rating for this project is shown in Table 23.

Table 6: Federal Geographic Data Committee monument rating for network accuracy

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

[5] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3.
http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), post-processed kinematic (PPK), and fast-static (FS) 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. PPK and FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK and PPK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. 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 7 for NV5 Geospatial ground survey equipment information.

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).

Table 7: NV5 Geospatial equipment identification table. Does not include CORS antennas.

Receiver Model	Antenna	OPUS Antenna ID	Serial Numbers	Use
Trimble R8 Model 3	Integrated Antenna	TRMR8_GNSS3	R8-9860	Rover
Trimble M3 Total Station	n/a	n/a	VVA	Trimble M3 Total Station

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 8, see Lidar Accuracy Assessments, page 26).

Table 8: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Type
Shrub Land	SHRUB, SH		Maintained or low growth herbaceous grasslands	VVA
Tall Grass	TALL_GRASS, TG		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FOREST, FR, FO		Forested areas	VVA

Land cover type	Land cover code	Example	Description	Accuracy Type
Bare Earth	BARE, BE		Areas of bare earth surface	NVA
Urban	URBAN, UA		Areas dominated by urban development, including parks	NVA

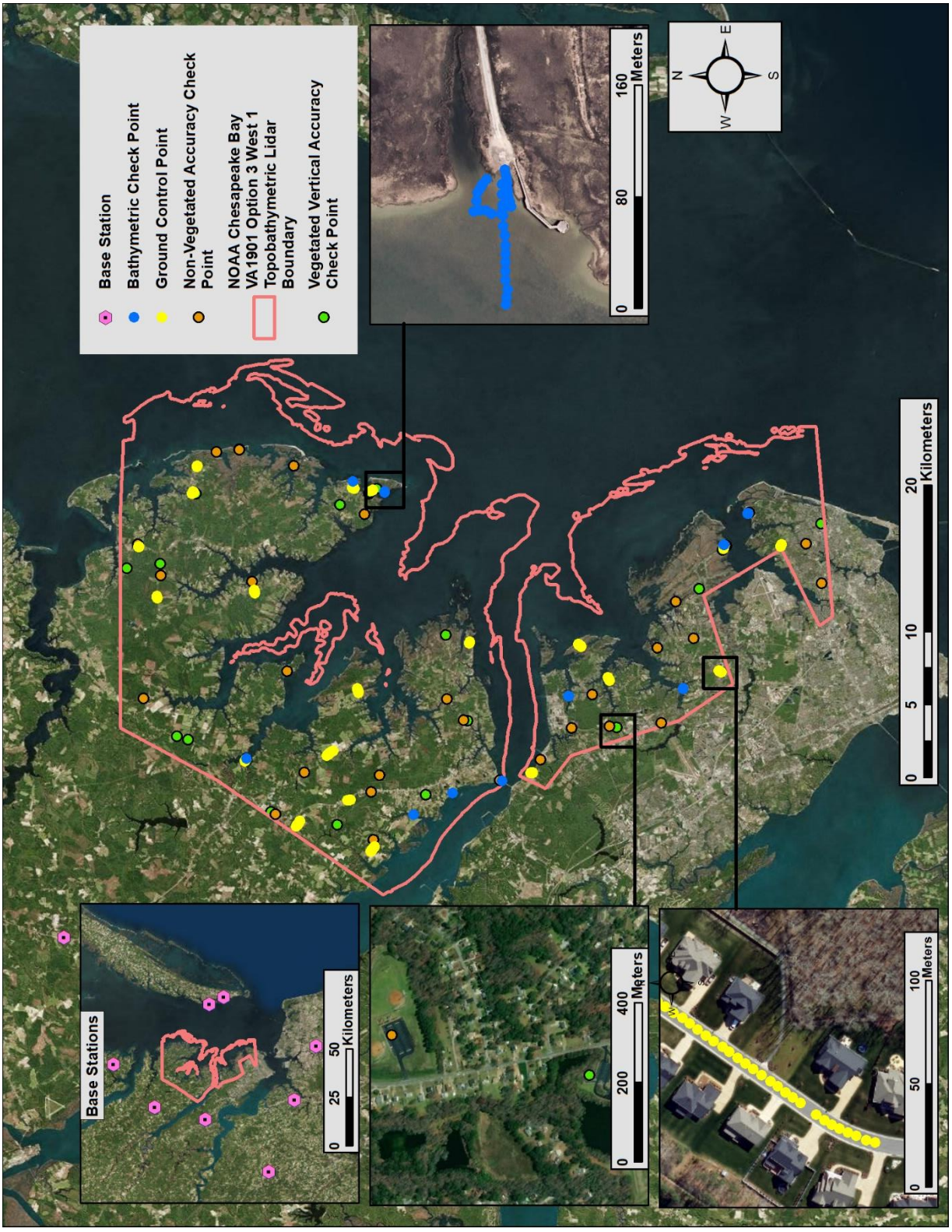


Figure 4: Ground survey location map

Digital Imagery

Survey Settings

Aerial imagery was collected by Keystone Aerial at a nominal ground sample distance of 0.26 meters using the UltraCam Eagle (UCE) camera with a 79.8 mm lens. The UCE is a large format digital aerial camera manufactured by Vexel. The system is gyro-stabilized and simultaneously collects panchromatic and multispectral (RGB, NIR) imagery. The 4band color photographs were acquired by Keystone Aerial on April 1, 2019.

All imagery was acquired using >60% forward overlap and >30% side overlap, sun angles >20 or >25 degrees (depending on the date of acquisition) and was coordinated with low tide. Acquisition settings particular to the Chesapeake Bay Option 1 project were provided to NOAA along with NV5 Geospatial's imagery delivery.

Table 9: Camera manufacturer's specifications

UltraCam Eagle	
Focal Length	79.8 mm
Data Format	RGB NIR
Pixel Size	5.2 µm
Image Size	20,010 x 13,080 pixels
Frame Rate	1.8 seconds
FOV	66° x 46°

Aerial Targets

All ground survey work in support of imagery production was completed by NV5 Geospatial's Lexington office. A detailed report of survey for imagery was provided to NOAA in previous delivery packages, and can be referenced in Appendix B.

Flight Line Diagram – 4 Band
VA1901

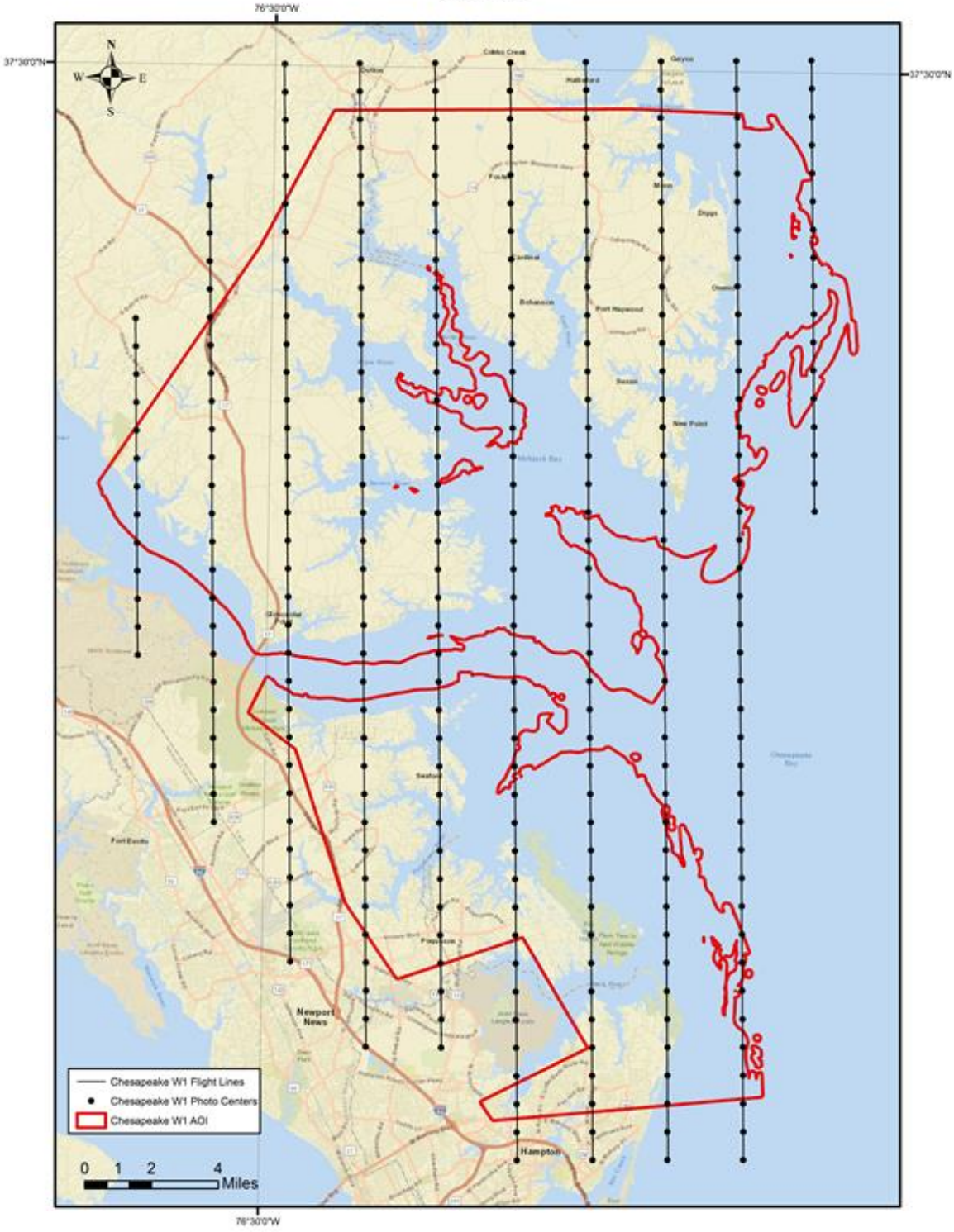
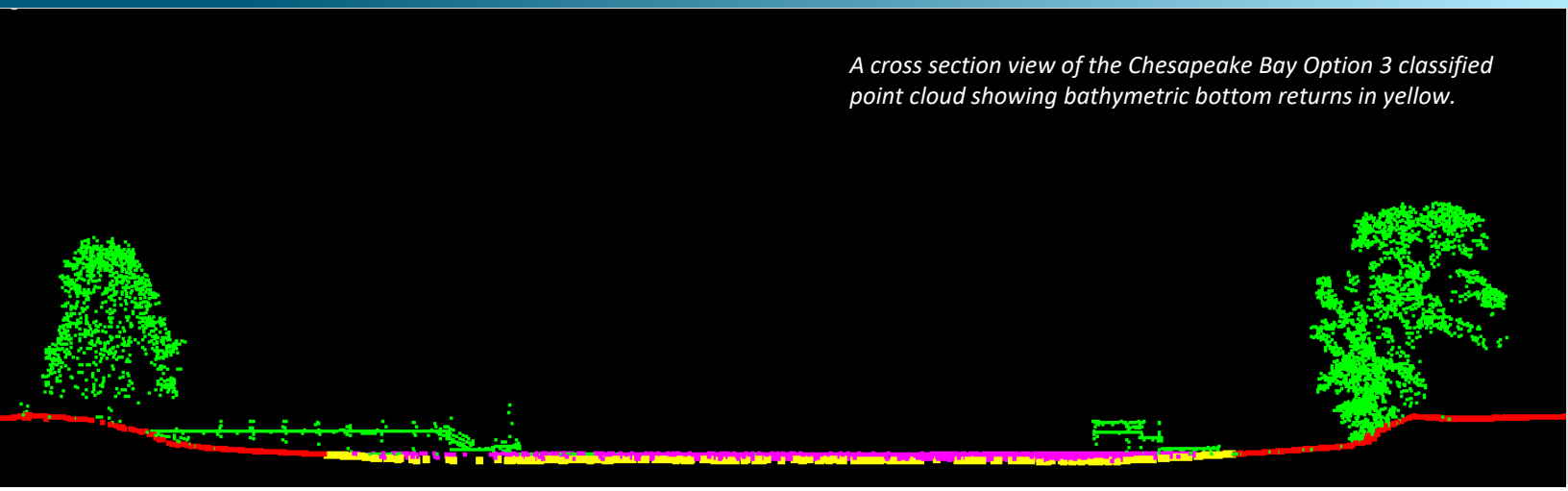


Figure 5: Map showing imagery acquisition lines



A cross section view of the Chesapeake Bay Option 3 classified point cloud showing bathymetric bottom returns in yellow.

Lidar Data Calibration

Upon completion of data acquisition, NV5 Geospatial processing staff initiated a suite of automated and manual techniques to process the data into a geo-referenced point cloud ready for refraction processing and classification routines. Solutions for Smoothed Best Estimates of Trajectory (SBET) were processed using Applanix POSPac 8.3 SP3 using their Trimble® CenterPoint™ Post-Processed Real-Time Extended (PP-RTX) solution. This process utilizes the GPS and IMU data recorded onboard the aircraft, real-time data from Trimble's global reference station infrastructure, and advanced positioning and compression algorithms to calculate a highly accurate SBET for each mission.

Laser return point position computations were completed in Riegl's SDCImport and RiWorld software using the SBET and raw range information. After extracting the laser swaths, swath-to-swath geometric corrections were found using least square fit regression of matching tie plane objects in RiProcess. Individual lifts were adjusted to match vertical ground control points where available, and then integrated with corresponding overlapping lifts. Any remaining swath-swath discrepancies were further resolved using Terrasolid's TerraMatch application.

Bathymetric Refraction

The water surface models used for refraction were generated using elevation information from the point cloud. Where possible, points from the NIR channel were preferred due to the clean characteristics of water surface returns from that wavelength. However, because the NIR and green channels are not spatially and temporally coincident in the VQ-880-GH system, where substantial wave action was present the green channels were used instead. Advanced classification routines were employed to ensure above-surface spray and below-surface backscatter points were not included in the model. Points were automatically classified, passed through filters appropriate to surface characteristics, and then manually edited to obtain the most accurate representation of the water surface. Models were created for each flightline to accommodate water level changes due to tide or other temporal factors.

The refraction correction was applied to submerged points using NV5 Geospatial's proprietary software Las Monkey. Points were flagged to refract based on their position relative to the triangulated irregular network model representing the water surface. Using the information from the trajectory and water surface model, each point was spatially corrected for refraction through the water column based on the angle of incidence of the laser to the model. The resulting point cloud was classified into its final scheme using both manual and automated techniques (Table 10).

Table 10: ASPRS LAS classification standards applied to the NOAA Chesapeake Bay Option 3 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)
42	Derived Water Surface	Synthetic water surface location used in computing refraction at water surface
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
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 11: Lidar Processing Workflow

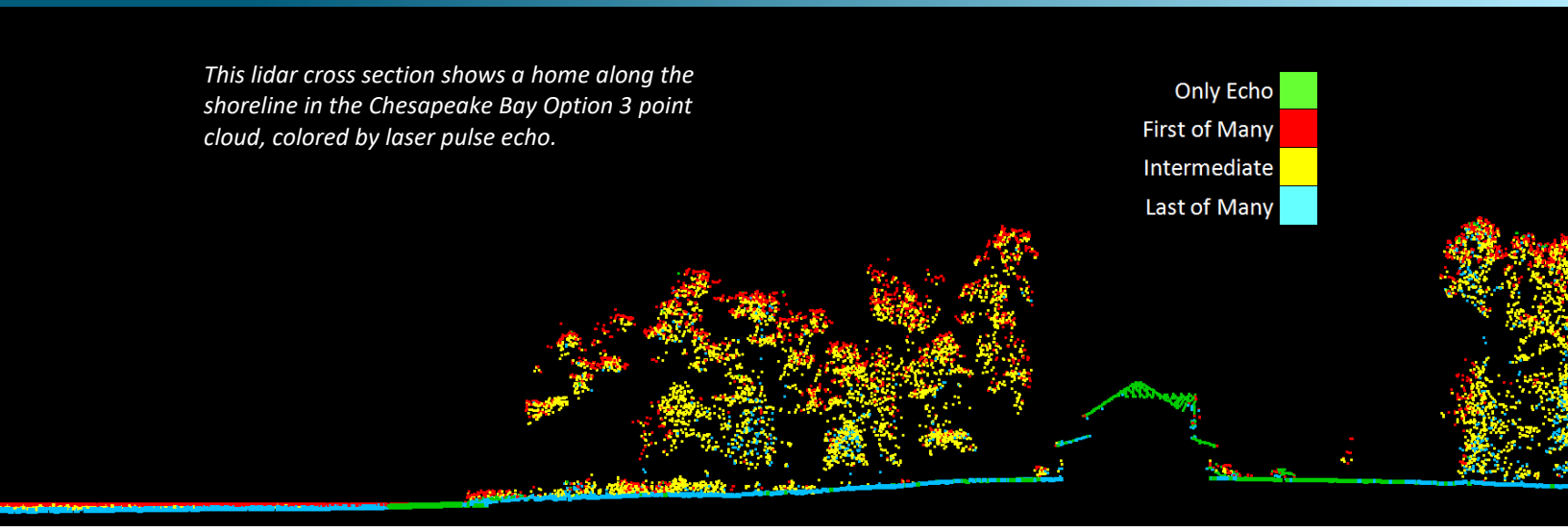
Lidar Processing Step	Software Used
GNSS/IMU processing to create smoothed best estimate of trajectory using PP-RTX technology.	Applanix POSPac v.8.3 Service Pack 3
Extract raw laser data and calculate laser point positions. Calculation combines raw ranging information, processed SBET, automated determination of MTA (Multiple-Time-Around) zone, and coordinate system information to extract and georeference each laser return.	Riegl SDCImport v.2.3 Riegl RiWorld v.5.1
Sensor boresight. Per-lift geometric adjustments based on least-squares adjustment of feature matched tie planes.	Riegl RiProcess v.1.8
Apply refraction correction and depth bias correction to subsurface returns.	LAS Monkey v.2.6.3 (NV5 Geospatial)
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
Using ground classified points per flight line, perform automated line-to-line calibrations for system attitude parameters (pitch, roll, and heading). Match data to vertical control points. Assess relative accuracies between overlapping lifts and relative within each lift and swath.	TerraMatch v.19 Las Product Creator v.3.5 (NV5 Geospatial)
Classify resulting data to ground and other client-designated classifications using manual and automated processes (Table 10). Assess statistical absolute accuracy via direct comparisons of ground classified points and the Bare Earth DEM to ground control survey data.	TerraScan v.19 TerraModeler v.19 ArcMap v.10.3.1
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 LasProjector v.1.3 (NV5 Geospatial) LPD v 3.0.28 (NV5 Geospatial) Las Product Creator v.3.4 (NV5 Geospatial)
Export intensity images layered under DZ Orthos as GeoTIFFs at a 1 meter pixel resolution.	ArcMap v.10.3.1 Las Product Creator v.3.4 (NV5 Geospatial)
Export standard deviation of ground, bathymetric bottom, and submerged objects in GeoTIFF (.tif) format at a 1 meter pixel resolution	LAS Tools Las Product Creator v.3.4 (NV5 Geospatial)

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 Riegl VQ-880-GH sensor is 1.5 Secchi depths on brightly reflective surfaces, it is expected for turbid or non-reflective areas to have 0 or no returns.

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, NV5 Geospatial created a polygon of bathymetric voids 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 all areas of no returns (> 9 m^2), were identified as bathymetric data voids.

Figure 6: Traditional interpolated topobathymetric bare earth digital elevation model colored by elevation.



This lidar cross section shows a home along the shoreline in the Chesapeake Bay Option 3 point cloud, colored by laser pulse echo.

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 NOAA Chesapeake Bay Option 3 topobathymetric lidar project was 12.86 points/m^2 (Table 12). The statistical distributions of all first return densities per 100 m x 100 m cell are portrayed in Figure 7.

Bathymetric and Ground Classified Point Densities

The density of ground and bathymetric bottom classified 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 NOAA Chesapeake Bay Option 3 project was 4.82 points/m^2(Table 12). The statistical distributions ground classified and bathymetric bottom return densities per 100 m x 100 m cell are portrayed in Figure 8.

Table 12: Average Lidar point densities

Density Type	Point Density
First Returns	12.86 points/m²
Ground and Bathymetric Bottom Classified Returns	4.82 points/m²

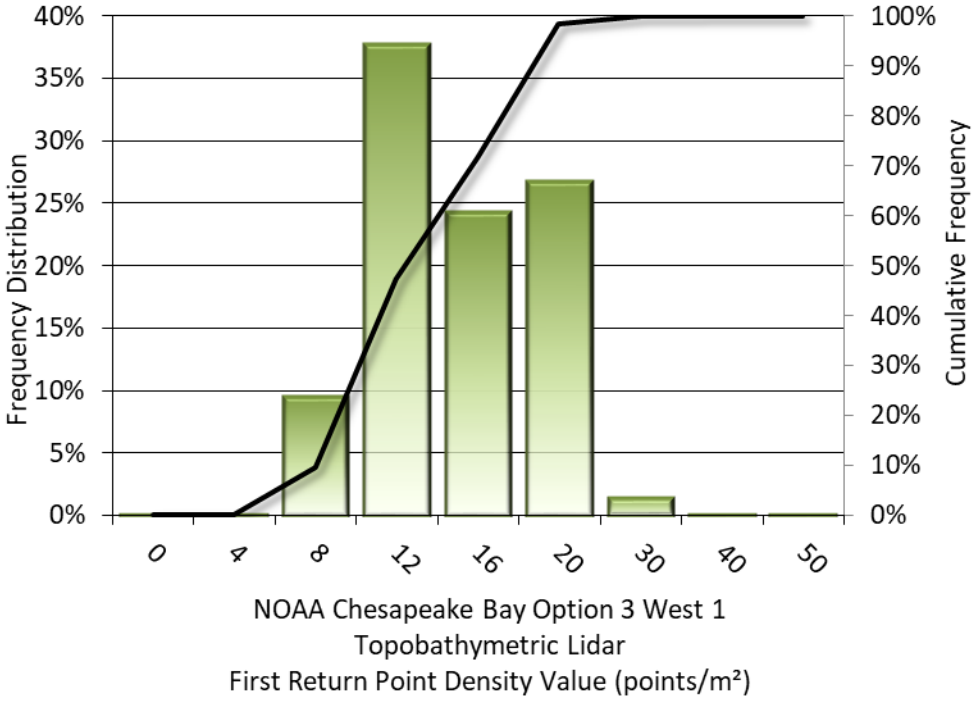


Figure 7: Frequency distribution of first return densities per 100 x 100 m cell

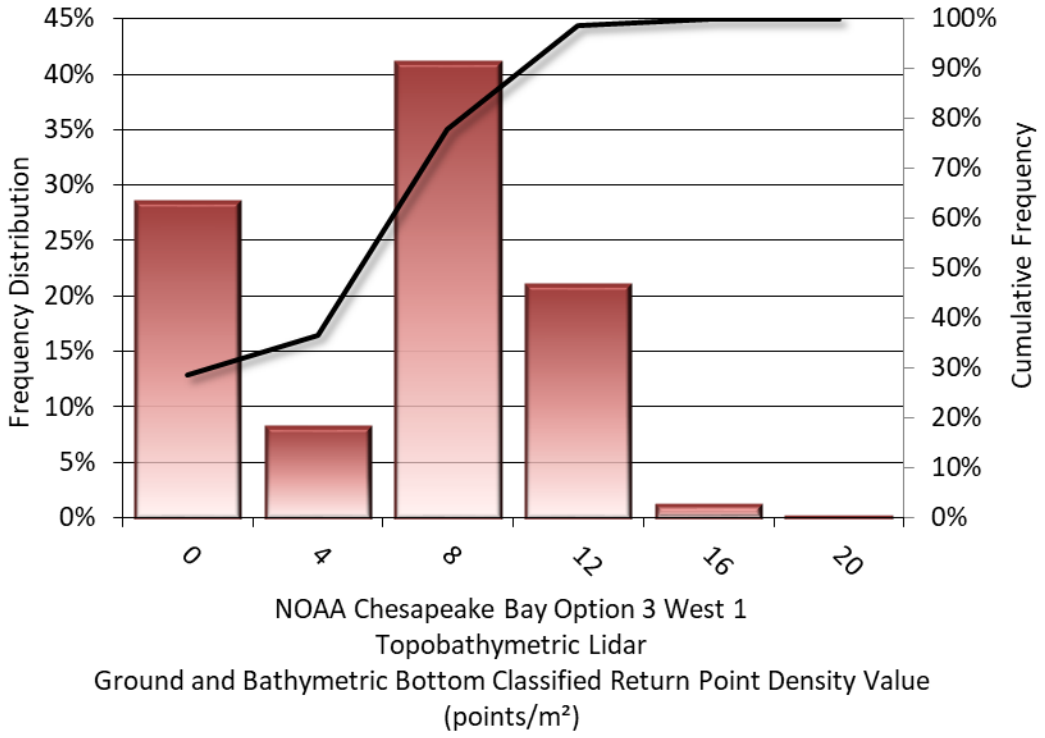


Figure 8: Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell

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[6]. 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 ground classified lidar point cloud as well as the derived gridded bare earth DEM. NVA compares known ground quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the lidar points. NVA is a measure of the accuracy of lidar point data in open areas where the lidar system has a

[6] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 13.

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 NOAA Chesapeake Bay Option 3 lidar survey, 30 ground check points were withheld from the calibration and post-processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.084 meters as compared to the ground classified LAS, and 0.082 meters as compared to the bare earth DEM, with 95% confidence.

Bathymetric (submerged) check points were also collected to assess the submerged surface vertical accuracy. Assessment of 45 bathymetric check points resulted in an average vertical accuracy of 0.083 meters (Table 13, Figure 11).

NV5 Geospatial also assessed absolute accuracy using 903 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 Table 13 and Figure 12.

Table 13: Absolute accuracy (NVA) results

Non-Vegetated Vertical Accuracy				
	NVA - Ground Check Points (LAS)	**NVA - Ground Check Points (DEM)**	**Bathymetric Check Points**	**Ground Control Points**
Sample	30 points	30 points	45 points	903 points
95% Confidence (1.96*RMSE)	0.084 m	0.082 m	0.083 m	0.068 m
Average	-0.006 m	-0.003 m	-0.004 m	0.000 m
Median	-0.009 m	-0.006 m	-0.002 m	0.002 m
RMSE	0.043 m	0.042 m	0.043 m	0.035 m
Standard Deviation (1σ)	0.043 m	0.042 m	0.043 m	0.035 m

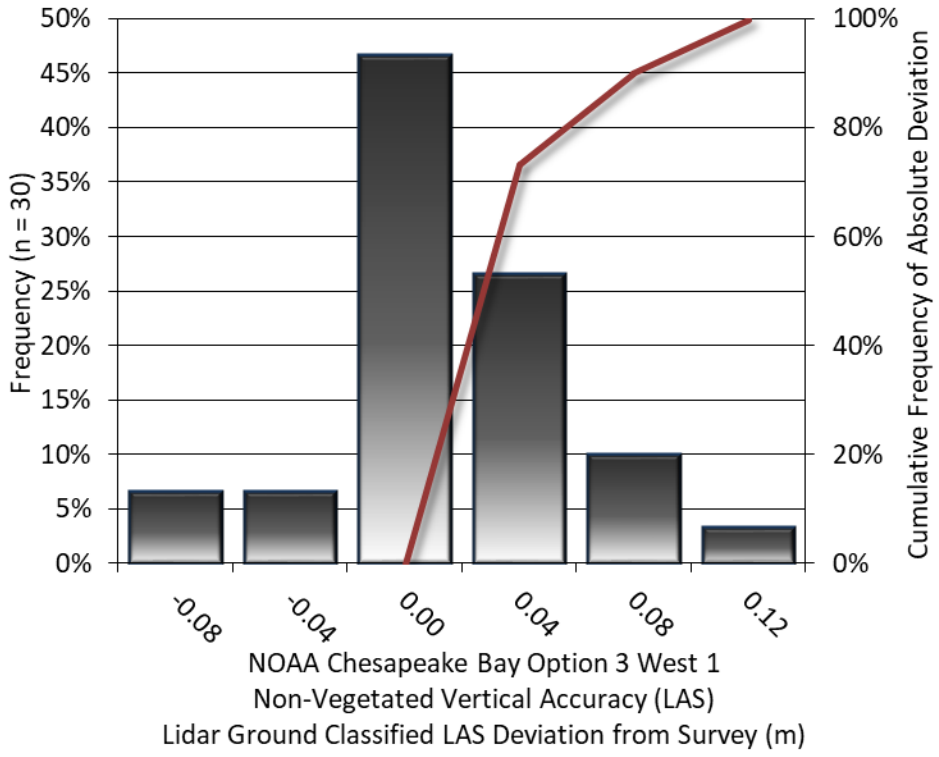


Figure 9: Frequency histogram for lidar surface deviation from ground check point values

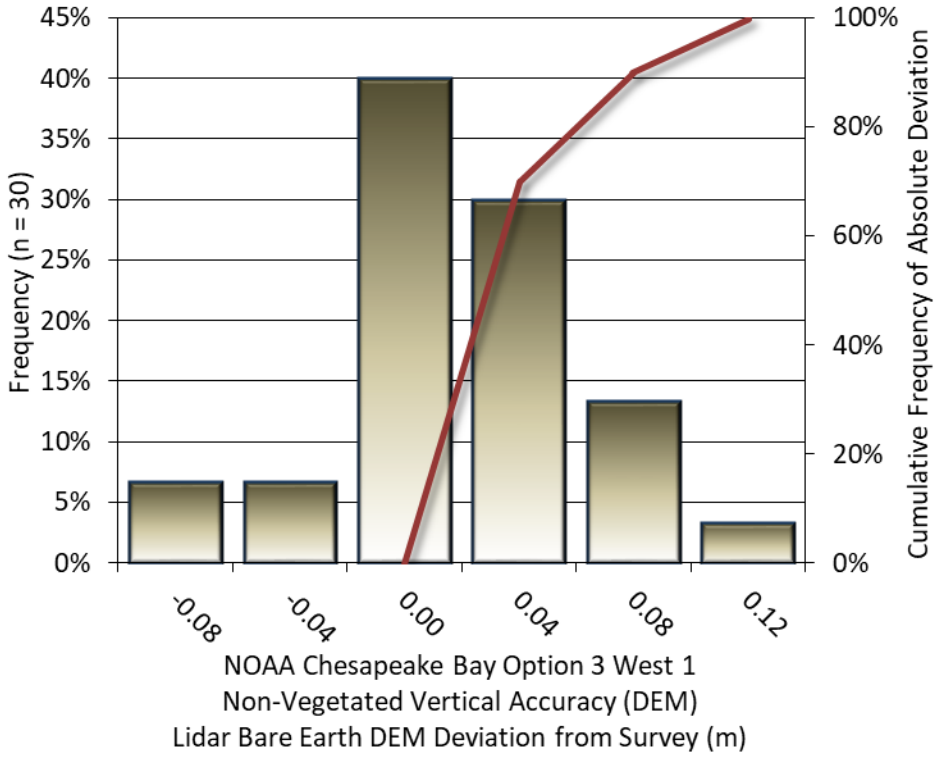


Figure 10: Frequency for lidar surface deviation from ground check point values against DEM surface

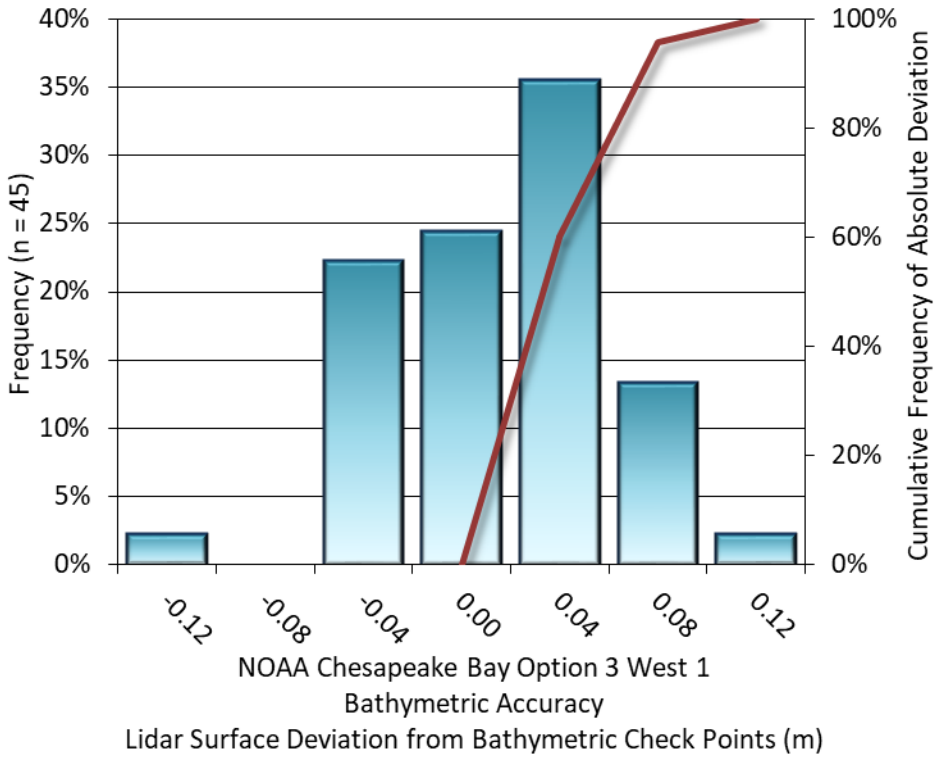


Figure 11: Frequency histogram for lidar surface deviation from bathymetric check point values

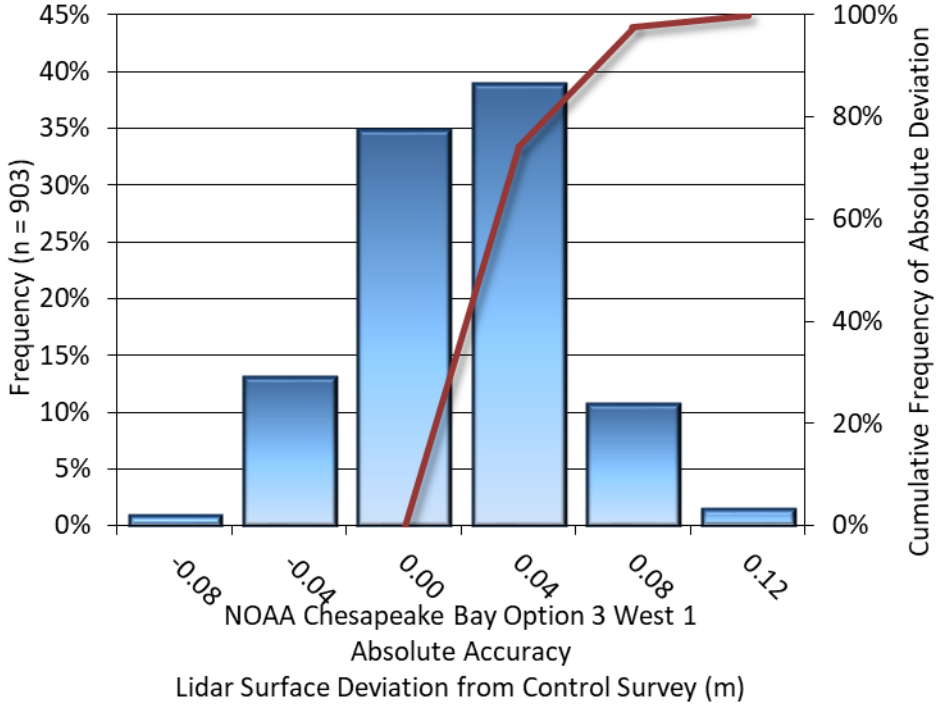


Figure 12: Frequency histogram for lidar surface deviation ground control point values

Lidar Vegetated Vertical Accuracies

NV5 Geospatial 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, Figure 13).

Table 14: Vegetated Vertical Accuracy for the NOAA Chesapeake Bay Option 3 Project

Vegetated Vertical Accuracy (VVA)	
Sample	21 points
Average Dz	0.079 m
Median	0.077 m
RMSE	0.092 m
Standard Deviation (1σ)	0.049 m
95th Percentile	0.141 m

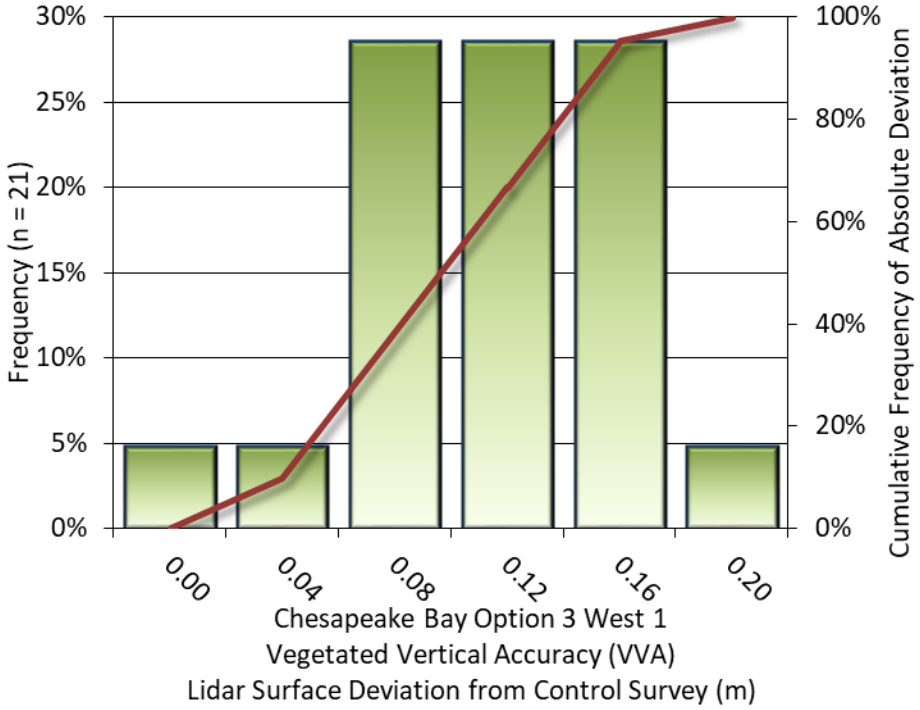


Figure 13: Frequency histogram for lidar surface deviation from all land cover class point values (VVA)

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 NOAA Chesapeake Bay Option 3 lidar project was 0.028 meters (Table 15, Figure 14).

Table 15: Relative accuracy results

Relative Accuracy	
Sample	238 surfaces
Average	0.028 m
Median	0.026 m
RMSE	0.046 m
Standard Deviation (1σ)	0.028 m
1.96σ	0.054 m

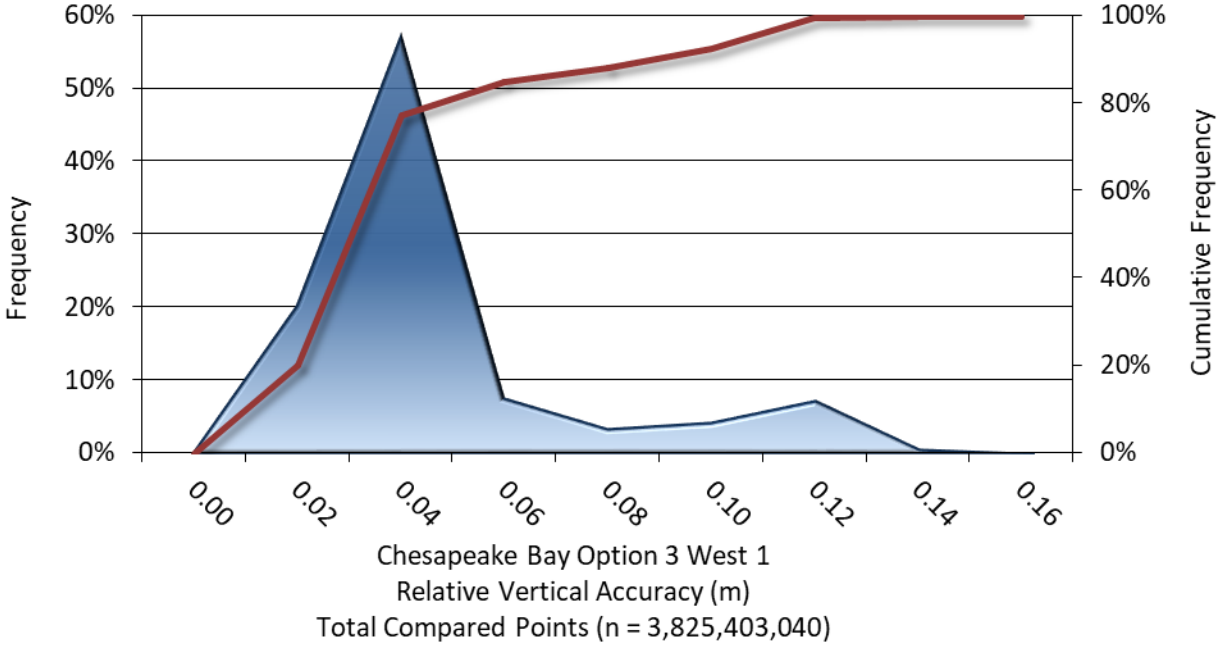


Figure 14: Frequency plot for relative vertical accuracy between flight lines

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 0.005 decimal degrees, and a GNSS positional error of 0.019 meters, this project was compiled to meet 1.13 m horizontal accuracy at the 95% confidence level.

Table 16: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.650 m
ACC_r	1.130 m

Digital Imagery Accuracy Assessment

Image accuracy was measured by air target locations and independent ground survey points. NV5 GEOSPATIAL provided imagery accuracy assessment along with the imagery deliverable reporting (Table 2), as ***VA1901_Chesapeake_Bay_Option3_West1_Aerotriangulation_Report.doc.***

Lessons Learned

The NOAA Chesapeake Bay Option 3 project required detailed ground and airborne survey coordination by NV5 Geospatial's acquisition team. Acquisition efforts were successful overall and included closely monitoring turbidity conditions in the Chesapeake Bay. All acquisition was able to occur between February and April of 2019, which allowed for fewer processing challenges encountered throughout.

The lidar processing component of the workflow experienced the biggest challenges in terrain and environmental conditions. Marshy and densely vegetated areas presented challenges in cleaning and identifying true bathymetric bottom returns, as did a large amount of sedimentation in shallow water bodies. Additionally, the project processing was largely delayed due to NV5 Geospatial prioritizing Supplemental tasking in 2019. Some small data gaps were identified in the dataset late in processing and were not able to be re-flown. These data gaps were deemed acceptable by NOAA and are delineated in the provided void shapefile.

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 were 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 ±20° 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.

Appendix B – Ground Survey Report for Imagery

December 23, 2020

Chesapeake Bay Option 3 Shoreline Mapping
VA1901: Revised West 1 Project Area

Ground Survey Report for Lidar

Prepared For:

National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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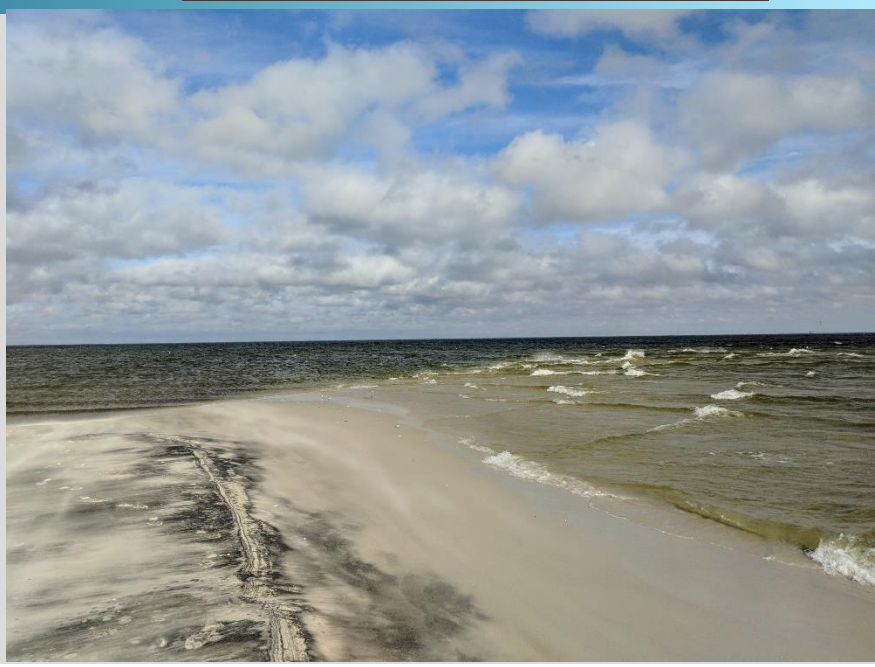
INTRODUCTION

A scenic view of the Chesapeake Bay project area in Virginia.

Credit: NV5 Geospatial Ground Professional Gabriel Rietmann



In November 2018, NV5 Geospatial (NV5) was contracted by the National Oceanic and Atmospheric Administration (NOAA), to collect topographic Light Detection and Ranging (lidar) data and digital imagery from February of 2019 through April of 2019, for the NOAA Chesapeake Bay Option 3 site along the coast of Virginia. The NOAA Chesapeake Bay Option 3 project is composed of the Revised West 1 project area and covers approximately 372.4 square miles of Virginia shoreline within Chesapeake Bay. Data were collected to aid NOAA in modeling the topographic and geophysical properties of the study area to support accurate measurement and mapping of the national shoreline and to support marine resource management.

This report accompanies the collected topobathymetric lidar data and documents the ground survey efforts conducted to support the airborne acquisition.

Vicinity of NVA check point BE019, in the Bethel Beach Natural Area Preserve in Chesapeake, Virginia.

Credit: NV5 Ground Professional Gabriel Rietmann

Ground control surveys were conducted to support the airborne acquisition. This section outlines the methodologies used to achieve alignment with the National Spatial Reference System (NSRS) and establish points for control and evaluation of the final products.

Primary Control

NV5 triangulated static Global Navigation Satellite System (GNSS) data (1 Hz recording frequency) from each base station with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[7]) to ensure alignment with the NSRS. Multiple independent sessions over the same control station were processed to confirm antenna height measurements and to refine position accuracy to ±2cm horizontal and ±3cm vertical accuracy.

Permanent reference stations from real-time networks (RTNs) were also evaluated in the same manner to ensure alignment with the NSRS, updating record positions as necessary if they deviated from the OPUS Projects results by more than 1.5cm.

Primary control stations were selected with consideration for satellite visibility, RTN/radio connectivity, and optimal location for survey point and mission planning.

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

Ground Survey Point Collection

Vertical control points and check points – collectively, ground survey points (GSPs) – were located throughout the project area in order to geospatially correct the airborne survey. GSPs must be at least three times as accurate as the airborne survey to be accepted, in accordance with ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014). Horizontal control and check points are not collected for the lidar survey.

Ground Survey Collection Methods

Ground survey points can be collected using real time kinematic (RTK), post-processed kinematic (PPK), fast-static (FS) and total station (TS) survey techniques.

For RTK surveys, a roving receiver receives GNSS corrections from a nearby base station or 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. PPK and FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK and PPK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each point in order to support longer baselines. All GNSS measurements must be 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.

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. GSP post-processing is conducted in Trimble Business Center version 5, unless subcontracted.

Lidar Control Point Selection

Vertical reference points are collected in areas where good satellite visibility can be 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.

Land Cover Check Points

In addition to hard surface points, land cover class check points are collected throughout the study area to evaluate non-vegetated vertical accuracy (NVA) and vegetated vertical accuracy (VVA) in land cover types that are dominant in the project area. The collection, distribution, and quantity of check points are in accordance with ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014).

Bathymetric Check Points

Bathymetric check points are also collected in submerged areas when feasible to be used for evaluation of the submerged ground surface, using the same methods as for land cover check points. These points tend to be concentrated in shallow, stable areas such as boat ramps and calm beaches to ensure field crew safety, surface stability, and an efficient ground survey. They are not equitably distributed throughout the project area, but nevertheless provide some indication of the accuracy of the airborne topobathymetric survey.

Ground control surveys including primary control stations, control points, and check points were conducted to support the airborne acquisition. This section summarizes the ground survey results including network stations utilized for this project, overall network accuracy, equipment used, and point tables for both the horizontal and vertical control points and check points – collectively, ground survey points (GSPs).

Static Control

Permanent continuously operating base stations from the HxGN SmartNet[8] and KeyNetGPS[9] Real-Time Networks (RTNs) were utilized for the ground survey, including aerial targets, lidar vertical control, and lidar vertical check points. RTN base stations were selected with consideration for satellite visibility, RTN connectivity, and optimal location for survey point and mission planning. No new monuments were set for this ground survey.

Base Stations

NV5 utilized eight permanent RTN stations for the NOAA Chesapeake Bay Option 3 project. Four base stations were from the KeyNetGPS RTN and four were from the HxGN SmartNet RTN. The position, precision, and network of each base station have been provided in Table 21. Network record positions were held as indicated, when found to be in alignment with the NSRS.

NV5 Geospatial triangulated static Global Navigation Satellite System (GNSS) data (1 Hz recording frequency) from each base station with nearby National Geodetic Survey (NGS) Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[10]) Projects[11] to ensure alignment with the National Spatial Reference System (NSRS), updating record positions as necessary. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

[8] https://hxgnsmartnet.com/en-us

[9] https://www.keynetgps.com/

[10] OPUS is a free service provided by NGS to process corrected monument positions aligned with NSRS. http://www.ngs.noaa.gov/OPUS.

[11] OPUS Projects is a free upgrade to standard OPUS that enables network processing of static data. https://www.ngs.noaa.gov/OPUS-Projects/

Table 17: Permanent Real-Time Network (RTN) stations utilized for the NOAA Chesapeake Bay Option 3 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00. Precision values shown are for the 68% (1-sigma) confidence interval. Units are in meters.

Station ID	Latitude	Longitude	Ellips.	σ X	σ Y	σ Z	Network	Held?
DP04	37° 30' 49.53128"	-76° 37' 48.86347"	4.225	0.002	0.002	0.013	KeyNet	No
HB15	37° 11' 57.19198"	-75° 58' 45.73318"	-23.982	0.002	0.002	0.002	KeyNet	Yes
JRE1	36° 58' 35.09218"	-76° 59' 34.10477"	-1.472	0.002	0.002	0.006	KeyNet	Yes
LOYX	37° 16' 35.03057"	-76° 41' 43.81957"	2.198	0.002	0.002	0.004	SmartNet	Yes
LOYZ	36° 51' 48.91944"	-76° 34' 24.80885"	-19.502	0.002	0.002	0.002	SmartNet	Yes
VACC	37° 15' 59.89409"	-76° 01' 22.32026"	-29.962	0.002	0.002	0.007	SmartNet	Yes
VAKI	37° 42' 39.58516"	-76° 22' 50.91365"	-1.883	0.002	0.002	0.004	SmartNet	No
WLP2	36° 45' 59.76765"	-76° 15' 30.56728"	-13.247	0.002	0.002	0.007	KeyNet	No

OPUS Project keys applicable to this project are 6ZT27M6K and 53UKRE6C; credentials are available by request. The five NGS CORS utilized during OPUS Project processing are listed in Table 22.

Table 18: NGS CORS utilized with OPUS Project. Published NAD83(2011) coordinates were held and can be retrieved from http://www.ngs.noaa.gov/CORS/.

CORS used in OPUS Project							
ANP5	BACO	CORB	DEMI	DRV5	DRV6	GODZ	HNPT
LOY2	LOY8	LOYF	LOYO	LOYW	LOYX	LOYZ	LS02
LS03	NCEL	NCGA	SCWT	UMBC	WDC6	YAGP	YORK

Network Accuracy

Base station coordinates 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.[12] 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 monument rating for this project is shown in Table 23.

[12] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3.
http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 19: Federal Geographic Data Committee monument rating for network accuracy

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

Equipment and Collection Methods

The RTK and TS survey techniques were utilized for the ground survey as described previously in this report. NV5 equipment used for the ground survey is summarized in Table 24.

Table 20: NV5 equipment identification table. Does not include CORS antennas.

Receiver Model	Antenna	OPUS Antenna ID	Serial Numbers	Use
Trimble R8 Model 3	Integrated Antenna	TRMR8_GNSS3	R8-9860	Rover
Trimble M3 Total Station	n/a	n/a	VVA	Trimble M3 Total Station

Lidar Survey Point Collection

A total of 1,144 GSPs were collected for the NOAA Chesapeake Bay Option 3 lidar project. Of these, 903 points were utilized as control during lidar processing, while 241 were withheld from processing for vertical accuracy checks – 30 for NVA, 21 for VVA, and 190 for bathymetric accuracy.

Horizontal reference points were not collected or utilized for lidar processing.

Lidar Point Positions

Lidar control and check point positions for the NOAA Chesapeake Bay Option 3 project were enclosed with Delivery Package 5, in shapefile format:

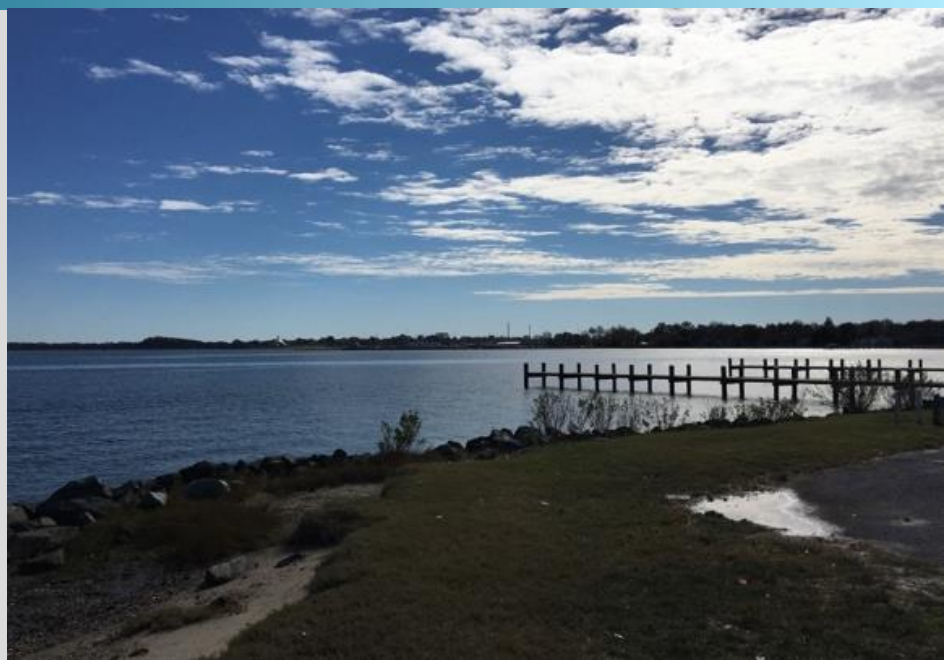
- ***NOAA_Chesapeake_Bay_Option3_ELLISPOIDAL_Ground_Check_Points.shp***
- ***NOAA_Chesapeake_Bay_Option3_GEOIDAL_Ground_Check_Points.shp***

Points used for NVA check points are labeled as “Non-Vegetated” while points used as VVA check points are labeled as “Vegetated.”

INTRODUCTION

A scenic view of the Chesapeake Bay project area, taken in Cambridge, Maryland.

Credit: NV5 Ground Professional Aaron Olsen



In April 2018, NV5 Geospatial (NV5) was contracted by the National Oceanic and Atmospheric Administration (NOAA), to collect topographic Light Detection and Ranging (lidar) data and digital imagery from November of 2018 through April of 2019, for the NOAA Chesapeake Bay Option 3 site along the coast of Virginia (Contract No. EA-133C-14-CQ-0007). The NOAA Chesapeake Bay Option 3 project includes two main project areas; East 4 and West 4 and covers approximately 217 square miles along the eastern and western shorelines of the Chesapeake Bay. Data were collected to aid NOAA in modeling the topographic and geophysical properties of the study area to support accurate measurement and mapping of the national shoreline and to support marine resource management.

This report accompanies the collected topobathymetric lidar data and documents the ground survey efforts conducted to support the airborne acquisition.

Vicinity of NVA check point BE012 in the East 4 area of interest.

Credit: NV5 Ground Professional Cameron Bremer

Ground control surveys were conducted to support the airborne acquisition. This section outlines the methodologies used to achieve alignment with the National Spatial Reference System (NSRS) and establish points for control and evaluation of the final products.

Primary Control

NV5 triangulated static Global Navigation Satellite System (GNSS) data (1 Hz recording frequency) from each base station with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[13]) to ensure alignment with the NSRS. Multiple independent sessions over the same control station were processed to confirm antenna height measurements and to refine position accuracy to ±2cm horizontal and ±3cm vertical accuracy.

Permanent reference stations from real-time networks (RTNs) were also evaluated in the same manner to ensure alignment with the NSRS, updating record positions as necessary if they deviated from the OPUS Projects results by more than 1.5cm.

Primary control stations were selected with consideration for satellite visibility, RTN/radio connectivity, and optimal location for survey point and mission planning.

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

Ground Survey Point Collection

Vertical control points and check points – collectively, ground survey points (GSPs) – were located throughout the project area in order to geospatially correct the airborne survey. GSPs must be at least three times as accurate as the airborne survey to be accepted, in accordance with ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014). Horizontal control and check points are not collected for the lidar survey.

Ground Survey Collection Methods

Ground survey points can be collected using real time kinematic (RTK), post-processed kinematic (PPK), fast-static (FS) and total station (TS) survey techniques.

For RTK surveys, a roving receiver receives GNSS corrections from a nearby base station or 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. PPK and FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK and PPK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each point in order to support longer baselines. All GNSS measurements must be 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.

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. GSP post-processing is conducted in Trimble Business Center version 5, unless subcontracted.

Lidar Control Point Selection

Vertical reference points are collected in areas where good satellite visibility can be 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.

Land Cover Check Points

In addition to hard surface points, land cover class check points are collected throughout the study area to evaluate non-vegetated vertical accuracy (NVA) and vegetated vertical accuracy (VVA) in land cover types that are dominant in the project area. The collection, distribution, and quantity of check points are in accordance with ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014).

Bathymetric Check Points

Bathymetric check points are also collected in submerged areas when feasible to be used for evaluation of the submerged ground surface, using the same methods as for land cover check points. These points tend to be concentrated in shallow, stable areas such as boat ramps and calm beaches to ensure field crew safety, surface stability, and an efficient ground survey. They are not equitably distributed throughout the project area, but nevertheless provide some indication of the accuracy of the airborne topobathymetric survey.

Ground control surveys including primary control stations, control points, and check points were conducted to support the airborne acquisition. This section summarizes the ground survey results including network stations utilized for this project, overall network accuracy, equipment used, and point tables for both the horizontal and vertical control points and check points – collectively, ground survey points (GSPs).

Static Control

Permanent continuously operating base stations from the Leica SmartNet[14] and KeyNetGPS[15] Real-Time Networks (RTNs) were utilized for the ground survey, including aerial targets, lidar vertical control, and lidar vertical check points. RTN base stations were selected with consideration for satellite visibility, RTN connectivity, and optimal location for survey point and mission planning. No new monuments were set for this ground survey.

Base Stations

NV5 utilized nine permanent RTN stations for the NOAA Chesapeake Bay Option 3 project. Four base stations were from the KeyNetGPS RTN and five were from the Leica SmartNet RTN. The position, precision, and network of each base station have been provided in Table 21. Network record positions were held as indicated, when found to be in alignment with the NSRS.

NV5 triangulated static Global Navigation Satellite System (GNSS) data (1 Hz recording frequency) from each base station with nearby National Geodetic Survey (NGS) Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[16]) Projects[17] to ensure alignment with the National Spatial Reference System (NSRS), updating record positions as necessary. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

[14] https://hxgnsmartnet.com/en-us

[15] https://www.keynetgps.com/

[16] OPUS is a free service provided by NGS to process corrected monument positions aligned with NSRS. http://www.ngs.noaa.gov/OPUS.

[17] OPUS Projects is a free upgrade to standard OPUS that enables network processing of static data. https://www.ngs.noaa.gov/OPUS-Projects/

Table 21: Permanent Real-Time Network (RTN) stations utilized for the NOAA Chesapeake Bay Option 3 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00. Precision values shown are for the 68% (1-sigma) confidence interval. Units are in meters.

Station ID	Latitude	Longitude	Ellips.	σ X	σ Y	σ Z	Network	Held?
DEW4	38° 46' 50.06257"	-76° 33' 14.26005"	-17.749	0.002	0.002	0.002	KeyNet	Yes
HB13	38° 17' 38.63553"	-76° 35' 57.79389"	7.411	0.003	0.002	0.002	KeyNet	Yes
HB6B	38° 30' 46.45353"	-76° 04' 14.87881"	-30.408	0.002	0.002	0.002	KeyNet	Yes
HOB9	37° 46' 28.28812"	-76° 22' 26.67101"	-4.573	0.006	0.002	0.002	KeyNet	No
MDHG	38° 31' 56.36319"	-76° 47' 04.32435"	29.030	0.006	0.002	0.002	SmartNet	No
MDLT	38° 18' 38.11891"	-76° 37' 57.97353"	6.161	0.002	0.002	0.002	SmartNet	No
MDNM	38° 33' 29.58686"	-75° 59' 12.76496"	-20.991	0.004	0.002	0.002	SmartNet	Yes
VAKI	37° 42' 39.58516"	-76° 22' 50.91365"	-1.883	0.002	0.002	0.002	SmartNet	No
VATA	37° 53' 41.67619"	-76° 52' 51.97764"	12.808	0.002	0.002	0.002	SmartNet	No

OPUS Project keys applicable to this project are 53UKRE6C and X3KEXEZW; credentials are available by request. The five NGS CORS utilized during OPUS Project processing are listed in Table 22.

Table 22: NGS CORS utilized with OPUS Project. Published NAD83(2011) coordinates were held and can be retrieved from http://www.ngs.noaa.gov/CORS/.

CORS used in OPUS Project							
ANP5	BACO	CORB	DED2	DEMI	DNRC	DRV5	GODZ
HNPT	LOY8	LOYF	LOYO	LOYW	LOYX	LOYZ	LS02
PASS	UMBC	WDC6	ZDC1				

Network Accuracy

Base station coordinates 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.[18] 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 monument rating for this project is shown in Table 23.

[18] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3.
http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 23: Federal Geographic Data Committee monument rating for network accuracy

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

Equipment and Collection Methods

The RTK survey techniques were utilized for the ground survey as described previously in this report. NV5 equipment used for the ground survey is summarized in Table 24.

Table 24: NV5 equipment identification table. Does not include CORS antennas.

Receiver Model	Antenna	OPUS Antenna ID	Serial Numbers	Use
Trimble R8 Model 2	Integrated Antenna	TRMR8_GNSS	R8-7337	Rover
Trimble R8 Model 3	Integrated Antenna	TRMR8_GNSS3	R8-9860 R8-4846	Rover

Lidar Survey Point Collection

A total of 3,135 GSPs were collected for the NOAA Chesapeake Bay Option 3 lidar project. Of these, 2,063 points were utilized as control during lidar processing, while 536 were withheld from processing for vertical accuracy checks – 33 for NVA, 19 for VVA, and 484 for bathymetric accuracy.

Horizontal reference points were not collected or utilized for lidar processing.

Lidar Point Positions

Lidar check point positions for the NOAA Chesapeake Bay Option 3 project were enclosed with Delivery Package 5, in shapefile format:

- ***NOAA_Chesapeake_Bay_Option1_ELLISPOIDAL_Ground_Check_Points.shp***
- ***NOAA_Chesapeake_Bay_Option1_GEOIDAL_Ground_Check_Points.shp***

Points used for NVA check points are labeled as “Non-Vegetated” while points used as VVA check points are labeled as “Vegetated.”

Aerotriangulation Report
VA1901 Chesapeake Bay West 1
August 2019

Area Covered

The project area covers one AOI (referenced as both VA1901 and "West 1") composed of (2) land areas on either side (north and south) of the York River's outlet into the Chesapeake Bay. In total, the AOI covers approximately 358 square miles and 949 miles of shoreline and runs 32 miles from north-northwest to south-southeast (varying from 5-20 miles wide). The AOI consists of most or all of the Chesapeake Bay-facing portions of three (3) Virginia Counties (Mathews, Gloucester, and York), as well as the Cities of Poquoson and Hampton, VA. The AOI encompasses all but the northernmost portions of Mathews County, and most of the southeastern half of Gloucester County, with the northwestern edge of the AOI running through Gloucester Courthouse, but including all of the significant estuaries emptying into Mobjack Bay. South of the York River, the AOI continues just south of the US Route 17 bridge at Yorktown, VA, and extends southeast to include the estuaries and streams of the City of Poquoson and the northeastern portions of the City of Hampton. It is critical to note that NOAA removed both land acreage and shoreline mileage from this AOI, including all of Langley Air Force Base (and environs) and the Naval Supply Annex northwest of Yorktown. To "make up for" this removal, NOAA added similar inland acreage to the West 4 AOI that is now fully part of the Option 1 Award for this Task Order. The project is located approximately between 37°02'37" and 37°28'57" North Latitude, and 76°10'54" and 76°35'31" West Longitude.

Imagery

The photography used in the aerotriangulation phase was flown by Keystone Aerial and consisted of ten (10) flight lines, and three hundred nineteen (319) 4Band color photographs. Two hundred fifty-one images were used, and sixty-eight were water models and were not used in the aerotriangulation solution. The photographs were acquired at a nominal ground sample distance of 0.26 meters using the UCE camera with a 79.8 mm lens. The 4band color photographs were acquired by Keystone Aerial on April 1, 2019. All imagery was acquired using >60% forward overlap and >30% side overlap, sun angles >20 or >25 degrees (depending on the date of acquisition) and was coordinated with low tide. The layout of the photographs is shown in the attached diagrams. Photographic coverage, resolution, overlap, and metric quality were adequate for the performance of the aerotriangulation phase.

The imagery that was not used in the aerotriangulation:

120006_23213 – 120006_23215
120006_23222
120007_23254 – 120007_23260
120007_23263 – 120007_23264
120008_23298 – 120008_23310
120009_23321 – 120009_23345
120010_23112 – 120010_23128

Control

A combination of photo identifiable ground control points and Airborne GPS/IMU data were used to control the imagery for aerotriangulation.

A. Airborne GPS/IMU: Airborne GPS and IMU data were collected and processed by Keystone Aerial and provided to NV5 Geospatial via external hard drive. ABGPS exposure stations were used as control in the aerotriangulation, and inertial measuring unit (IMU) measurements were used to refine these.

B. Ground Points: NV5 was dispatched to survey one hundred and fourty-one (141) photo ID control points (horizontal and vertical), Four (4) surveyed points were used to check the horizontal and vertical accuracy of the aerotriangulation. The results of the survey have been published in the final ground control report that has been included in this Aerotriangulation submission to NGS.

   Overall, the ground control points were found to be adequate to supplement the airborne GPS control.

Methodology

The photographs were bridged using digital aerotriangulation methods to establish the network of photogrammetric control required for the compilation phase. The images were bridged in a bundle adjustment that included all 319 4Band color non-tide coordinated images. Measurements were made utilizing a digital photogrammetric workstation running the Windows 10 operating system. Hexagon's ImageStation Automatic Triangulation (ISAT) software was used to perform automatic point measurements and interactive point measurements of tie points. The final adjustment of the block was accomplished by using a rigorous simultaneous least squares bundle adjustment, and analysis tools within ISAT were used to refine the aerotriangulation solution and to evaluate the accuracy of the adjustment.

Analysis of Results

The final ISAT results were evaluated for the triangulation adjustment providing a display of the image and point residuals and connections between frames. Weak points and blunders were identified and corrected. The final aerotriangulation solution for the image block was computed in ISAT as a full bundle block adjustment. The RMS of the standard deviations in both X and Y directions were calculated and used to determine the radius of the 95% confidence circle for each image block. The predicted horizontal circular error accuracy (RMSE or 95% CI) is 0.35m for the 4band photos. (see Annex 3 for details of the computations). This accuracy refers to the overall block, but in the bundle adjustments the error was distributed such that the largest errors are associated with points around the edges of the project and areas of vast water where the strength of the solution is weakest, while points down the middle of each block located on areas of extensive land cover have the smallest errors because those points are measured on a greater number of images. In addition, each of the four (4) ground control check points measured in and the coordinates and elevations of these check points were not constrained at all in any of the block adjustments, but were treated as pass points, and adjusted coordinates were computed and the differences are shown below:

	4Band		
POINT ID	**ΔX M**	**ΔY M**	**ΔZ M**
AT004B	0.236	0.061	0.178
AT016D	0.005	-0.154	0.171
AT021C	-0.026	0.014	0.035
AT165B	0.192	-0.068	0.058

As a final check select models from each strip of photography were examined in DAT/EM Summit Evolution to ensure the horizontal and vertical integrity of the ISAT 2015 solution, and to verify the suitability of the database for use in the compilation phase. The images were checked for proper parallax, ground control tolerance, and check point tolerance. Models covering the four check points referenced above were specifically reviewed in this manner, and included the following:

Point ID	Flight Lines & Images	Image Dates
AT004B	120005	04-01-2019
	120005_23133 - 120005_23134	
AT016D	120005	04-01-2019
	120005_23162-120005-23164, 120006_23234-120006_23236	
AT021C	120001	04-01-2019
	120001_23371, 120002_23398-120002_23400	
AT165B	120002 120002_23385 - 120002_23387	04-01-2019

To conclude, the aerotriangulation block meets the horizontal standards set forth by NOAA in Chapter I of the Version 14A Statement of Work for Shoreline Mapping.

Project Database

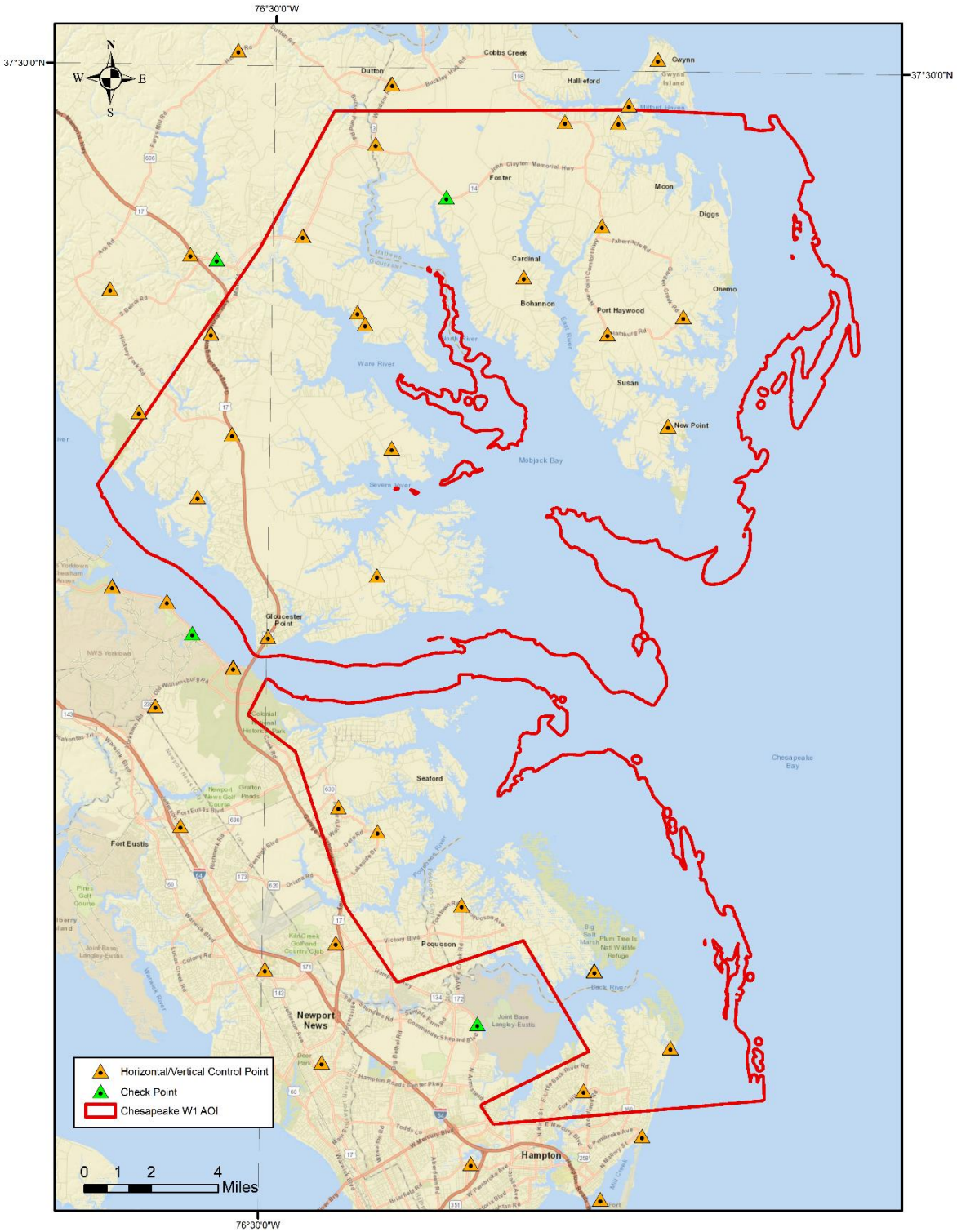
A project database containing the following files has been included in this submittal.

- Exposure Stations
- Electronic Exposure Data (EED)
- Camera calibration data
- Ground Control File
- Ground Control Report
- Airborne GPS Control File and IMU Orientation Original DG
- Adjusted Exterior Orientation parameters for each frame
- RGB/NIR Stereo Imagery
- RGB/NIR Stereo Imagery Metadata
- Flight Line and Frame Shapefile
- Airborne Positioning and Orientation Report (APOR)
- Tabulation of Aerial Photography
- AT Report

Positional data is based on the North American Datum of 1983 (NAD83 (2011)), and is referenced to the Universal Transverse Mercator (UTM) Zone 18 coordinate system

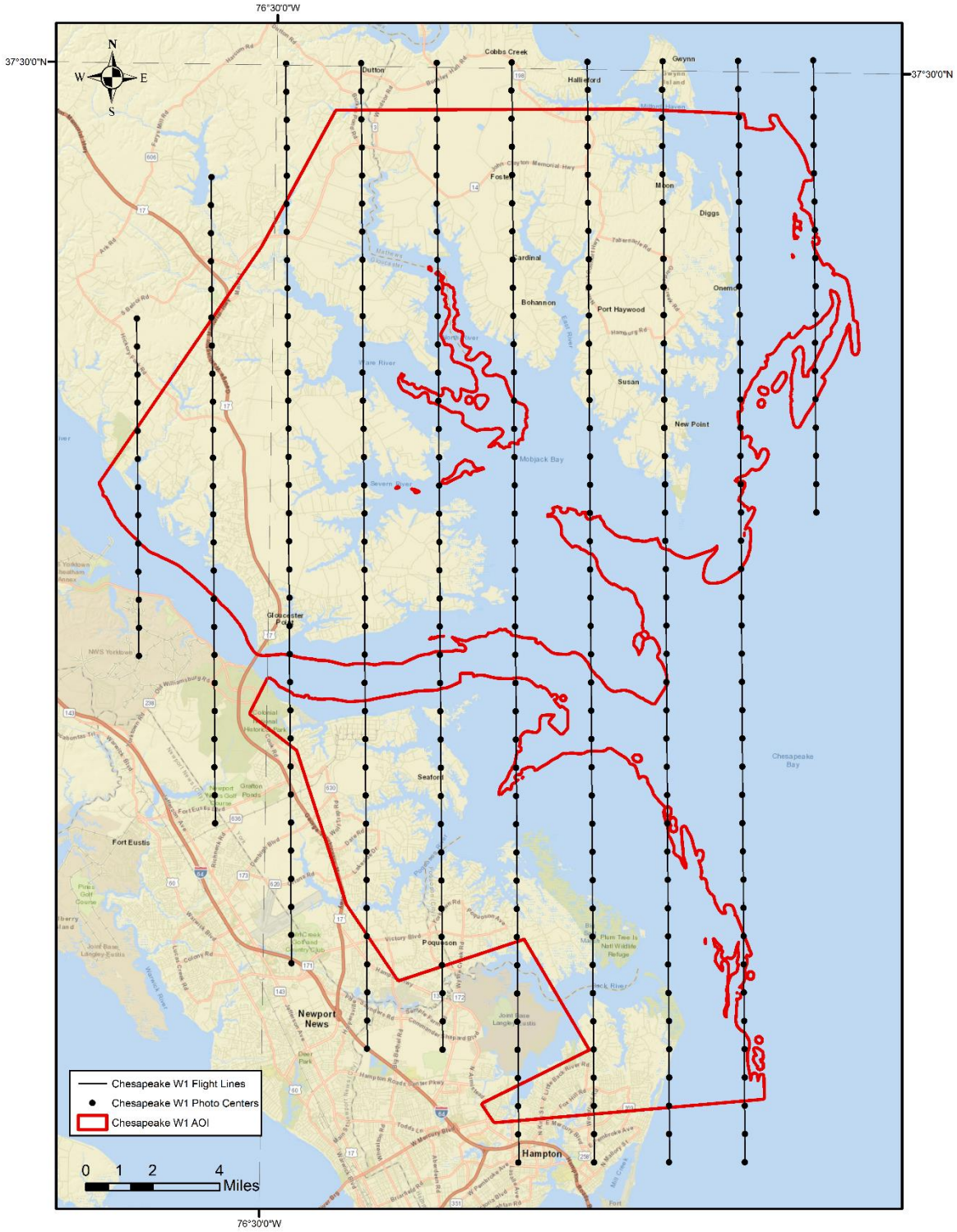
ANNEX 1 – Project Location

Project Location Diagram



ANNEX 2A – 4Band – Flight Lines

Flight Line Diagram – 4 Band
VA1901



ANNEX 2B – 4Band– Flight Line Table

Location	Altitude (m)	Bands	Date	Line Number	Frame Number Start / End		Photography Time Start / End	
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120001	120001_23370	120001_23382	18:18:29	18:20:33
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120002	120002_23383	120002_23406	18:22:59	18:26:35
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120003	120003_23407	120003_23439	18:29:20	18:34:46
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120004	120004_23165	120004_23200	17:27:44	17:33:47
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120005	120005_23129	120005_23164	17:20:02	17:25:30
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120006	120006_23201	120006_23240	17:35:36	17:41:44
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120007	120007_23241	120007_23280	17:44:17	17:51:01
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120008	120008_23281	120008_23290	17:53:29	17:54:53
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120008	120008_23294	120008_23320	17:55:51	17:59:36
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120009	120009_23321	120009_23369	18:02:09	18:13:37
Chesapeake Bay Option1 West 1	4004	4	4/1/2019	120010	120010_23112	120010_23128	17:13:30	17:16:18

ANNEX 3 - Horizontal Accuracy Computation

The Horizontal Accuracy Statement reported in the Analysis of Results is based on the predicted circular horizontal accuracy of adjusted points in the aerotriangulation solution. This circular accuracy equals the radius of the 95% confidence circle as calculated from the horizontal (x and y) root-mean-square (RMS) values of the standard deviations for all triangulated ground points, rounded to the nearest tenth of a meter.

The root mean square of all standard deviations of triangulated ground points:
Block 1 (NC) RMS(x) = 0.081621 meters RMS(y) = 0.072745 meters

The value for the confidence circle radius is given by the following expression:
R=K*Sx
Where Sx is defined as the larger of the two (X and Y) RMS values, and K is interpolated using the C ratio from the Table of Cumulative Probability.

The C ratio equals the smaller of the RMS values divided by the larger:
Block 1 (NC): C = 0.072745/0.081621 = 0.891256

The following line (95% probability level) from the Table of Cumulative Probability was used to determine the value of K by a simple linear interpolation between the two nearest values of C:

C	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
K(95%)	1.95996	1.96253	1.97041	1.98420	2.00514	2.03586	2.08130	2.14598	2.23029	2.33180	2.44775

Block 1 (NC)

K =2.23029 + [(.891256 -0.8) / (0.1) * (2.33180 – 2.23029)]
=2.23029 + (.91256 * 0.10151)
=2.23029 + .09263
K =2.32
R = K * Sx = 2.32 * 0.081 = .190

The Radius of the 95% Confidence Circle 0.190 **meters**