USGS Maryland Potomac River Topobathymetric Lidar Project

Report Produced for U.S. Geological Survey

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

SUBMITTED TO:
U.S. Geological Survey
1400 Independence Road
Rolla, MO 65401
573.308.3810

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Executive Summary

Dewberry was tasked with developing a consistent and accurate topographic and bathymetric (topobathymetric) elevation dataset derived from high-accuracy Light Detection and Ranging (lidar) technology for the USGS Maryland Potomac River study area.

The lidar data were processed and classified according to project specifications. Topobathymetric Digital Elevation Models (DEMs) were produced for the project area. Data were formatted according to tiles with each tile covering an area of 1000 m by 1000 m. A total of 247 tiles were produced for the project encompassing an area of approximately 39.2 sq. miles.

THE PROJECT TEAM

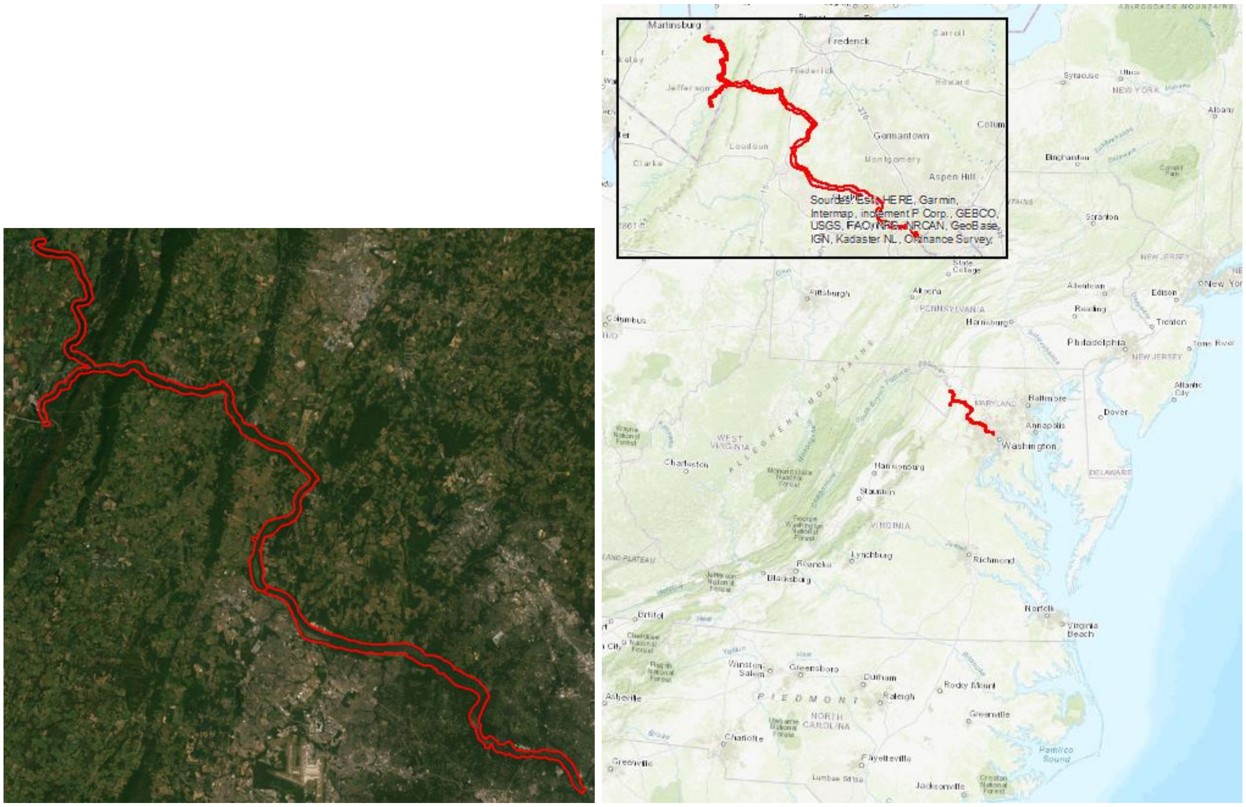
Dewberry served as the prime contractor for the project. In addition to project management, Dewberry was responsible for LAS classification, all lidar products, breakline production, Digital Elevation Model (DEM) production, and quality assurance.

Dewberry's Gary Simpson completed ground surveying for the project and delivered surveyed checkpoints. His task was to acquire surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the lidar-derived model. He also verified the GPS base station coordinates used during lidar data acquisition to ensure that the base station coordinates were accurate. Please see Appendix A to view the separate Survey Report that was created for this portion of the project.

IIC Technologies, Inc. (IIC) completed lidar data acquisition and data calibration for the project area.

SURVEY AREA

The USGS Maryland Potomac topobathymetric lidar survey project area covers approximately 39.2 square miles. The Base Order, which covers the western portion of the AOI, is approximately 22.2 square miles. The Option, which covers the eastern portion of the AOI, is approximately 17 square miles. There are 247 1000 m x 1000 m lidar tiles delivered for the project area. The project area boundary and overview are shown in Figure 1.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey

Figure 1 – The left image shows USGS Maryland Potomac Topobathy collection area shaded in red. The right image shows an overview map of where the project is located.

DATE OF SURVEY

The lidar aerial acquisition was conducted from October 21, 2019 thru October 26, 2019.

COORDINATE REFERENCE SYSTEM

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

Horizontal Datum: North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011))
Vertical Datum: North American Vertical Datum of 1988 (NAVD88)
Coordinate System: UTM Zone 18
Units: Meters
Geiod Model: Geoid12B

LIDAR VERTICAL ACCURACY

For the Maryland Potomac River topobathy project, the tested RMSE$_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled **3.9 cm** compared with the 10 cm specification; and the non-vegetated vertical accuracy (NVA) of the classified lidar data computed using RMSE$_z$ x 1.9600 was equal to **7.6 cm**, compared with the 19.6 cm specification.

The tested RMSE$_z$ of the classified lidar data for checkpoints in submerged topography equaled **8.4 cm** compared with the 18 cm specification; and the bathymetric vertical accuracy (BVA) of the classified lidar data computed using RMSE$_z$ x 1.9600 was equal to **16.5 cm**, compared with the 35.3 cm specification.

The tested vegetated vertical accuracy (VVA) of the classified lidar data computed using the 95th percentile was equal to **5.9 cm,** compared with the 29.4 cm specification.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and topobathymetric DEM data are found in the following sections of this report.

PROJECT DELIVERABLES

The deliverables for the project are listed below.

1. Project boundary and tile grid shapefiles)
2. Breaklines used to delineate the land-water interface for bathymetric bottom classification (GDB and shapefiles)
3. Final classified lidar tiles (LAS)
4. Tiled topobathymetric DEMs with voids enforced (IMG)
5. Mosaic topobathymetric DEM with voids enforced (IMG)
6. Void layer (GDB and shapefile)
7. Tiled green intensity images (geoTIFF)
8. Tiled NIR intensity images (geoTiff)
9. Survey data
10. Metadata (XML)
11. Final project report

OVERVIEW OF CLASSIFICATION

The raw lidar from the bathymetric and topographic sensors were kept in the classes that were output by the Leica processing software. This aided in the classification of the ground and bathymetric bottom.

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

Lidar Classification – Manual Editing and Final Deliverables	
Class	**Description**
Class 0	Created, never classified
Class 1	Unclassified (includes buildings and vegetation)
Class 2	Ground
Class 7	Noise
Class 17	Bridge deck
Class 18	High noise
Class 40	Bathymetric bottom
Class 41	Water surface
Class 42	Synthetic water surface used in computing refraction
Class 43	Submerged object, not otherwise specified
Class 44	International Hydrographic Organization (IHO) S-57 object, not otherwise specified
Class 45	No bathymetric bottom found (water column)

Table 1 – Final lidar classification schema.

Lidar Acquisition Report

Dewberry elected to subcontract the lidar acquisition and calibration activities to IIC. IIC was responsible for providing lidar acquisition, calibration, refraction, and delivery of lidar data files to Dewberry.

Dewberry received calibrated swath data from IIC on December 19, 2019.

LIDAR ACQUISITION DETAILS

IIC lidar sensors are calibrated at a designated site located in Saint Hyacinthe, QC, Canada, and are periodically checked and adjusted to minimize corrections at project sites.

IIC planned 145 passes for the project area as a series of parallel flight lines, with cross flightlines for quality control. The flight plan included zig-zag (alternating heading directions) flight line collection to compensate for the drift commonly associated with onboard inertial measurement unit (IMU) systems and ensure proper coverage. In order to reduce potential errors in the data attributable to flight planning, IIC followed FEMA's *Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A: Guidance for Aerial Mapping and Survey*. The guidance includes the following minimum criteria:

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

IIC monitored weather and atmospheric conditions and conducted lidar missions only when no conditions existed below the sensor that would affect the collection of data. These conditions include leaf-off for hardwoods, no snow, rain, fog, smoke, mist and low clouds. Lidar systems are active sensors that do not require light, thus allowing missions to be conducted during night hours if weather or flight restrictions do not prevent collection. IIC accessed reliable weather sites and indicators (webcams) to establish the highest probability for successful data acquisition.

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

The project area included many restricted airspace zones (figure 2). Permission to fly in these areas required submittal of credentials for the pilots and operators, as well as details for the aircraft and planned flight lines. The submittal was done over a month before the planned flights, and IIC received a waiver two weeks prior to the collection. However, IIC were informed by ATC that even with the waiver they could be asked to leave at any time or denied entry to any or all of the areas. The last two miles of the collection AOI also extended into the 7.5-mile radius of the White House (the "Freeze Zone"). As such, IIC needed to have an armed federal agent onboard the aircraft to monitor each mission.

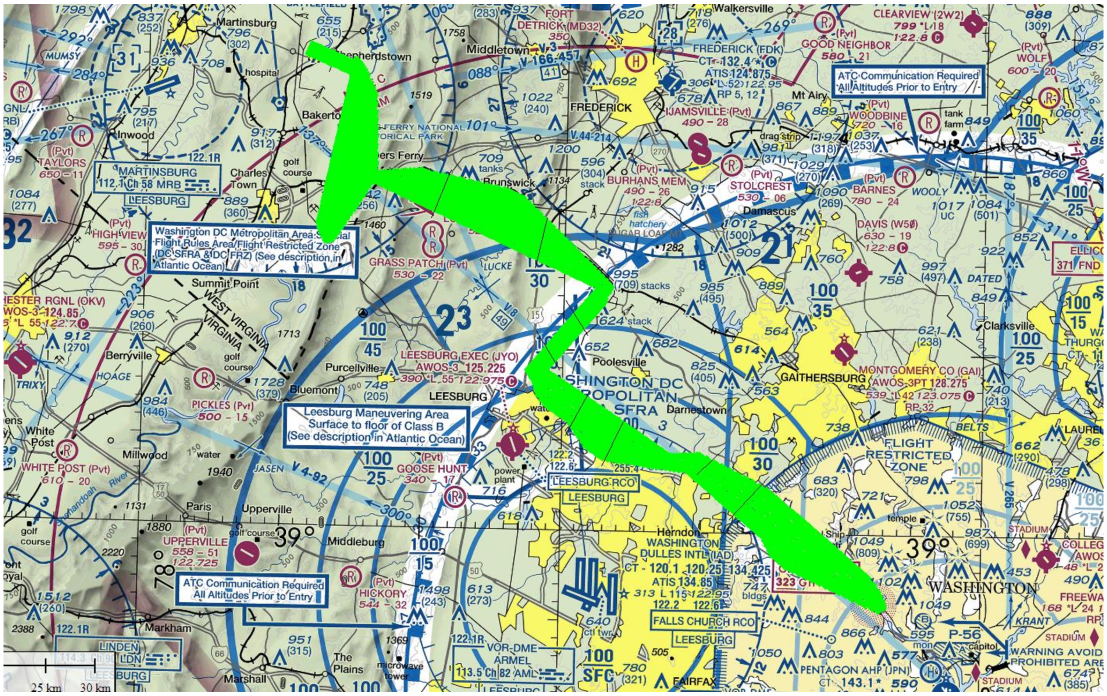


Figure 2 – This graphic shows the flight lines (green) on top of the aviation chart. The blue rings indicate restricted airspace.

During the first attempt to collect in the Freeze Zone, on October 25, 2019, IIC was denied access and told to return to base. On the second attempt to collect the area in the Freeze Zone, IIC was allowed access and did collect that area. Following the initial collection, small slivers/gaps were identified in some of the topo areas on the edge of the AOI. With steep relief on either side of the river, there were areas where IIC had to descend quickly to be online to collect. IIC was denied permission to reenter the flight areas to try and re-collect data for these small topo gaps. However, 100% coverage for the river/bathymetry was achieved.

LIDAR SYSTEM PARAMETERS

IIC operated a Piper PA-31 Navajo outfitted with a Leica Hawkeye 4X (consisting of a Chiroptera 4X sensor and Hawkeye deep water module) during the collection of the study area. Table 1 illustrates the system parameters used during acquisition for this project.

Parameter	Value	Value
Channel	Topo	Shallow/Deep Bathy
Altitude (AGL meters)	400	400
Approx. Flight Speed (knots)	140	140
Scanner Pulse Rate (kHz)	500	35/10
Scan Frequency (hz)	140	140

Parameter	Value	Value
Central Wavelength of the Sensor Laser (nanometers)	1064	515
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	No	No
Beam Divergence (milliradians)	0.5	4
Nominal Swath Width on the Ground (m)	280	280
Swath Overlap (%)	30	30
Total Sensor Scan Angle (degree)	40	40
Nominal Pulse Spacing (single swath), (m)	0.35	0.71
Nominal Pulse Density (single swath) (ppsm), (m)	8	2
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.35	0.71
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	8	2
Maximum Number of Returns per Pulse	15	15

Table 2 – IIC lidar system parameters.

ACQUISITION STATUS REPORT AND FLIGHTLINES

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

Figure 2 shows the combined trajectories of the flightlines.

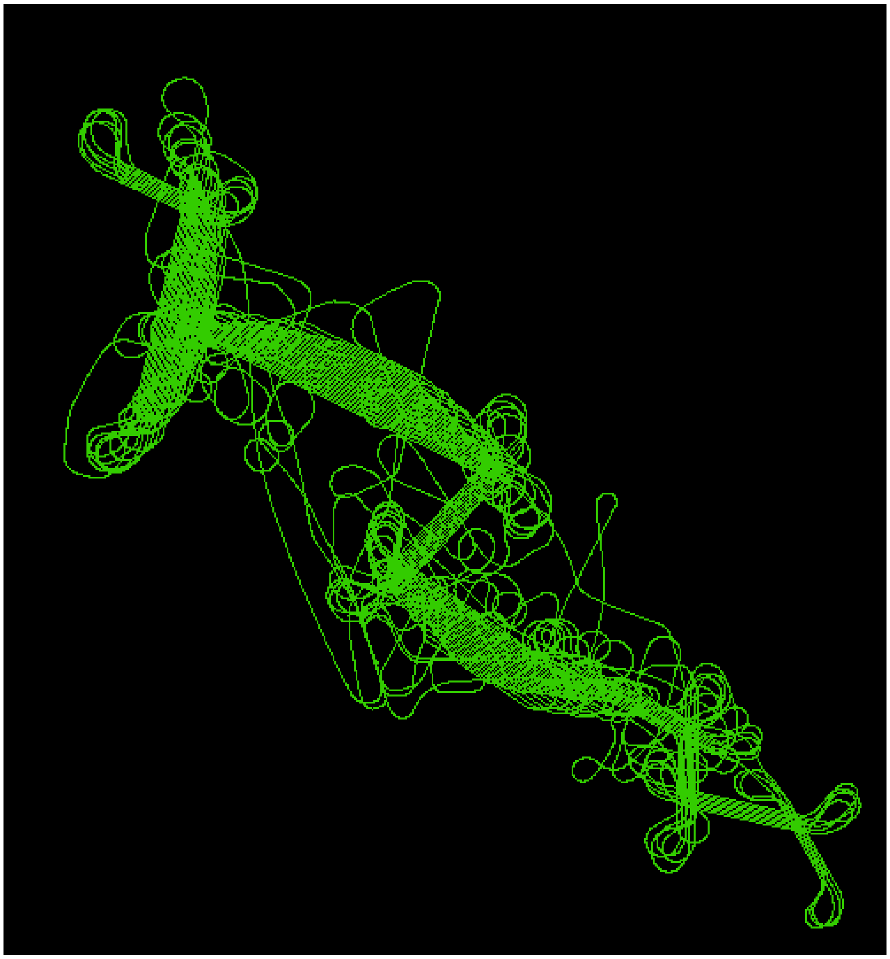


Figure 3 – Trajectories as flown by IIC.

LIDAR CONTROL

One existing NGS monument was used to control the lidar acquisition for the USGS Maryland Potomac lidar project area. The coordinates of the base station is provided in the table below. All control and calibration points are also provided in shapefile format as part of the final deliverables.

Name	NAD83(2011) UTM 18		Ellipsoid Ht (NAD83, m)	Orthometric Ht (NAVD88 Geoid12B, m)
	Easting X (m)	Northing Y (m)		
DC WAAS 1	1069125.825	-4839598.645	79.600	127.349

Table 3 – Base stations used to control lidar acquisition.

AIRBORNE GPS KINEMATIC

Airborne GPS data was processed using Inertial Explorer software. Flights were flown with a minimum of six satellites in view (13° above the horizon) and with PDOP less than 4. Distances from base station to aircraft were kept to a maximum of 40 km.

The GPS residuals for all flights were 3 cm or better, with no residuals greater than 10 cm recorded.

GPS processing reports for each mission are included in Appendix B.

GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

Availability and status of all required GPS and laser data were verified against field reports and any data inconsistencies were addressed.

Subsequently the mission points were output using Leica Lidar Survey Studio, initially with default values from Leica or the last mission calibrated for the system.

Dewberry verified the initial point generation for each mission calibration within Microstation/Terrascan for calibration errors. If a calibration error greater than specification was observed within the mission, the roll, pitch and scanner scale corrections were calculated. The missions with the new calibration values were regenerated and validated internally once again to ensure quality.

Dewberry reviewed data collected by the lidar unit for completeness, acceptable density and to make sure all data was captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files were reviewed. Dewberry noted two data gaps, each near the edge of the AOI and outside of the bathymetry areas. IIC made an effort to refly these areas but was unable to complete the reflights due to the flight restrictions discussed above.

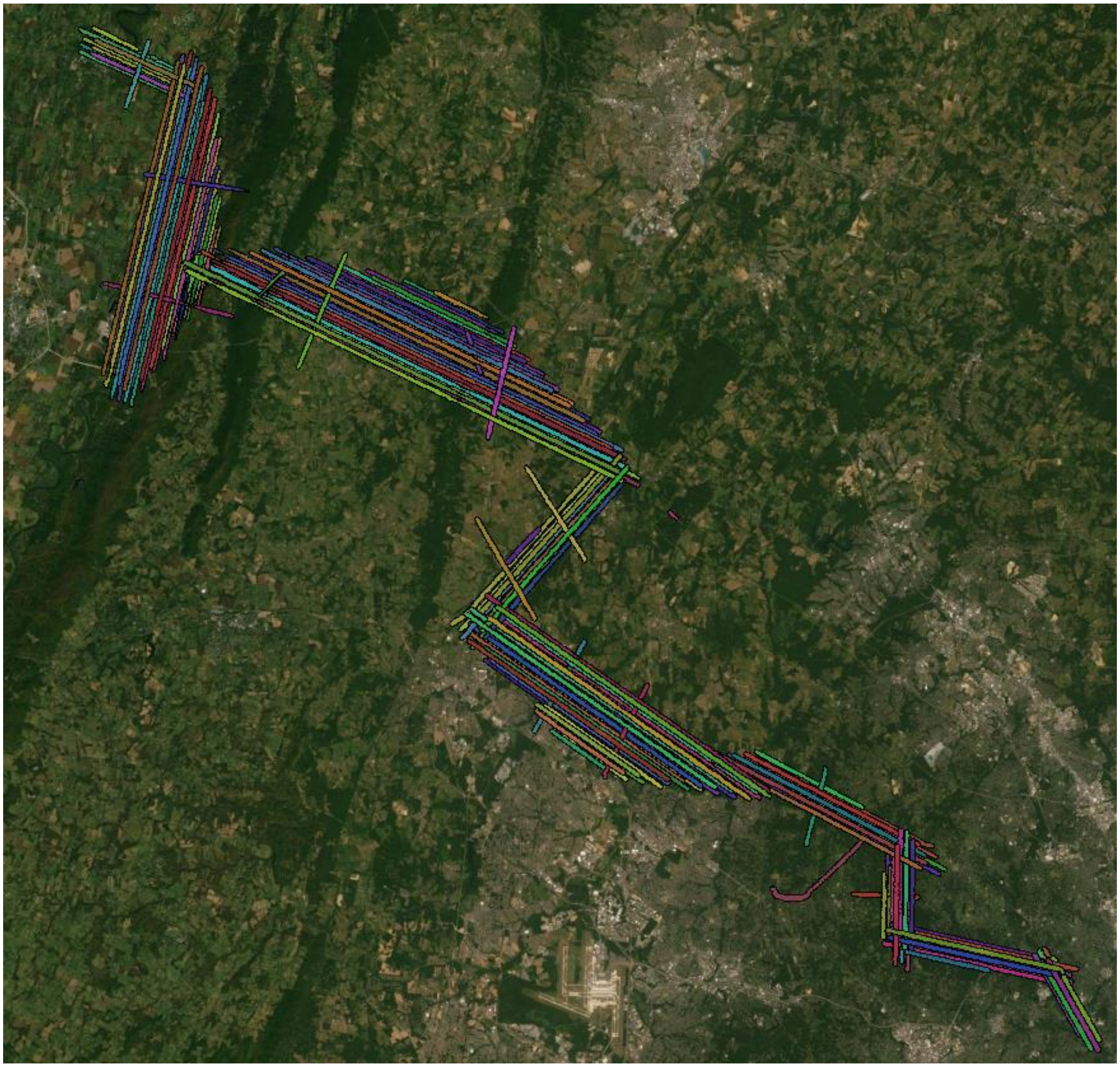


Figure 4 – Lidar swath output showing complete coverage.

Boresight and Relative accuracy

The initial points for each mission calibration were inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the lidar unit or GPS. Roll, pitch and scanner scale were optimized during the calibration process until the relative accuracy was met.

Data calibration/swath alignment was the final positioning processing step to ensure a high degree of relative (swath to swath) and absolute (real world) accuracy in the point cloud. Dewberry utilized Bayesmap StripAlign for this alignment procedure. This alignment procedure corrected systematic issues globally, per aircraft lift, per flightline, and finally based on local errors along the flight trajectory. Error adjustments included internal sensor parameters. Due to the complex geometric relationship of the elliptical scan pattern the forward and reverse directions must be aligned independently. Additionally, since the green and NIR scanner map different surfaces, they were also aligned independently, then corrected to match each other.

Many quality control measures were utilized for this process, including generation of difference rasters (DZ orthos), review of adjustment parameters, and review of registration/match regions. After this process was completed the data were compared to independently collected checkpoints to ensure that absolute accuracy met RMSEz specification.

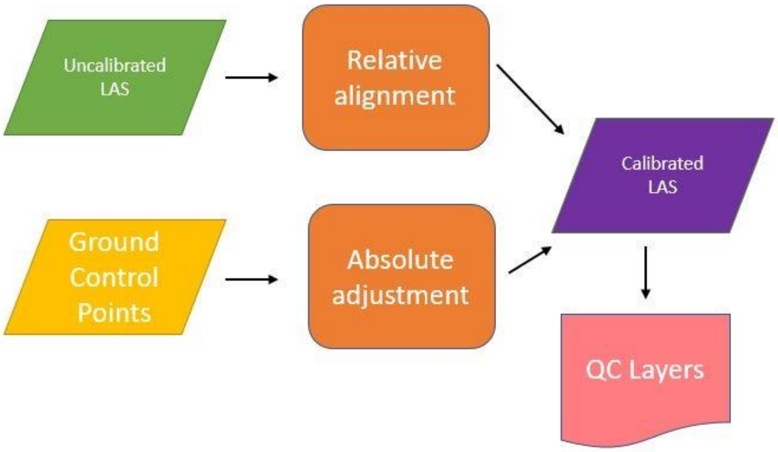


Figure 5: Alignment / Calibration workflow

For this project the specifications used are as follow:
Relative accuracy <= 6 cm maximum difference within individual swaths and <= 8 cm RMSDz between adjacent and overlapping swaths.

Refraction Correction

Bathymetric data must have a refraction correction applied, which corrects the horizontal and vertical (depth) positions of each data point by accounting for the change in direction and speed of light as it enters and travels through water. The refraction correction was performed by IIC using Leica's Lidar Survey Studio (LSS) application.

Lidar Processing & Qualitative Assessment

INITIAL PROCESSING

Dewberry performs several validations on the dataset prior to starting full-scale production on the project. These validations include vertical accuracy of the swath data, inter-swath (between swath) relative accuracy validation, intra-swath (within a single swath) relative accuracy validation, verification of horizontal alignment between swaths, and confirmation of point density and spatial distribution. This initial assessment allows Dewberry to determine if the data are suitable for full-scale production. Addressing issues at this stage allows the data to be corrected while imposing the least disruption possible on the overall production workflow and overall schedule.

Refraction Correction and Synthetic Water Surface

The refraction correction was performed by IIC as part of the swath data processing and calibration. Dewberry received refracted swath data for review and continued production.

The Leica Survey Studio software automated refraction correction adds synthetic water surface points (class 42) to the data to represent a planar surface at the approximate water surface elevation for each flightline. These points are differentiated from real data with a return number of 0. In some cases, typically along the edges of flightlines that coincide with steep elevation changes such as the riverbanks, the sensor added erroneous water surface points. Erroneous synthetic water surface placement resulted in incorrect refraction correction and geometrically incorrect ground point locations. Therefore, before manual lidar classification was performed, these erroneous areas—all points associated with green sensor channels, including synthetic and real lidar points—were manually reclassed to withheld default to prevent incorrect surfaces being grounded. As these artifacts were located along the edge of flight lines, no data voids were created during this process. Following final classification, return number was used as a filter to return the synthetic water surface points to class 42.

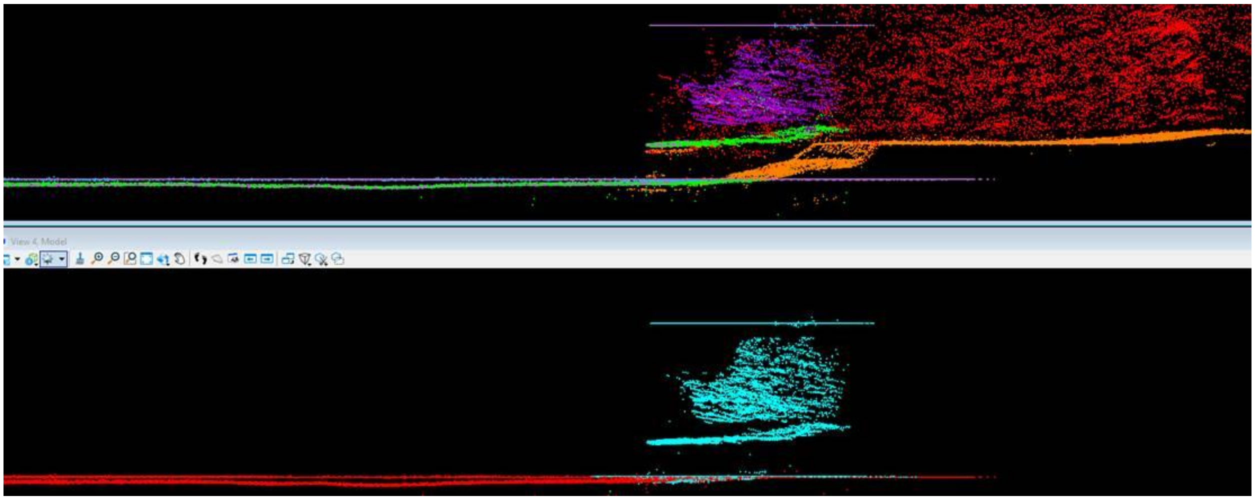


Figure 6: Refraction offsets caused by erroneous synthetic water surface points. The upper profile shows points colored by class. Bathy bottom (green), default (red), ground (orange), noise (purple), and synthetic water surface (light purple) classes are shown. The lower profile shows the ponts colored by flightline.

All synthetic water surface points had the “synthetic” flag applied using Terrascan, while synthetic water surface points along flight line edges also had the “withheld” flag applied using Terrascan. The synthetic water surface points were used only for the refraction correction and were not used in any way during data production.

Final Swath Vertical Accuracy Assessment

Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to additional processing. Dewberry tested the vertical accuracy of the swath data using 15 (open terrain and urban) independent survey check points. The vertical accuracy is tested by comparing survey checkpoints in non-vegetated terrain to a triangulated irregular network (TIN) that is created from the raw swath points. Only checkpoints in non-vegetated terrain can be tested against raw swath data because the data has not undergone classification techniques to remove vegetation, buildings, and other artifacts from the ground surface. Checkpoints are always compared to interpolated surfaces from the lidar point cloud because it is unlikely that a survey checkpoint will be located at the location of a discrete lidar point. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project. Project specifications require a NVA of 19.6 cm based on the $RMSE_z$ (10 cm) x 1.96. The dataset for the USGS Maryland Potomac project satisfies this criteria. This raw lidar swath data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 5.1 cm, equating to +/- 10.1 cm at 95% confidence level. The table below shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	$RMSE_z$ NVA Spec=0.10 m	NVA –Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Non-Vegetated Terrain	15	0.051	0.101	0.002	-0.009	2.823	0.053	-0.061	0.179	9.897

Table 4 – NVA at 95% Confidence Level for Raw Swaths

Only non-vegetated terrain checkpoints are used to test the raw swath data because the raw swath data has not been classified to remove vegetation, structures, and other above ground features from the ground classification. Seven checkpoints (NVA-2, NVA-7, NVA-9, NVA-12, NVA-16, NVA-21, NVA-22) were determined to be in areas of significant lidar noise and were removed from the raw swath vertical accuracy testing. While these checkpoints are in open terrain, the sensor noise points below the ground surface are modeled by the lidar point cloud, causing erroneous high values during the swath vertical accuracy. Once the data underwent the classification process, the noise were removed from the final ground classification and these checkpoints could be used in the final vertical accuracy testing for the fully classified lidar data. Table 6, below, provides the coordinates for these checkpoints and the vertical accuracy results from the raw swath data. Table 7 provides the usable vertical accuracy results of these checkpoint from the fully classified lidar. The differences between the delta z values in each table show the effect of the noise on the vertical accuracy results in the raw swath data. Figures 4 trough 10, below, show profiles in the lidar point cloud with the locations of the excluded checkpoints in areas of noise.

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)		DeltaZ
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-LiDAR (m)	
NVA-2	263628.019	4366857.962	91.103	90.266	-0.837
NVA-7	285810.417	4347489.689	66.513	65.561	-0.952
NVA-9	282400.367	4337005.340	62.123	61.443	-0.680
NVA-12	287500.992	4327635.018	63.741	65.931	2.190
NVA-16	305609.544	4321203.568	48.576	48.019	-0.557

NVA-21	313326.340	4315782.577	35.822	35.054	-0.768
NVA-22	315363.922	4314322.211	45.353	44.881	-0.472

Table 5 – Checkpoints removed from raw swath vertical accuracy testing

Point ID	NAD83(2011) UTM Zone 18N		NAVD88 (Geoid 12B)		DeltaZ
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-LiDAR (m)	
NVA-2	263628.019	4366857.962	91.103	91.030	-0.073
NVA-7	285810.417	4347489.689	66.513	66.450	-0.063
NVA-9	282400.367	4337005.340	62.123	62.060	-0.063
NVA-12	287500.992	4327635.018	63.741	63.700	-0.041
NVA-16	305609.544	4321203.568	48.576	48.550	-0.026
NVA-21	313326.340	4315782.577	35.822	35.820	-0.002
NVA-22	315363.922	4314322.211	45.353	45.370	0.017

Table 6 – Final tested vertical accuracy for OT-130 post ground classification

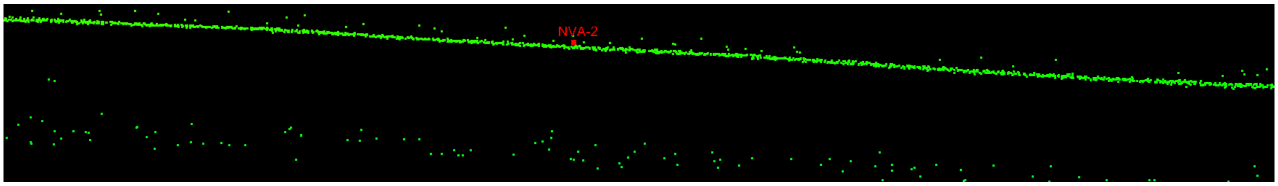


Figure 7 – NVA-2 shown as a red marker on the ground surface with sensor noise below.

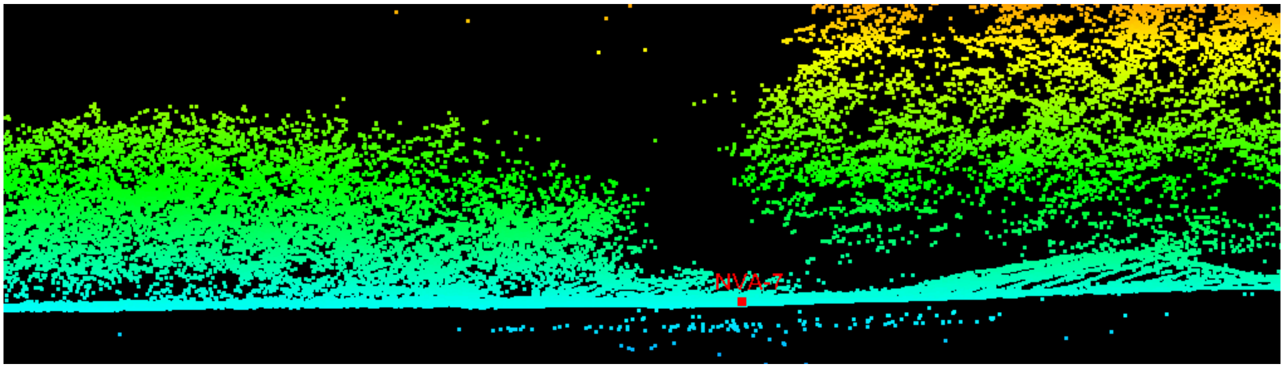


Figure 8 – NVA-7 shown as a red marker in open terrain with sensor noise below the ground.

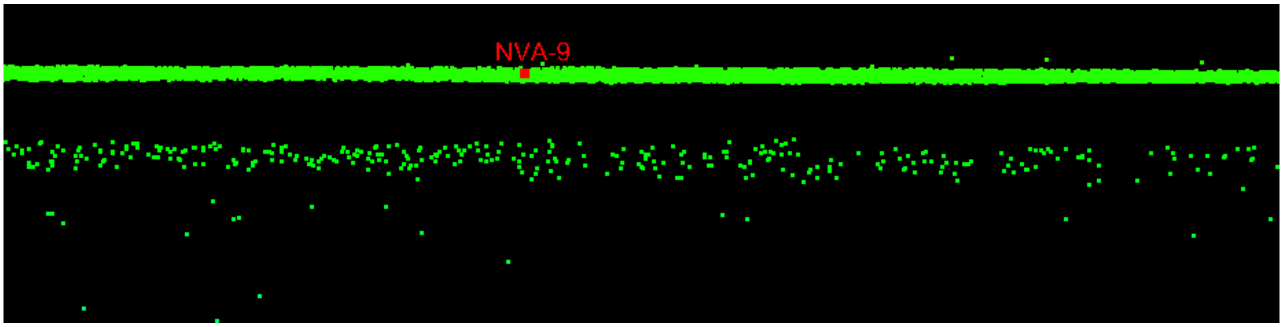


Figure 9 – Lidar profile of NVA-9 showing noise below the ground surface.

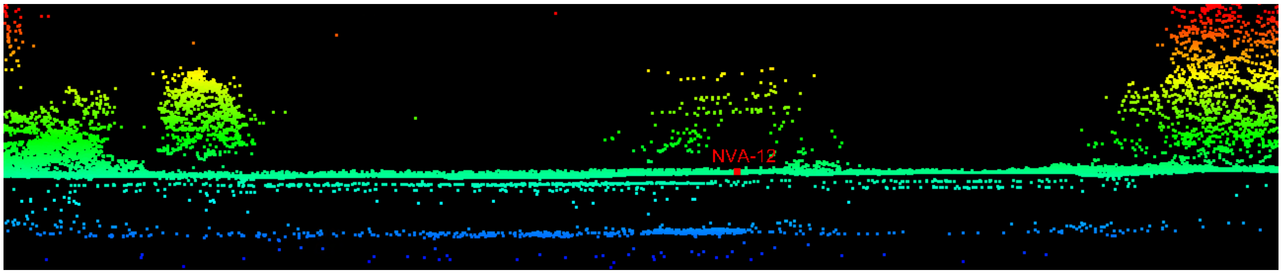


Figure 10 – Lidar profile showing checkpoint NVA-12 surrounded by low and high noise.

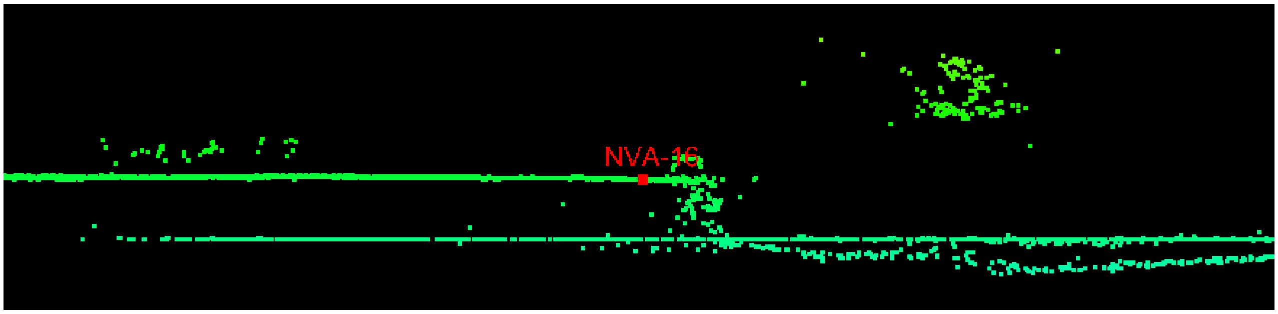


Figure 11 – NVA-16 shown as a red marker near an embankment with noise below.

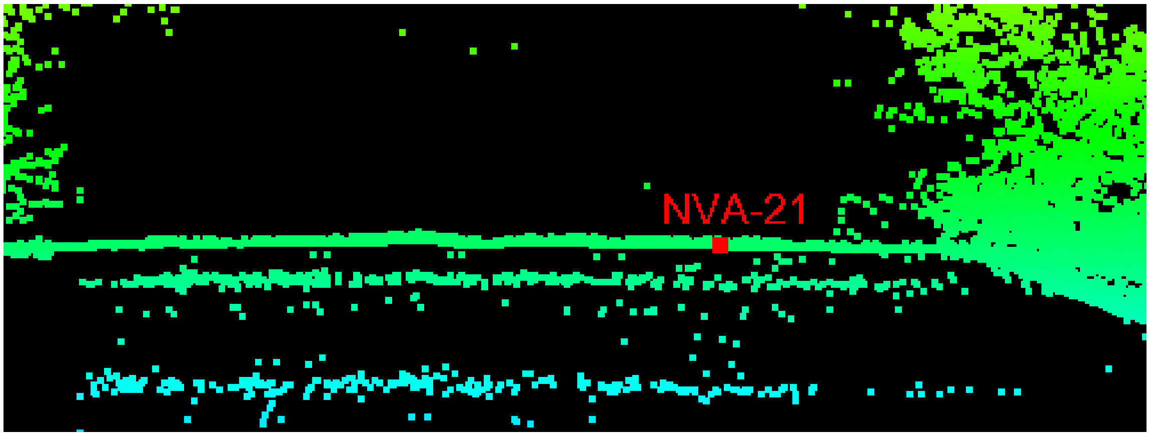


Figure 12 – Lidar profile showing NVA-21 with abundant low noise.

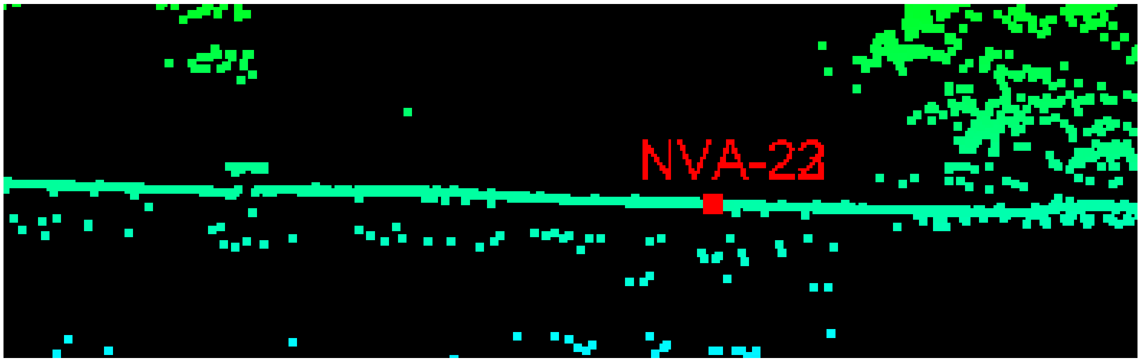


Figure 13 – NVA-23 shown as a red marker on the ground surface with noise below.

Inter-Swath (Between Swath) Relative Accuracy

Dewberry verified inter-swath or between swath relative accuracy of the dataset by creating Delta-Z (DZ) orthos. According to the SOW, USGS Lidar Base Specifications v1.3, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL1 data must meet inter-swath relative accuracy of 8 cm RMSDz or less with maximum differences less than 16 cm. These measurements are to be taken in non-vegetated and flat open terrain using single or only returns from all classes. Measurements are calculated in the DZ orthos on 1-meter pixels or cell sizes. Areas in the dataset where overlapping flight lines are within 8 cm of each other within each pixel are colored green, areas in the dataset where overlapping flight lines have elevation differences in each pixel between 8 cm to 16 cm are colored yellow, and areas in the dataset where overlapping flight lines have elevation differences in each pixel greater than 16 cm are colored red. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values. Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across 1 linear meter) are expected to appear yellow or red in the DZ orthos. If the project area is heavily vegetated, Dewberry may also create DZ Orthos from the initial ground classification only, while keeping all other parameters consistent. This allows Dewberry to review the ground classification relative accuracy beneath vegetation and to ensure flight line ridges or other issues do not exist in the final classified data.

Flat, open areas are expected to be green in the DZ orthos. Bathymetric areas may be yellow or red due to varying elevations of returns within the water column. Large or continuous sections of yellow or red pixels following flight line patterns and not the terrain, vegetation, or bathymetric areas can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data. The DZ orthos for USGS Maryland Potomac are shown in the figure below; this project meets inter-swath relative accuracy specifications.

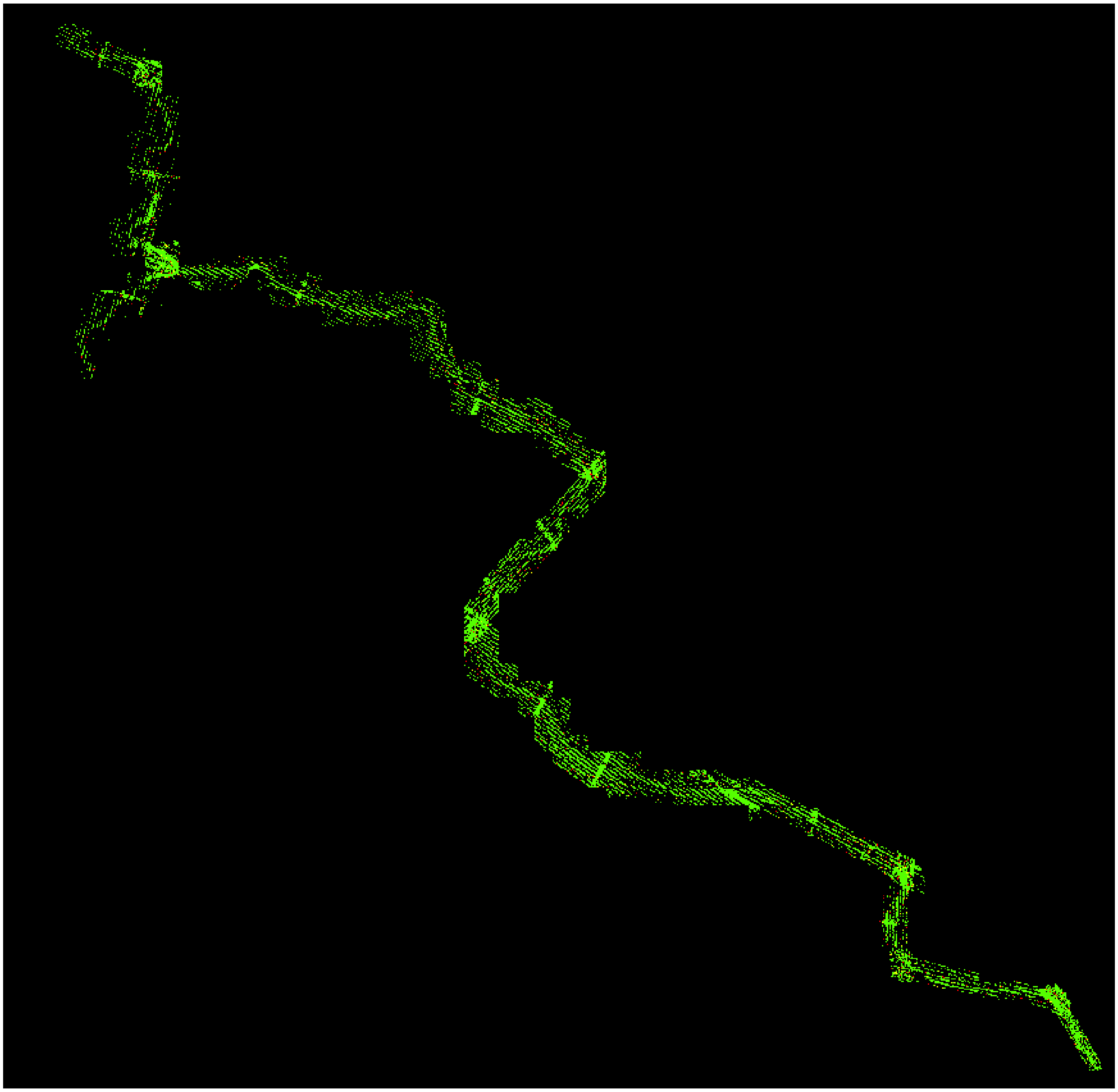


Figure 14 – DZ Orthos. Offsets between flight lines of 0-8 cm are green, 8-16 cm are yellow, and above 16 cm are red. Larger offsets in vegetated and bathymetric areas are expected as different returns from water column and vegetation can occur between different flight lines. Inter-swath relative accuracy passes specifications.

Intra-Swath (Within a Single Swath) Relative Accuracy

Dewberry verifies the intra-swath or within swath relative accuracy by using Quick Terrain Modeler (QTM) scripting and visual reviews. QTM scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Dewberry analysts then identify planar surfaces acceptable for repeatability testing and analysts review the QTM results in those areas. According to the SOW, USGS Lidar Base Specifications v1.3, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL1 data must meet intra-swath relative accuracy of 6 cm maximum difference or less. The image below shows two examples of the intra-swath relative accuracy of USGS Maryland Potomac; this project meets intra-swath relative accuracy specifications.

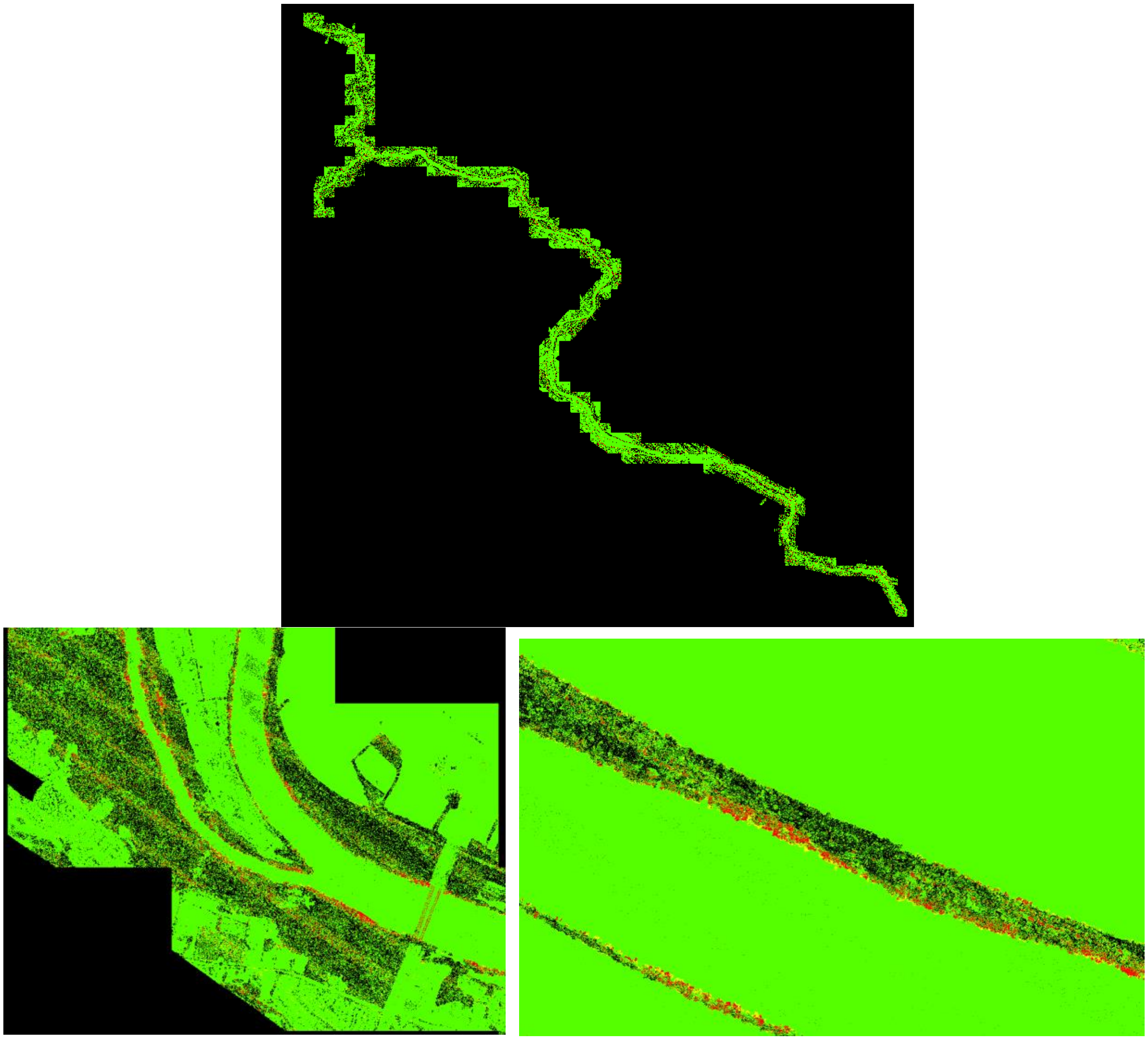


Figure 15 – The top image shows the full project area; areas where the maximum difference is ≤6 cm per pixel within each swath are colored green and areas exceeding 6 cm are colored red. The bottom left image shows a large portion of the dataset; flat, open areas are colored green as they are within 6 cm whereas sloped terrain is colored red because it exceeds 6 cm maximum difference, as expected, due to actual slope/terrain change. The bottom right image is a close-up of a flat area. With the exception of few trees (shown in red as the elevation/height difference in vegetated areas will exceed 6 cm) this open flat area is acceptable for repeatability testing. Intra-swath relative accuracy passes specifications.

Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Dewberry uses QTM scripting and visual reviews. QTM scripting is used to create files similar to DZ orthos for each swath but this process highlights planar surfaces, such as roof tops. In particular, horizontal shifts or misalignments between swaths on roof tops and other elevated planar surfaces are highlighted. Visual reviews of these features, including additional profile verifications, are used to confirm the results of this process. The image below shows an example of the horizontal alignment between swaths for USGS Maryland Potomac; no horizontal alignment issues were identified.

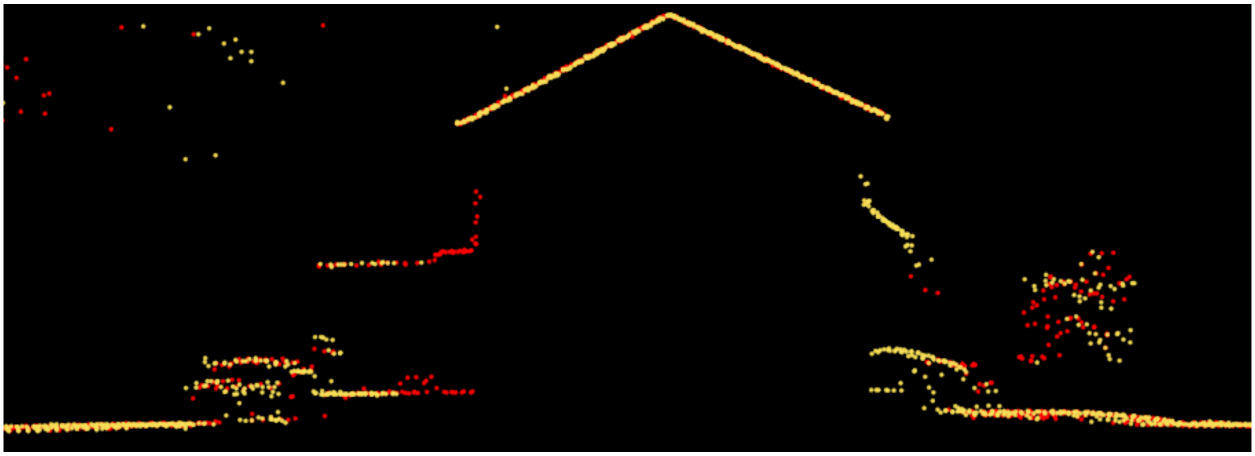


Figure 16 – Two separate flight lines differentiated by color (Red/Yellow) are shown in this profile. There is no visible offset between these two flight lines. No horizontal alignment issues were identified.

Point Density and Spatial Distribution

For topographic areas, the required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.35 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 8 points per square meter or greater. For bathymetric areas, the required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.71 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 2.0 points per square meter or greater. Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. The project area was determined to have a combined topobathy ANPS of 0.23 meters or an ANPD of 18.79 points per square meter which satisfies the project requirements. A visual review of a 1-square meter density grid (figure below) shows that there are some 1-meter cells that do not contain 8 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-square meter cells contain at least 8 points per square meter (green areas) and when density is viewed/analyzed by representative 1-square kilometer areas (to account for the irregular spacing of lidar point clouds), density passes with no issues.

Figure 17 – 1-square meter density grid. There are some 1-meter cells that do not contain 8 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-sqaure meter cells contain at least 8 points per square meter (green areas) showing there are no systematic density issues. When density is viewed/analyzed by representative 1-square kilometer areas, density passes with no issues.

The spatial distribution of points must be uniform and free of clustering. This specification is tested by creating a grid with cell sizes equal to the design NPS*2. ArcGIS tools are then used to calculate the number of first return points of each swath within each grid cell. At least 90% of the cells must contain 1 lidar point, excluding acceptable void areas such as low NIR reflectivity features, i.e. some asphalt and roof composition materials. This project passes spatial distribution requirements, as shown in the image below.

Figure 18 – Spatial Distribution. All cells (2*NPS cellsize) containing at least one lidar point are colored green. Cells that do not contain a lidar point are colored red. 99.2% of cells contain at least one lidar point.

DATA CLASSIFICATION AND EDITING

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data were confirmed, Dewberry utilized a variety of software suites for data processing. Data processing included breakline creation to define the land/water interface, automated and manual editing of the lidar tiles, QA/QC, and final formatting of the LAS files.

Breakline Creation and QA/QC

Breaklines representing the land/water interface must be created so that bathymetric bottom and ground points can be classified properly in the lidar. The processing software for the Leica Chiroptera 4X system does a basic classification on the lidar, differentiating between land and bathymetric areas. Dewberry aggregated the points classified as bathymetric areas by the sensor processing software into polygons using ArcGIS. These polygons were then compared to downloaded RGB imagery and intensity and adjusted as necessary.

The final land/water interface delineation was used in the lidar classification of ground and bathymetric points.

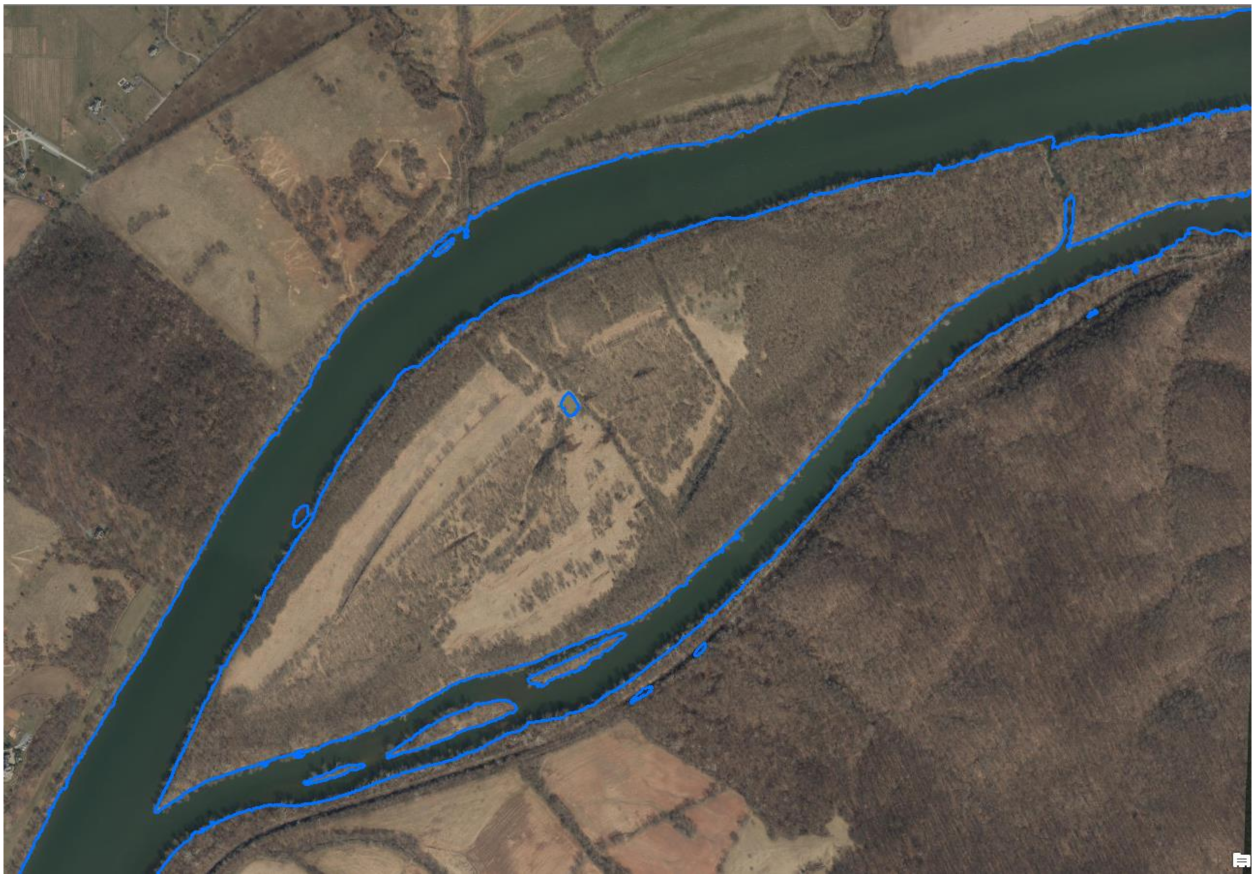


Figure 19 – Tile 0200E_6400N. The breakline representing the land/water interface is shown outlined in blue along with RGB imagery.

GeoCue and Terrascan Processing

The acquired 3D laser point clouds, in LAS binary format, were tiled according to the project tile grid using LASTools and proprietary Dewberry tools. Once tiled, the laser points were classified using a proprietary routine in TerraScan to create the initial automated ground and bathy bottom classifications, using the final project classification schema.

This routine classifies any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. Points along flight line edges that are geometrically unusable are identified as withheld and classified to a separate class so that they will not be used in the initial ground algorithm. After points that could negatively affect the ground are removed from class 1, the ground layer is extracted from this remaining point cloud. The ground extraction process encompassed in this routine takes place by building an iterative surface model.

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

The final breaklines defining the land/water interface are then used to classify “ground” points within the water breaklines as bathymetric bottom. The breaklines are also used as part of the classification routines to ensure water surface and water column points are classified correctly.

Each tile is then imported into Terrascan and a surface model is created to examine the ground (class 2) and bathy bottom (class 40) classification. Dewberry analysts employ 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points are removed from the ground classification and that class 40 accurately represents submerged topography. Dewberry analysts visually review the surface models and correct errors in the ground classification such as vegetation, buildings, and bridges that are present following the initial processing conducted by Dewberry. Common errors in the bathymetric classification that were corrected by Dewberry include some of the issues outlined below.

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

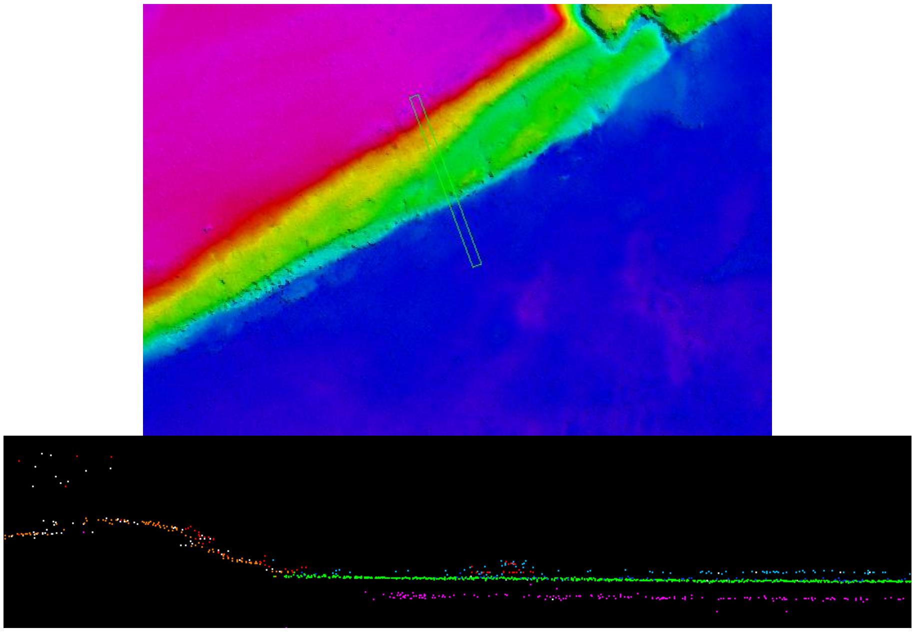


Figure 20 – The land-water interface should be seamless with no hard edges or seamlines. The topobathy surface model is shown above with a profile location overlaid. The profile is shown in the bottom image where bathy bottom points are green, ground points are orange, water column points are blue, and unclassified points are red.

Areas of rapids or swift moving water may also need to be removed from the bathy bottom class as these may be surface or water column points and not bathy bottom points due to the water movement and stirring of sediment (increased turbidity). When possible, color orthos were used to help determine water clarity and likelihood of full penetration to the submerged bottom. Generally, editors looked for consistency in data, especially continuous topography (connecting the dots method to ensure channel geometry is reasonable).

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

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

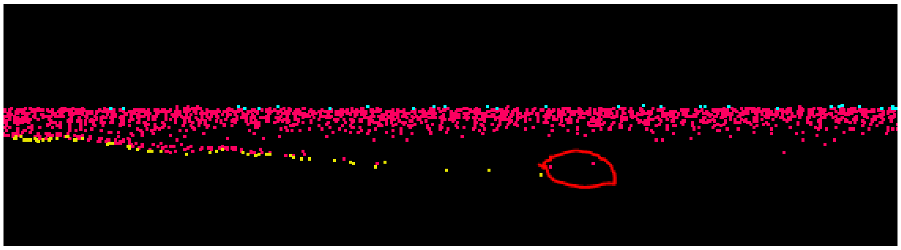


Figure 21 – Bathy bottom points (yellow) are shown with water column (pink) and water surface points (turquoise) in this profile. The two water column points circled in red would cause inconsistent and upward changes in the topobathy model if these points were classified to bathy bottom. These points should remain classified as water column.

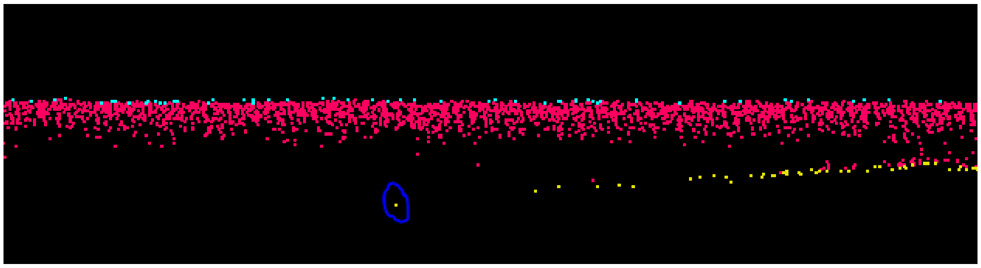


Figure 22 – Bathy bottom points (yellow) are shown with water column (pink) and water surface points (turquoise) in this profile. The bathy bottom point circled in blue is isolated, but maintains a consistent gradient with other bathy bottom points to the east. This point should remain classified as bathy bottom.

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

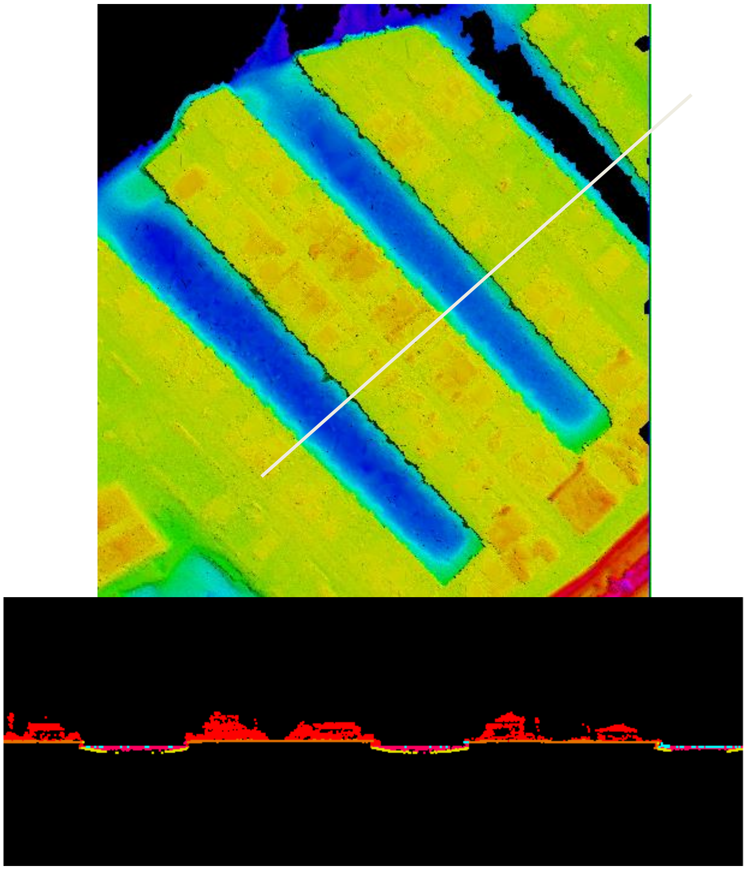


Figure 23 – The topobathy surface model is shown on the top with a profile location overlaid. The profile is shown in the bottom image where bathy bottom points are yellow, ground points are orange, water column points are pink, water surface points are turquoise, and unclassified points are red. These three marina inlets are man-made and likely at very similar depths, as shown in the overview profile. In locations similar to this, points significantly deeper (lower) or shallower (higher) are likely not legitimate bathy bottom, but are more likely to be noise or water column, respectively.

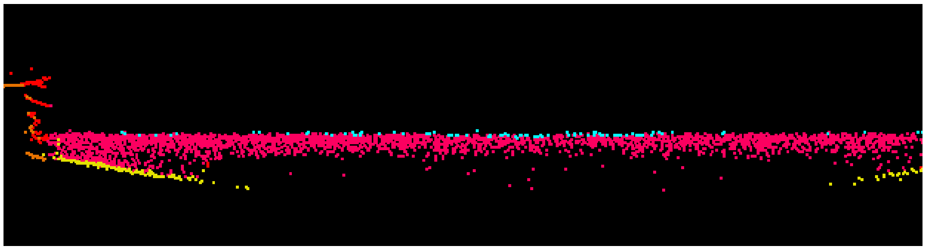


Figure 24 – This profile is a close-up of one of the marina inlets shown in Figure 12. Bathy bottom points are yellow, ground points are orange, water column points are pink, water surface points are turquoise, and unclassified points are red. These marina inlets are man-made and likely at very similar depths. The low water column points are not classified as possible bathy bottom because that classification would cause this inlet to be much shallower than its neighboring inlets in close proximity.

3. Small gap verification—If bathy bottom was obtained for the vast majority of a channel, but small random gaps or voids in the bathy bottom exist after the initial grounding where it is unclear if existing points are bathy bottom or low water column, these small

gaps should usually be filled by classifying the points in question to bathy bottom. It is unlikely such small portions of the channel are that much deeper where no bathy bottom was obtained when the lidar penetrated to the bathy bottom in the rest of the channel. However, if the gaps/voids are larger or consistently form over specific areas or locations, then these areas are more likely to represent deeper areas where the lidar may not have penetrated to the submerged bottom. In these areas. Classify the points as low water column.

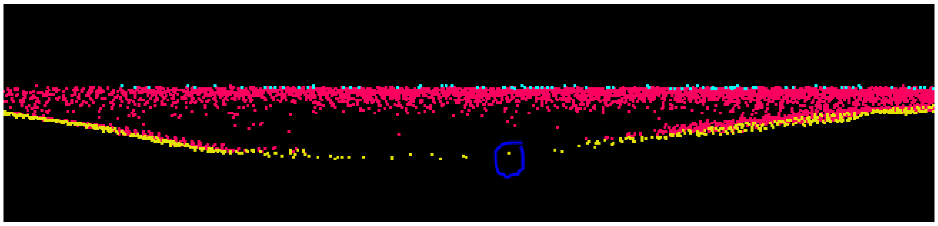


Figure 25 – Bathy bottom points (yellow) are shown with water column (pink) and water surface points (turquoise) in this profile. The bathy bottom point circled in blue was classified as bathy noise by the initial grounding macro, resulting in a small void. This point was re-classified as bathy bottom to the fill the small gap because this point is at the same depth as surrounding points, maintains a consistent gradient, and is more likely to be submerged bottom rather than low water column noise. Based on the surrounding data, this point most likely represents bathy bottom.

Bridge decks are classified to class 17 using bridge breaklines compiled by Dewberry. Overage points are then identified in Terrascan and the withheld bit is set on the withheld points previously identified in Terrascan before the ground classification routine was performed.

After manual classification, the LAS tiles are peer reviewed and then undergo a final QA/QC. After the final QA/QC and corrections, all headers, appropriate point data records, and variable length records, including spatial reference information, are updated in GeoCue software and then verified using proprietary Dewberry tools.

Submerged Objects

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

Temporal Changes

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

LIDAR QUALITATIVE ASSESSMENT

Dewberry's qualitative assessment utilizes a combination of statistical analysis and interpretative methodology to assess the quality of the data for a topobathymetric DEM. This includes creating pseudo image products such as lidar orthos produced from the intensity returns, TINs, DEMs, void polygons and 3-dimensional models as well as reviewing the actual point cloud data.

Visual Review

During QA/QC, reviewers check for consistent and correct classification. This process looks for anomalies in the data, areas where man-made structures or vegetation points may not have been classified properly to produce a bare-earth model, areas where bathymetry was not classified correctly to produce an accurate submerged topography model, and other classification errors. Reviewers verified all guidelines outlined in the Data Classification and Editing section above have been adhered too.

Create Void Polygons

Void polygons were created as part of the QA/QC. The void polygons identify areas of sparse to no bathy bottom (class 40) points. The void polygons were loaded when reviewing the data to ensure correct and full classification of bathy bottom. All void areas in the bathymetry domain 9 sq m or larger were delineated with a void polygon.

The void polygon layer was generated using LAStools and ArcGIS to eliminate interpolation across areas greater than 9 sq m in the bathy domain for the final elevation raster. The LAStools las2dem utility was used to rasterize the LAS data using a 4 m threshold as the maximum allowable TIN edge length during triangulation. This threshold restricted rasterization in areas of sparse data. Once the constrained DEM was created, ArcGIS was used to vectorize the void (NoData) areas. The resulting polygons were then used to constrain interpolation in the final elevation raster.

Formatting

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

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
LAS Version	1.4	Pass
Point Data Format	Format 6	Pass
Coordinate Reference System	NAD83 (2011) UTM Zone 18, meters and NAVD88 (Geoid 12B), meters in WKT Format	Pass
Global Encoder Bit	Should be set to 17 for Adjusted GPS Time	Pass
Time Stamp	Adjusted GPS Time (unique timestamps)	Pass
System ID	Should be set to the processing system/software and is set to Chiroptera for Chiropter Sensor	Pass
Multiple Returns	The sensor shall be able to collect multiple returns per pulse and the return numbers are recorded	Pass
Intensity	16 bit intensity values are recorded for each pulse	Pass

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
Classification	Required Classes include: Class 0: Created, Never Classified Class 1: Unclassified Class 2: Ground Class 7: Noise Class 17: Bridge Decks Class 18: High Noise Class 40: Bathymetric Bottom Class 41: Water Surface Class 42: Synthetic Water Surface Class 43: Submerged Object, not otherwise specified Class 44: IHO S-57 object Class 45: No bathymetric bottom found (water column)	Pass
Overlap and Withheld Points	Withheld points are set to the Withheld bits	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates are recorded for each pulse	Pass

Table 7 – Classified lidar formatting requirements.

This dataset used a synthetic water surface added automatically by the Leica Chiroptera sensor to aid in performing the refraction correction. These points represent a planar surface at the approximate water surface elevation for each flightline and were added to the dataset as class 42. Terrascan was used to set the "synthetic" flag on all synthetic water surface points and to set the "withheld" flag for incorrectly placed synthetic water surface points.

Lidar Positional Accuracy

BACKGROUND

Dewberry quantitatively tested the dataset by testing the vertical accuracy of the lidar. The vertical accuracy is tested by comparing the discreet measurement of the survey checkpoints to that of the interpolated value within the three closest lidar points that constitute the vertices of a three-dimensional triangular face of the TIN. Therefore, the end result is that only a small sample of the lidar data is actually tested. However, there is an increased level of confidence with lidar data due to the relative accuracy. This relative accuracy in turn is based on how well one lidar point "fits" in comparison to the next contiguous lidar measurement, and is verified as part of the initial processing. If the relative accuracy of a dataset is within specifications and the dataset passes vertical accuracy requirements at the location of survey checkpoints, the vertical accuracy results can be applied to the whole dataset with high confidence due to the passing relative accuracy. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

Dewberry also tests the horizontal accuracy of lidar datasets when checkpoints are photo-identifiable in the intensity imagery. Photo-identifiable checkpoints in intensity imagery typically include checkpoints located at the ends of paint stripes on concrete or asphalt surfaces or checkpoints located at 90 degree corners of different reflectivity, e.g. a sidewalk corner adjoining a grass surface. The XY coordinates of checkpoints, as defined in the intensity imagery, are compared to surveyed XY coordinates for each photo-identifiable checkpoint. These differences are used to compute the tested horizontal accuracy of the lidar. As not all projects contain photo-identifiable checkpoints, the horizontal accuracy of the lidar cannot always be tested.

SURVEY VERTICAL ACCURACY CHECKPOINTS

For the vertical accuracy assessment, 40 checkpoints were surveyed in bare earth/open terrain, grass/weeds/crops, and submerged topography land cover categories. Please see appendix A to view the survey report which details and validates how the survey was completed for this project and contains a list of all surveyed checkpoints.

Checkpoints were evenly distributed throughout the project area so as to cover as many flight lines as possible using the “dispersed method” of placement.

One checkpoint was reviewed by the surveyor for issues. Dewberry requested checkpoint VVA-7 be reviewed by the surveyor because the delta Z between the lidar and survey was over 3 meters and there was no issue in the lidar data to support this discrepancy. Other survey points within the same flight line tested within anticipated thresholds. Upon review, it was determined that the checkpoint was collected according to specifications, but that tall trees within twenty feet of the checkpoint may have introduced multipath error (figure 23). VVA-7 was therefore excluded from accuracy testing.

Figure 26 – Checkpoint VVA-7. The surveyed elevation of this forest checkpoint is over 3 meters above the ground surface in the lidar data. Review by the surveyor deemed this survey checkpoint erroneous and unsuitable to use in the final vertical accuracy testing.

Figure 26 shows the location of the QA/QC checkpoints used to test the positional accuracy of the dataset.

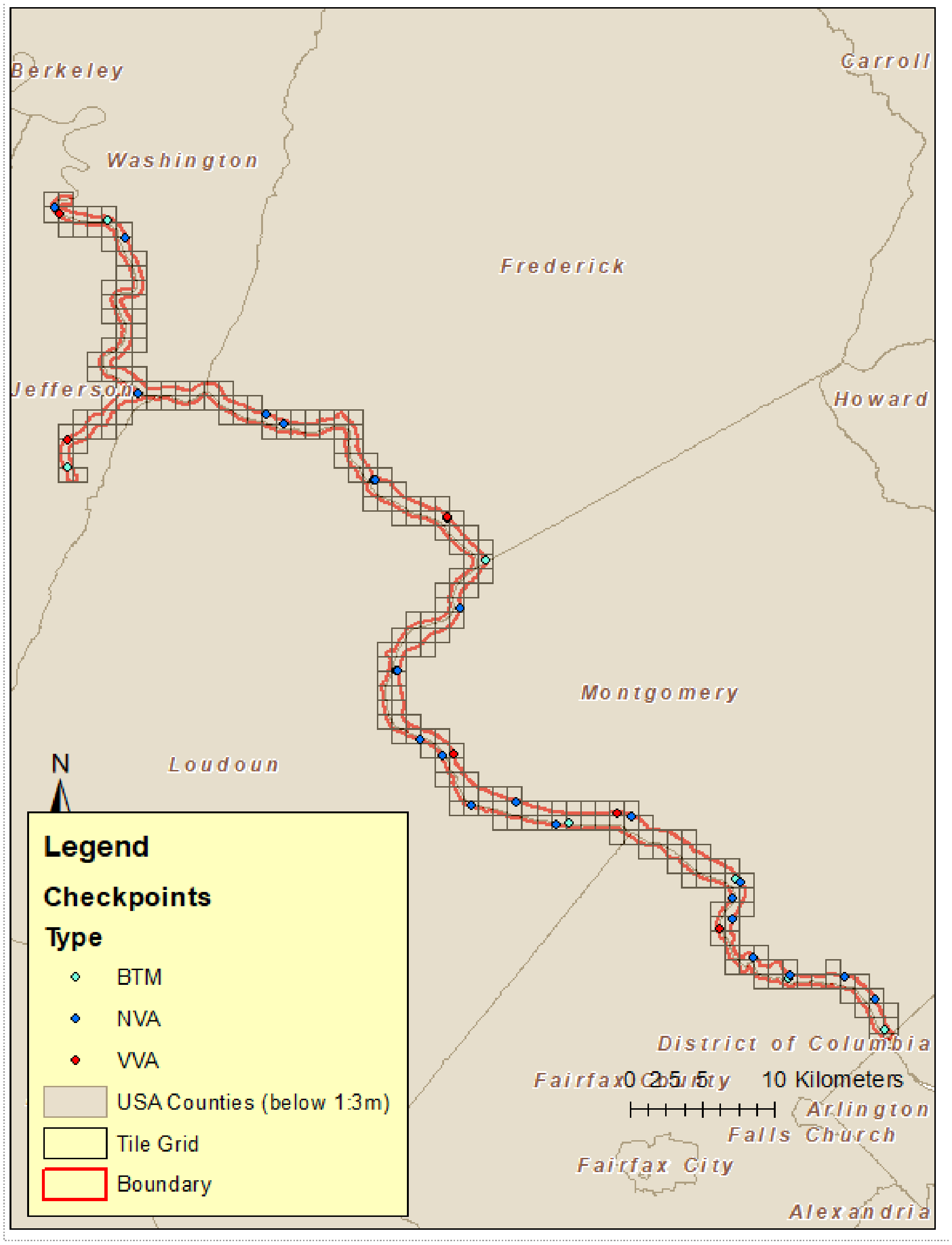


Figure 27 – Location of surveyed QA/QC checkpoints.

VERTICAL ACCURACY TEST PROCEDURES

NVA is determined with check points located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas, where there is a very high probability that the lidar sensor will have detected the bare-earth ground surface and where random errors are expected to follow a normal error distribution. The NVA determines how well the calibrated lidar sensor performed. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_z$) of the checkpoints x 1.9600. For the USGS Maryland Potomac project, vertical accuracy must be 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

BVA is determined with check points located only in submerged topography. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_z$) of the checkpoints x 1.9600. For the USGS Maryland Potomac lidar project, bathymetric vertical accuracy must be 35.3 cm or less based on an $RMSE_z$ of 18 cm x 1.9600.

VVA is determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas, where there is a possibility that the lidar sensor and post-processing may yield elevation errors that do not follow a normal error distribution. VVA at the 95% confidence level equals the 95th percentile error for all checkpoints in all vegetated land cover categories combined. The USGS Maryland Potomac Lidar Project VVA standard is 29.4 cm based on the 95th percentile. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the VVA; these are always the largest outliers that may depart from a normal error distribution. $Accuracy_z$ differs from VVA because $Accuracy_z$ assumes elevation errors follow a normal error distribution where RMSE procedures are valid, whereas VVA assumes lidar errors may not follow a normal error distribution in vegetated categories, making the RMSE process invalid.

The relevant testing criteria are summarized in Table 9.

Quantitative Criteria	Measure of Acceptability
Non-Vegetated Vertical Accuracy (NVA) in open terrain and urban land cover categories using $RMSE_z$ *1.9600	19.6 cm (based on $RMSE_z$ (10 cm) * 1.9600)
Bathymetric Vertical Accuracy in submerged topography using $RMSE_z$ *1.9600	35.3 cm (based on $RMSE_z$ (18 cm) * 1.9600)
Vegetated Vertical Accuracy (VVA) in all vegetated land cover categories combined at the 95% confidence level	29.4 cm (based on combined 95th percentile)

Table 8 — Acceptance criteria.

The primary QA/QC vertical accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications.
2. Dewberry interpolated the topobathy lidar DEM to provide the z-value for every checkpoint.
3. Dewberry computed the associated z-value differences between the interpolated z-value from the lidar data and the ground truth survey checkpoints and computed NVA, VVA, BVA and other statistics.
4. The data were analyzed by Dewberry to assess accuracy. The review process examined the various accuracy parameters as defined by the scope of work. The overall descriptive statistics of each dataset were computed to assess any trends or anomalies. This report provides tables, graphs and figures to summarize and illustrate data quality.

VERTICAL ACCURACY RESULTS

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

Land Cover Category	# of Points	NVA – Non-vegetated Vertical Accuracy (RMSE$_z$ x 1.9600) Spec=19.6 cm	VVA – Vegetated Vertical Accuracy (95th Percentile) Spec=29.4 cm	Bathymetric Vertical Accuracy (RMSE$_z$ x 1.9600) Spec=35.3 cm
NVA	23	7.6		
VVA	6		5.9	
BVA	10			16.5

Table 9 – Tested vertical accuracy.

The topographic portion of this lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be RMSE$_z$ =3.9 cm, equating to +/- 7.6 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 5.9 cm at the 95th percentile. The bathymetric portion of this lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for an 18.5 cm RMSEz Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be RMSEz = 8.4 cm, equating to +/- 16.5 cm at 95% confidence level.

Table 11 lists the 5% outliers that are larger than the VVA 95th percentile. Table 11 provides overall descriptive statistics for NVA, BVA, and VVA.

Point ID	NAD83(2011) UTM Zone 18		NAVD88 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-2	259650.296	4352917.798	93.652	93.590	-0.062	0.062

Table 10 – VVA 5% outliers.

100 % of Totals	# of Points	RMSEz (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	23	0.039	-0.019	-0.017	0.224	0.034	1.054	-0.087	0.070
VVA	6	N/A	-0.020	-0.022	0.199	0.036	-1.903	-0.062	0.029
BVA	10	0.084	-0.033	-0.027	0.282	0.082	0.722	-0.168	0.126

Table 11 – Vertical accuracy descriptive statistics.

Figure 25 illustrates a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the lidar TIN. The frequency shows the number of discrepancies within each band of elevation differences. Although the discrepancies vary between a low of -0.17 meters and a high of +0.13 meters, the histogram shows that the majority of the discrepancies are skewed on the positive side. The vast majority of points are within the ranges of -0.075 meters to +0.025 meters.

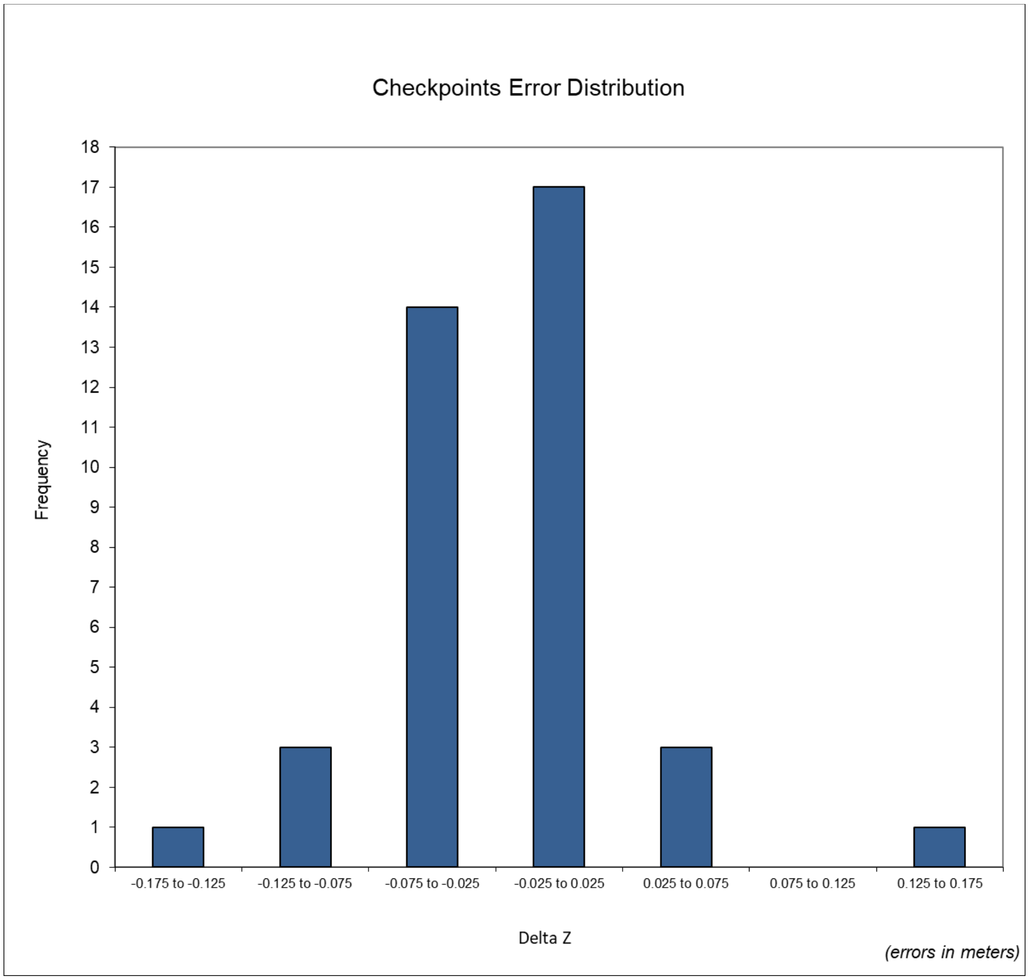


Figure 28 — Histogram of Elevation Discrepancies with errors in meters

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the USGS Maryland Potomac satisfies the project's pre-defined vertical accuracy criteria.

HORIZONTAL ACCURACY TEST PROCEDURES

Horizontal accuracy testing requires well-defined checkpoints that can be identified in the dataset. Elevation datasets, including lidar datasets, do not always contain well-defined checkpoints suitable for horizontal accuracy assessment. However, the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) recommends at least half of the NVA vertical check points should be located at the ends of paint stripes or other point features visible on the lidar intensity image, allowing them to double as horizontal check points.

Dewberry reviews all NVA checkpoints to determine which, if any, of these checkpoints are located on photo-identifiable features in the intensity imagery. This subset of checkpoints are then used for horizontal accuracy testing.

The primary QA/QC horizontal accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications and tried to locate half of the NVA checkpoints on features photo-identifiable in the intensity imagery.
2. Dewberry identified the well-defined features in the intensity imagery.
3. Dewberry computed the associated xy-value differences between the coordinates of the well-defined feature in the lidar intensity imagery and the ground truth survey checkpoints.
4. The data were analyzed to assess the accuracy of the data. Horizontal accuracy was assessed using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. This report provides the results of the horizontal accuracy testing.

HORIZONTAL ACCURACY RESULTS

Six checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. As only six checkpoints were photo-identifiable, the results are not statistically significant enough to report as a final tested value, but the results of the testing are still shown in the Table below.

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called ACCURACYr) is computed by the formula RMSEr * 1.7308 or RMSExy * 2.448.

No horizontal accuracy requirements or thresholds were provided for this project. However, lidar datasets are generally calibrated by methods designed to ensure a horizontal accuracy of 1 meter or less at the 95% confidence level.

# of Points	RMSE_x (Target=41 cm)	RMSE_y (Target=41 cm)	RMSE_r (Target=58 cm)	ACCURACY_r (RMSE_r x 1.7308) Target=100 cm
6	28.5	38.5	47.9	82.8

Table 12 - Tested horizontal accuracy at the 95% confidence level.

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSEx/RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 1 meter at a 95% confidence level. Six checkpoints were photo-identifiable but do not produce a statistically significant tested horizontal accuracy value. Using this small sample set of photo-identifiable checkpoints, positional accuracy of this dataset was found to be RMSEx = 28.5 cm and RMSEy = 38.5 cm which equates to +/- 82.8 cm at 95% confidence level. While not statistically significant, the results of the small sample set of checkpoints are within the produced to meet horizontal accuracy.

DEM Processing & Qualitative Assessment

The final topobathy DEMs are IMG format with 1 meter pixel cell size. Both a mosaic and tiled DEMs are delivered with this report. Tiled DEMs are named according to the U.S. National Grid (USNG) per project specifications. Void polygons were enforced in the DEMs so that bathymetric areas where no bathymetry was collected are NoData in the DEMs.

FINAL VOID POLYGONS

Final void polygons were created for use in the topobathymetric DEM production after all edits to the lidar were complete. Void polygons were revised after any subsequent QA/QC.

DEM GENERATION

DEMs were created using ground (class 2) and submerged topography (class 40) lidar point data. A TIN was generated from these data and rasterized at a 1 m spatial resolution using the LAStools blast2dem utility. Void polygons were used to eliminate areas of interpolation greater than 9 sq m in the DEMs. DEMs were created on a tile-by-tile basis based on the bounds of the source LAS tiles and, in the case of the merged DEM, mosaicked together into a single raster dataset.

DEM QUALITATIVE REVIEW

Dewberry performed a comprehensive qualitative assessment of the topobathy DEM deliverables to ensure that all DEM products were delivered with the proper extents, formatting, and contained the proper referencing information. This process was performed in ArcGIS software with the use of a tool set Dewberry has developed to verify that the raster extents match those of the tile grid, are formatted correctly, and contain the correct coordinate reference system information.

The final topobathy DEMs were then reviewed in ArcMap at a 1:5000 scale. A review with the void polygons visible and another review without the void polygons visible was performed in order to ensure voids were enforced properly and there were no issues along the boundaries of the void layer. Special attention was given along the land/water interface to ensure there were no hard edges along the interface (figure 26). Any remaining lidar issues and DEM artifacts were flagged by the reviewer and corrected by the editing team as necessary.

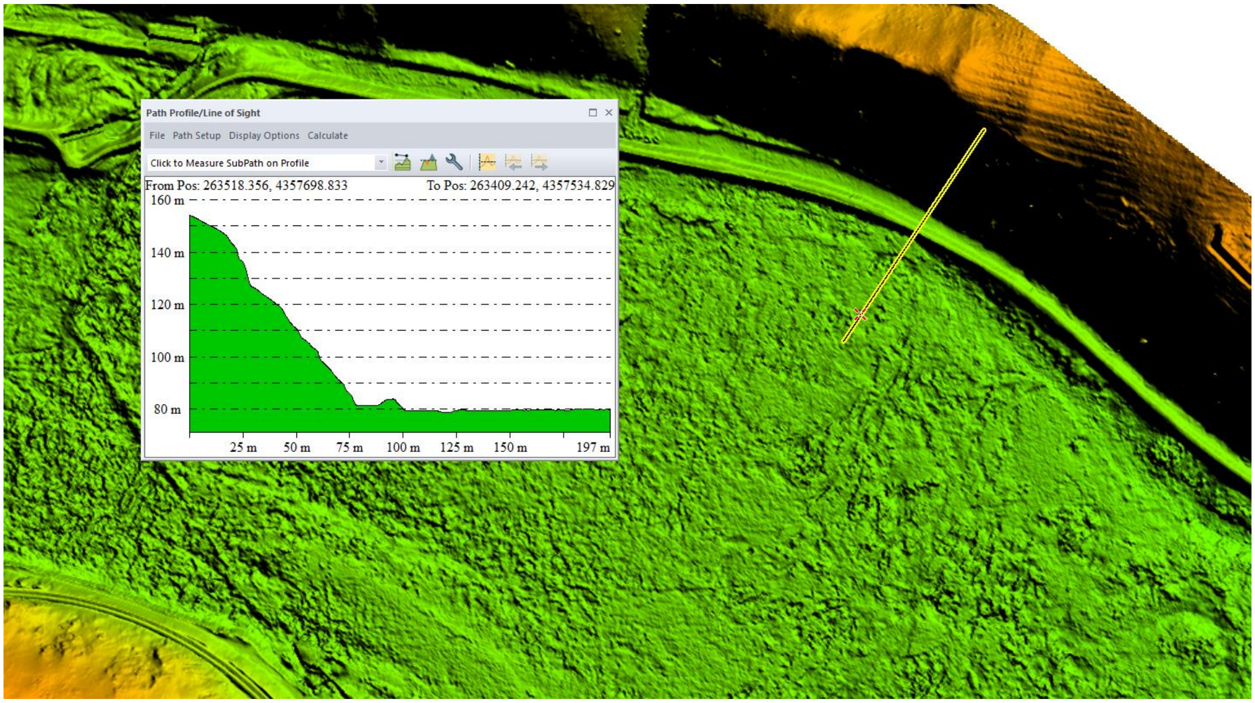


Figure 29 – DEM tile 18STJ630570. An example of the land-water interface is shown. No hard edges along the interface were identified during DEM QA/QC.

DEM QUANTITATIVE ASSESSMENT

The same 39 checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by averaging several lidar points within each pixel which may result in slightly different elevation values at each survey checkpoint when compared to the source LAS, which does not average several lidar points together but may interpolate (linearly) between two or three points to derive an elevation value. The vertical accuracy of the DEM is tested by extracting the elevation of the pixel that contains the x/y coordinates of the checkpoint and comparing these DEM elevations to the surveyed elevations. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

The survey checkpoints used to test this topobathymetric dataset are listed in the survey report included as Appendix A.

Table 14 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final DEM dataset.

Land Cover Category	# of Points	NVA – Non-vegetated Vertical Accuracy (RMSE_z x 1.9600) Spec=19.6 cm	VVA – Vegetated Vertical Accuracy (95th Percentile) Spec=29.4 cm	Bathymetric Vertical Accuracy (RMSE_z x 1.9600) Spec=35.3 cm
NVA	23	6.5		
VVA	6		5.0	
BVA	10			21.3

Table 13 – DEM tested NVA and VVA

The topographic portion of this DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be RMSE_z =3.3 cm, equating to +/- 6.5 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 5.0 cm at the 95th percentile. The bathymetric portion of this DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for an 18.5 cm RMSEz Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be RMSEz = 10.9 cm, equating to +/- 21.3 cm at 95% confidence level.

Table 15 lists the 5% outliers that are larger than the VVA 95^{th} percentile. Table 16 provides overall descriptive statistics.

Point ID	NAD83 UTM Zone 15		NAVD88 (Geoid 12B)	DEM Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-1	259047.208	4368522.729	114.999	114.947	-0.052	0.052

Table 14 – VVA 5% outliers.

100 % of Totals	# of Points	RMSEz (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	23	0.033	-0.019	-0.014	-0.375	0.028	-0.777	-0.069	0.019
VVA	6	N/A	-0.017	-0.030	0.854	0.036	-0.925	-0.052	0.038
BVA	10	0.109	-0.010	-0.027	0.935	0.114	0.873	-0.153	0.225

Table 15 – DEM vertical accuracy descriptive statistics.

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the USGS Maryland Potomac River satisfies the project's pre-defined vertical accuracy criteria.

DEM CHECKLIST

The following table represents a portion of the high-level steps in Dewberry's DEM Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	LAStools utilities were configured to meet project specifications for grid type, formatting, and cell size.
Pass	Manually review topobathymetric DEMs to check for issues
Pass	Special attention should be paid along the land/water interface
Pass	DEMs should be seamless across tile boundaries
Pass	Void polygons should be enforced.
Pass	Bridges should NOT be present in final topobathy DEMs.
Pass	Any remaining bridge saddles where below bridge breaklines were not used need to be fixed by adding below bridge breaklines and re-processing.
Pass	All qualitative issues present in the DEMs as a result of lidar processing and editing issues must be marked for corrections in the lidar These DEMs will need to be recreated after the lidar has been corrected.
Pass	Calculate DEM Vertical Accuracy including NVA, VVA, Bathymetric Vertical Accuracy and other statistics
Pass	Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression has not been applied to the tiled DEMs
Pass	Load all tiled DEMs into Global Mapper to verify complete coverage to the (buffered) project boundary and that no tiles are corrupt.

Table 16 – A subset of the high-level steps from Dewberry's bare earth DEM Production and QA/QC checklist performed for this project.

Metadata

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

Appendix A: Survey Report

Appendix B: GPS Processing Reports