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Potomac Topobathy

Report Produced for U.S. Geological Survey

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1. EXECUTIVE SUMMARY

The primary purpose of this project was to develop a consistent and accurate surface elevation dataset derived from high-accuracy Light Detection and Ranging (lidar) technology for the Potomac Topobathy Project Area.

The lidar data were processed and classified according to project specifications. Detailed breaklines and bare-earth Digital Elevation Models (DEMs) were produced for the project area. Data was formatted according to tiles with each tile covering an area of 1,000 m by 1,000 m. A total of 139 tiles were produced for the project encompassing an area of approximately 12.5 sq. miles.

Digital Direct-Georeferenced imagery was acquired for the project area. Imagery was tiled according to a 1,000 m by 1,000 m tile grid. A total of 116 imagery tiles were produced. Imagery could not be produced for 23 tiles because an area of the AOI was flown at night. This was approved by during coordination meetings with USGS NGTOC, ISGS EROS, and Dewberry.

1.1 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 was also responsible for georeferenced-imagery production, including ortho-rectification, and quality assurance of the ortho-mosaics, including horizontal accuracy testing.

Dewberry completed ground surveying for the project and delivered surveyed checkpoints. Their task was to acquire surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the lidar-derived surface model. They also verified the GPS base station coordinates used during lidar data acquisition to ensure that the base station coordinates were accurate.

Dewberry completed lidar data acquisition and data calibration for the project area.

Dewberry acquired the digital imagery, performed all ground control survey for the imagery, and performed the Aerotriangulation of the raw image frames.

1.2 Survey Area

The Potomac topobathymetric lidar survey project area covers approximately 12.5 square miles. There are 139 1,000 m x 1,000 m lidar tiles and DEM tiles, and 116 imagery tiles delivered for the project area. The project area boundary and overview are shown in Figure 1. Each tile's extent is 1,000 meters by 1,000 meters.

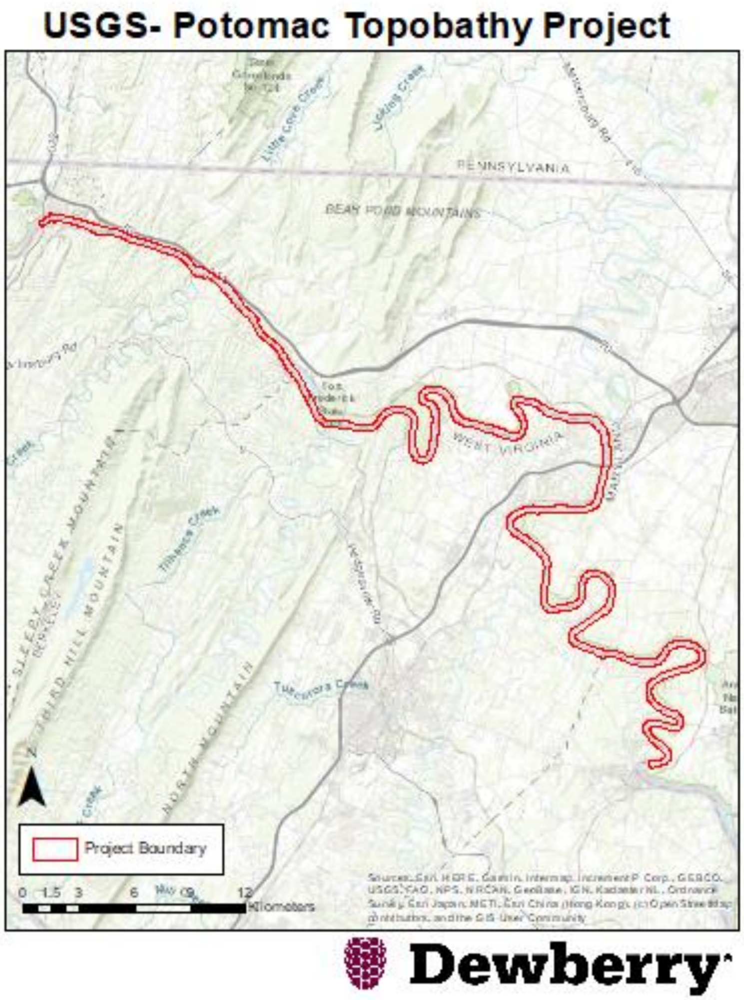

Figure 1. The image shows Potomac Topobathy collection area overview.

1.3 Date of Survey

The lidar aerial acquisition was conducted from October 03, 2021 through October 05, 2021.

1.4 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

Geoid Model: Geoid18

1.5 Lidar Vertical Accuracy

For the Potomac Topobathy project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain is **8.8 cm** and the non-vegetated vertical accuracy (NVA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **17.3 cm**.

For the Potomac Topobathy project, the tested $RMSE_z$ of the classified lidar data for checkpoints in submerged topography is **6.1 cm** and the bathymetric vertical accuracy (SBA) of the classified lidar data computed using $RMSE_z$ x 1.9600 is **12.0 cm**.

For the Potomac Topobathy project, the tested vegetated vertical accuracy (VVA) of the classified lidar data computed using the 95^{th} percentile is **9.8 cm**.

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

1.6 Project Deliverables

The deliverables for the project are listed below.

1. Classified Point Cloud Data (Tiled)
2. Bare Earth Surface (Raster DEM – GeoTIFF Format)
3. Intensity Images (8-bit gray scale, tiled, GeoTIFF format)
4. Direct-Georeferenced Imagery (tiled, GeoTIFF)
5. Height Separation Rasters (tiled, GeoTIFF Format)
6. Refraction Extent (File GDB)
7. Void shapefile (SHP)
8. Swath Separation Images (tiled, GeoTiFF Format)
9. Flightline Index (File GDB)
10. Independent Survey Checkpoint Data (Report, Photos, & Points)
11. Calibration Points
12. Metadata
13. Project Report
14. Project Extents, Including a shapefile derived from the lidar deliverable.

2. LIDAR ACQUISITION CONTROL

Dewberry acquired and calibrated the lidar data for this project. Acquisition was completed on October 3, 2021 and October 5, 2021.

2.1 Lidar Acquisition Details

Dewberry planned 116 passes for the project area as a series of parallel flight lines with cross flightlines for the purposes of quality control. The flight plan included zigzag flight line collection as a result of the inherent IMU drift associated with all IMU systems. In order to reduce any margin for error in the flight plan, Dewberry followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

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

Dewberry monitored weather and atmospheric conditions and conducted lidar missions only when no conditions exist below the sensor that will affect the collection of data. These conditions include leaf-off for hardwoods, no snow, rain, fog, smoke, mist and low clouds. Lidar systems are active sensors, not requiring light, thus missions may be conducted during night hours when weather restrictions do not prevent collection. Dewberry accesses reliable weather sites and indicators (webcams) to establish the highest probability for successful collection in order to position our sensor to maximize successful data acquisition.

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

Dewberry lidar sensors are calibrated at a designated site located at the Stennis International Airport in Stennis, Mississippi and are periodically checked and adjusted to minimize corrections at project sites.

2.1.1 Water Clarity and Water Flow Volume

Dewberry monitored the water clarity and flow volume to meet the clarity requirement specific to the Potomac River. Real-time water quality monitoring stations USGS 01613000 Potomac River at Hancock and USGS 01618000 Potomac River at Shepherdstown along the river gradient were used to monitor and analyze water clarity trends. Dewberry hosted weekly meetings with the client and project stakeholders prior to acquisition to review current environmental conditions. After several meetings it was determined by all parties involved that the conditions within the AOI were suitable for lidar collection based on flow rates from the stream gauges, turbidity readings provided by the stakeholders, and review of the weather forecast. Acquisition occurred during low-flow turbidity periods, however the flow rates were slightly above the desired levels listed in the original scope, which were stated as no more than 1000 cubic feet per second (cfs) at the Hancock Gauge and no more than 2000 cfs at the Shepherdstown Gauge. In reviewing these flow rates with the client and stakeholders, due to the precipitation forecasted in the coming days it was determined the levels were dropping and were low enough for acquisition to occur. At the time of acquisition, the flow rates were between 1280 cfs and 1490 cfs at the Hancock Gauge and between 2200 cfs and 2490 cfs at the Shepherdstown Gauge.

2.2 Lidar System Parameters

Dewberry operated a Cessna T-208 Caravan outfitted with a CZMIL SuperNova lidar system during the collection of the study area. Table 1 illustrates Dewberry system parameters for lidar acquisition on this project.

Table 1. Dewberry lidar system parameters

Item	Parameter(Bathy)	Parameter (Topo)
System	CZMIL SuperNova	CZMIL SuperNova
Altitude (AGL meters)	400	400
Approx. Flight Speed (knots)	120	120
Scanner Pulse Rate (kHz)	Proprietary	Proprietary
Scan Frequency (hz)	Proprietary	Proprietary
Pulse Duration of the Scanner (nanoseconds)	Proprietary	Proprietary
Pulse Width of the Scanner (m)	Proprietary	Proprietary
Swath width (m)	291	291
Central Wavelength of the Sensor Laser (nanometers)	532	1064
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	Yes	Yes
Beam Divergence (milliradians)	5	5
Nominal Swath Width on the Ground (m)	Proprietary	Proprietary
Swath Overlap (%)	20	20
Total Sensor Scan Angle (degree)	27	27
Computed Down Track spacing (m) per beam	Proprietary	Proprietary
Computed Cross Track Spacing (m) per beam	Proprietary	Proprietary
Nominal Pulse Spacing (single swath), (m)	0.35	0.35
Nominal Pulse Density (single swath) (ppsm), (m)	8	8
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.35	0.35
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	8	8
Maximum Number of Returns per Pulse	15	15

2.3 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 trajectory of the flightlines.

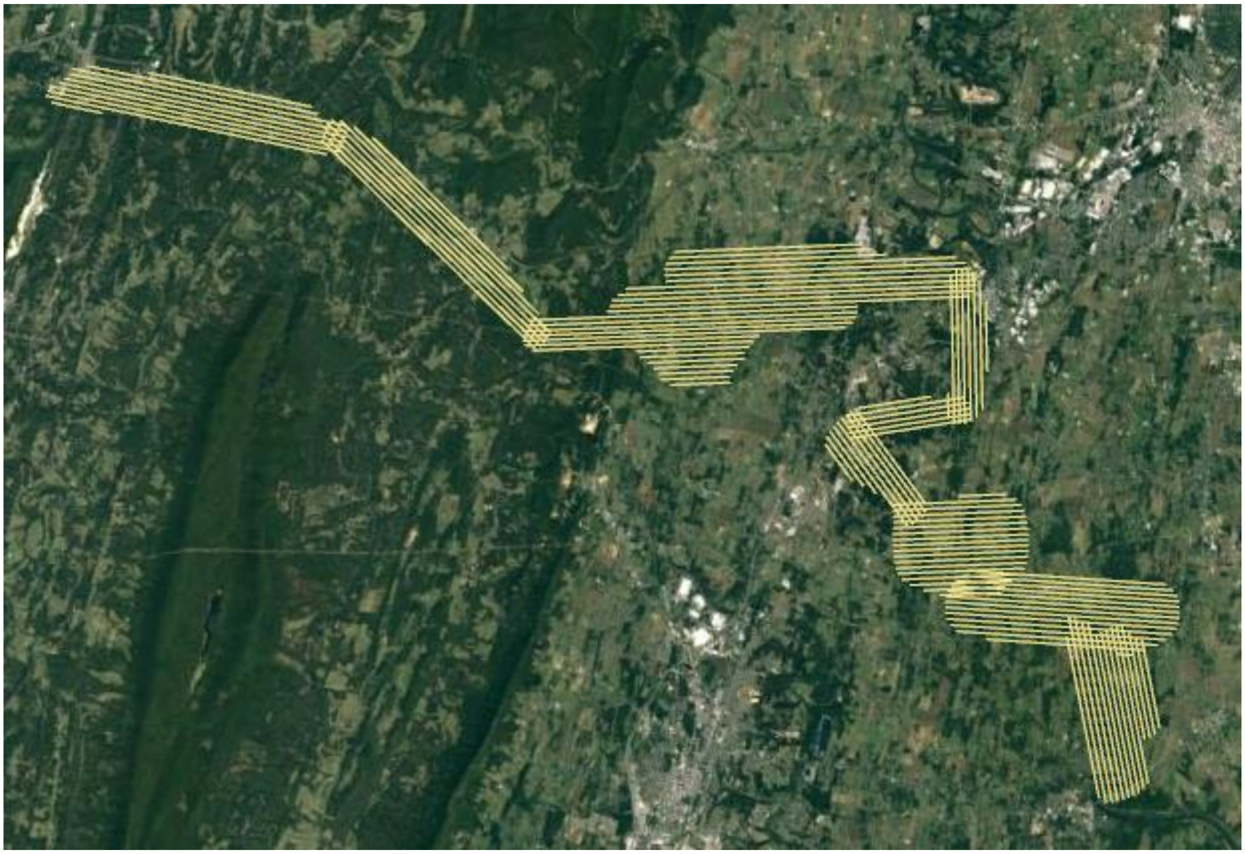

Figure 2. Trajectories as flown by Acquisition Provider X.

2.4 Lidar Acquisition Static Control

Two existing NGS monuments were used to control the lidar acquisition for the Potomac project area. The coordinates of all base stations used for acquisition control are provided in Table 2. All control and calibration points were also provided as part of the previously delivered survey package.

Table 2. Base stations used to control lidar acquisition

Station Name	NAD83(2011), UTM 18, m		NAD83(2011), m
	Easting (x)	Northing (y)	Elevation (Z)
DEW5	269247.58	4269247.58	-34.01
WVKE	248736.77	4358218.77	-33.92

2.5 Airborne Kinematic Control

Airborne GPS data was processed using the Applanix PosPac software suite. 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 average residuals for all flights were 3 cm or better, with no residuals greater than 10 cm recorded.

GPS processing reports for each mission were provided as part of the previously delivered survey package.

2.6 Generation and Calibration of Raw Lidar 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 Teledyne Geospatial's CARIS software suite. After applying the initial system calibration in CARIS, the refined swath to swath alignment was done using BayesMap Stripalign and then shifted to control. This aligned data was then reviewed for any remaining interswath relative accuracy issues.

Data collected by the lidar unit was reviewed for completeness, acceptable density, and to make sure all data were captured without errors or corrupted values. All GPS, aircraft trajectory, mission information, and ground control files were reviewed and logged. A supplementary coverage check was carried out (Figure 3) to ensure that there were no unreported gaps in data coverage.

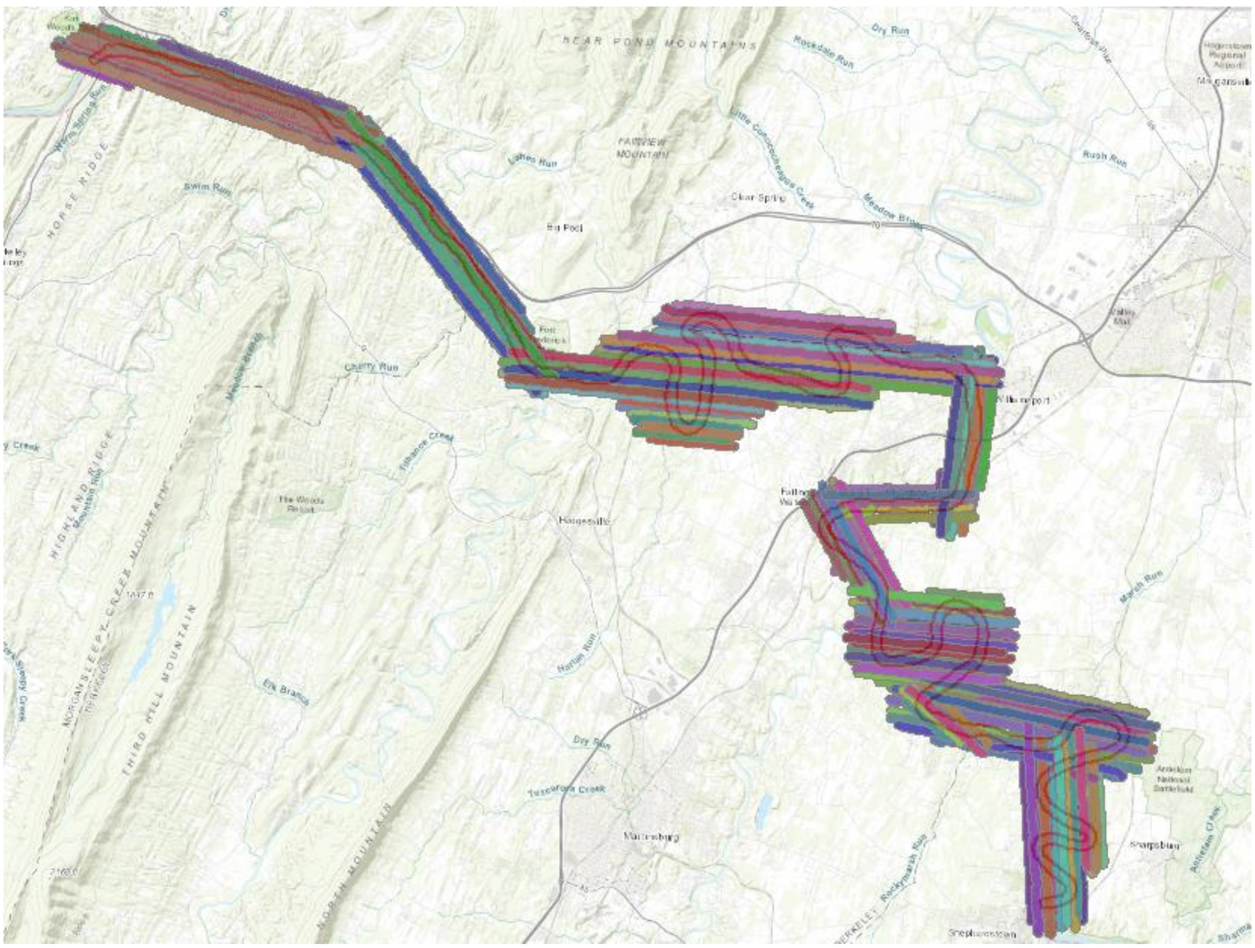

Figure 3. Lidar swath output showing complete coverage

2.7 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 relative accuracy requirements were met.

Relative accuracy and internal quality were checked using at least 3 regularly spaced QC blocks in which points from all lines were loaded and inspected. Vertical differences between ground surfaces of each line were displayed. Color scale was adjusted to flag errors that were not within project specifications (Figure 5). Cross sections were visually inspected across each block to validate point to point, flight line to flight line, and mission to mission agreement.

The following relative accuracy specifications were used for this project:

- ≤ 6 cm maximum difference within individual swaths (intra-swath); and
- ≤ 8 cm RMSDz between adjacent and overlapping swaths (inter-swath).

A different set of QC blocks were generated for final review after any necessary transformations were applied.

2.8 Refraction Correction

Bathymetric data must have a refraction correction applied. This process 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 initial automated refraction correction for this dataset was performed by Dewberry using Teledyne CARIS BASE Editor software. Additional local refraction corrections were performed using a Dewberry proprietary toolset in select areas where bathymetric/topographic domain differentiation in the point cloud was particularly complex (e.g., some nearshore areas).

2.9 Preliminary Vertical Accuracy Assessment

Dewberry performed a preliminary $RMSE_z$ error check in the raw lidar dataset against GPS static and kinematic data and compared the results to project specifications. The lidar data was examined in non-vegetated, flat areas away from breaks. An automated grounding routine was used by the provider to classify an initial ground surface for this analysis.

The calibrated Potomac lidar dataset was tested to 0.094 m $RMSE_z$ and 0.184 m vertical accuracy at the 95% confidence level when compared to 8 GPS static checkpoints (Table 3) surveyed by Dewberry. The results of the preliminary vertical accuracy assessment conducted by Dewberry are summarized in Table 4.

Upon delivery to Dewberry, the calibrated lidar data products collected by Dewberry met or exceeded the requirements set out in the Statement of Work. The quality control requirements of Dewberry's quality management program were adhered to throughout the data acquisition stage.

Table 3. Static GPS points used for acquisition provider's preliminary vertical accuracy assessment.

Number	NAD83(2011) UTM zone 18, m		NAVD88 Geoid 18 m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
GCP_1	259656.016	4371824.851	95.968	95.976	0.008
GCP_2	257005.074	4375276.362	101.301	101.418	0.117
GCP_3	252356.652	4383162.566	105.190	105.222	0.032
GCP_4	256013.601	4387925.379	119.838	119.901	0.063
GCP_5	248927.521	4388084.355	112.108	112.109	0.001
GCP_6	246105.873	4388414.690	115.081	115.075	-0.006
GCP_7	235841.136	4395581.757	119.142	119.169	0.027
GCP_8	228764.195	4398835.087	135.731	135.506	-0.225

Table 4. Summary of acquisition provider's vertical accuracy assessment results.

Land Cover Type	# of Points	$RMSE_z$ (m)	NVA (m)	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Project Specification	**-**	**0.100**	**0.196**	**-**	**-**	**-**	**-**
Non-Vegetated Terrain	8	0.094	0.184	0.002	0.100	-0.225	0.017

3. LIDAR PROCESSING & QUALITATIVE ASSESSMENT

3.1 Initial Processing

Dewberry performed vertical accuracy validation of the swath data, inter-swath relative accuracy validation, intra-swath relative accuracy validation, verification of horizontal alignment between swaths, validation of the refraction correction, and confirmation of point density and spatial distribution. This initial assessment allowed Dewberry to determine whether the data was suitable for full-scale production. Details are provided in the following sections.

3.1.1 Final Swath Vertical Accuracy Assessment

Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to further processing. Swath vertical accuracy was tested using 23 non-vegetated (open terrain and urban) independent survey checkpoints. Checkpoints were compared to a triangulated irregular network (TIN) 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 to remove vegetation, buildings, and other artifacts from the ground surface.) Dewberry used LP360 software to test the swath lidar vertical accuracy.

This raw lidar swath dataset 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 $RMSE_z$ = 6.9 cm, equating to ± 13.6 cm at the 95% confidence level. Project specifications required a NVA of 19.6 cm based on the $RMSE_z$ (10 cm) x 1.96. The swath data for the Potomac Topobathy Project satisfied these criteria. Table 5 shows calculated statistics for the raw swath data.

Table 5. NVA at the 95% confidence level for raw swaths.

Land Cover Type	# of Points	$RMSE_z$ (m)	NVA (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Project Specification	**-**	**0.100**	**0.196**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Non-Vegetated Terrain	23	0.069	0.136	0.047	0.059	-0.560	0.052	-0.046	0.123	-0.919

Checkpoint NVA-17 was removed from the raw swath vertical accuracy testing due to its location next to a rock pile. Though NVA-17 was located in open terrain, the rock pile was modeled by the lidar point cloud. Because the point cloud was not yet classified to remove vegetation, structures, and other above-ground features from the ground model, these high points produced erroneous elevation values during the swath vertical accuracy testing. Therefore, this point was removed from the final calculations. Once the data underwent classification, the rock piles were removed from the final ground classification and NVA-17 was usable in the final vertical accuracy testing, the results of which are reported in Section 4 of this report.

Table 6illustrates the effect of the rock pile on the apparent positional accuracy of the lidar data by comparing the surveyed elevation of NVA-17 with the elevation of the surface generated from the raw swath data (which includes the power line). Table 7 demonstrates that the effect of the rock pile is removed following classification of the lidar data. Figure 6 shows a 3D model of the lidar point cloud colored by elevation, with the location of the checkpoint beneath the power line marked by a pin.

Table 6. Vertical accuracy information for checkpoint removed from raw swath assessment.

Point ID	NAD83(2011) UTM zone 18, m		NAVD88 Geoid 18, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
NVA_17	257260.524	4379419.125	100.168	100.804	0.636

Table 7. Vertical accuracy information for checkpoint removed in final classified lidar.

Point ID	NAD83(2011) UTM zone 18, m		NAVD88 Geoid 18, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
NVA_17	257260.524	4379419.125	100.168	100.590	0.422

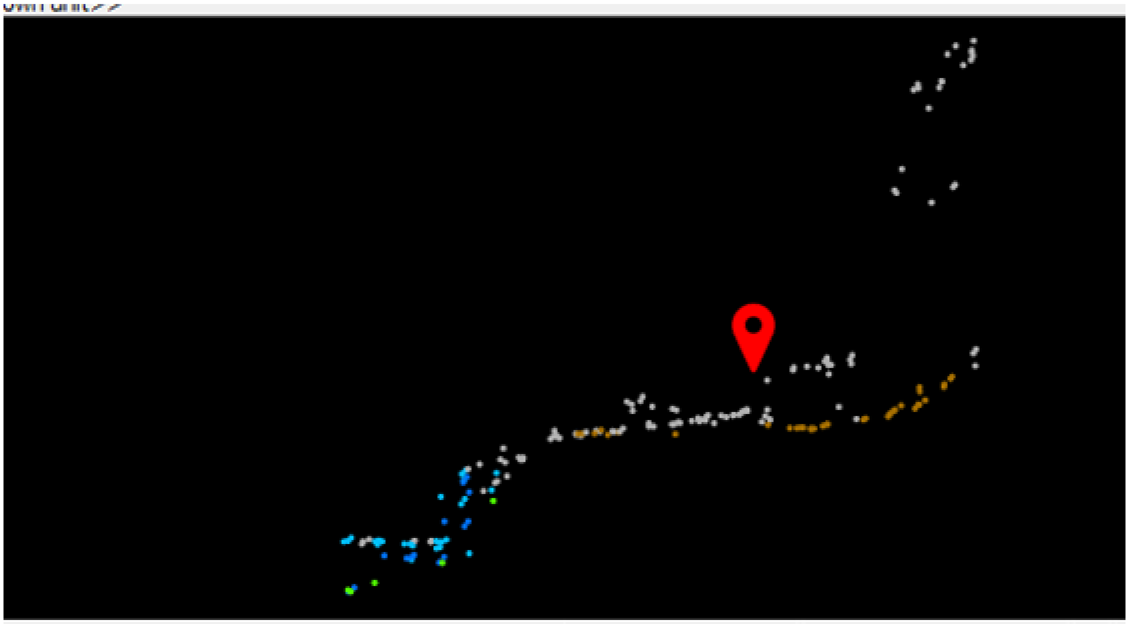

Figure 4. NVA-17 shown with the large pin. This point was removed from raw swath vertical accuracy testing because the overlying rock pile.

3.1.2 Interswath Relative Accuracy

According to the SOW, USGS Lidar Base Specifications v2.1, and *ASPRS Positional Accuracy Standards for Digital Geospatial Data*, data required to meet 10 cm accuracy class standards must have an interswath (between-swath) relative accuracy of 8 cm $RMSD_Z$ or less.

Prior to classification, Dewberry validated the precision of the lidar calibration by creating delta-Z (DZ) rasters to visualize interswath accuracy. These rasters were generated with 1 m cell resolution based on the maximum difference in elevation between undifferentiated only returns in non-vegetated areas of overlap between flight lines. Each pixel of the raster was colorized according to the resulting value. Cells where overlapping flight lines were within 8 cm of each other were colored green, cells where overlapping flight lines had elevation differences between 8 cm and 16 cm were colored yellow, and cells where overlapping flight lines had elevation differences greater than 16 cm were colored red. Pixels that did not contain points from overlapping flight lines were designated as NoData and left empty.

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 rasters. Bathymetric areas can also appear yellow or red due to factors like different tidal stages between missions. Large or continuous sections of yellow or red pixels following terrain features or land cover zones are typically reflective of variable or unfavorable (e.g., vegetated) conditions for DZ measurements, whereas large or continued sections of yellow or red pixels following flight line patterns can indicate acquisition or calibration issues. The interswath DZ rasters for Potomac Topobathy are shown in Figure 5. Based on visual inspection, no issues with swath-to-swath calibration were noted.

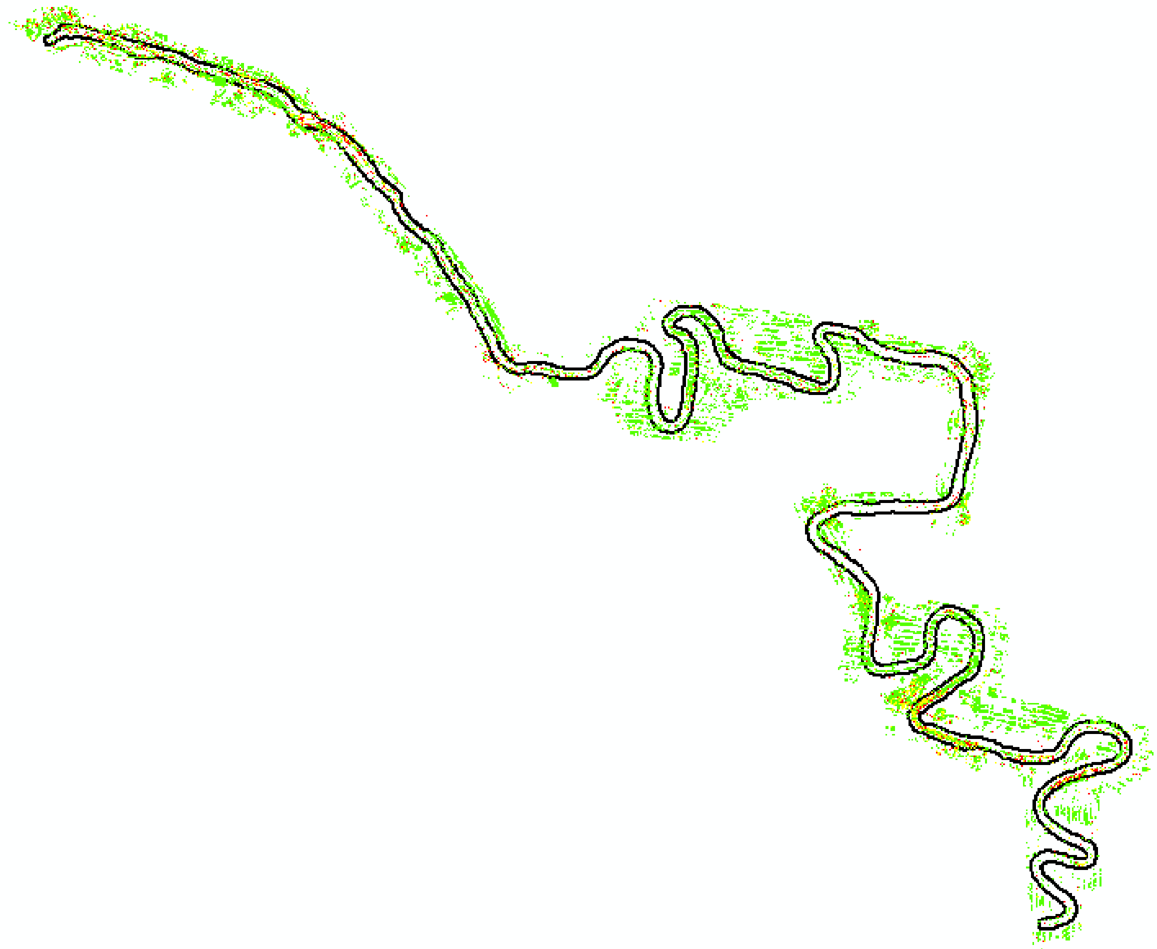

Figure 5. Single return interswath DZ rasters for the Potomac Topobathy Project.

3.1.3 Intraswath Relative Accuracy

According to the SOW, USGS Lidar Base Specifications v2.1, and *ASPRS Positional Accuracy Standards for Digital Geospatial Data*, data required to meet 10 cm accuracy class standards must have an intraswath (within-swath) relative accuracy of 6 cm maximum difference or less.

Dewberry validated the intraswath relative accuracy prior to classification by generating and reviewing DZ rasters. These rasters were generated with 1 m cell resolution based on the maximum difference in elevation between undifferentiated only returns in non-vegetated areas of single flight line coverage. Each pixel of the raster was colorized according to the average difference in elevation between overlapping points. Cells where the maximum elevation difference between points was within 6 cm were colored green, and cells where the maximum difference was greater than 6 cm were colored red.

Areas of vegetation and steep slopes (slopes with 6 cm or more of valid elevation change across 1 linear meter) are expected to appear red in the DZ rasters, as are areas of bathymetric coverage since bathymetric returns are typically not only returns. Overlap areas can also appear red due to different acquisition conditions between missions. Large or continuous sections red pixels following terrain features or land cover zones are typically reflective of variable or unfavorable (e.g., vegetated) conditions for DZ measurements, whereas large or continued sections of red pixels in flat, relatively featureless areas can indicate sensor issues. The intraswath DZ rasters for Potomac Topobathy are shown in Figure 6. Based on visual inspection, no issues with hard surface repeatability were noted.

Figure 6. Intraswath DZ rasters for the Potomac Topobathy project, flat, open areas are colored green as they are within 6 cm whereas sloped terrain is colored red because it exceeds 6 cm.

3.1.4 Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Dewberry reviews point cloud profiles in areas of overlap to identify horizontal shifts or misalignments between swaths on roof tops and other elevated planar surfaces. Figure 7 shows an example of the horizontal alignment between swaths for Potomac Topobathy; no horizontal alignment issues were identified.

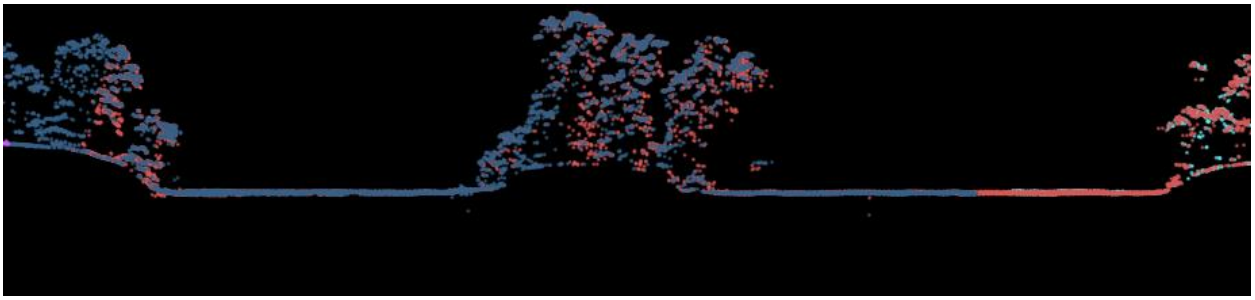

Figure 7. Three separate flight lines are differentiated by color (Blue, pink, and teal) to determine whether horizontal misalignments are present. This is a representative example; there is no visible offset between these flight lines.

3.1.5 Point Density

The required topo-lidar data 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 (ppsm) or greater; the planning bathymetric-lidar data at no less than 1.5 ppsm in shallow water (Shallow bathymetry Dmax = 2.4 / k (~1.5 Secchi depth), however, it is understood that a required ANPD may not be met in the bathymetric domain due to environmental conditions. Density calculations were performed using only first return data located in the geometrically usable center portion (typically ~90%) of each swath. LAS dataset statistics yielded an average bathymetric ANPS of 0.4 meters (equivalent to an ANPD of 6.25 ppsm), exclusive of bathymetric void areas, which meets project specifications.

Spatial distribution was reviewed to verify that there was no clustering of points or unacceptable void areas. This evaluation was based on the number of 1-meter cells in the dataset that contained at least one lidar point. No distribution anomalies were noted.

3.2 Data Classification and Editing

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data were validated, the lidar dataset was moved into processing and production. These steps included refraction extent creation to define the land/water interface and constrain void polygons, automated and manual editing of the lidar tiles, QA/QC, and final formatting of all products.

3.2.1 Point Cloud Processing

Dewberry utilized CARIS and TerraScan software for processing. The acquired raw point clouds were imported into CARIS for conversion to LAS format and output with an initial classification schema based on stored sensor data. The LAS were tiled according to the project tile grid. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine classified any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. After points that could negatively affect the ground were removed from class 1, the ground layer was extracted from this remaining point cloud using an iterative surface model.

After the initial automated ground routine, each tile was imported into TerraScan and a surface model was created. Dewberry analysts visually reviewed the topo-bathymetric surface model and corrected errors in the ground classification such as vegetation, buildings, bridges, and grounded water column or surface that were in ground classes following the initial processing. Analysts also looked for features that were present in the point cloud but not reflected in the ground model, including obstacles to marine navigation.

The withheld bit was set for points deemed to be noise, outliers, blunders, or geometrically unreliable outside the flight line overlap areas.

The synthetic bit was set for artificial points introduced in the point cloud by the processing software.

The final classification schema is detailed in Table 8.

Table 8. Final classification schema used in delivered lidar data.

Class	Definition
1	Unclassified, used for all other features that do not fit into the Classes 2, 7, 9, 17, 18, or 20. Includes vegetation, buildings, etc.
2	Bare-Earth Ground
7	Low Noise
18	High Noise
40	Bathymetric Point, Submerged Topography
41	Water Surface
42	Derived Water Surface, used in computing refraction
45	Water Column, Neither surface nor bottom

After manual classification, the LAS tiles were peer reviewed and then underwent a final independent QA/QC (detailed in Section 3.3). After the final QA/QC and corrections, all headers, appropriate point data records, and variable length records, including spatial reference information, were updated and verified using proprietary Dewberry tools.

3.3 Lidar Qualitative Assessment

Dewberry's qualitative assessment of lidar point cloud data utilized a combination of statistical analyses and visual interpretation. Methods and products used in the assessment included profile- and map view-based point cloud review, pseudo image products (e.g., intensity orthoimages), TINs, DEMs, DSMs and point density rasters. This assessment looked for incorrect classification and other errors sourced in the LAS data. Lidar data are peer reviewed, reviewed by task leads (senior level analysts), and verified by an independent QA/QC team at key points within the lidar workflow.

3.3.1 Qualitative Review

The following table describes Dewberry's standard editing and review guidelines for specific types of features, land covers, and lidar characteristics.

Table 9. Lidar editing and review guidelines.

Category	Editing Guideline	Additional Comments
No Data Voids	The SOW for the project defines unacceptable data voids as voids greater than 4 x $ANPS^2$, or 1.96 m^2, that are not related to water bodies or other areas of low near-infrared reflectivity and are not appropriately filled by data from an adjacent swath. The LAS files were used to produce density grids based on Class 2 (ground) and class 40 (bathymetric bottom) points for review.	No unacceptable voids were identified in this dataset
Artifacts	Artifacts in the point cloud are typically caused by misclassification of points in vegetation or man-made structures as ground. Low-lying vegetation and buildings are difficult for automated grounding algorithms to differentiate and often must be manually removed from the ground class. Dewberry identified these features during lidar editing and reclassified them to Class 1 (unassigned). Artifacts up to 0.3 m above the true ground surface may have been left as Class 2 because they do not negatively impact the usability of the dataset.	None
Culverts and Bridges	It is Dewberry's standard operating procedure to leave culverts in the bare earth surface model and remove bridges from the model. In instances where it is difficult to determine whether the feature was a culvert or bridge, Dewberry errs on the side of culverts, especially if the feature is on a secondary or tertiary road.	None
In-Ground Structures	In-ground structures typically occur on military bases and at facilities designed for munitions testing and storage. When present, Dewberry identifies these structures in the	No in-ground structures present in this dataset

Category	Editing Guideline	Additional Comments
	project and includes them in the ground classification.	
Dirt Mounds	Irregularities in the natural ground, including dirt piles and boulders, are common and may be misinterpreted as artifacts that should be removed. To verify their inclusion in the ground class, Dewberry checked the features for any points above or below the surface that might indicate vegetation or lidar penetration and reviews ancillary layers in these locations as well. Whenever determined to be natural or ground features, Dewberry edits the features to class 2 (ground)	No dirt mounds or other irregularities in the natural ground were present in this dataset
Wetland/Marsh Areas	Vegetated areas within wetlands/marsh areas are not considered water bodies and are not hydroflattened in the final DEMs. However, it is sometimes difficult to determine true ground in low wet areas due to low reflectivity. In these areas, the lowest points available are used to represent ground, resulting in a sparse and variable ground surface.	No marshes present in the data
Flight Line Ridges	Flight line ridges occur when there is a difference in elevation between adjacent flight lines or swaths. If ridges are visible in the final DEMs, Dewberry ensures that any ridges remaining after editing and QA/QC are within project relative accuracy specifications.	No flight line ridges are present in the data
Temporal Changes	If temporal differences are present in the dataset, the offsets are identified with a shapefile.	No temporal offsets are present in the data
Low NIR Reflectivity	Some materials, such as asphalt, tars, and other petroleum-based products, have low NIR reflectivity. Large-scale applications of these products, including roadways and roofing, may have diminished to absent lidar returns. USGS LBS allow for this characteristic of lidar but if low NIR	No Low NIR Reflectivity is present in the data

Category	Editing Guideline	Additional Comments
	reflectivity is causing voids in the final bare earth surface, these locations are identified with a shapefile.	
Laser Shadowing	Shadows in the LAS can be caused when solid features like trees or buildings obstruct the lidar pulse, preventing data collection on one or more sides of these features. First return data is typically collected on the side of the feature facing toward the incident angle of transmission (toward the sensor), while the opposite side is not collected because the feature itself blocks the incoming laser pulses. Laser shadowing typically occurs in areas of single swath coverage because data is only collected from one direction. It can be more pronounced at the outer edges of the single coverage area where higher scanning angles correspond to more area obstructed by features. Building shadow in particular can be more pronounced in urban areas where structures are taller. Data are edited to the fullest extent possible within the point cloud. As long as data meet other project requirements (density, spatial distribution, etc.), no additional action taken.	No Laser Shadowing is present in the data

3.3.2 Formatting

After the final QA/QC was performed and all corrections were applied to the dataset, all lidar files were updated to the final format requirements as defined in the SOW. These requirements are detailed in Table 10.

Table 10. Final formatting of the delivered data.

Parameter	Requirement
LAS Version	1.4
Point Data Record Format	6
Coordinate Reference System	NAD83 (2011) UTM zone 18, meters and NAVD88 (Geoid 18), meters in WKT Format
Global Encoder Bit	17 (for Adjusted GPS Time)
Time Stamp	Adjusted GPS Time (unique timestamps)
Intensity	8 bit, recorded for each pulse
Withheld and Synthetic Points	Withheld and Synthetic flags, properly set

4. LIDAR POSITIONAL ACCURACY

4.1 Background

Dewberry quantitatively tested the vertical accuracy of the lidar to confirm adherence of the dataset to project specifications. Discrete surveyed (real-world) checkpoint elevation coordinates were compared to the surface elevation values at the corresponding X and Y coordinates on TIN surfaces created from the unclassified (swath) and classified lidar data. Relative accuracy testing determined how consistently the lidar data was collected and enabled extrapolation of the point-based absolute accuracy results to the broader dataset. I.e., if the relative accuracy of the dataset was found to be within specifications *and* the dataset passed absolute vertical accuracy requirements at the locations of survey checkpoints, the vertical accuracy results were considered valid throughout the whole dataset with high confidence. Dewberry used LP360 to test the swath lidar vertical accuracy, TerraScan to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different methods were used to validate the vertical accuracy for the project.

Horizontal accuracy testing requires survey checkpoints located such that the checkpoints are photo-identifiable in the intensity imagery. No photo-identifiable checkpoints were surveyed for this project, so the horizontal accuracy was not tested.

4.2 Survey Vertical Accuracy Checkpoints

Dewberry surveyed 42 checkpoints for the project. Survey checkpoints were located within bare earth/open terrain, grass/weeds/crops, brush/low trees, forested/fully grown, and submerged topography land cover categories. Checkpoints were evenly distributed throughout the project area to cover as many flight lines as possible. The locations of the QA/QC checkpoints used to test the positional accuracy of the dataset are shown in Figure 9. All checkpoints surveyed for vertical accuracy testing purposes are listed in Table 11.

Table 11. Surveyed accuracy checkpoints

Point ID	NAD83(2011) UTM zone 18, m		NAVD88 Geoid 18, m
	Easting (x)	Northing (y)	Elevation (z)
NVA_1	227175.200	4399065.865	125.585
NVA_2	229584.461	4398561.396	126.232
NVA_3	232386.907	4397415.944	122.827
NVA_4	236079.841	4395351.624	119.945
NVA_6	239785.504	4390942.695	118.428
NVA_7	241521.413	4388385.924	118.259
NVA_8	245137.287	4388498.011	115.347
NVA_9	246441.239	4386680.502	115.615
NVA_10	246682.950	4385966.239	114.868
NVA_11	248480.663	4389081.918	113.772
NVA_12	255398.079	4388334.795	110.077
NVA_13	254687.411	4383414.503	107.708
NVA_14	251800.017	4382813.271	108.536
NVA_15	247037.065	4389147.008	112.187
NVA_16	253657.595	4377918.108	102.696
NVA_18	255339.990	4376262.934	100.745

Point ID	NAD83(2011) UTM zone 18, m		NAVD88 Geoid 18, m
	Easting (x)	Northing (y)	Elevation (z)
NVA_19	256967.651	4375638.030	102.168
NVA_20	262004.474	4375885.833	97.988
NVA_21	261072.151	4372092.875	95.585
NVA_22	260471.874	4371641.237	95.655
NVA_23	259477.075	4369622.474	94.293
NVA_24	261114.219	4376097.527	97.802
NVA_25	257095.898	4387132.120	103.261
VVA_1	227280.714	4399046.072	124.554
VVA_2	236180.331	4395331.450	120.132
VVA_3	241524.491	4388365.052	118.313
VVA_4	250025.794	4387945.720	110.464
VVA_5	257157.149	4387034.650	104.301
VVA_6	254033.386	4383303.638	106.823
VVA_7	253752.538	4379881.900	103.911
VVA_8	255150.213	4376515.733	101.462
VVA_9	260607.539	4372368.461	100.813
SBA_1	260952.410	4372111.843	86.165
SBA_2	261970.480	4375814.603	89.273
SBA_3	257069.799	4375369.086	91.574
SBA_4	255336.989	4376194.039	97.647
SBA_5	257064.268	4387072.628	100.747
SBA_6	249158.608	4388184.723	103.852
SBA_7	245147.761	4388457.846	108.814
SBA_8	239853.675	4390974.508	111.539
SBA_9	227165.071	4398992.744	117.969

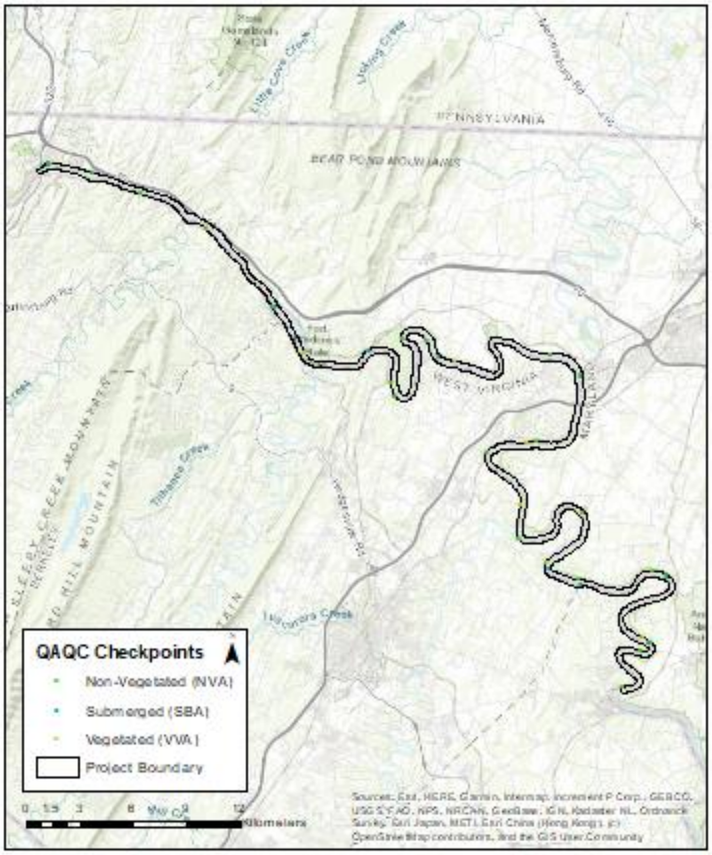

Figure 8. Location of all surveyed checkpoints

Dewberry surveyed 42 checkpoints for vertical accuracy testing. While reviewing the coordinates of the survey checkpoints against the field sketches and lidar intensity imagery, Dewberry identified issues with one checkpoint. The one checkpoint had no recorded location, but survey photos were included in the survey report.

Three checkpoints were removed from the classified lidar vertical accuracy testing. VVA_9 (Figure 9) showed a 4-meter difference between the surveyed elevation and the lidar elevation, with no issues in the lidar data to support the discrepancy. The surveyor reviewed and recalculated this checkpoint but could not account for the issue. The checkpoint was therefore considered low confidence and removed from the final vertical accuracy testing. Even without this checkpoint, there were enough total checkpoints and enough checkpoints per land cover category to satisfy project requirements.

Figure 9. The surveyed elevation of checkpoint VVA_9 is over 4 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.

One checkpoint (NVA_17) was removed from the classified lidar vertical accuracy testing due to its proximity to breaks in the terrain. Per the task order, checkpoints should not be located within 5 meters of a significant change in slope. Breaks in the terrain may cause erroneous vertical accuracy results due to interpolation of the surface. Points on such terrain do not adequately test how well a sensor or a vegetation filtering technique performed. The coordinates of this checkpoint are provided in Table 11, and a profile showing the checkpoint located near breaks in the terrain are shown in Figure 8.

Table 12. Checkpoints removed from classified vertical accuracy testing

Point ID	State Plane VA North NAD83(2011), ft		NAVD88 Geoid 12B, ft		Delta z, ft
	Easting (x)	Northing (y)	Survey z	Lidar z	
NVA_17	257260.524	4379419.125	100.168	100.590	0.422
VVA_9	260607.539	4372368.461	100.813	96.600	-4.213

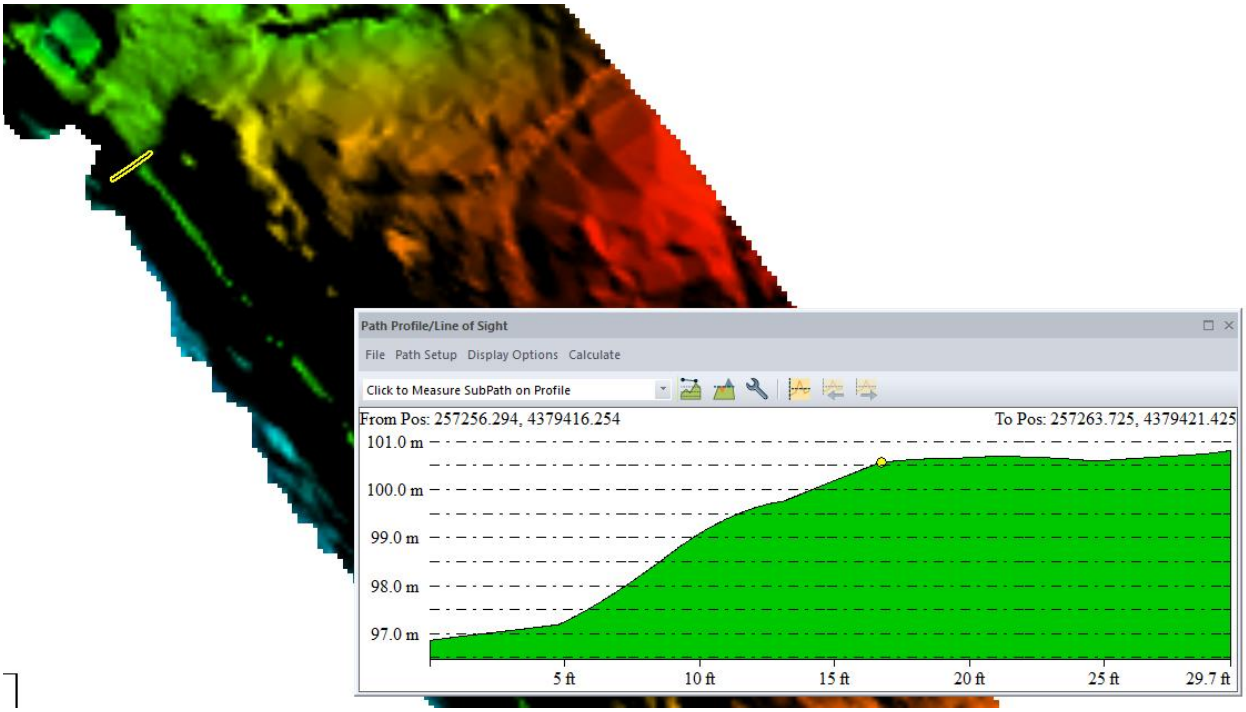

Figure 8. Checkpoint NVA_17, shown as the yellow circle in the profile, is located near a pile or rock. This checkpoint was removed from final classified vertical accuracy testing due to its location on a slope.

4.3 Vertical Accuracy Test Procedures

NVA reflects the calibration and performance of the lidar sensor. NVA was determined with checkpoints located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas. In these locations it is likely that the lidar sensor detected the bare-earth ground surface and random errors are expected to follow a normal error distribution. Assuming 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 Potomac Topobathy lidar project, the vertical accuracy specification is 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

SBA was determined with check points located only on 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. The $RMSE_z$ for the SBA is a depth-dependent value that takes into account increasing uncertainty with depth using two uncertainty coefficients. For the Potomac Topobathy lidar project, bathymetric vertical accuracy specification is 36.3 cm or less based on an $RMSE_z$ of 19.5 cm x 1.9600.

VVA was determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas. In these locations 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 Potomac Topobathy lidar project VVA specification is 30.0 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. In addition to the combined VVA, separate assessments were conducted for tall grass/weeds/crops and fully forested land cover categories.

The relevant testing criteria are summarized in Table 13.

Table 13. Vertical accuracy acceptance criteria

Land Cover Type	Quantitative Criteria	Measure of Acceptability
NVA	Accuracy in open terrain and urban land cover categories using $RMSE_z$ *1.9600	19.6 cm
SBA	Accuracy in submerged topography using $RMSE_z$ *1.9600	36.3 cm
VVA	Accuracy in vegetated land cover categories combined at the 95% confidence level	30.0 cm

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

1. Dewberry's team surveyed X, Y, and z coordinates for discrete checkpoints in accordance with project specifications.
2. Dewberry interpolated the bare-earth lidar DTM to determine a lidar surface z coordinate for every surveyed X and Y coordinate.
3. Dewberry computed difference between each surveyed z coordinate and lidar surface z coordinate.
4. The resulting differences were analyzed by Dewberry to assess the accuracy of the data. The overall descriptive statistics of each dataset were computed to assess any trends or anomalies. The results are provided in the following section.

4.4 Vertical Accuracy Results

Table 14 summarizes the tested vertical accuracy of the classified lidar LAS files.

Table 14. Classified lidar vertical accuracy results

Land Cover Type	# of Points	NVA (m)	SBA (m)	VVA (m)
Project Specification		**0.196**	**0.363**	**0.300**
NVA	23	0.173		
SBA	9		0.120	
VVA	8			0.098

The topographic portion of this dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 8.8 cm, equating to ± 17.3 cm at 95% confidence level. Actual VVA accuracy was found to be ± 9.8 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 $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 6.1 cm, equating to ± 12.0 cm at 95% confidence level.

The VVA 5% outliers are listed in Table 15. Descriptive statistics for all categories are presented in Table 16.

Table 15. VVA 5% outliers

Point ID	UTM zone 15N NAD83(2011), m		Ellipsoid Heights, NAD83(2011), m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
VVA_8	255150.213	4376515.733	101.462	101.570	0.108

Table 16. Classified lidar vertical accuracy descriptive statistics

Land Cover Type	# of Points	$RMSE_z$ (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	23	0.088	0.017	0.033	-2.175	0.089	-0.295	0.115	6.241
SBA	9	0.061	0.028	0.056	-1.111	0.058	-0.089	0.091	0.621
VVA	8	0.057	0.031	0.038	-0.023	0.052	-0.042	0.108	-1.043

Figure 9 and Figure 10 show histograms illustrating the distribution of discrepancies between the survey checkpoint elevations and the corresponding lidar surface elevations.

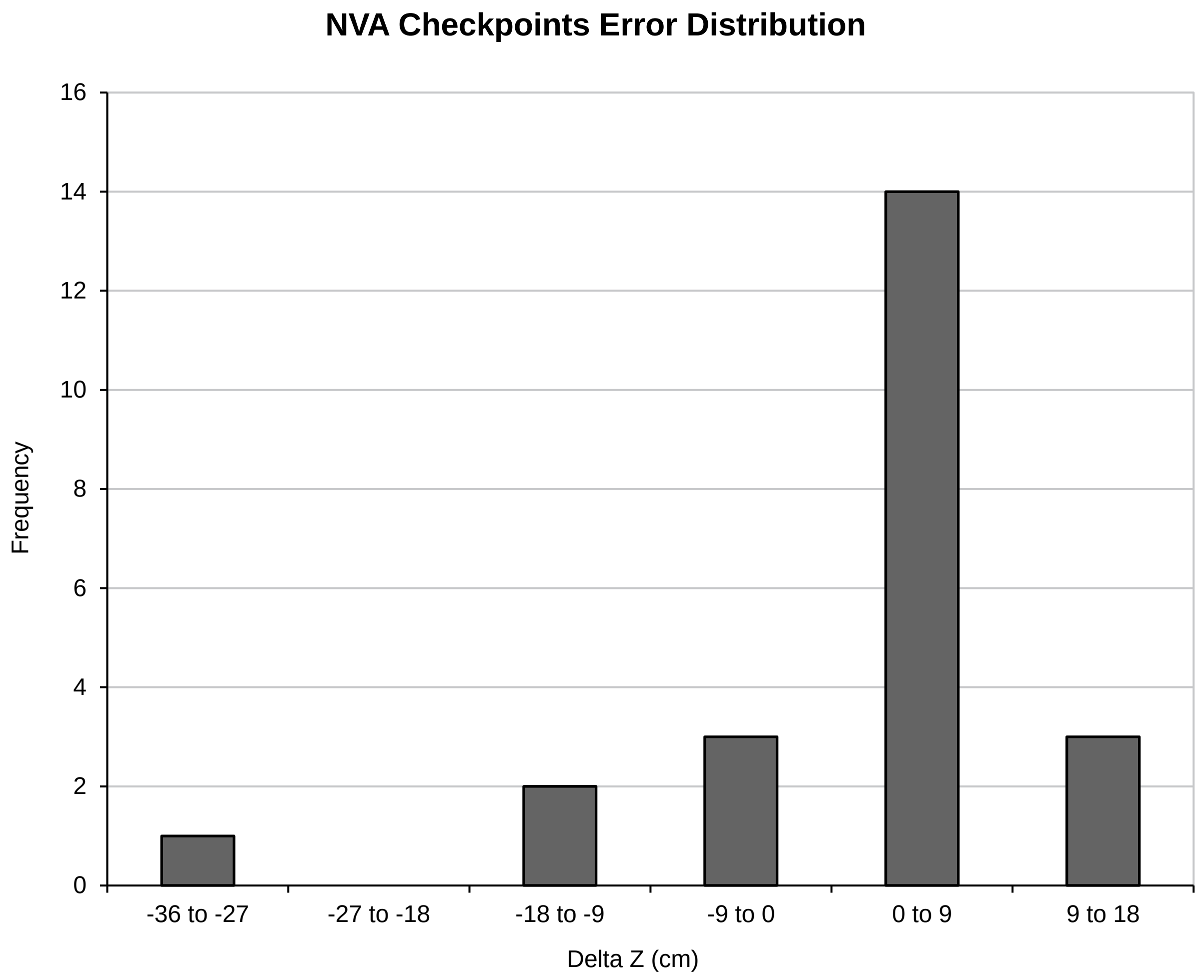

Figure 9. Distribution of elevation discrepancies between non-vegetated surveyed checkpoints and lidar surface. All individual NVA checkpoints meet NVA requirements.

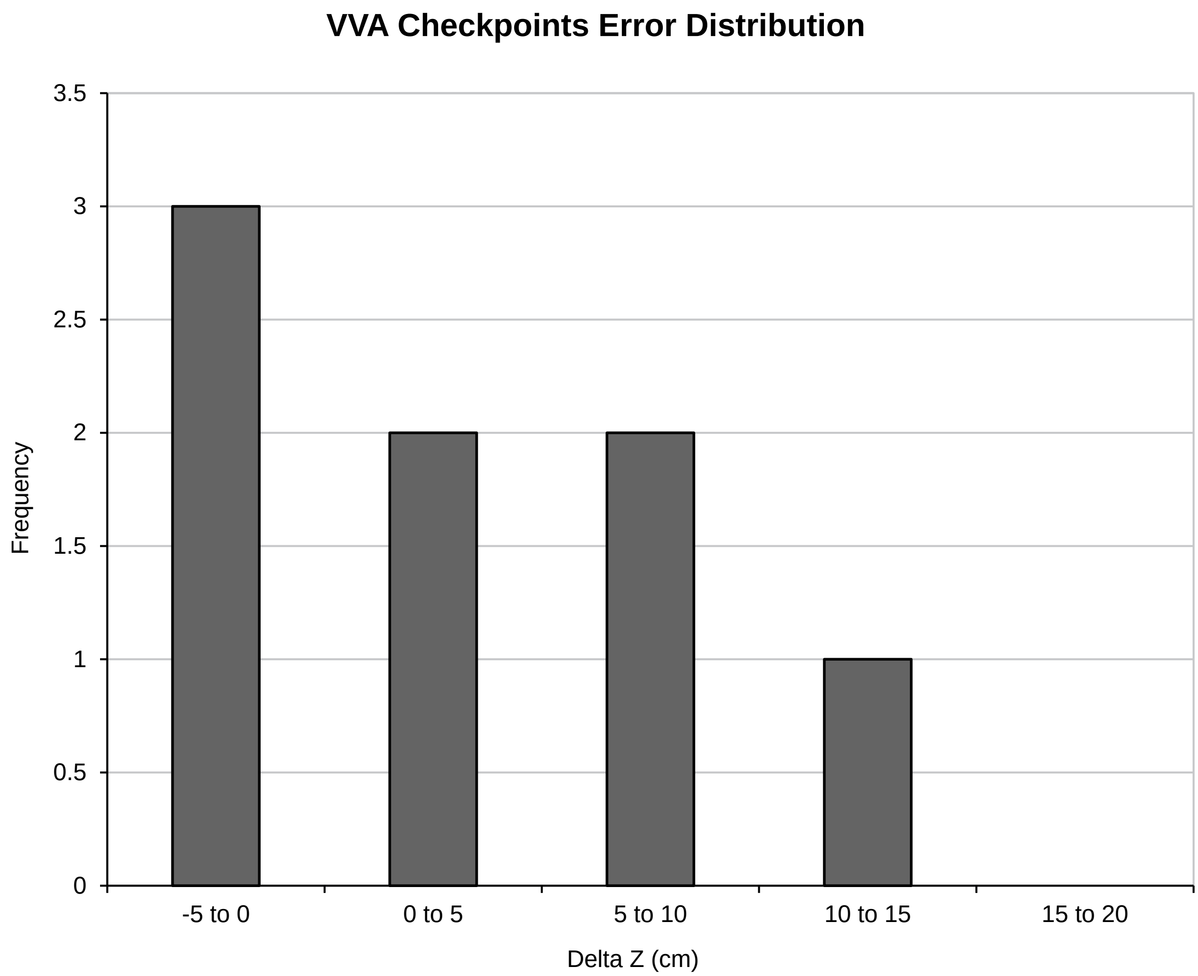

Figure 10. Distribution of elevation discrepancies between vegetated surveyed checkpoints and lidar surface. The dataset meets the VVA specification, with one VVA checkpoint falling outside of the specification.

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

5. DERIVATIVE LIDAR PRODUCTS

USGS required several derivative lidar products to be created. Each type of derived product is described below.

5.1 Void Polygons

Void polygons delineating areas of extremely sparse or no valid bathymetric returns have been created for this project area. The polygons reflect void areas greater than or equal to 9 square meters in area and were utilized to constrain interpolation in the bathymetry domain in the final merged topo-bathymetric DEM.

5.2 Refraction Extents

The refraction extent layer was created by using rasterized aggregate extents of refracted points to create automated, smoothed 2-D refraction extent vectors with LASTools. These refraction extents delineate areas where the refraction correction was applied to the lidar data by CZMIL's automated refraction correction software based on the software's detection of water.

5.3 Intensity Imagery

Intensity orthoimages representing normalized seabed reflectance have been created for the entire project area on a per-tile basis. Each 1-meter grid cell has an associated 8-bit intensity value, 256 color gray scale that has been normalized to account for attenuation due to depth and swath-to-swath variability in acquisition. The intensity layer extents are the same as the extents for the final classified topo-bathymetric LAS and DEMs.

5.4 Height Separation Raster

Maximum height separation raster have been created for the entire project areas on a per-tile basis. The rasters provide a method for quickly assessing withheld-flagged points in the lidar. They are created using the highest non-withheld point. Properly flagged points will produce rasters with uniform appearance. The height separation rasters are tiled according to the tile grid.

5.5 Direct-Georeferenced Imagery

Four-band (Red, Green, Blue, and Near-Infrared or RGBNIR channels) digital imagery covering the project area. The 10 cm pixel imagery was direct-georeferenced using Hexagon Geospatial's ImageStation OrthoPro software. The lidar dataset collected for this project was used to generate the orthorectification reference surface. Seamlines were auto-generated and then reviewed prior to creating the orthoimage tiles. Four-band (RGBNIR), uncompressed direct georeferenced tiles (1,000 m x 1,000 m) in GeoTIFF format with 30 cm Ground Sample Distance (GSD) were created for the project area.

6. DEM PROCESSING & QUALITATIVE ASSESSMENT

6.1 DEM Production Methodology

Dewberry utilized a proprietary routine to generate DEM products. ArcGIS, LP360, LAStools, Global Mapper and proprietary tools were used for QA/QC.

The DEM bare earth surface was sourced from the final classified lidar points in bare earth classes—class 2 for subaerial ground and class 40 for submerged topography (bathymetry). Void polygons were enforced in the final raster to delineate areas larger than 9 square meters where no valid bathymetric returns were received. The DEM was reviewed for any issues requiring corrections, including remaining calibration issues, lidar point misclassification, and processing artifacts. After corrections were applied, the DEM was split into tiles per the project tiling scheme. The formatting of the DEM tiles was verified before the tiles were loaded into Global Mapper to ensure that there was no missing or corrupt data and that the DEMs matched seamlessly across tile boundaries. A final qualitative review was then conducted by an independent review department within Dewberry.

6.2 DEM Qualitative Assessment

Dewberry performed a comprehensive qualitative assessment of the bare earth DEM deliverables to ensure that all tiled DEM products were delivered with the proper extents, were free of processing artifacts, and contained the proper referencing information. Dewberry conducted the review in ArcGIS using a hillshade model of the full dataset with a partially transparent colorized elevation model overlaid. The tiled DEMs were reviewed at a scale of 1:5,000 to look for artifacts caused by the DEM generation process and to verify correct enforcement of void areas. Upon correction of any outstanding issues, the DEM data was loaded into Global Mapper for its second review and to verify corrections.

Table 17 below outlines high level steps verified for every DEM dataset.

Table 17. DEM verification steps.

Parameter	Requirement	Pass/Fail
Digital Elevation Model (DEM) of bare-earth with voids	DEM of bare-earth terrain surface (1 m) is created from lidar ground and bathymetric bottom points and void polygons. DEMs are tiled without overlaps or gaps, show no edge artifact or mismatch, DEM deliverables are .tif format	Pass
DEM Compression	DEMs are not compressed	Pass
DEM NoData	Areas outside survey boundary are coded as NoData. Internal voids are coded as NoData (-999999)	Pass
Bridge Removal	Verify removal of bridges from bare-earth DEMs	Pass
DEM Artifacts	Correct any issues in the lidar classification that were visually expressed in the DEMs. Reprocess the DEMs following lidar corrections.	Pass
DEM Voids	Bathymetric voids greater than 9 sq mi are enforced in the DEM.	Pass
DEM Tiles	Split the DEMs into tiles according to the project tiling scheme	Pass
DEM Formatting	Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression is not applied to the tiled DEMs	Pass
DEM Extents	Load all tiled DEMs into Global Mapper and verify complete coverage within the (buffered) project boundary and verify that no tiles are corrupt	Pass

6.3 DEM Vertical Accuracy Results

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. DEMs were created by averaging the elevations of ground points within each pixel, which may result in slightly different elevation values at each survey checkpoint when compared to the linearly interpolated TIN created from the source LAS. The vertical accuracy of the DEM was tested by comparing the elevation of a given surveyed checkpoint with the elevation of the horizontally coincident pixel in the DEM. Dewberry used Esri ArcMap to test the DEM vertical accuracy.

The survey checkpoints used to test this topobathymetric dataset are listed in the previously delivered ground survey report previously delivered. Table 18summarizes the tested vertical accuracy results from the final DEM dataset.

Table 18. DEM vertical accuracy results

Land Cover Type	# of Points	NVA (m)	SBA (m)	VVA (m)
Project Specification		**0.196**	**0.363**	**0.300**
NVA	23	0.164		
SBA	9		0.115	
VVA	8			0.104

The topographic portion of this DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 8.4 cm, equating to ± 16.4 cm at 95% confidence level. Actual VVA accuracy was found to be ± 10.4 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 $RMSE_z$ Vertical Accuracy Class. Actual bathymetric vertical accuracy was found to be $RMSE_z$ = 5.9 cm, equating to ± 11.5 cm at 95% confidence level.

The VVA 5% outliers are listed in Table 19. Descriptive statistics for all categories are presented in Table 20.

Table 19. VVA 5% outliers

Point ID	UTM zone 15N NAD83(2011), m		NAVD88 Geoid 12B, m		Delta z (m)
	Easting (x)	Northing (y)	Survey z	Lidar z	
VVA_8	4376515.733	255150.213	101.462	101.583	0.121

Table 20. Classified lidar vertical accuracy descriptive statistics

Land Cover Type	# of Points	$RMSE_z$ (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	23	0.084	0.017	0.043	-2.152	0.084	-0.275	0.126	5.940
SBA	9	0.059	0.031	0.051	-1.503	0.053	-0.087	0.087	2.289
VVA	8	0.060	0.038	0.033	0.262	0.050	-0.032	0.121	-0.249

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

6.4 DEM Checklist

Table 21 represents a portion of the high-level steps in Dewberry's DEM Production and QA/QC checklist that were performed for this project.

Table 21. A subset of the high-level steps from Dewberry's bare earth DEM Production and QA/QC checklist performed for this project.

Pass/Fail	Validation Step
Pass	Final void polygons are created
Pass	DEM created from Triangulated Irregular Network (TIN) of ground classes in LASTools
Pass	Final void polygons used to clip areas of large interpolation (>9 sqm) in DEM
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	Bridges should NOT be present in final topobathy DEMs.
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, SBA and other statistics
Pass	Split the DEMs into tiles according to the project tiling scheme
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.