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Virginia Fairfax County Lidar Project

Report Produced for U.S. Geological Survey

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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 Virginia Fairfax County 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 1000 m by 1000 m. A total of 1765 tiles were produced for the project encompassing an area of approximately 597 sq. mi.

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 D. 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 surface model. He also verified the GPS base station coordinates used during lidar data acquisition to ensure that the base station coordinates were accurate. Appendix A contains the checkpoint survey report created for this project.

Axis Geospatial, LLC completed lidar data acquisition and data calibration for the project area.

SURVEY AREA

The project area addressed by this report falls within the states of Virginia, Maryland, and the District of Columbia. Virginia counties include the City of Fairfax, City of Falls Church, City of Alexandria, Fairfax, Arlington, Loudoun, Manassas, Manassas Park, and Prince William. Maryland counties include Charles, Montgomery, and Prince George's.

DATE OF SURVEY

The lidar aerial acquisition was conducted between December 6, 2018 and December 26, 2018.

COORDINATE REFERENCE SYSTEM

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

Horizontal Datum: The horizontal datum for the project is North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011))
Vertical Datum: The Vertical datum for the project is North American Vertical Datum of 1988 (NAVD88)
Coordinate System: Albers Equal Area
Units: Horizontal units are meters, vertical units are meters.
Geiod Model: Geoid12B (Geoid 12B was used to convert ellipsoid heights to orthometric heights).

LIDAR VERTICAL ACCURACY

There were 74 independent vertical accuracy checkpoints (42 non-vegetated and 32 vegetated) collected for vertical accuracy testing. One non-vegetated points was removed from swath accuracy testing due to proximity to a vehicle. For the Virginia Fairfax County Lidar Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled **8.8 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 **17.3 cm**, compared with the 19.6 cm specification.

The tested vegetated vertical accuracy (VVA) of the classified lidar data computed using the 95^{th} percentile was **12.4 cm,** compared with the 29.4 cm specification.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and bare earth DEM data, including lists of excluded points, are found in the following sections of this report.

PROJECT DELIVERABLES

The deliverables for the project are listed below.

1. Classified Point Cloud Data (Tiled LAS)
2. Bare Earth Surface (Tiled Raster, IMG Format)
3. Intensity Imagery (Tiled Raster, TIF Format)
4. Breakline Data (File GDB Format)
5. Independent Survey Checkpoint Data (Report, Photos, Coordinates, and Shapefile)
6. Calibration Point Data (Coordinates and Shapefiles)
7. Metadata
8. Project Report
9. Project Extents (ESRI Shapefile Format)
10. Contours (File GDB Format)

PROJECT TILING FOOTPRINT

A total of 1765 tiles were delivered for the project, covering the areas shown in Figure 1. Each tile's extent is 1000 m by 1000 m.

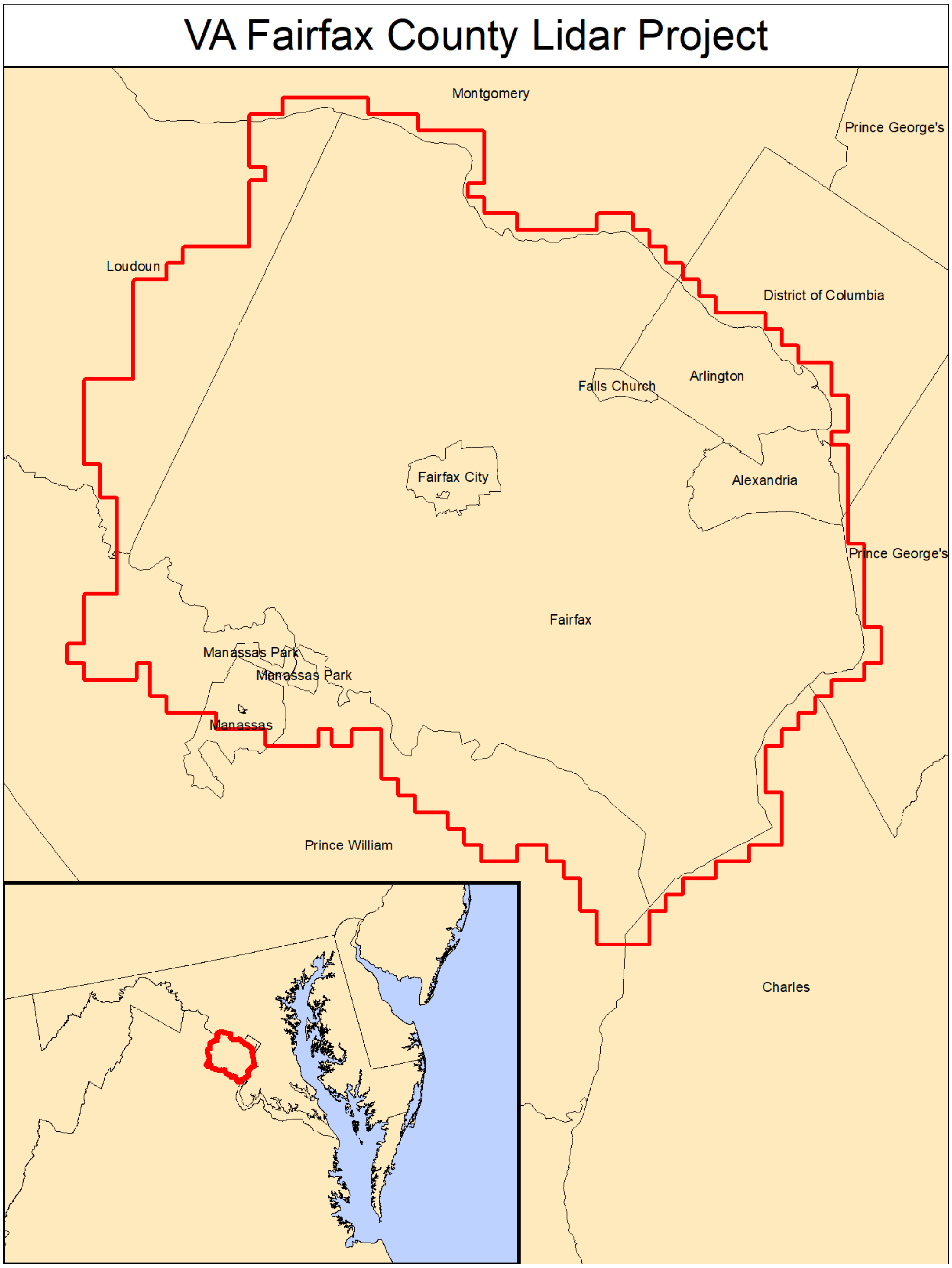

Figure 1 – Project Map

Lidar Acquisition Report

Dewberry elected to subcontract the lidar acquisition and calibration activities to Axis Geospatial, LLC (Axis). Axis was responsible for providing lidar acquisition, calibration, and delivery of lidar data files to Dewberry.

Dewberry received final calibrated swath data from Axis on May 23, 2019.

LIDAR ACQUISITION DETAILS

Axis planned a total of 52 lines to cover the area of interest. 46 passes for the project area as a series of parallel flight lines with cross flightlines for the purposes of quality control with another 6 lines flown in a perpendicular direction due to air space restrictions around Washington D.C. In order to reduce any margin for error in the flight plan, Axis 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 Track Air 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 schedule; and
- Filed flight plans as required by local Air Traffic Control (ATC) prior to each mission.

Axis monitored weather and atmospheric conditions and conducted lidar missions only when no conditions existed below the sensor that would affect the collection of data. Good lidar collection conditions include leaf-off for hardwoods and no snow, rain, fog, smoke, mist, or low clouds. Lidar systems are active sensors that do not require ambient light, thus allowing missions to be conducted during night hours when weather restrictions do not prevent collection. Axis 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, Axis 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.

Axis lidar sensors are calibrated at a designated site located at the Easton Airport in Easton, MD. Sensors are periodically checked and adjusted to minimize corrections at project sites.

LIDAR SYSTEM PARAMETERS

Axis operated a Navajo PA31 Twin Engine CR aircraft tail number N359RX with a VQ-1560i lidar system throughout the collection of the project. Table 1 illustrates Axis' system parameters for lidar acquisition on this project.

Item	Parameter (Axis)
System	VQ-1560i

Item	Parameter (Axis)
Altitude (AGL meters)	1303
Approx. Flight Speed (knots)	160
Scanner Pulse Rate (kHz)	376
Scan Frequency (hz)	2000
Pulse Duration of the Scanner (nanoseconds)	3
Pulse Width of the Scanner (m)	0.9
Central Wavelength of the Sensor Laser (nanometers)	1064
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	Yes
Beam Divergence (milliradians)	0.25
Nominal Swath Width on the Ground (m)	1460
Swath Overlap (%)	30
Total Sensor Scan Angle (degree)	58.52
Nominal Pulse Spacing (single swath), (m)	0.35
Nominal Pulse Density (single swath) (ppsm), (m)	8
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.35
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	8
Maximum Number of Returns per Pulse	N/A

Table 1 – Axis 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. The sensor operator monitored the sensor, the status of position dilution of precision (PDOP), 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.

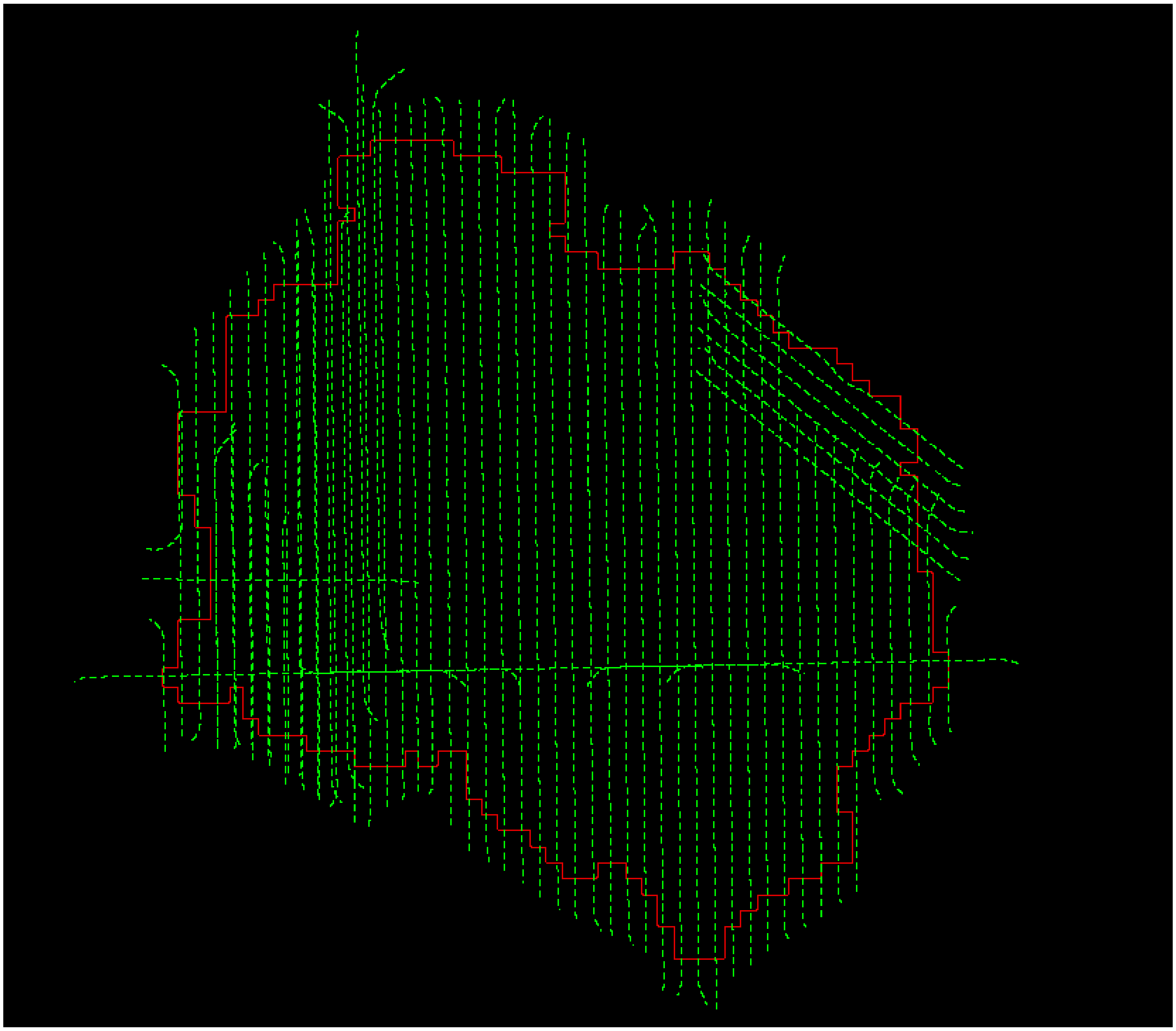

Figure 2 - Trajectories flown by Axis

LIDAR CONTROL

The coordinates of all CORS stations used by Axis are provided in table 2, below. All control and calibration points are also provided in shapefile format as part of the final deliverables.

Point ID	NAD83 (2011) Albers Equal Area		NAVD88 (Geoid 12B)
	Easting X (m)	Northing Y (m)	Elevation (m)
BACO	1643375.313	1987945.313	160.852
GODE	1633468.123	1942684.605	48.136
HPT	1702022.898	1907403.902	8.189
LOY8	1596900.815	1850870.095	27.623
LOYJ	1545495.388	1862503.587	137.466
LOYQ	1545703.267	1995140.825	162.586
LOYY	1495420.731	1900497.207	255.292
ZDC1	1571531.721	1939389.292	113.230
BACO	1643375.313	1987945.308	160.862
GODE	1633468.119	1942684.605	48.147
HPT	1702022.899	1907403.899	8.205
LOY8	1596900.816	1850870.095	27.643
LOYC	1515789.615	1930744.308	236.739
LOYJ	1545495.393	1862503.588	137.477
LOYK	1634049.447	1955314.156	67.695
LOYQ	1545703.266	1995140.821	162.596
ZDC1	1571531.720	1939389.292	113.229
CORB	1605390.873	1843320.084	69.801
GODE	1633468.124	1942684.606	48.140
GODZ	1633468.123	1942684.606	48.140
HPT	1702022.899	1907403.902	8.191
LOY8	1596900.816	1850870.097	27.616
LOYJ	1545495.391	1862503.590	137.464
LOYK	1634049.447	1955314.157	67.681
LOYO	1610920.590	1827048.860	75.841
ZDC1	1571531.725	1939389.294	113.220
CORB	1605390.883	1843320.080	69.808
GODE	1633468.134	1942684.602	48.147
GODZ	1633468.134	1942684.601	48.147
HPT	1702022.909	1907403.897	8.198
LOY8	1596900.826	1850870.093	27.623
LOYJ	1545495.401	1862503.586	137.471
LOYK	1634049.458	1955314.152	67.689
ZDC1	1571531.735	1939389.289	113.228
DCDC	1612356.822	1929744.590	88.679
LOY8	1596900.819	1850870.096	27.607
LOYK	1634049.452	1955314.156	67.670
MDDM	1595899.082	1968992.253	234.898
MDHG	1648037.935	1889675.825	62.496
VAAH	1579199.011	1936176.521	93.372

VAGV	1573202.246	1904784.472	113.892
VAL	1609911.670	1904361.452	30.572

Table 2 – Base stations used by Axis to control lidar acquisition

AIRBORNE GPS KINEMATIC

Airborne GPS data was processed using the PosPac MMS software suite. Flights were flown with a minimum of 6 satellites in view (13° above the horizon) and with a PDOP of better than 4. Distances from base station to aircraft were kept to a maximum of 40 km.
For all flights, the GPS data can be classified as excellent, with GPS residuals of 2 cm average or better but no larger than 4.5 cm being recorded.
GPS processing reports for each mission are included as a separate attachment, Appendix A.

GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

The initial step of calibration was to verify availability and status of all required GPS and Laser data against field notes and compile any data if not complete.

Subsequently the mission points were output using Riegl's RiProcess. The initial point generation for each mission calibration was verified within Microstation/Terrascan for calibration errors. If a calibration error greater than specification was observed within the mission, the necessary 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.

Data collected by the lidar unit was reviewed 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 and logged into a database.

On a project level, a supplementary coverage check was carried out to ensure no data voids unreported by Field Operations were present.

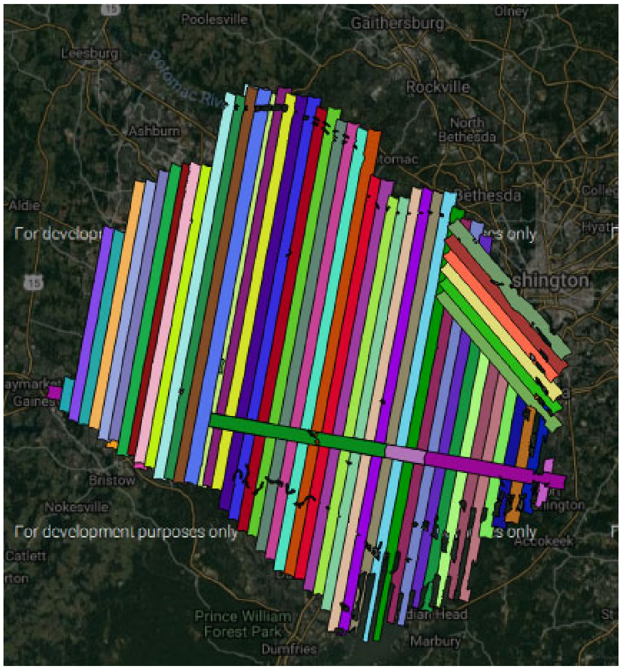

Figure 3 – Lidar swath output showing complete coverage of the project area by Axis

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.

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 so that errors greater than the specifications were flagged. Cross sections were visually inspected across each block to validate point to point, flight line to flight line, and mission to mission agreement.

For this project the specifications used are as follow:

- Relative accuracy <= 6 cm maximum differences within individual swaths and
- <=8 cm RMSDz between adjacent and overlapping swaths.

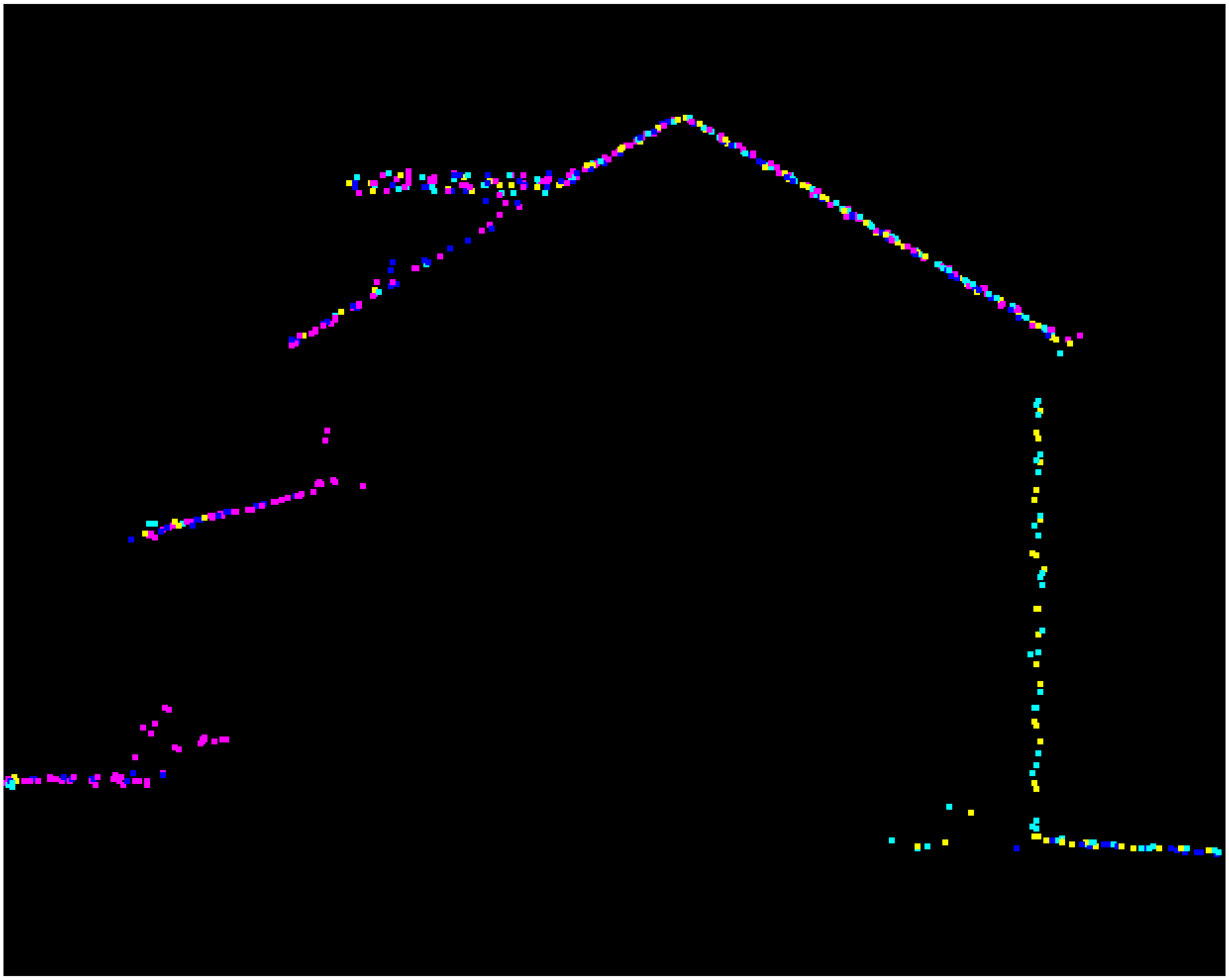

Figure 4 – Profile views showing correct roll and pitch adjustments from Axis

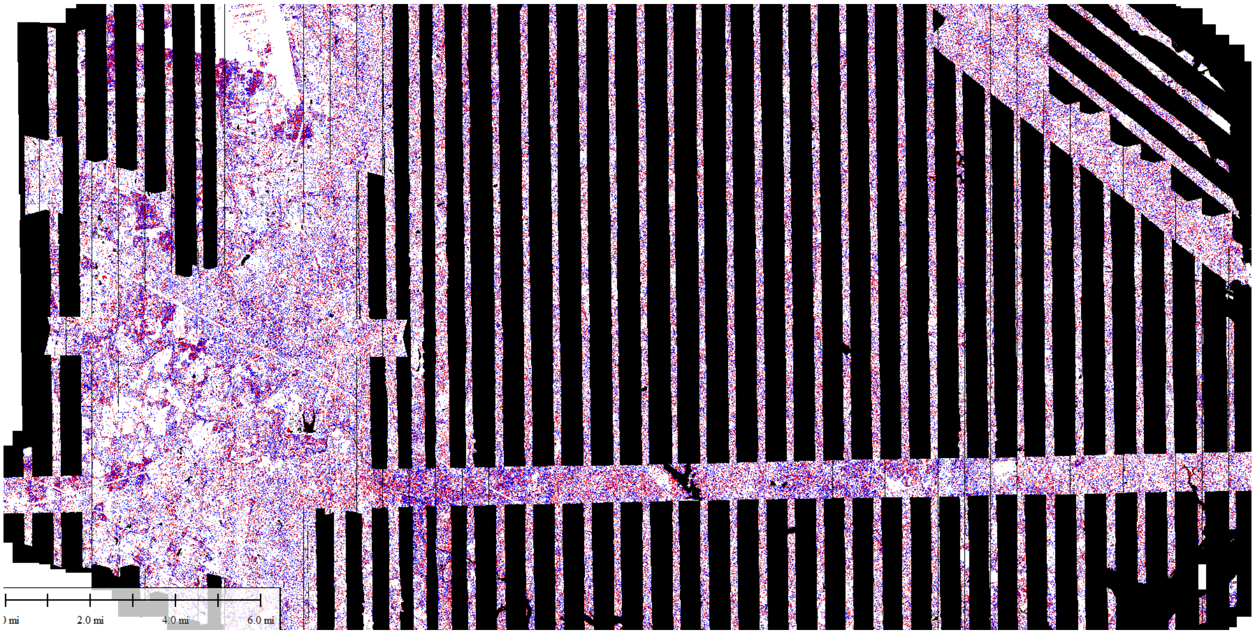

Figure 5 – QC block colored by distance to ensure accuracy at swath edges for Axis data

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

FINAL CALIBRATION VERIFICATION

Dewberry conducted the survey for 26 ground control points (GCPs) which were used to test the accuracy of the calibrated swath data. These 26 GCPs were available to use as control in case the swath data exhibited any biases which would need to be adjusted or removed. The coordinates of all GCPs are provided in table 3 and the accuracy results from testing the calibrated swath data against the GCPs is provided in table 4; no further adjustments to the swath data were required based on the accuracy results of the GCPs.

Number	NAD83 (2011) Albers Equal Area		NAVD88 (Geoid 12B)	Laser Z (m)	Delta Z (m)
	Easting X (m)	Northing Y (m)	Known Z (m)		
GCP-9	1579461.97	1911607.17	56.637	56.75	0.113
GCP-5	1576296.06	1920352.84	97.805	97.91	0.105
GCP-3	1592207.49	1925912.5	122.18	122.28	0.1
GCP-6	1593404.43	1920662.58	120.701	120.8	0.099
GCP-13	1587195.7	1905397.43	77.544	77.64	0.096
GCP-23	1584733.5	1918204.8	89.175	89.27	0.095
GCP-2	1582738.97	1927857.98	82.293	82.37	0.077
GCP-16	1590008.9	1900752.82	85.719	85.77	0.051
GCP-20	1595376.84	1909582.94	98.65	98.7	0.05

GCP-25	1595322	1932341.41	97.841	97.89	0.049
GCP-14	1601716.7	1905269.85	97.525	97.56	0.035
GCP-10	1590956.75	1914302.64	135.496	135.53	0.034
GCP-17	1598716.74	1895535	107.823	107.85	0.027
GCP-1	1588970.81	1937153.95	92.083	92.09	0.007
GCP-24	1601457.64	1925809.49	132.191	132.19	-0.001
GCP-7	1603100.93	1920185.39	113.058	113.03	-0.028
GCP-4	1607519.26	1928584.39	77.198	77.16	-0.038
GCP-26	1607417.37	1897837.99	16.202	16.15	-0.052
GCP-18	1615361.96	1894892.01	2.559	2.5	-0.059
GCP-21	1607271.09	1888046.85	9.255	9.18	-0.075
GCP-11	1609904.96	1912206.02	69.642	69.55	-0.092
GCP-19	1613841.78	1903530.06	38.46	38.34	-0.12
GCP-15	1620342.22	1908059.65	10.824	10.7	-0.124
GCP-8	1617438.9	1920687.03	16.439	16.29	-0.149
GCP-22	1611331.22	1920144.07	78.977	78.8	-0.177
GCP-12	1575309	1905252.93	100.497	100.62	0.123

Table 3 – Fairfax County Lidar surveyed ground control points (GCPs).

This project must meet Non-vegetated Vertical Accuracy (NVA) ≤ 19.6 cm at the 95% confidence level based on $RMSE_z$ ≤ 10 cm x 1.9600.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	NVA at 95% Spec=0.196 m	Mean (m)	Std Dev (m)	Min (m)	Max (m)
Non-Vegetated Terrain	26	0.088	0.172	0.006	0.089	-0.177	0.123

Table 4 –

Ground control points (GCPs) vertical accuracy results.

Overall the calibrated lidar data products collected by Axis meet or exceed the requirements set out in the Statement of Work. The quality control requirements of Axis quality management program were adhered to throughout the acquisition stage for this project to ensure product quality.

Lidar Processing & Qualitative Assessment

INITIAL PROCESSING

Once Dewberry receives the calibrated swath data from the acquisition provider, 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.

Final Swath Vertical Accuracy Assessment

Once Dewberry received the calibrated swath data from Axis, 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 41 non-vegetated (open terrain and urban) independent survey checkpoints. 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 Virginia Fairfax County Lidar Project satisfies this criteria. The 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 calculated to be $RMSE_z$ = 9.0 cm, equating to +/- 17.7 cm at 95% confidence level. The table below shows 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	41	0.090	0.177	0.002	0.022	-0.590	0.091	-0.184	0.158	-0.713

Table 5 - NVA at 95% confidence level for raw swaths

One checkpoint (NVA-17) was removed from the raw swath vertical accuracy testing due to proximity to a vehicle. 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. This high point caused an erroneous high value during the swath vertical accuracy testing; therefore, the point was removed from the final calculations. Once the data underwent the classification process, the vegetation, objects and high noise were removed from the final ground classification and this checkpoint was added back into the final vertical accuracy testing.

Table 6, below, provides the coordinates for the checkpoint removed from testing of the raw swath data. Table 7 provides the usable vertical accuracy results of this checkpoint from the fully classified lidar. Figure 6 shows a 3D model of the lidar point cloud and the location of the checkpoint beneath a vehicle.

Point ID	NAD83 (2011) Albers Equal Area		NAVD88 (Geoid 12B)
	Easting X (m)	Northing Y (m)	Z-Survey (m)
NVA-17	1583965.880	1903505.610	77.253

Table 6 – Checkpoint removed from raw swath vertical accuracy testing

Point ID	NAD83 (2011) Albers Equal Area		NAVD88 (Geoid 12B)		Delta Z	AbsDelta Z
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-LiDAR (m)		
NVA-17	NVA-17	1583965.88	1903505.61	77.253	0.087	0.087

Table 7 - Final tested vertical accuracy post ground classification

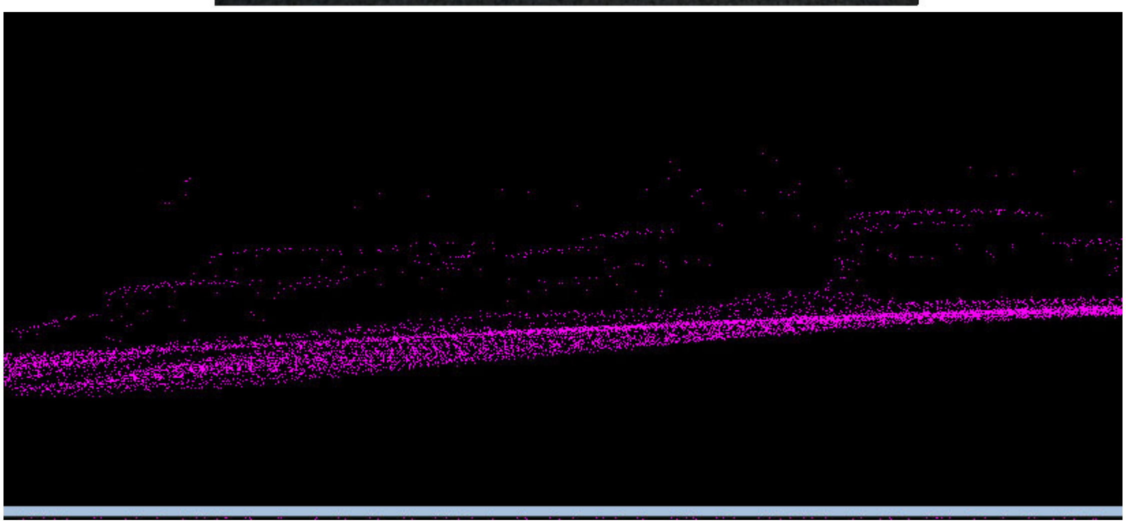

Figure 6 – Open terrain checkpoint NVA-17, shown in top image, is located underneath a vehicle; lidar profile of vehicle shown in bottom image. This point was removed from raw swath vertical accuracy testing because above ground features had not been separated from the ground classification yet.

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 $RMSD_z$ or less. 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 pixels with a 1 m cell size. 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. Large or continuous sections of yellow or red pixels can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data, especially when these yellow/red sections follow the flight lines and not the terrain or areas of vegetation. The DZ orthos for Virginia Fairfax County are shown in the figure below; this project meets inter-swath relative accuracy specifications.

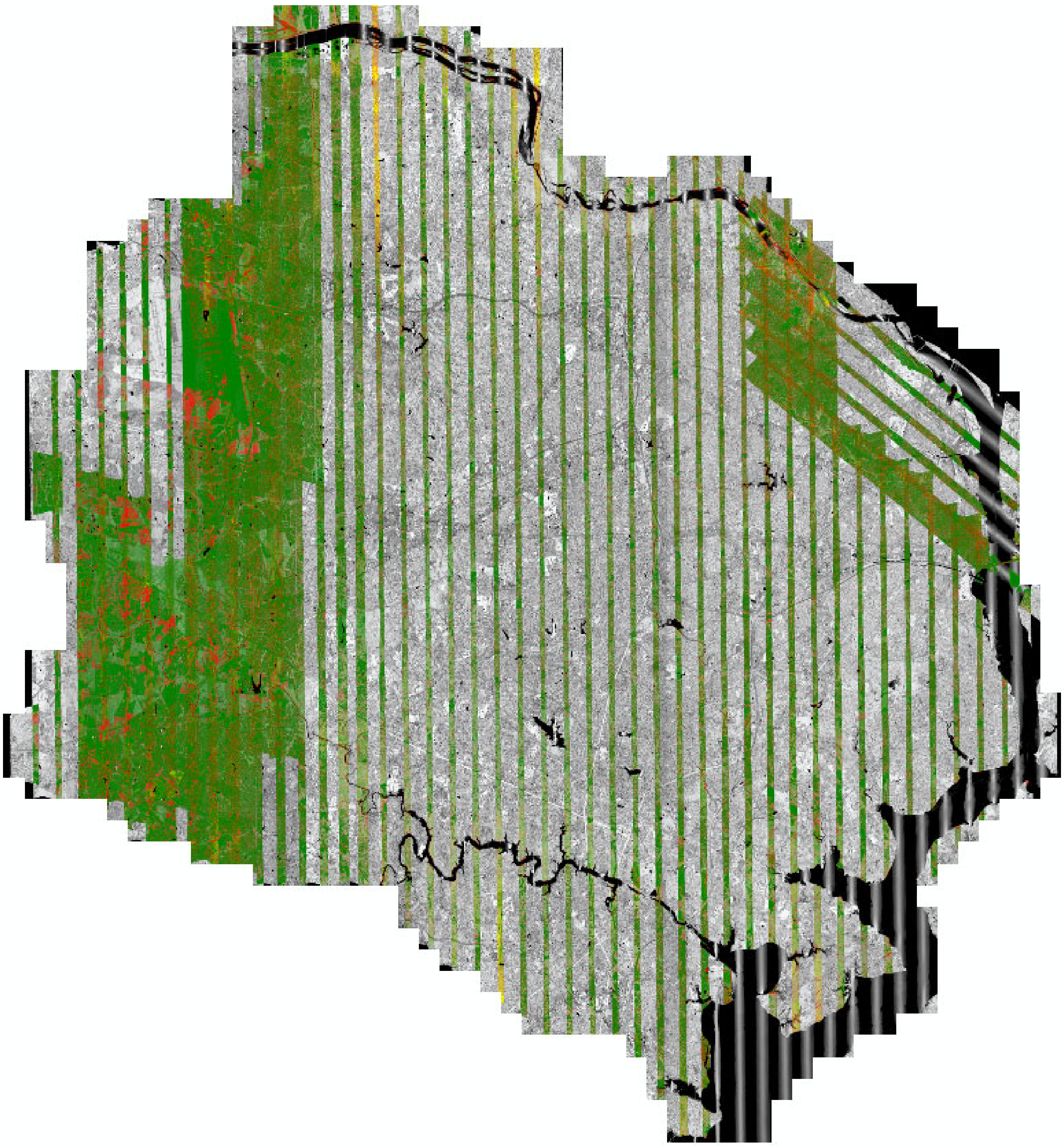

Figure 7 – Single return DZ Orthos for the Virginia Fairfax County lidar project. Inter-swath relative accuracy passes specifications.

Intra-Swath (Within a Single Swath) Relative Accuracy

Dewberry verified 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 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 accuracy of 6 cm $RMSD_z$. The image below shows two examples of the intra-swath relative accuracy of Virginia Fairfax County; this project meets intra-swath relative accuracy specifications.

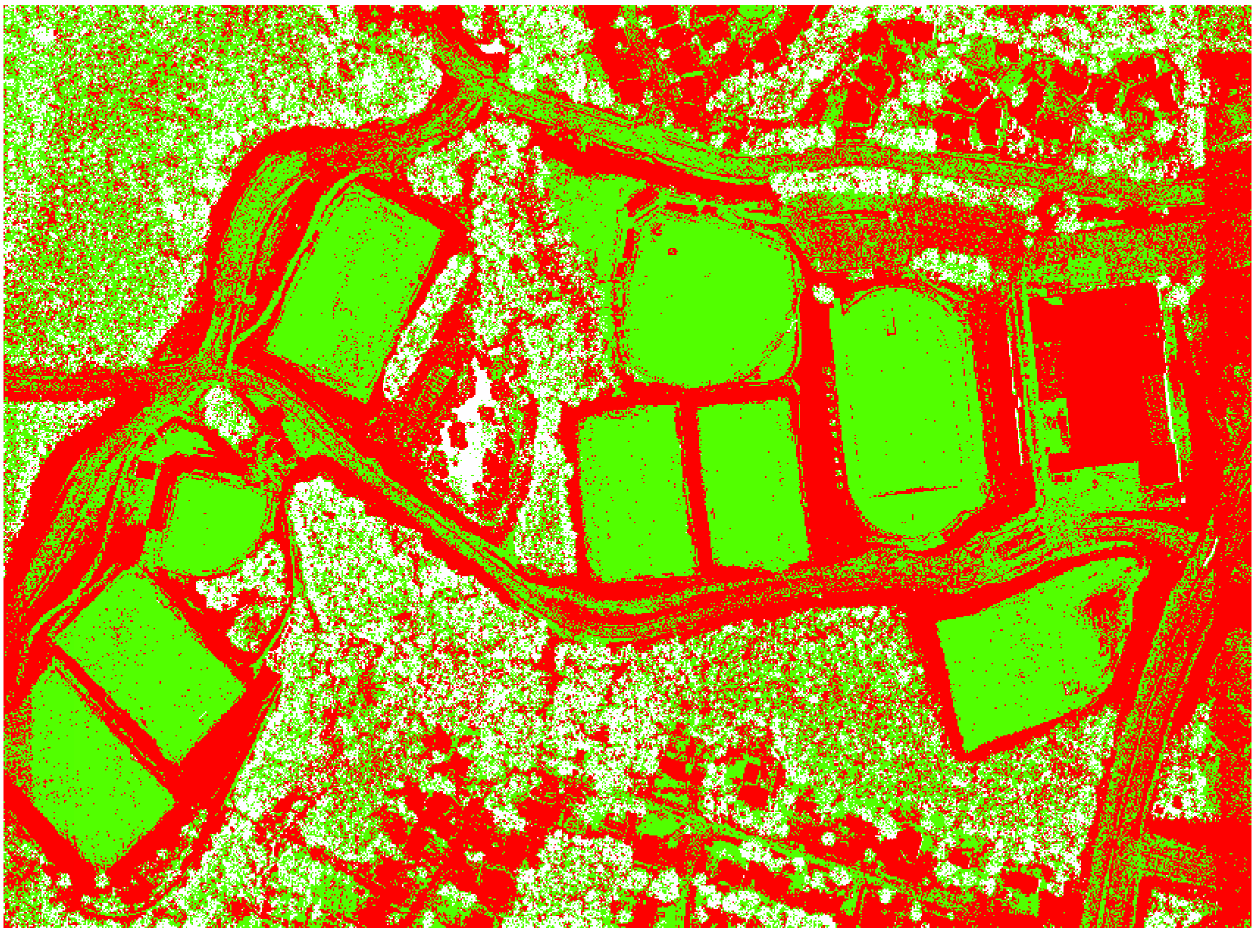

Figure 8 – Intra-swath relative accuracy. Areas where the maximum difference is ≤6 cm per pixel within each swath are colored green and areas exceeding 6 cm are colored red. The image above shows multiple flat, open areas colored green, whereas sloped terrain is colored red because the terrain itself exceed the 6 cm threshold. This is expected. Intra-swath relative accuracy passes specifications.

Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Dewberry used 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 Virginia Fairfax County; no horizontal alignment issues were identified.

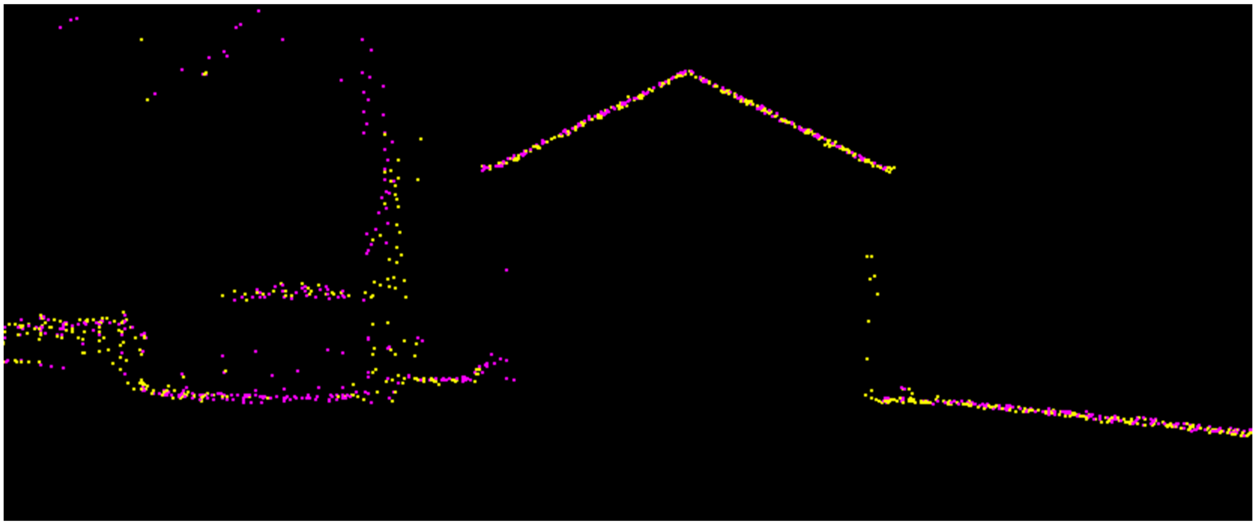

Figure 9 – Two separate flight lines differentiated by color (Purple/Yellow) are shown in this profile. There is no visible offset between these two flight lines. No horizontal alignment issues were identified.

Point Density and Spatial Distribution

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. Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing statistics, the project area was determined to have an ANPS of 0.285 meters and an ANPD of 12.3 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.

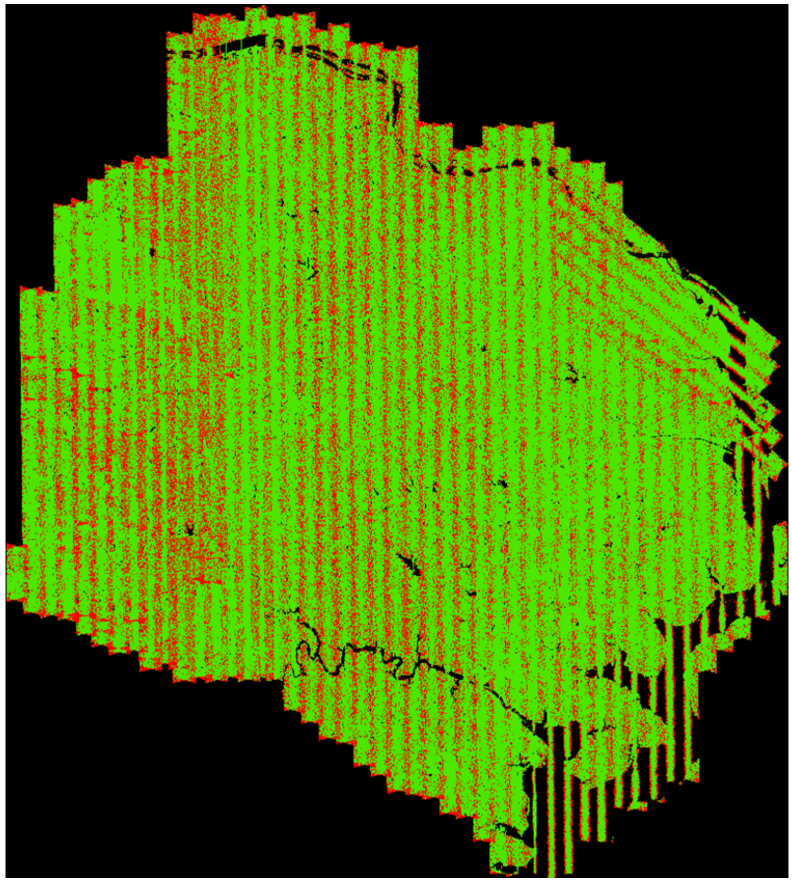

Figure 10 – 1-square meter density grid. There are some 1-meter cells that do not contain 8 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-square meter cells contain at least 8 points per square meter (green areas) showing there are no systematic density 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 water or low NIR reflectivity features, e.g., some asphalt and roof composition materials. This project passes spatial distribution requirements, as shown in the image below.

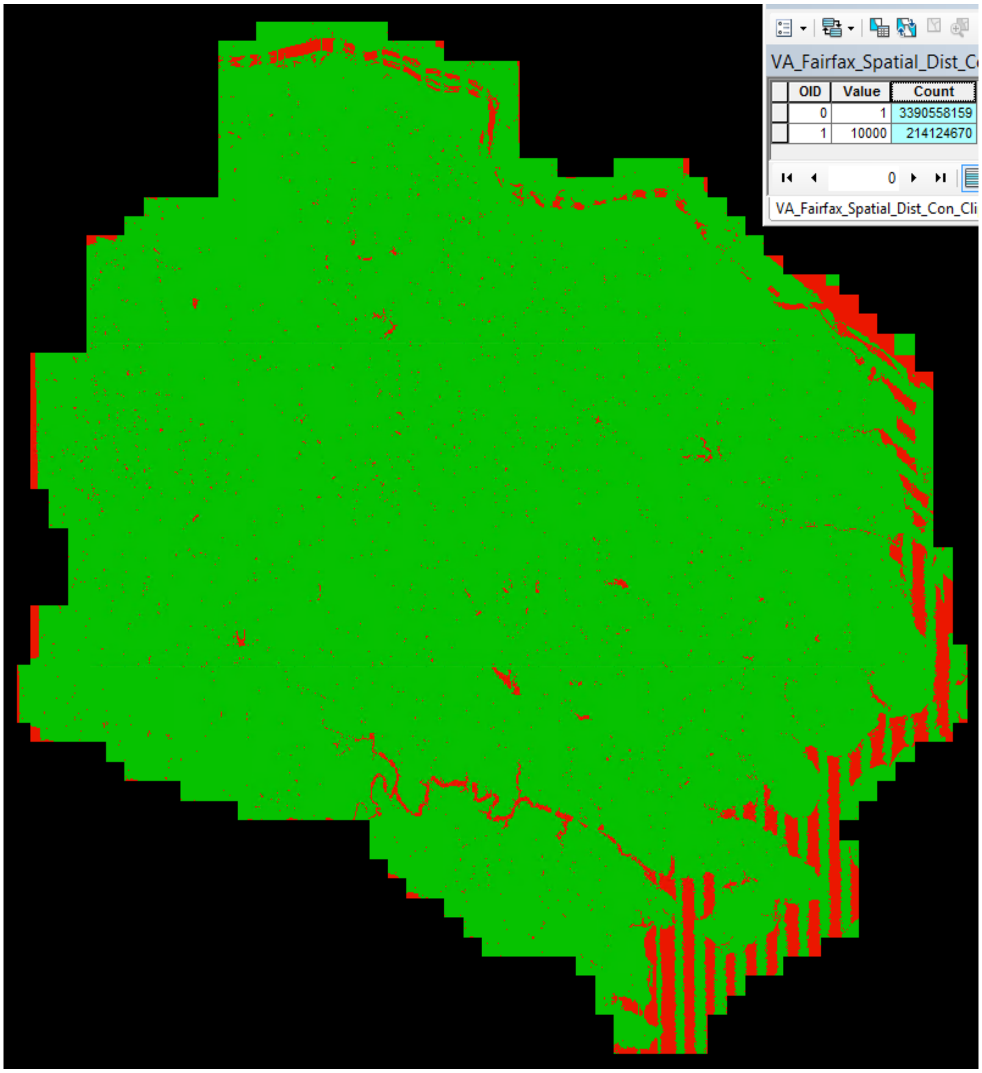

Figure 11 – All cells (2*NPS cellsize) containing at least one lidar point are colored green. Cells that do not contain a lidar point, including water bodies and other acceptable NoData areas, are colored red. Including acceptable NoData areas, 94.05% of cells contain at least one lidar point.

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. The data were processed using GeoCue and TerraScan software. The acquired 3D laser point clouds, in LAS binary format, were imported into a GeoCue project and tiled according to the project tile grid. Once tiled, the laser points were classified using a proprietary routine in TerraScan.

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 these points are classified (i.e., removed from class 1), the ground layer is extracted from this remaining point cloud by 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.

After the initial automated ground routine, each tile was imported into Terrascan and a surface model was created to examine the ground classification. Dewberry analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing conducted by Dewberry. Dewberry analysts employed 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. Bridge decks were classified to class 17 using bridge breaklines compiled by Dewberry. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilizes breaklines compiled by Dewberry to automatically classify hydro features. The water classification routine selects ground points within the breakline polygons and automatically classifies them as class 9, water. During this water classification routine, points that are within 1 NPS distance of the hydrographic feature boundaries are moved to class 20, ignored ground, to avoid hydro flattening artifacts along the edges of hydro features.

Overage points were then identified in Terrascan and GeoCue was used to set the overlap bit for the overage points. The withheld bit was set on the withheld points previously identified in Terrascan before the ground classification routine was performed.

The lidar tiles were classified to the following classification schema:

- Class 1 = Unclassified, used for all other features that do not fit into classes 2, 7, 9, 20, 17, or 18, including vegetation, buildings, etc.
- Class 2 = Bare-Earth Ground
- Class 7 = Low Noise
- Class 9 = Water
- Class 20 = Ignored Ground
- Class 17 = Bridge Decks
- Class 18 = High Noise

After manual classification, the LAS tiles were peer reviewed and then underwent 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, were updated in GeoCue software and then verified using proprietary Dewberry tools.

Lidar Qualitative Assessment

Dewberry's qualitative assessment utilizes a combination of statistical analysis and interpretative methodology or visualization to assess the quality of the data for a bare-earth digital terrain model (DTM). This includes creating pseudo image products such as lidar orthoimages produced from the intensity returns, Triangular Irregular Networks (TINs), Digital Elevation Models (DEMs) and 3-dimensional models as well as reviewing the actual point cloud data. 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, and other classification errors. This report presents representative examples where issues occurred in the lidar and post processing as well as examples where the lidar performed well.

VISUAL REVIEW

The following sections describe common types of issues identified in lidar data and summarize the results of the visual qualitative assessment for Virginia Fairfax County.

Artifacts

Artifacts are caused by the misclassification of ground points and usually represent vegetation and/or man-made structures. The artifacts identified are usually low lying structures, such as porches, or low vegetation used as landscaping in neighborhoods and other developed areas. These low lying features are extremely difficult for the automated algorithms to detect as non-ground and must be removed manually. The vast majority of these features have been removed but a small number of these features are still in the ground classification. The limited numbers of features remaining in the ground are usually 0.3 meters or less above the actual ground surface, and should not negatively impact the usability of the dataset.

Figure 12 – e1604n1922. A profile with points colored by class (class 1=white, class 2=orange) is shown in the top view and a TIN of the surface is shown in the bottom view. The arrow identifies low vegetation points. A limited number of these small features are still classified as ground but do not impact the usability of the dataset.

Bridge Removal Artifacts

The DEM surface models are created from TINs or Terrains. TIN and Terrain models create continuous surfaces from the inputs. Because a continuous surface is being created, the TIN or Terrain will use interpolation to continue the surface beneath the bridge where no lidar data was acquired. Locations where bridges were removed will generally contain less detail in the bare-earth surface because these areas are interpolated.

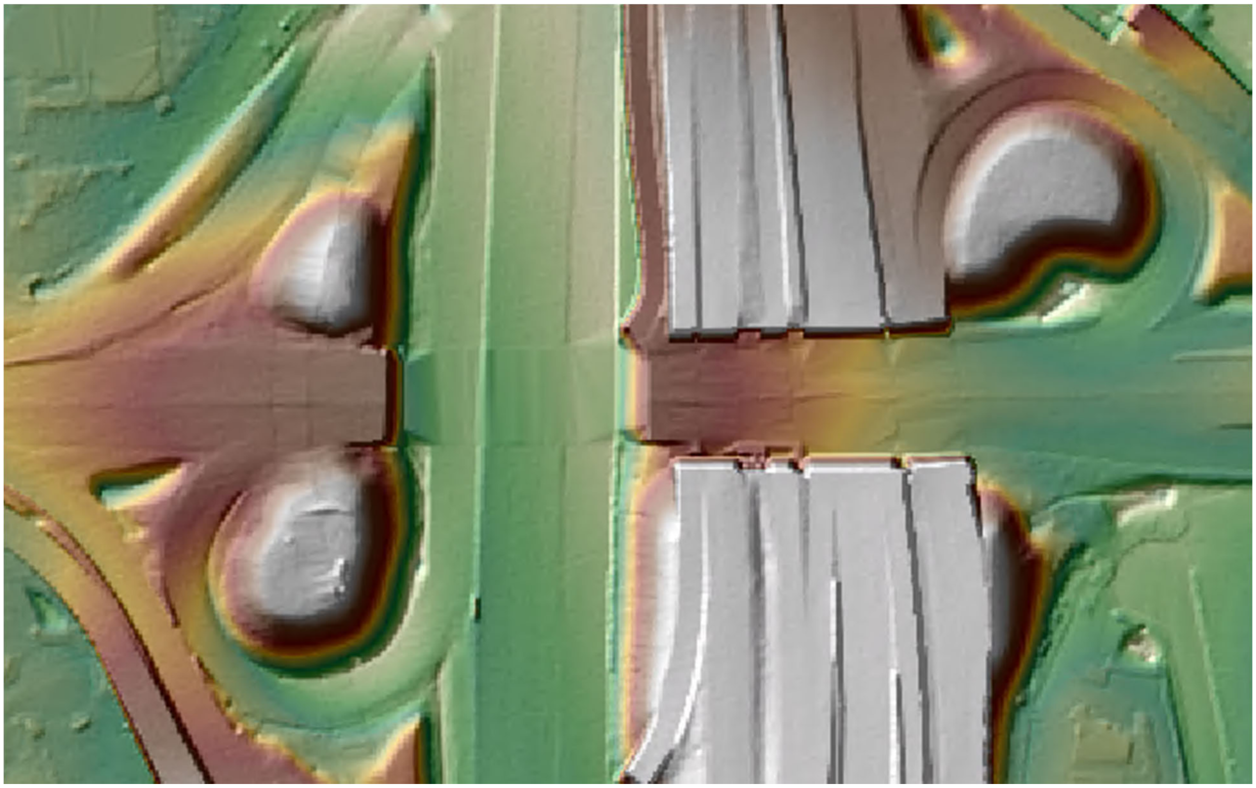

Figure 13 – e1609n1909. The DEM above shows an area where a bridge has been removed from ground. The surface model must make a continuous model and in order to do so, points are connected through interpolation. This results in less detail where the surface must be interpolated.

Culverts and Bridges

Bridges have been removed from the bare earth surface while culverts remain in the bare earth surface. In instances where it is difficult to determine if the feature is a culvert or bridge, such as with some small bridges, Dewberry errs toward assuming the feature is a culvert, especially if it is on a secondary or tertiary road. Below is an example of a culvert that has been left in the ground surface.

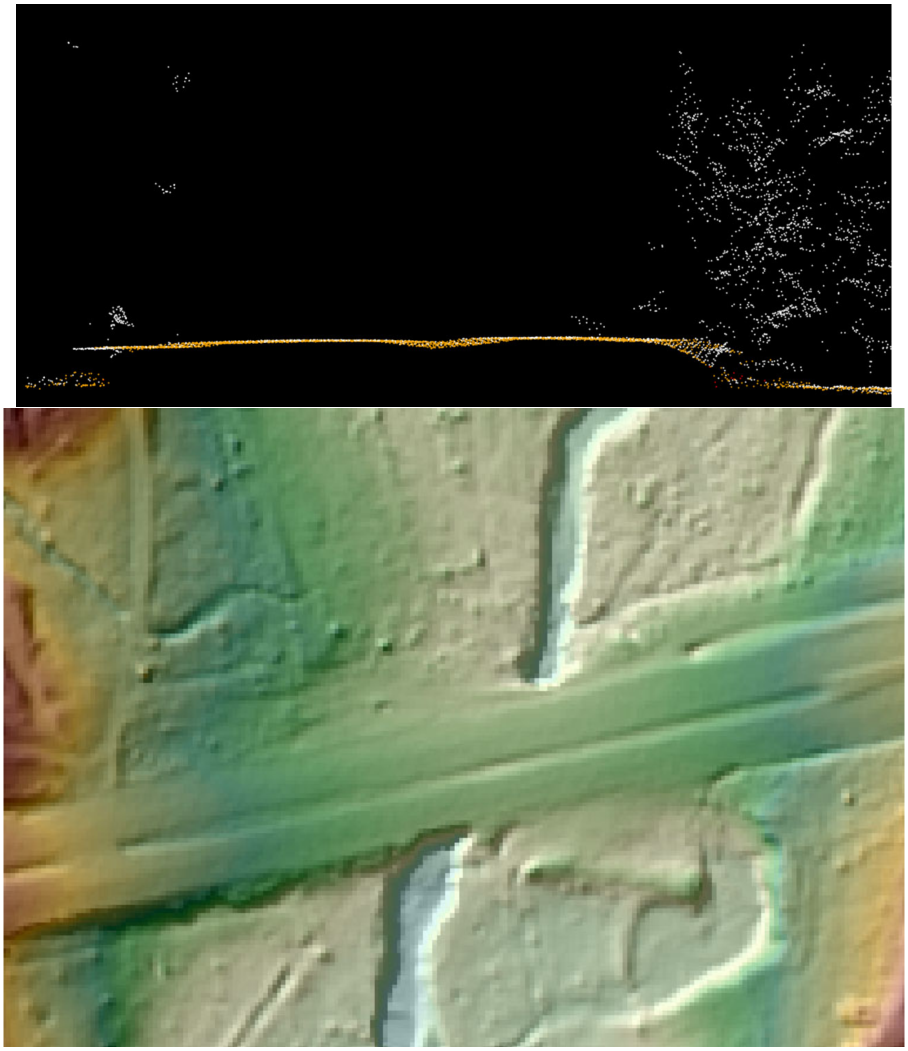

Figure 14– e1601n1918. A profile with points colored by class (class 1=white, class 2=orange) is shown in the top view and the DEM is shown in the bottom view. This culvert remains in the bare earth surface. Bridges have been removed from the bare earth surface and classified to class 17.

Elevation Change within Breaklines

While water bodies are flattened in the final DEMs, other features, such as linear hydrographic features, can have significant changes in elevation within a small distance. In linear hydrographic features, this is often due to the presence of a structure that affects flow such as a dam or spillway. Dewberry has reviewed the DEMs to ensure that changes in elevation are shown from bank to bank. These changes are often shown as steps to reduce the presence of artifacts while ensuring consistent downhill flow. An example is shown below.

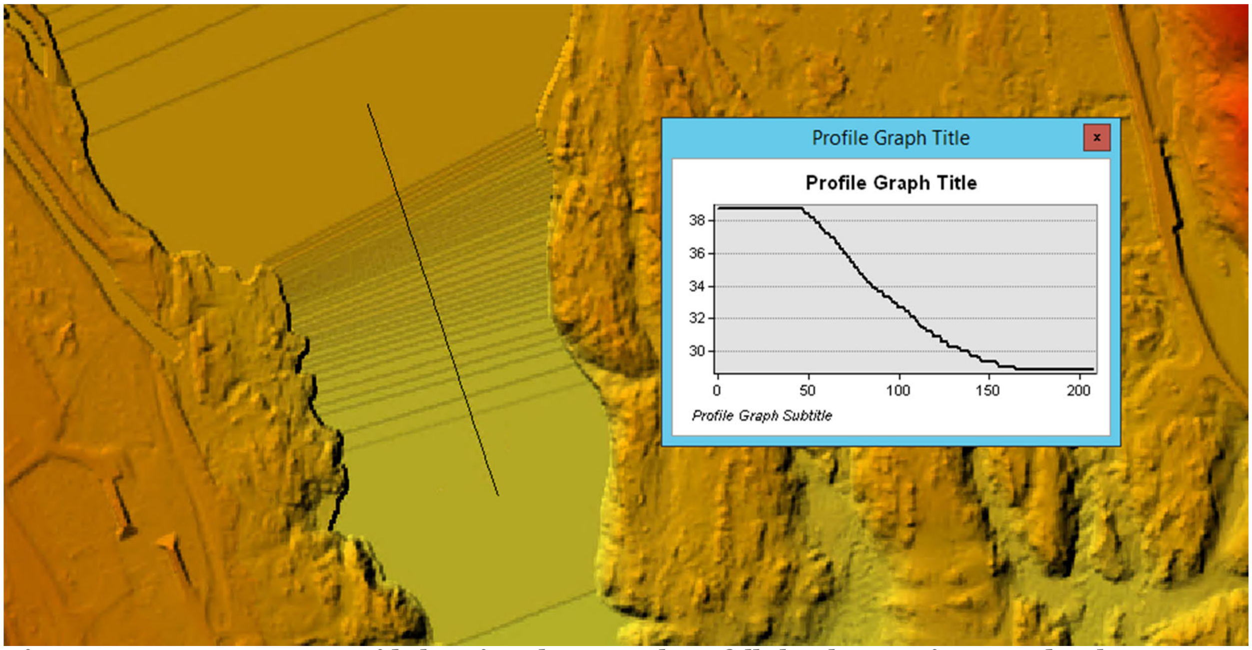

Figure 15 – e1598n1932. A rapid elevation change at these falls has been stair stepped. The steps are flat from bank to bank and are consistently monotonic.

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	6	Pass
Coordinate Reference System	NAD83 (2011) Albers Equal Area, meters and NAVD88 (Geoid 12B), meters in WKT format	Pass
Global Encoder Bit	17 (adjusted GPS time)	Pass
Time Stamp	Adjusted GPS time (unique timestamps)	Pass
System ID	Set to the processing system/software (NIIRS10 for GeoCue software)	Pass
Multiple Returns	Yes, and the return numbers are recorded	Pass
Intensity	16 bit intensity values for each pulse	Pass
Classification	Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 9: Water Class 20: Ignored Ground Class 17: Bridge Decks Class 18: High Noise	Pass
Overlap and Withheld Points	Set to the Overlap and Withheld bits	Pass

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates are recorded for each pulse	Pass

Table 8 – Lidar header data that is updated and verified for correct formatting

Synthetic Points

Time of flight laser measurements have their maximum unambiguous range restricted by the maximum distance the laser can travel round-trip before the next laser pulse is emitted. One solution to this problem is to limit "valid" returns to a certain window between specified elevations, or a "range gate"; however, this technique can prevent some returns from being captured if there is terrain outside of the range gate. It can also cause some late returns to be georeferenced as part subsequent pulses.

The multiple time around (MTA) capabilities of Riegl sensors enable the recording of lidar returns any distance from the laser (within detection capabilities) without forcing range gate restrictions. However, there is still a possibility that a late return will occur simultaneously with a pulse emission. The backscatter energy from the laser optics and the atmosphere directly below the aircraft during this event can effectively blind the sensor, making it unable to discern information about the laser return. Because this occurs more consistently with later returns, this blind zone is typically found in a narrow band along the edges of the sensor's range. The result is a predictable geometry of voids (typically within project specifications) in the point cloud.

During post-processing of the lidar data, Riegl software interpolates coordinates within the blind zones between last returns on each side of the gap. These are flagged as "synthetic" points and are assigned a valid time stamp, though they do not have any waveform data or pulse width information. Amplitude and reflectance are averaged from surrounding points. The assignment of synthetic points does not change the original raw point cloud data.

This dataset contains flagged synthetic points. The images below show an example from a different dataset of synthetic points applied to the ground class of the lidar point cloud.

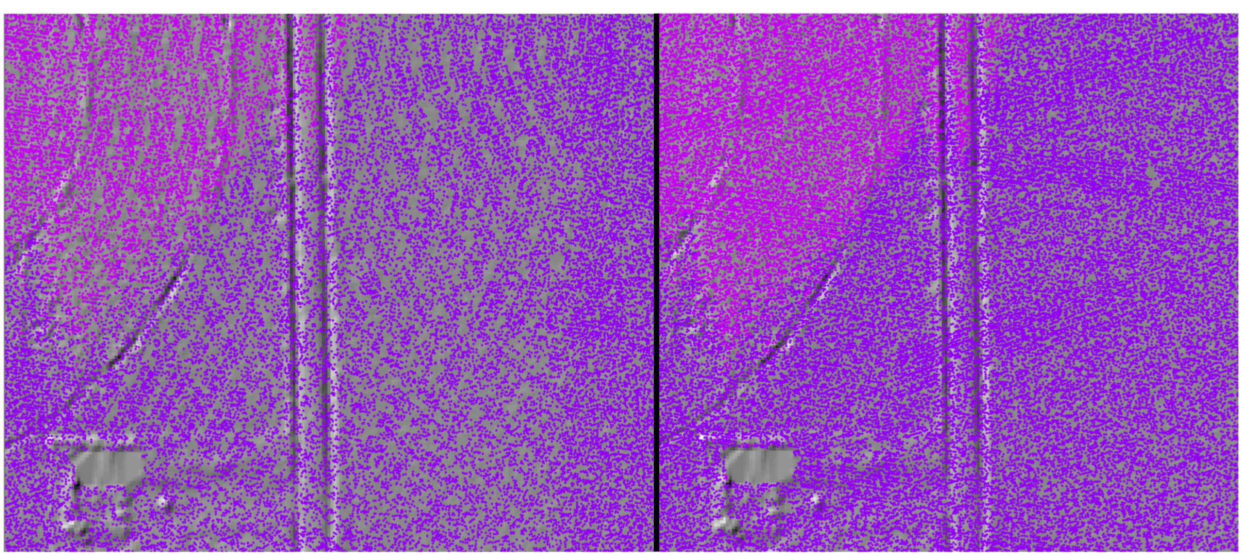

Figure 16 – The left image shows ground classified without synthetic points. The right image shows ground classified with synthetic points. Both images are overlaid on a hillshade of the example area.

Derivative Lidar Products

CONTOURS

One-foot contours have been created for the full project area. The contour attributes include labeling as either Index or Intermediate and an elevation value. The contours are also 3D, storing the elevation value within their internal geometry. Some smoothing has been applied to the contours to enhance their aesthetic quality. The contour tiles are all located within one file GDB and are named according to the final project tile grid.

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 discrete positional measurement of each survey checkpoint to the position of the interpolated value triangulated between the three closest lidar points to that checkpoint. The relative accuracy of the dataset, which is verified as part of initial processing, is then used to extrapolate the validity of the absolute vertical accuracy. If the relative accuracy of the dataset is within specifications and the dataset passes vertical accuracy requirements at the survey checkpoints, the vertical accuracy results can be applied to the whole dataset with high confidence. 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 tested the horizontal accuracy of the lidar dataset with a subset of checkpoints that were 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.

SURVEY VERTICAL ACCURACY CHECKPOINTS

For the vertical accuracy assessment, 74 checkpoints—located within bare earth/open terrain, grass/weeds/crops, and forested/fully grown land cover categories—were surveyed. Survey details and validation are included in the survey report, included as separate document. Checkpoints were evenly distributed throughout the project area to cover as many flight lines as possible using the “dispersed method” of placement.

All checkpoints surveyed for vertical accuracy testing purposes are listed in the following table.

Point ID	NAD83 (2011) Albers Equal Area		NAVD88 (Geoid 12B)
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-1	1586485.52	1936593.62	66.316
NVA-2	1593086.8	1935222.07	104.65
NVA-3	1593967.73	1931101.48	106.897
NVA-4	1587137.98	1932780.18	86.182
NVA-5	1585286.38	1927138.5	110.889
NVA-6	1590999.79	1925805.28	126.001
NVA-7	1595281.7	1924688.42	70.661
NVA-8	1596287.7	1918822.49	125.661
NVA-9	1587925.21	1919764.1	108.451
NVA-10	1579449.54	1919738	106.308
NVA-11	1579057.92	1912929.09	70.56
NVA-12	1587850.72	1913312.37	103.285
NVA-13	1596442.39	1912652.55	122.619
NVA-14	1597033.77	1907335.82	122.285
NVA-15	1588342.36	1908647.28	109.124
NVA-16	1577399.42	1907625.32	77.017
NVA-17	1583965.88	1903505.61	77.253
NVA-18	1593589.09	1903859.64	92.819
NVA-19	1600139.76	1904667.13	99.244
NVA-20	1601221.4	1898785.35	75.956
NVA-21	1604684.97	1892842.53	36.08
NVA-22	1610917.03	1897686.32	43.649
NVA-23	1613791.74	1903066.58	41.044
NVA-24	1605668.97	1901366.19	65.481
NVA-25	1604305.68	1906777.57	88.827
NVA-26	1610640.7	1904780.45	45.079
NVA-27	1615930.04	1905858.43	8.079
NVA-28	1619253.5	1911320.72	6.615
NVA-29	1613308.79	1909959.68	44.666
NVA-30	1612599.05	1914372.6	67.76
NVA-31	1604699.79	1913101.12	72.005
NVA-32	1601488.93	1918161.56	100.591
NVA-33	1608089.04	1917774.49	74.586
NVA-34	1616881.93	1917093.13	56.257
NVA-35	1616219.85	1921654.68	48.337
NVA-36	1609729.83	1923147.68	104.848
NVA-37	1604191.55	1922520.42	133.536
NVA-38	1598816.34	1923560.6	128.26
NVA-39	1609109.02	1927764.6	58.287
NVA-40	1604228.92	1928949.93	91.761

NVA-41	1598708.95	1929318.57	87.064
NVA-42	1596292.95	1934858.2	109.576
VVA-1	1610587.99	1894664.19	10.017
VVA-2	1609667.2	1902255.23	39.311
VVA-3	1602159.54	1901687.79	94.106
VVA-4	1616134.89	1903287.85	10.02
VVA-5	1616491.96	1909107.11	14.059
VVA-6	1606978.9	1906409.69	78.865
VVA-7	1603875.22	1912056.06	71.251
VVA-8	1608276.48	1913533.8	87.896
VVA-9	1616462.37	1919679.06	13.146
VVA-10	1607325.39	1920060.18	77.661
VVA-11	1599628.65	1917534.55	87.035
VVA-12	1600940.53	1922920.46	125.417
VVA-13	1606088.92	1926554.71	80.311
VVA-14	1607611.24	1929568.51	73.551
VVA-15	1600821.34	1928901.17	95.469
VVA-16	1597395.15	1929499.55	56.086
VVA-17	1593426.02	1934505	107.109
VVA-18	1588745.13	1935908.66	82.496
VVA-19	1587123.99	1930235.53	111.071
VVA-20	1594507.44	1929213.71	91.838
VVA-21	1596260.99	1927309.27	62.275
VVA-22	1588865.71	1922168.88	119.155
VVA-23	1577495.13	1917211.26	97.718
VVA-24	1595127.24	1917558.73	133.26
VVA-25	1595550.13	1913593.73	118.523
VVA-26	1580780.42	1914365.44	83.379
VVA-27	1578253.29	1909273.29	77.516
VVA-28	1588607.36	1910588.36	113.192
VVA-29	1592931.4	1906775.73	61.828
VVA-30	1597339.76	1903761.33	95.418
VVA-31	1582789.08	1904401.96	58.122
VVA-32	1596865.47	1896756	91.722

Table 9 – Virginia Fairfax County lidar surveyed accuracy checkpoints

The figure below shows the location of the QA/QC checkpoints used to test the positional accuracy of the dataset.

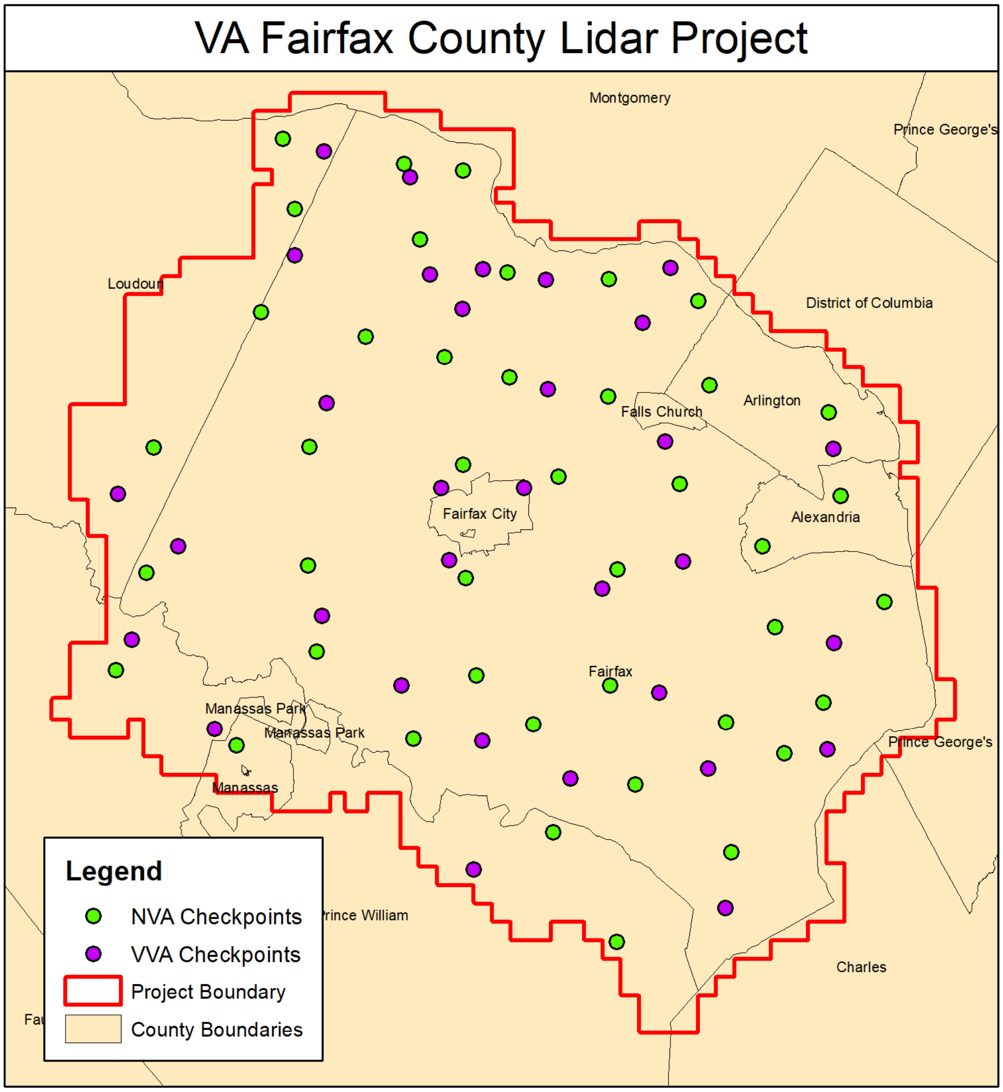

Figure 17 – Location of QA/QC Checkpoints

VERTICAL ACCURACY TEST PROCEDURES

Non-Vegetated Vertical Accuracy

NVA is determined with checkpoints 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 has detected the bare-earth ground surface and where random errors in the point cloud 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 Virginia Fairfax County lidar project, vertical accuracy must be 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

Vegetated Vertical Accuracy

VVA is determined with 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 Virginia Fairfax County Lidar Project VVA standard is 30 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. Here, $Accuracy_z$ 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 10.

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)
Vegetated Vertical Accuracy (VVA) in all vegetated land cover categories combined at the 95% confidence level	30 cm (based on combined 95th percentile)

Table 10 — 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 specifications.
2. Dewberry interpolated the bare-earth lidar DTM to provide a corresponding z-value for every checkpoint.
3. Dewberry computed the associated z-value differences between the interpolated z-value from the lidar data and the survey checkpoints and computed NVA, VVA, and associated 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 results from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar 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=30 cm
NVA	42	17.3	
VVA	32		12.4

Table 11 — Tested lidar NVA and VVA

This lidar 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 ± 12.4 cm at the 95th percentile.

The figure below illustrates the magnitude of the differences between the QA/QC checkpoints and lidar data. This shows that the all of lidar elevations were within ± 20 cm of the checkpoints elevations.

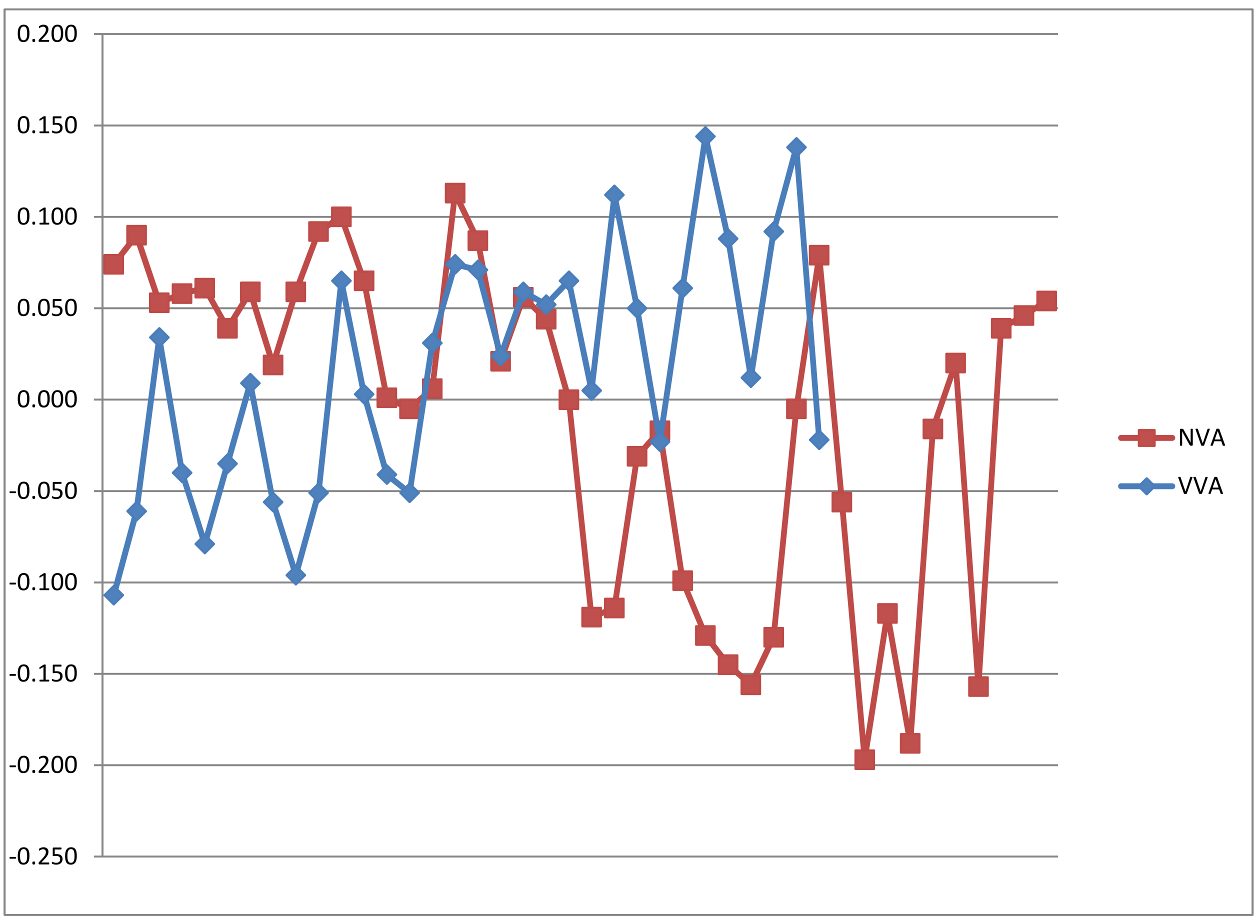

Figure 18 – Magnitude of elevation discrepancies per land cover category

Table 12 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83(2011) Albers Equal Area		NAVD88 (Geoid 12B)		Delta Z	AbsDelta Z
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-LiDAR (m)		
VVA-31	1582789.08	1904401.96	58.122	58.26	0.138	0.138
VVA-27	1578253.29	1909273.29	77.516	77.66	0.144	0.144

Table 12— Lidar VVA 5% outliers

Table 13 provides overall descriptive statistics for NVA and VVA assessments.

100 % of Totals	# of Points	RMSE (m) Spec=0.100 m NVA	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	42	0.088	-0.008	0.020	-0.722	0.089	-0.763	-0.197	0.113
VVA	32	N/A	0.016	0.018	0.013	0.067	-0.811	-0.107	0.144

Table 13 — Lidar NVA and VVA descriptive statistics

The figure below shows a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the lidar triangulated irregular network (TIN). The frequency shows the number of discrepancies within each band of elevation differences. The vast majority of points are within the ranges of -0.025 meters to +0.075 meters.

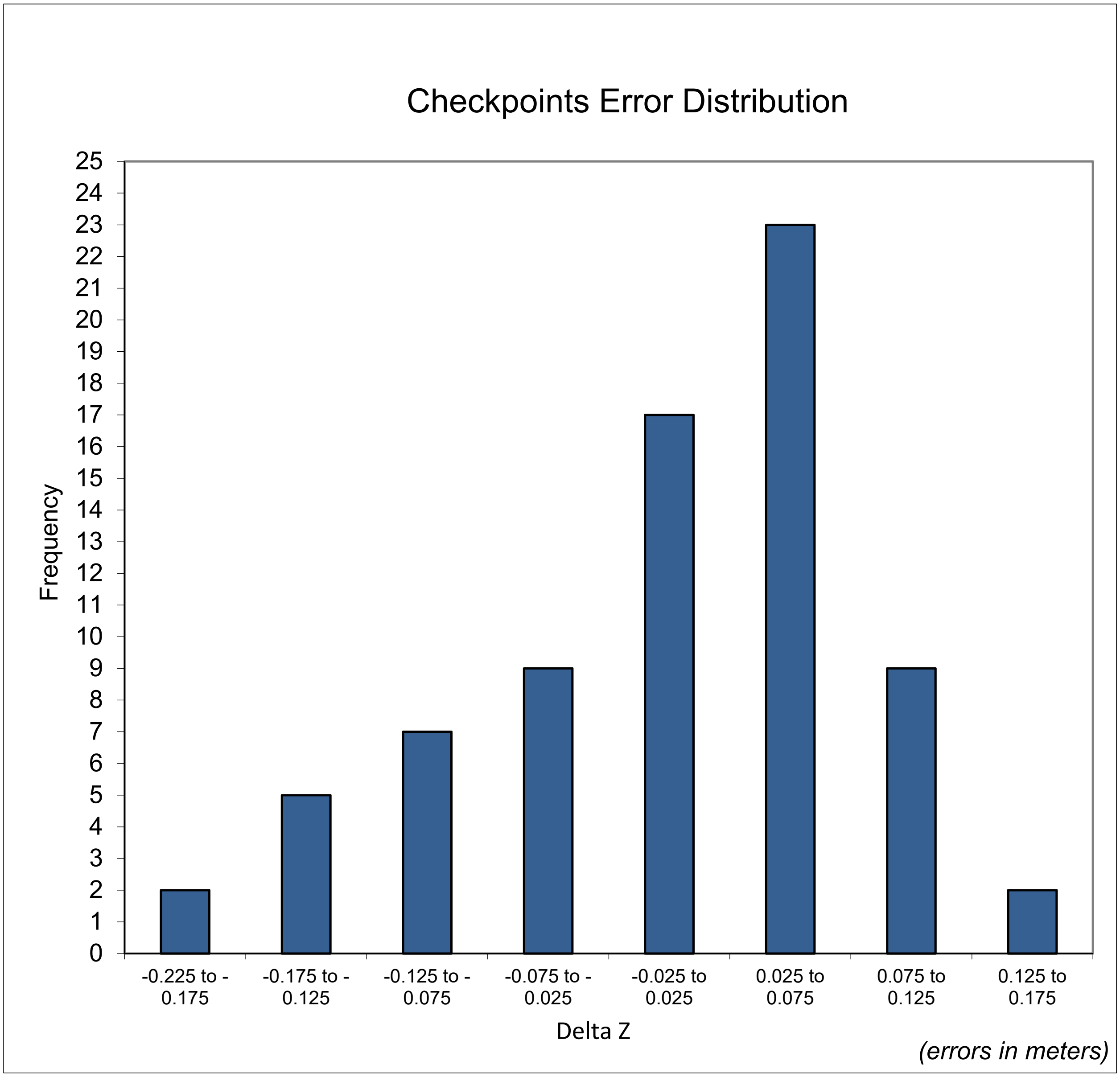

Figure 19 — Histogram of elevation Discrepancies with errors in meters

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the USGS Virginia Fairfax County Lidar Project satisfies the project's defined vertical accuracy criteria.

HORIZONTAL ACCURACY TEST PROCEDURES

Horizontal accuracy testing requires well-defined checkpoints that can be photo-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 checkpoints 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 checkpoints.

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 differences in x and y coordinates between the photo-identifiable feature in the lidar intensity imagery and the survey checkpoints.
4. The data were analyzed by Dewberry 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

Twelve checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called $Accuracy_r$) is computed by the formula $RMSE_r$ x 1.7308 or $RMSE_{xy}$ x 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
12	26.5	31.8	41.4	71.7

Table 14 – Tested horizontal accuracy at the 95% confidence level

This data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm $RMSE_x$/$RMSE_y$ Horizontal Accuracy Class which equates to a positional horizontal accuracy of ± 1 meter at a 95% confidence level. Twelve checkpoints were used for horizontal accuracy testing. Actual positional accuracy of this dataset was found to be $RMSE_x$ = 26.5 cm and $RMSE_y$ = 31.8 cm, which equates to ± 71.7 cm at 95% confidence level.

Breakline Production & Qualitative Assessment Report

BREAKLINE PRODUCTION METHODOLOGY

Dewberry used GeoCue software to develop lidar stereo models of the project area so the lidar derived data could be viewed in 3-D stereo using Socet Set softcopy photogrammetric software. Using lidargrammetry procedures with lidar intensity imagery, Dewberry used the stereo models to stereo-compile the two types of hydrographic breaklines in accordance with the project's Data Dictionary.

All drainage breaklines are monotonically enforced to show downhill flow. Water bodies are at a constant elevation where the lowest elevation of the water body has been applied to the entire water body.

BREAKLINE QUALITATIVE ASSESSMENT

Dewberry completed breakline qualitative assessments according to a defined workflow. The workflow diagram below represents the steps taken by Dewberry to provide a thorough qualitative assessment of the breakline data.

Completeness and horizontal placement were verified through visual reviews against lidar intensity imagery. Automated checks were applied on all breakline features to validate topology, including the 3D connectivity of features, enforced monotonicity on linear hydrographic breaklines, and flatness on water bodies.

The next step compared the elevation of the breakline vertices against the ground elevation extracted from the Esri Terrain built from the lidar ground points, keeping in mind that a discrepancy was expected because of the hydro-enforcement applied to the breaklines and because of the interpolated imagery used to acquire the breaklines. A given tolerance was used to validate if the elevations differed too much from the lidar.

After all corrections and edits to the breakline features, the breaklines were imported into the final GDB and verified for correct formatting.

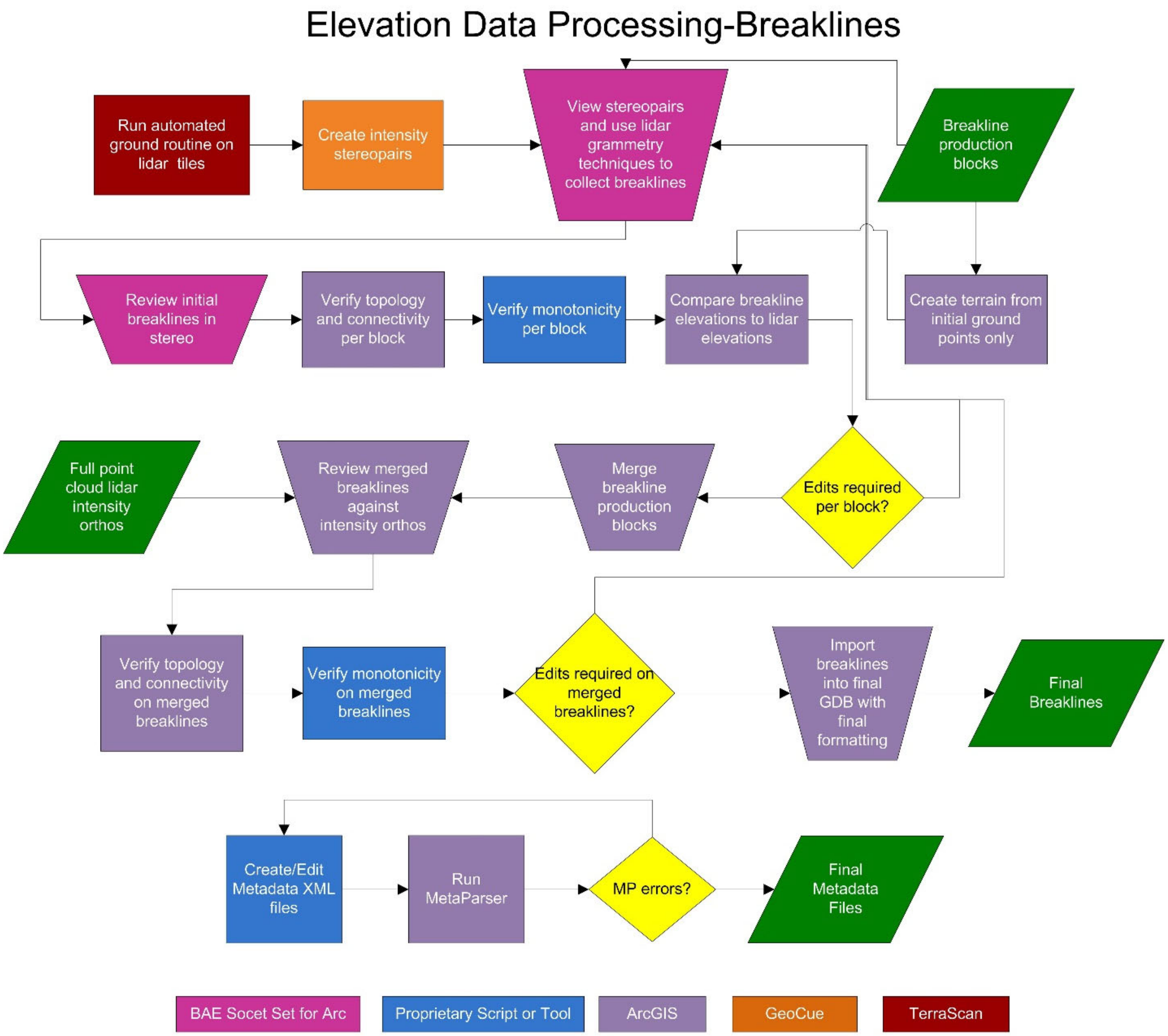

Figure 20 – Breakline QA/QC workflow

BREAKLINE CHECKLIST

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

Pass/Fail	Validation Step
Pass	Use lidar-derived data, which may include intensity imagery, stereo pairs, bare earth ground models, density models, slope models, and terrains, to collect breaklines according to project specifications.
Pass	In areas of heavy vegetation or where the exact shoreline is hard to delineate, it is better to err on placing the breakline *slightly* inside or seaward of the shoreline (breakline can be inside shoreline by 1x-2x NPS).

Pass/Fail	Validation Step
Pass	After each producer finishes breakline collection for a block, each producer must perform a completeness check, breakline variance check, and all automated checks on their block before calling that block complete and ready for the final merge and QC
Pass	After breaklines are completed for production blocks, all production blocks should be merged together and completeness and automated checks should be performed on the final, merged GDB. Ensure correct snapping-horizontal (x,y) and vertical (z)-between all production blocks.
Pass	Check entire dataset for missing features that were not captured, but should be to meet baseline specifications or for consistency. Features should be collected consistently across tile bounds. Check that the horizontal placement of breaklines is correct. Breaklines should be compared to full point cloud intensity imagery and terrains
Pass	Breaklines are correctly edge-matched to adjoining datasets in completion, coding, and horizontal placement.
Pass	Using a terrain created from lidar ground (all ground including 2, 8, and 20) and water points (class 9), compare breakline Z values to interpolated lidar elevations.
Pass	Perform all Topology and Data Integrity Checks
Pass	Perform hydro-flattening and hydro-enforcement checks including monotonicity and flatness from bank to bank on linear hydrographic features and flatness of water bodies. Tidal waters should preserve as much ground as possible and can include variations or be non-monotonic.

Table 15 – A subset of the high-level steps from Dewberry's Production and QA/QC checklist performed for this project.

DATA DICTIONARY

The following data dictionary was used for this project.

Horizontal and Vertical Datum

The horizontal datum is North American Datum of 1983 (2011 adjustment), units in meters. The vertical datum is North American Vertical Datum of 1988, units in meters. Geoid12B is used to convert ellipsoidal heights to orthometric heights.

Coordinate System and Projection

All data is projected to Albers Equal Area, with horizontal and vertical units in meters.

Inland Streams and Rivers

Feature Dataset: Breaklines
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: 0.0001
XY Tolerance: 0.001

Feature Class: Rivers_Streams
Contains M Values: No
Annotation Subclass: None
Z Resolution: 0.0001
Z Tolerance: 0.001

Description

This polygon feature class depicts linear hydrographic features with a width greater than 50 feet.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Streams and Rivers	Linear hydrographic features such as streams, rivers, canals, etc. with an average width greater than 50 feet. In the case of embankments, if the feature forms a natural dual line channel, then capture it consistent with the capture rules. Other natural or manmade embankments will not qualify for this project.	Capture features showing dual line (one on each side of the feature). Average width shall be greater than 50 feet to show as a double line. Each vertex placed should maintain vertical integrity. Generally both banks shall be collected to show consistent downhill flow. There are exceptions to this rule where a small branch or offshoot of the stream or river is present. The banks of the stream must be captured at the same elevation to ensure flatness of the water feature. If the elevation of the banks appears to be different see the task manager or PM for further guidance. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water. Every effort should be made to avoid breaking a stream or river into segments. Dual line features shall break at road crossings (culverts). In areas where a bridge is present the dual line feature shall continue through the bridge. Islands: The double line stream shall be captured around an island if the island is greater than 1 acre. In this case a segmented polygon shall be used around the island in order to allow for the island feature to remain as a "hole" in the feature.

Inland Ponds and Lakes

Feature Dataset: Breaklines
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: 0.0001
XY Tolerance: 0.001

Feature Class: Ponds_Lakes
Contains M Values: No
Annotation Subclass: None
Z Resolution: 0.0001
Z Tolerance: 0.001

Description

This polygon feature class depicts closed water body features that are at a constant elevation.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Ponds and Lakes	Land/Water boundaries of constant elevation water bodies such as lakes, reservoirs, ponds, etc. Features shall be defined as closed polygons and contain an elevation value that reflects the best estimate of the water elevation at the time of data capture. Water body features will be captured for features 1 acres in size or greater. "Donuts" will exist where there are islands within a closed water body feature.	Water bodies shall be captured as closed polygons with the water feature to the right. The compiler shall take care to ensure that the z-value remains consistent for all vertices placed on the water body. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. An Island within a Closed Water Body Feature that is 1 acre in size or greater will also have a "donut polygon" compiled. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water.

Beneath Bridge Breaklines

Feature Dataset: Breaklines
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: 0.0001
XY Tolerance: 0.001
Feature Class: Bridge_Saddle_Breaklines
Contains M Values: No
Annotation Subclass: None
Z Resolution: 0.0001
Z Tolerance: 0.001

Description

This polyline feature class is used to enforce terrain beneath bridge decks where ground data may not have been acquired. Enforcing the terrain beneath bridge decks prevents bridge saddles.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Bridge Breaklines	Bridge Breaklines should be used where necessary to enforce terrain beneath bridge decks and to prevent bridge saddles in the bare earth DEMs.	Bridge breaklines should be collected beneath bridges where bridge saddles exist or are likely to exist in the bare earth DEMs. Bridge breaklines should be collected perpendicular to the bridge deck so that the endpoints are on either side of the bridge deck. Typically two bridge breaklines are collected per bridge deck, one at either end of the bridge deck to enforce the terrain under the full bridge deck. The endpoints of the bridge breaklines will match the elevation of the ground at their xy position to enforce the ground/bare earth elevations beneath the bridge deck and prevent bridge saddles from forming.

DEM Production & Qualitative Assessment

DEM PRODUCTION METHODOLOGY

Dewberry utilized Esri software and Global Mapper for the DEM production and QC process. ArcGIS software is used to generate the products and the QC is performed in both ArcGIS and Global Mapper. The workflow diagram below shows the entire process necessary for bare earth DEM production, starting from the lidar swath processing.

The final bare-earth lidar points were used to create a terrain. The final 3D breaklines collected for the project were also enforced in the terrain. The terrain was then converted to raster format using linear interpolation. The DEM was reviewed for any issues requiring corrections, including remaining lidar mis-classifications, erroneous breakline elevations, poor hydro-flattening or hydro-enforcement, and processing artifacts. After corrections were applied, the DEM was then split into individual tiles following the project tiling scheme. The tiles were verified for final formatting and then loaded into Global Mapper to ensure no missing or corrupt tiles and to ensure seamlessness across tile boundaries.

Figure 21 – DEM production workflow

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. 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 and contain the correct projection information. The DEM data was reviewed at a scale of 1:5000 to review for artifacts caused by the DEM generation process and to review the hydro-flattened features. To perform this review Dewberry created hillshade models and overlaid a partially transparent colorized elevation model to review for these issues. All corrections were completed using Dewberry's proprietary correction workflow. Upon completion of the corrections, the DEM data was loaded into Global Mapper for its second review and to verify corrections. Once the DEMs were tiled out, the final tiles were again loaded into Global Mapper to ensure coverage and extents and to ensure that the final tiles were seamless.

The image below shows an example of a bare earth DEM.

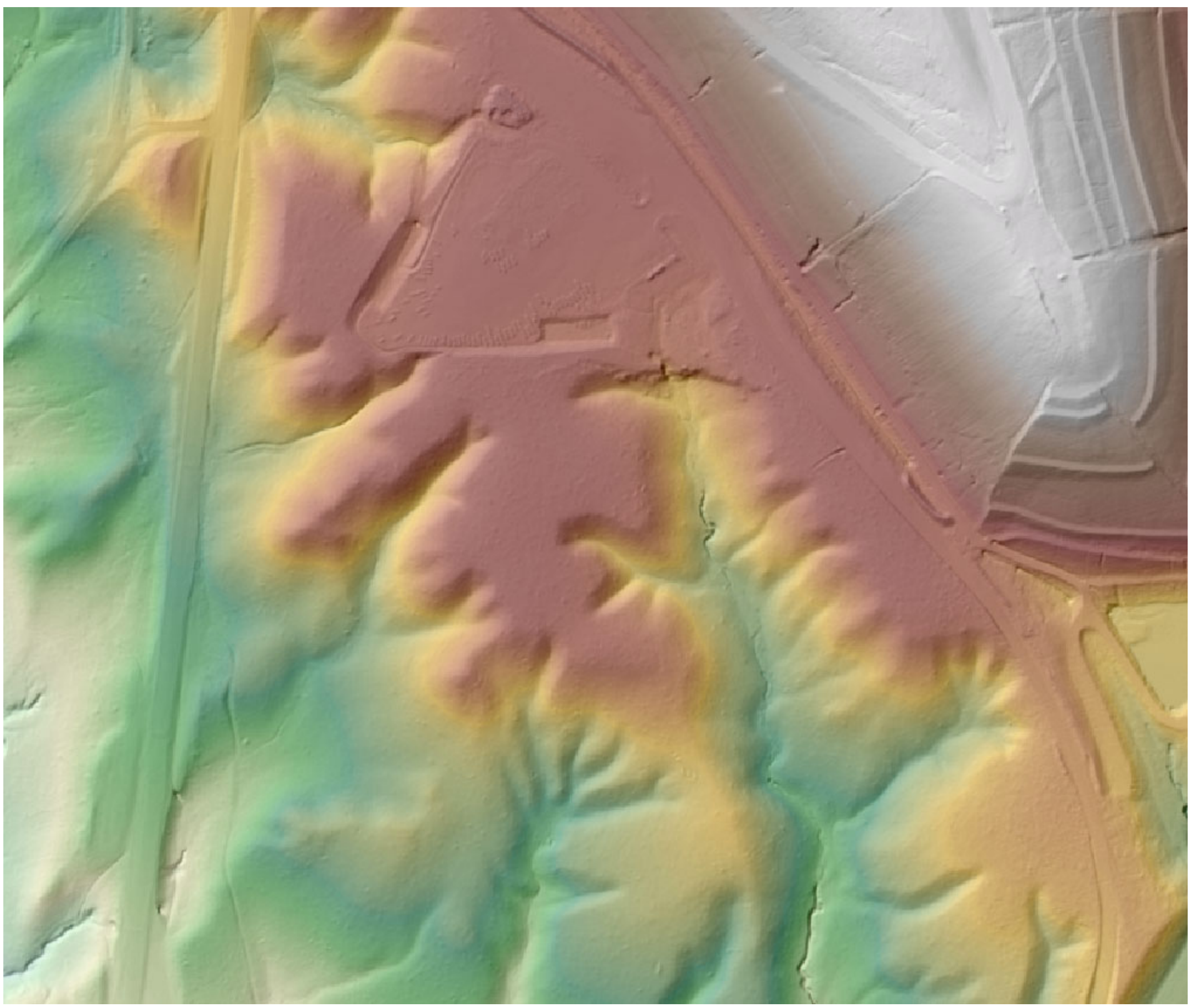

Figure 22 –e1606n1898. Map view of the bare Earth DEM with hillshade

When some bridges are removed from the ground surface, the distance from bridge abutment to bridge abutment is small enough that the DEM interpolates across the entire bridge opening, forming 'bridge saddles.' Dewberry collected 3D bridge breaklines in locations where bridge saddles were present and enforced these breaklines in the final DEM creation to help mitigate the bridge saddle artifacts. The image below shows an example of a bridge saddle that required bridge breaklines to enforce a better DEM surface.

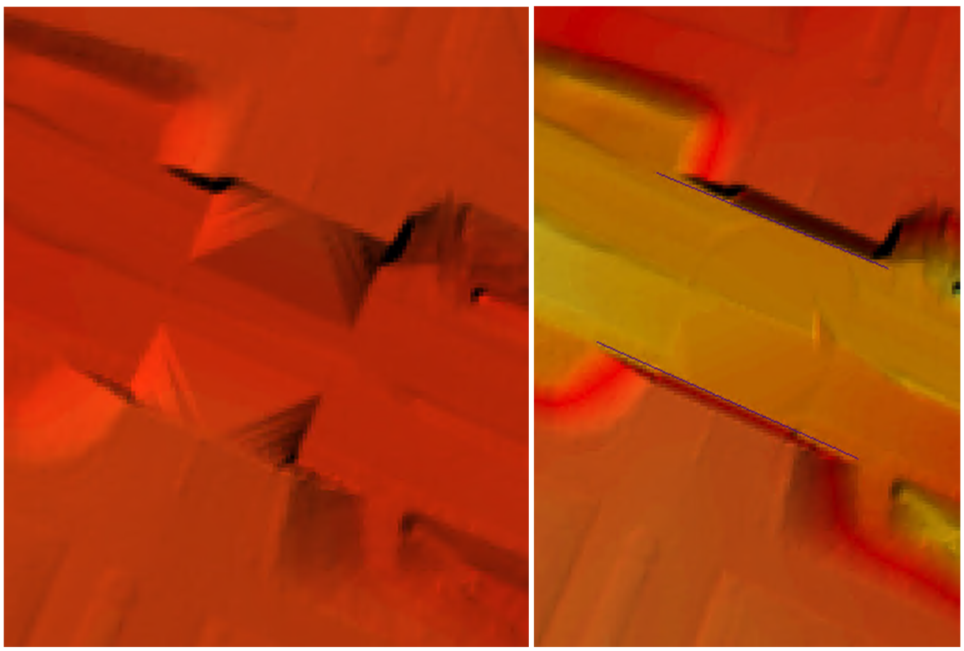

Figure 23 – e1588n1932. The DEM on the left shows a bridge saddle artifact while the DEM on the right shows the same location after bridge breaklines have been enforced

DEM VERTICAL ACCURACY RESULTS

The same 74 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.

Table 16 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=30 cm
NVA	42	17.1	
VVA	32		12.2

Table 16 — Tested DEM NVA and VVA

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 $RMSE_z$ = 8.7 cm, equating to ± 17.1 cm at 95% confidence level. Actual VVA accuracy was found to be ± 12.2 cm at the 95th percentile.

Table 17 lists the 5% outliers that are larger than the VVA 95th percentile and Table 18 shows the descriptive statistics of the VVA dataset.

Point ID	NAD83 (2011) Albers Equal Area		NAVD88 (Geoid 12B)		Delta Z	AbsDelta Z
	Easting X (m)	Northing Y (m)	Z-Survey (m)	Z-DEM (m)		
VVA-31	1582789.080	1904401.960	58.122	58.258	0.136	0.136
VVA-27	1578253.290	1909273.290	77.516	77.659	0.143	0.143

Table 17 — DEM 5% Outliers

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	42	0.087	-0.012	0.016	-0.706	0.087	-0.821	-0.199	0.108
VVA	32	N/A	0.019	0.028	-0.203	0.066	-0.672	-0.110	0.143

Table 18 — DEM NVA and VVA descriptive statistics

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the USGS Virginia Fairfax County Lidar Project 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 bare earth DEM Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Masspoints (LAS to multipoint) are created from ground points only (class 2 and class 8 if model key points created, but no class 20 ignored ground points or class 9 water points
Pass	Create a terrain for each production block using the final bare earth lidar points and final breaklines.
Pass	Convert terrains to rasters using project specifications for grid type, formatting, and cell size
Pass	Create hillshades for all DEMs
Pass	Manually review bare-earth DEMs in ArcMap with hillshades to check for issues

Pass	DEMs should be hydro-flattened or hydro-enforced as required by project specifications
Pass	DEMs should be seamless across tile boundaries
Pass	Water should be flowing downhill without excessive water artifacts present
Pass	Water features should NOT be floating above surrounding
Pass	Bridges should NOT be present in bare-earth 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, 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.

Table 19– A subset of the high-level steps from Dewberry's bare earth DEM Production and QA/QC checklist performed for this project

Appendix A: Checkpoint Survey Report

Appendix A has been included as a separate document.

Appendix B: Axis GPS and IMU Reports

Appendix B has been included as an attachment.