Berkeley County - South Carolina Lidar

Report Produced for South Carolina Department of Natural Resources

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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 SC DNR Berkeley 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 5000ft by 5000ft. A total of 1526 tiles were produced for the project encompassing an area of approximately 1265 sq. miles.

This report encompasses both deliverables for the USGS and South Carolina DNR products for this project. Note that some characteristics unique to the DNR requirements may not be present in the USGS deliverables.

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.

South Carolina Geodetic Survey 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. Please see Appendix A to view the separate Survey Report that was created for this portion of the 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 South Carolina county of Berkeley.

DATE OF SURVEY

The lidar aerial acquisition was conducted from February 25, 2017 and March 09, 2017.

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: South Carolina State Plane
Units: Horizontal units are in international feet, Vertical units are in U.S Survey feet.
Geoid Model: Geoid12B (Geoid 12B was used to convert ellipsoid heights to orthometric heights).

LIDAR VERTICAL ACCURACY

For the South Carolina Berkeley County Lidar Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled **0.15 ft (4.6 cm)** compared with the 0.33 ft (10 cm) specification; and the NVA of the classified lidar data computed using $RMSE_z$ x 1.9600 was equal to **0.30 ft (9.1 cm)**, compared with the 0.64 ft (19.6 cm) specification.

For the South Carolina Berkeley County Lidar Project, the tested VVA of the classified lidar data computed using the 95^{th} percentile was equal to **0.58 ft (17.7cm),** compared with the 0.96 ft (29.4 cm) specification.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and bare earth DEM data 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)
2. Bare Earth Surface (Raster DEM – Mosaic Grid for SC DNR and IMG tiles for USGS)
3. Intensity Images (8-bit gray scale, mosaic Grid for SC DNR and GeoTIFF tiles for USGS)
4. Breakline Data (File GDB)
5. Independent Survey Checkpoint Data (Report & Points)
6. Metadata
7. Project Report (Acquisition, Processing, QC)
8. Project Extents, Including a shapefile derived from the lidar deliverable
9. 1-foot contours
10. Hydro-enforced Terrain (File GDB)

PROJECT TILING FOOTPRINT

Fifteen hundred and twenty six (1526) tiles were delivered for the project. Each tile's extent is 5,000 feet by 5,000 feet (see Appendix B for a complete listing of delivered tiles).

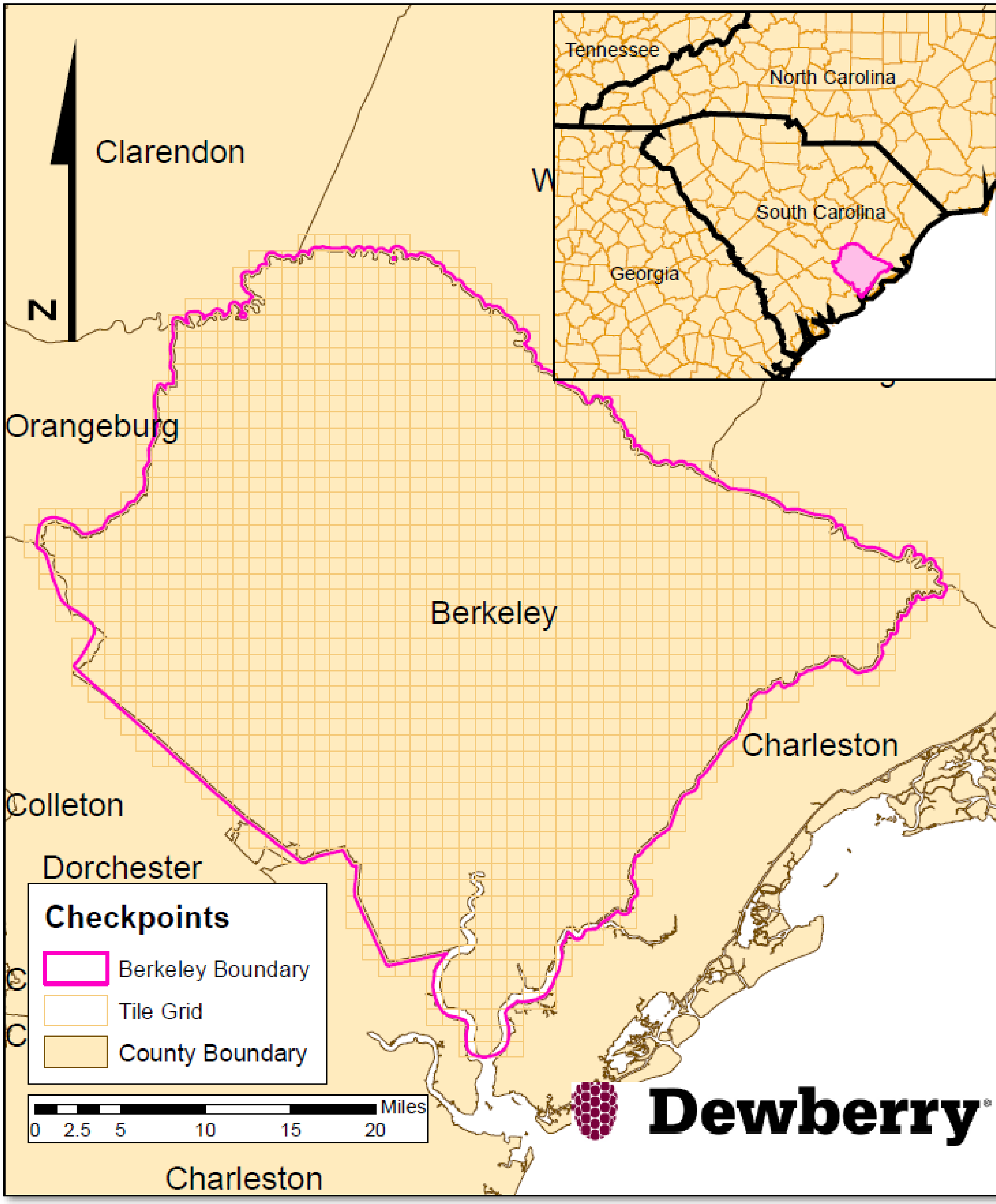

Figure 1 - Project Map

Lidar Acquisition Report

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

LIDAR ACQUISITION DETAILS

Axis GeoSpatial planned 100 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, Axis GeoSpatial followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using TrackAir 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, Axis GeoSpatial will file our flight plans as required by local Air Traffic Control (ATC) prior to each mission.

Axis GeoSpatial 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. Axis GeoSpatial 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, Axis GeoSpatial 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.

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

LIDAR SYSTEM PARAMETERS

Axis GeoSpatial operated a Cessna 206H (Tail # N223TC) outfitted with a Riegl LMS-Q1560 dual channel laser scanner system during the collection of the study area. Table 1 illustrates Axis GeoSpatial system parameters for lidar acquisition on this project.

Item	Parameter
System	Riegl LMS-Q1560
Altitude (AGL meters)	2043
Approx. Flight Speed (knots)	150
Scanner Pulse Rate (kHz)	800
Scan Frequency (hz)	169
Pulse Duration of the Scanner (nanoseconds)	3
Pulse Width of the Scanner (m)	0.9
Swath width (m)	2289
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 mrad
Nominal Swath Width on the Ground (m)	2289
Swath Overlap (%)	30
Total Sensor Scan Angle (degree)	58.52
Computed Down Track spacing (m) per beam	0.68
Computed Cross Track Spacing (m) per beam	0.68
Nominal Pulse Spacing (single swath), (m)	0.7
Nominal Pulse Density (single swath) (ppsm), (m)	2
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.7
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	2
Maximum Number of Returns per Pulse	unlimited

Table 1: Axis GeoSpatial lidar system parameters

ACQUISITION STATUS REPORT AND FLIGHTLINES

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

Figure 2 shows the combined trajectory of the flightlines.

Figure 2: Trajectories as flown by Axis GeoSpatial

LIDAR CONTROL

NGS CORS Base Stations were used to control the lidar acquisition for the South Carolina Berkeley County lidar project area. The coordinates of all used base stations are provided in the table below.

Name	North American Datum 1983 (2011) State Plane South Carolina, International Feet		Orthometric Ht (NAVD88, ft)
	Northing	Easting	
COLA	1963161.38	817796.01	112.38

GAAE	1674265.36	581601.53	154.15
GAAU	1684785.78	597570.51	142.9
GACC	1654600.84	624931.08	128.14
NCFF	2928036.57	787727.66	6.87
NCLU	2578262.74	1021754.34	48.12
NCMR	2142650.66	1145956.42	173.26
NCPO	2246468.08	1150491.21	114.16
NCRO	2360585.73	1141378.61	121.57
NCSL	2790988.73	791947.69	24.34
NCWH	2689689.98	897969.05	30.94
SCEB	2205935.96	237052.98	6.81
SCHA	2330270.86	345971.86	18.59
SCHY	2686738.46	773973.88	17.35
SCSR	2199966.67	760848.31	67.05
SCWT	2101763.94	389516.71	28.28

Table 2 – Base stations used to control lidar acquisition

AIRBORNE GPS KINEMATIC

Airborne GPS data was processed using the PosPac Mobile Mapping System (MMS) version 8.0 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 40km.

For all flights, the GPS data can be classified as excellent, with GPS residuals of 3cm average or better but no larger than 10cm being recorded.

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

GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

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

Subsequently the mission points are output using Riegl's RiProcess, initially with default values from Riegl or the last mission calibrated for the system. The initial point generation for each mission calibration is verified within Microstation/Terrascan for calibration errors. If a calibration error greater than specification is observed within the mission, the roll, pitch and scanner scale corrections that need to be applied are calculated. The missions with the new calibration values are regenerated and validated internally once again to ensure quality.

Data collected by the lidar unit is reviewed for completeness, acceptable density and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database.

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

BORESIGHT AND RELATIVE ACCURACY

The initial points for each mission calibration are 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 are optimized during the calibration process until the relative accuracy is met.

Relative accuracy and internal quality are checked using at least 3 regularly spaced QC blocks in which points from all lines are loaded and inspected. Vertical differences between ground surfaces of each line are displayed. Color scale is adjusted so that errors greater than the specifications are flagged. Cross sections are 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 <= 6cm RMSDz within individual swaths and <=8 cm RMSDz between adjacent and overlapping swaths.

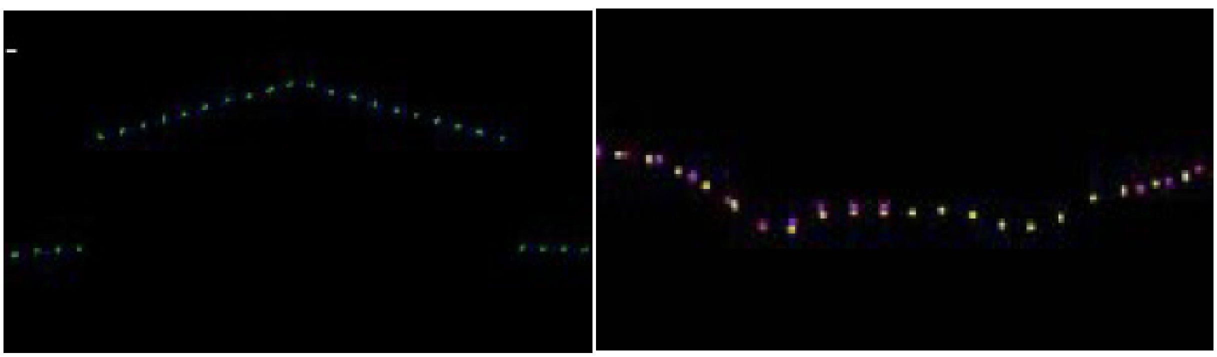

Figure 3 – Profile views showing correct roll and pitch adjustments.

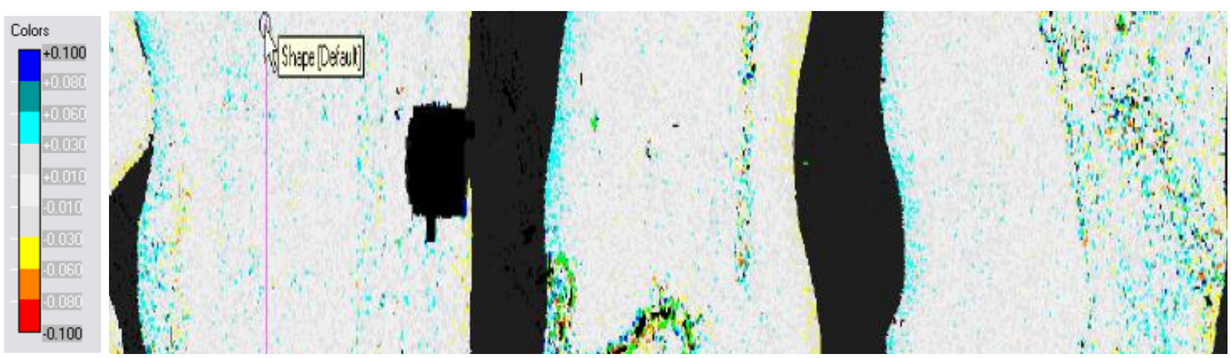

Figure 4 – QC block colored by distance to ensure accuracy at swath edges.

A different set of QC blocks are generated for final review after all transformations have been applied.

PRELIMINARY VERTICAL ACCURACY ASSESSMENT

A preliminary $RMSE_z$ error check is performed by Axis GeoSpatial at this stage of the project life cycle in the raw lidar dataset against GPS static and kinematic data and compared to $RMSE_z$ project specifications. The lidar data is examined in non-vegetated, flat areas away from breaks. Lidar ground points for each flight line generated by an automatic classification routine are used.

Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met Non-vegetated Vertical Accuracy (NVA) requirements ($RMSE_z$ ≤ 0.33 ft (10 cm) and $Accuracy_z$ at the 95% confidence level ≤ 0.64 ft (19.6 cm)) when compared to static and kinematic GPS checkpoints. Below is a summary for the test:

The calibrated Charleston-Berkeley lidar dataset was tested to 0.45 ft (0.136 m) vertical accuracy at 95% confidence level based on $RMSE_z$ (0.23 ft (0.069 m) x 1.9600) when compared to 47 GPS static check points.

The following are the final statistics for the GPS static checkpoints used by Axis GeoSpatial to internally verify vertical accuracy.

Number	NAD83(2011) South Carolina State Plane		NAVD88 (Geoid 12B)	Laser Z (ft)	Delta Z (ft)	Delta Z (cm)
	Easting X (ft)	Northing Y (ft)	Known Z (ft)			
GC_01	2332887.908	573656.397	75.127	75.5	0.373	11.4
GC_02	2348924.281	527733.623	45.447	45.48	0.033	1.0
GC_03	2355585.9	415454.745	37.077	37.12	0.043	1.3
GC_04	2436050.393	496792.046	45.438	45.27	-0.168	-5.1
GC_05	2394077.187	475658.141	32.882	32.92	0.038	1.2
GC_06	2257148.189	527432.402	72.885	73.04	0.155	4.7
GC_07	2263011.415	441396.482	70.289	70.64	0.351	10.7
GC_08	2330569.855	373952.351	12.291	12.45	0.159	4.8
GC_09	2326994.084	421335.317	7.257	7.7	0.443	13.5
GC_10	2302477.179	497319.919	55.974	55.98	0.006	0.2
GC_11	2332766.243	573636.237	75.879	76.04	0.161	4.9
GC_12	2342949.052	529236.915	41.054	40.94	-0.114	-3.5
GC_13	2350582.511	414295.285	35.858	35.59	-0.268	-8.2
GC_14	2358109.382	485487.927	51.838	51.42	-0.418	-12.7
GC_15	2257285.521	525215.335	68.557	68.39	-0.167	-5.1
GC_16	2258502.786	437789.31	70.171	69.87	-0.301	-9.2
GC_17	2337893.97	377141.143	9.15	9.06	-0.09	-2.7
GC_18	2327034.087	424170.542	17.073	17.05	-0.023	-0.7
GC_19	2302261.59	497461.136	57.03	56.99	-0.04	-1.2
GC_20	2266281.499	332346.719	16.355	16.39	0.035	1.1
GC_21	2485857.073	485987.639	23.196	23.04	-0.156	-4.8
GC_22	2205657.763	318597.455	26.657	26.65	-0.007	-0.2
GC_23	2328198.388	334119.034	8.765	8.71	-0.055	-1.7
GC_24	2284587.298	403586.633	22.134	22.19	0.056	1.7
GC_25	2298461.784	352089.173	9.172	9.15	-0.022	-0.7
GC_26	2447486.191	449858.77	16.202	15.96	-0.242	-7.4
GC_27	2394686.972	399808.209	12.321	12.45	0.129	3.9
GC_28	2375934.683	351976.643	6.097	6.46	0.363	11.1
GC_29	2184357.722	348711.842	17.777	17.86	0.083	2.5
GC_30	2228685.325	343343.528	40.81	41.2	0.39	11.9
GC_31	2212387.512	271850.885	14.348	14.37	0.022	0.7
GC_32	2252778.838	300830.121	13.812	14.27	0.458	14.0
GC_33	2278683.08	294011.301	9.891	10.2	0.309	9.4
GC_34	2275024.169	336907.261	14.363	14.19	-0.173	-5.3
GC_35	2485655.839	487245.32	27.677	27.6	-0.077	-2.3
GC_36	2211617.303	323823.396	33.819	33.41	-0.409	-12.5
GC_37	2328910.379	332564.142	9.859	9.77	-0.089	-2.7
GC_38	2284720.282	400053.825	34.7	34.73	0.03	0.9

GC_39	2297602.244	351137.446	6.68	6.32	-0.36	-11.0
GC_40	2447690.52	449590.91	15.101	15.12	0.019	0.6
GC_41	2411828.699	405318.041	6.734	6.68	-0.054	-1.6
GC_42	2363599.53	361436.538	9.375	9.68	0.305	9.3
GC_43	2187338.49	337396.168	29.59	29.49	-0.1	-3.0
GC_44	2230674.255	343632.085	40.963	41.07	0.107	3.3
GC_45	2215834.395	272679.71	14.914	14.52	-0.394	-12.0
GC_46	2255061.027	299948.287	9.256	9.45	0.194	5.9
GC_47	2285119.436	298538.685	12.626	12.28	-0.346	-10.5

Table 3 - Static GPS Points

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	47	0.069	0.136	0.100	0.069	-0.127	0.140

Table 4 - Static GPS Vertical Accuracy Results

Overall the calibrated lidar data products collected by Axis GeoSpatial meet or exceed the requirements set out in the Statement of Work. The quality control requirements of Axis GeoSpatial 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 GeoSpatial, 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 the sixty non-vegetated (open terrain and urban) independent survey check points. One point was removed from swath vertical accuracy testing as errant noise points created an incorrect measurement against all points. This point excluded from the swath assessment however was retained for the classified NVA assessment as it was not an issue with the checkpoint itself. 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 0.64 ft (19.6 cm) based on the $RMSE_z$ (0.33 ft/10 cm) x 1.96. The dataset for the South Carolina Berkeley County Lidar Project satisfies this criteria. This raw lidar swath data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 0.33 ft (10 cm) $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 0.18 ft (5.5 cm), equating to +/- 0.36 ft (11 cm) at 95% confidence level. The table below shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	$RMSE_z$ NVA Spec=0.33 ft	NVA –Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.64 ft	Mean (ft)	Median (ft)	Skew	Std Dev (ft)	Min (ft)	Max (ft)	Kurtosis
Non-Vegetated Terrain	60	0.18	0.36	0.04	0.03	0.16	0.18	-0.42	0.47	0.09

Table 5: NVA at 95% Confidence Level for Raw Swaths

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 v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet inter-swath relative accuracy of 8 cm RMSDz or less with maximum differences less than 16 cm. These measurements are to be taken in non-vegetated and flat open terrain using single or only returns from all classes. Measurements are calculated in the DZ orthos on 1-meter pixels or cell sizes. Areas in the dataset where overlapping flight lines are within 8 cm of each other within each pixel are colored green, areas in the dataset where overlapping flight lines have elevation differences in each pixel between 8 cm to 16 cm are colored yellow, and areas in the dataset where overlapping flight lines have elevation differences in each pixel greater than 16 cm are colored red. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values. Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across 1 linear meter) are expected to appear yellow or red in the DZ orthos. If the project area is heavily vegetated, Dewberry may also create DZ Orthos from the initial ground classification only, while keeping all other parameters consistent. This allows Dewberry to review the ground classification relative accuracy beneath vegetation and to ensure flight line ridges or other issues do not exist in the final classified data.

Flat, open areas are expected to be green in the DZ orthos. 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 South Carolina Berkeley County are shown in the figure below; this project meets inter-swath relative accuracy specifications.

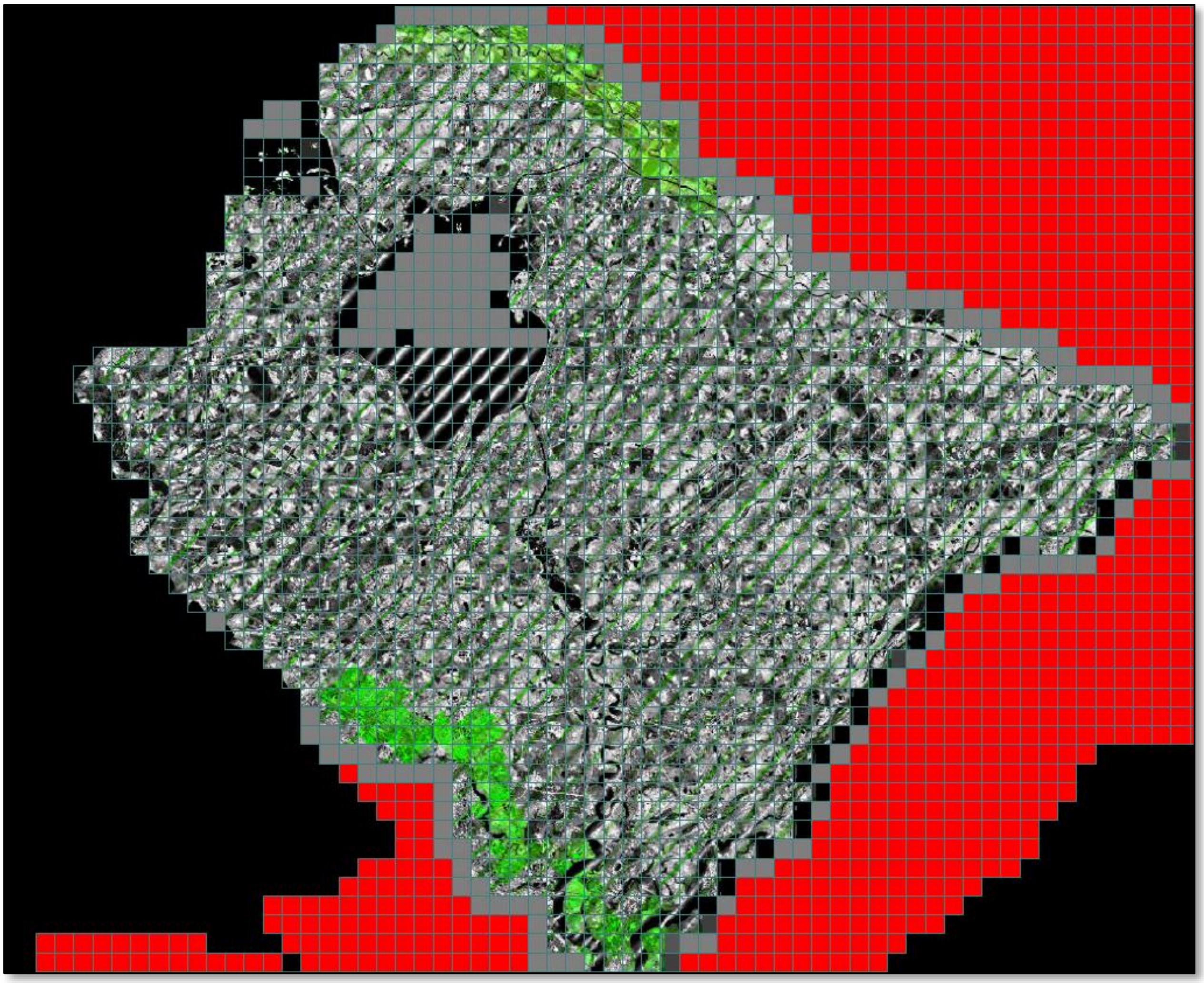

Figure 5 - Single return DZ Orthos for the South Carolina Berkeley County. Inter-swath relative accuracy passes specifications.

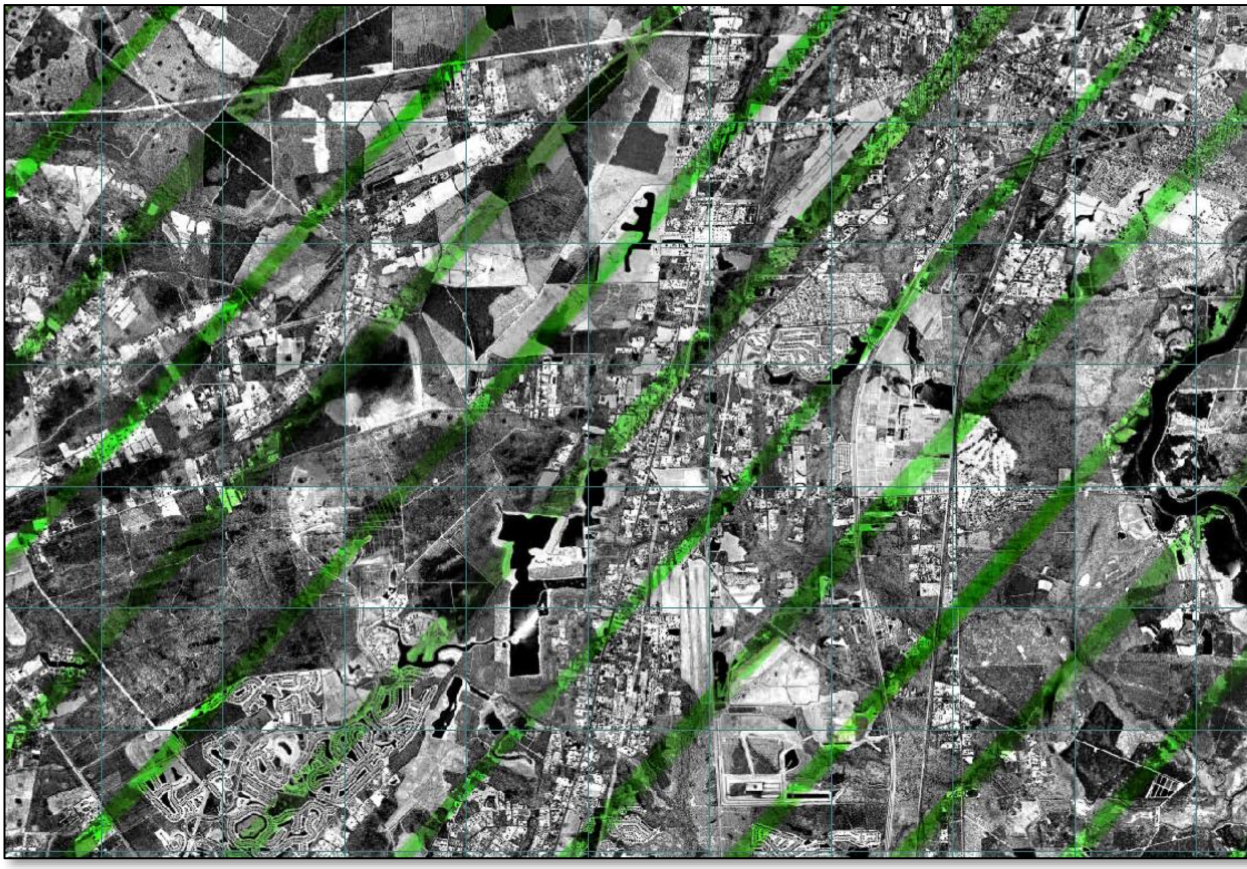

Figure 6 – close-up of DZ orthos created from the final full point cloud.

Intra-Swath (Within a Single Swath) Relative Accuracy

Dewberry verifies the intra-swath or within swath relative accuracy by using Quick Terrain Modeler (QTM) scripting and visual reviews. QTM scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Dewberry analysts then identify planar surfaces acceptable for repeatability testing and analysts review the QTM results in those areas. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet intra-swath relative accuracy of 6 cm maximum difference or less. The image below shows two examples of the intra-swath relative accuracy of South Carolina Berkeley County; this project meets intra-swath relative accuracy specifications.

Horizontal Alignment

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

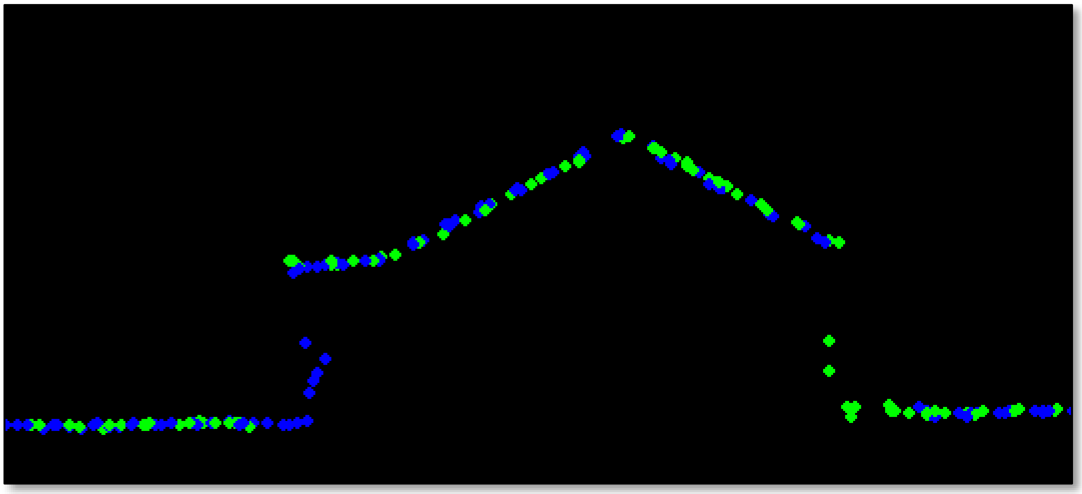

Figure 7– Horizontal Alignment. Two separate flight lines differentiated by color (blue/green) are shown in this profile. There is no visible offset between these two flight lines. No horizontal alignment issues were identified.

Point Density and Spatial Distribution

The required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.71 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 2 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 NPS of 0.52 meters or an ANPD of 3.77 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 2 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-sqaure meter cells contain at least 2 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.

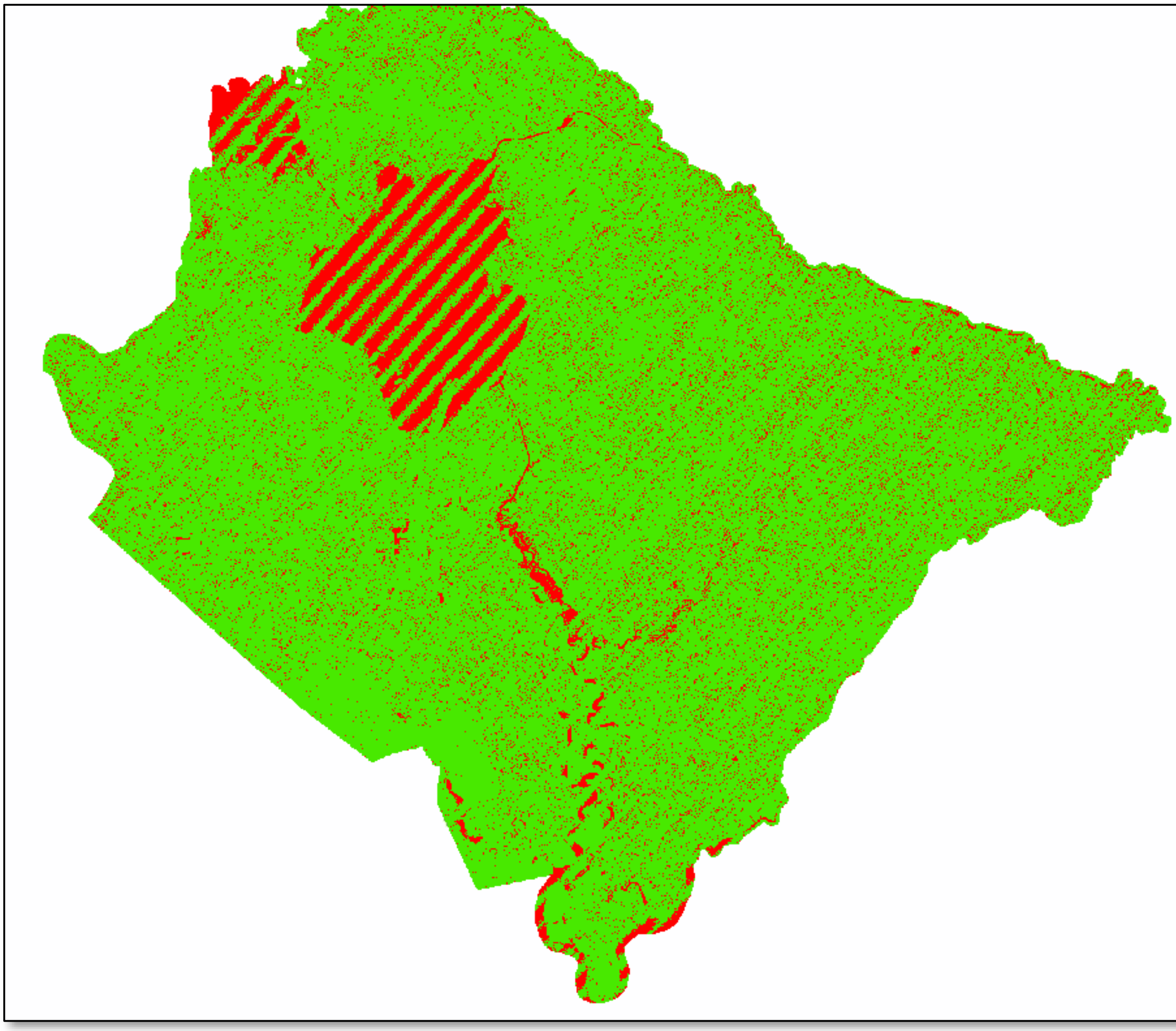

Figure 8 – 1-square meter density grid. There are some 1-meter cells that do not contain 2 points per square meter (red areas) due to the irregular spacing of lidar point cloud data. Most 1-sqaure meter cells contain at least 2 points per square meter (green areas) showing there are no systematic density issues. When density is viewed/analyzed by representative 1-square kilometer areas, density passes with no issues.

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

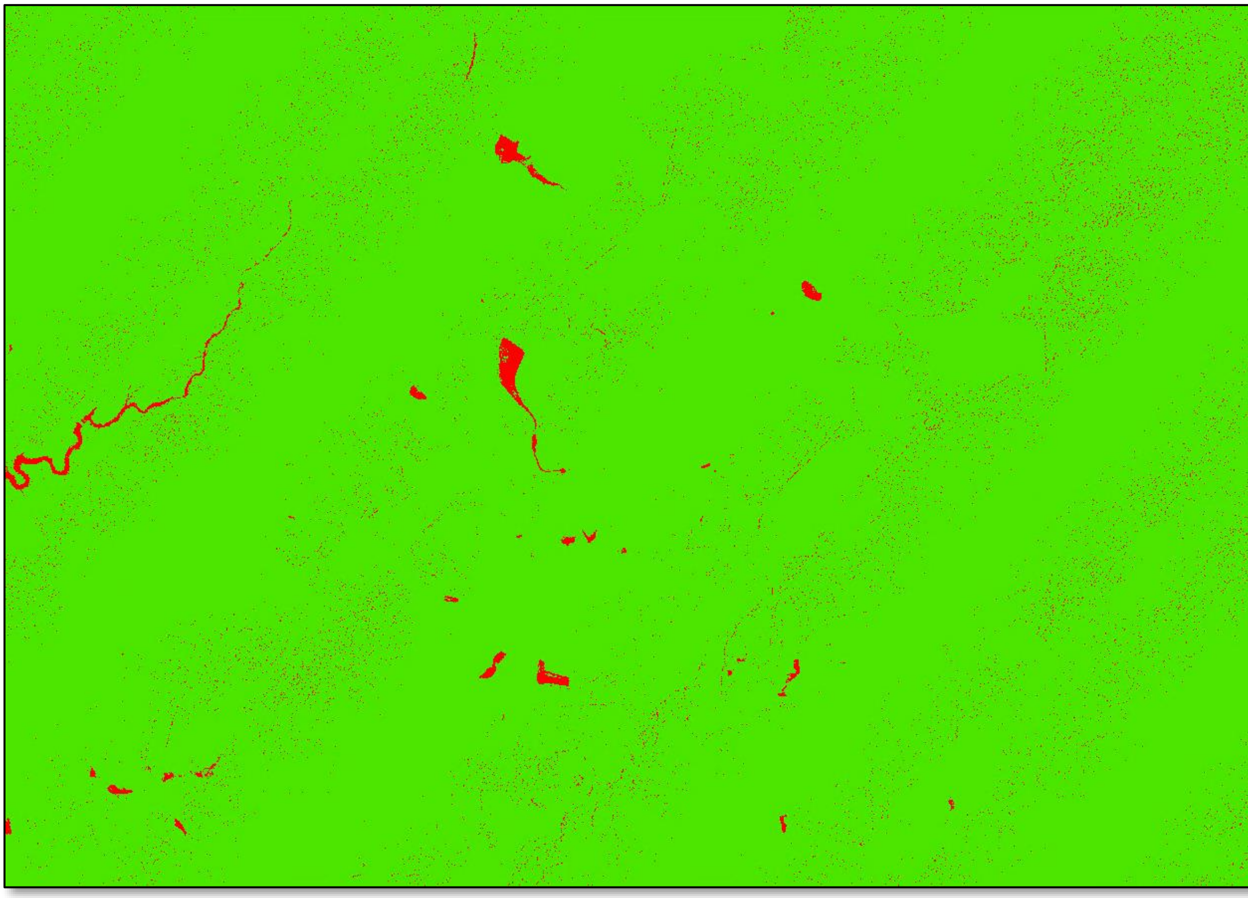

Figure 9 Spatial Distribution. All cells (2*NPS cellsize) containing at least one lidar point are colored green. Cells that do not contain a lidar point, including water bodies which are acceptable NoData area, are colored red. Without removing acceptable NoData areas due to water, 94.3% of cells contain at least one lidar point.

DATA CLASSIFICATION AND EDITING

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data was confirmed, Dewberry utilized a variety of software suites for data processing. The data was processed using GeoCue and TerraScan software. The initial step is the setup of the GeoCue project, which is done by importing a project defined tile boundary index encompassing the entire project area. The acquired 3D laser point clouds, in LAS binary format, were imported into the 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 points that could negatively affect the ground are removed from class 1, the ground layer is extracted from this remaining point cloud. The ground extraction process encompassed in this routine takes place by building an iterative surface model.

This surface model is generated using three main parameters: building size, iteration angle and iteration distance. 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. A second critical parameter is the maximum terrain angle constraint, which determines the maximum terrain angle allowed within the classification model.

Each tile was then 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 employ 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points are removed from the ground classification. Bridge decks are classified to class 17 using bridge breaklines compiled by Dewberry and culverts are classified to class 13. 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 1x NPS or less of the hydrographic features are moved to class 10, an ignored ground due to breakline proximity. Model Keypoints are then classified by using an algorithm in Terrascan which thins the ground points according to set parameters. Overage points are then identified in Terrascan and GeoCue is used to set the overlap bit for the overage points and the withheld bit is 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 the Classes 2, 7, 8,9, 10, 13, 17, or 18, including vegetation, buildings, etc.
- Class 2 = Bare-Earth Ground
- Class 7 = Low Noise
- Class 8 = Model Keypoints (SC DNR deliverables only)
- Class 9 = Water, points located within collected breaklines
- Class 10 = Ignored Ground due to breakline proximity
- Class 13 = Culverts (SC DNR deliverables only)
- 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, are 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 orthos produced from the intensity returns, Triangular Irregular Network (TIN)'s, Digital Elevation Models (DEM) 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 will present representative examples where the lidar and post processing had issues as well as examples of where the lidar performed well.

VISUAL REVIEW

The following sections describe common types of issues identified in lidar data and the results of the visual review for South Carolina Berkeley County.

Data Voids

The LAS files are used to produce density grids using the commercial software package QT Modeler (QTM) which creates a 3-dimensional data model derived from Class 2 (ground) points in the LAS files. Grid spacing is based on the project density deliverable requirement for un-obscured areas. Acceptable voids (areas with no lidar returns in the LAS files) that are present in the majority of lidar projects include voids caused by bodies of water. No unacceptable voids are present in the South Carolina Berkeley County lidar project.

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.

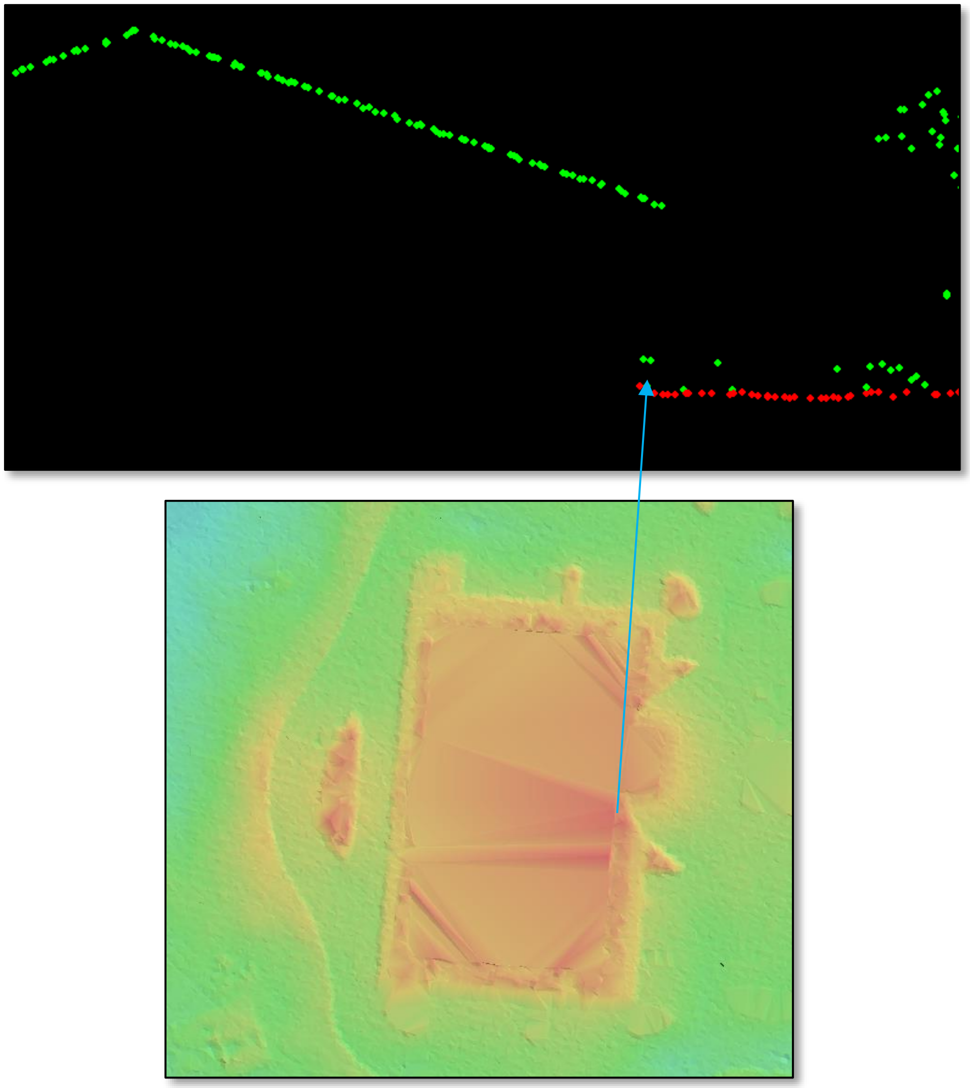

Figure 10 – Tile number 2493-02. Profile with points colored by class (class 1=green, class 2=red) is shown in the top view and a TIN of the surface is shown in the bottom view. The arrow identifies low vegetation points. A limited number of these small features are still classified as ground but do 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.

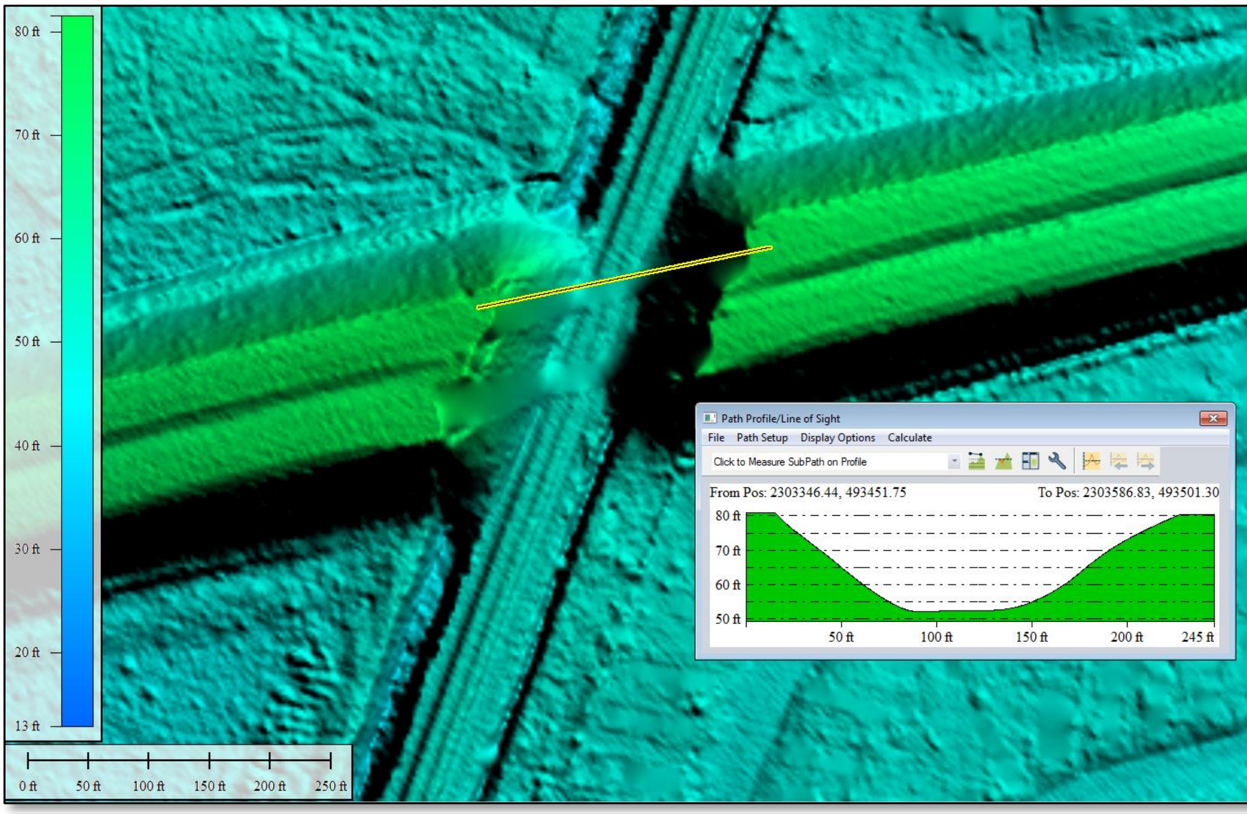

Figure 11 – Tile number 3409-03. The DEM in the view shows an area where a bridge has been removed from ground. The surface model must make a continuous model and in order to do so, points are connected through interpolation. This results in less detail where the surface must be interpolated.

Culverts and Bridges

Bridges have been removed from the bare earth surface while culverts are classified to class 13 (in the USGS deliverables, culverts remain in the bare earth surface or class 2). In instances where it is difficult to determine if the feature is a culvert or bridge, such as with some small bridges, Dewberry erred on assuming they would be culverts especially if they are on secondary or tertiary roads. Below is an example of a culvert classified to class 13. Ground and culvert classifications were used to generate the final bare earth DEMs.

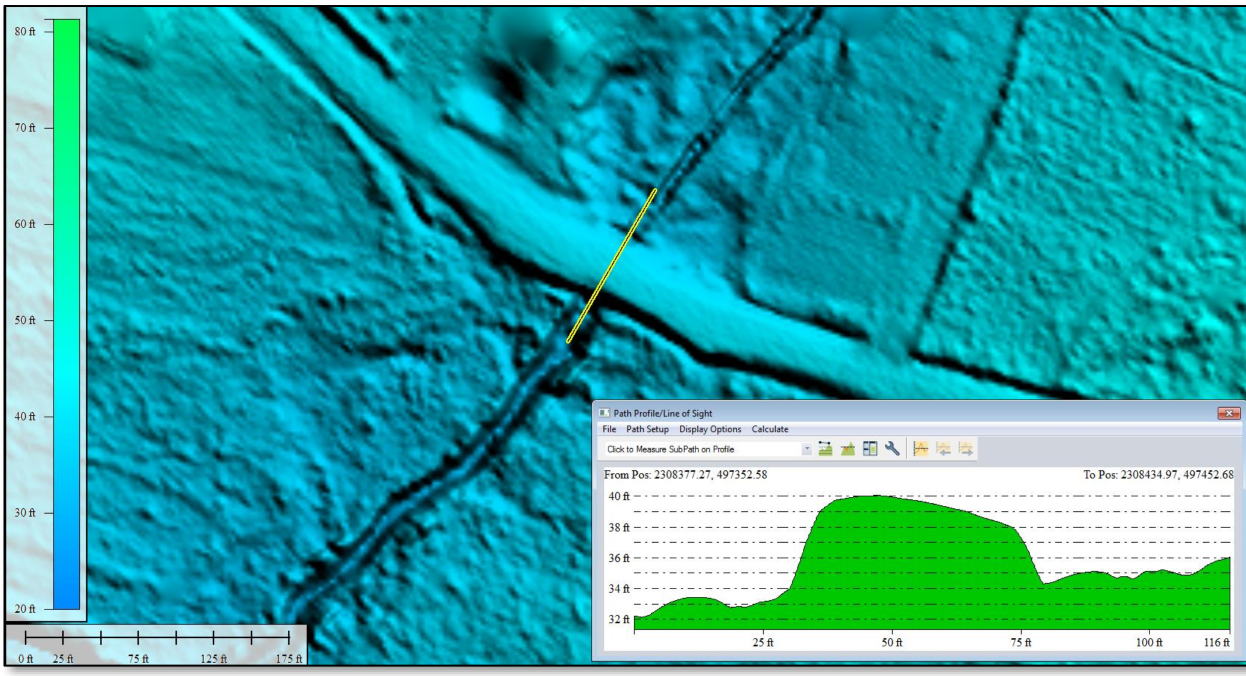

Figure 12– Tile 3409-02 DEM and profile are shown. This culvert has been classified to class 13 and used in the DEM generation so that culverts are modeled in the bare earth DEMs.. Bridges have been removed from the bare earth surface and classified to class 17.

In Ground Structures

In ground structures exist within the project area. These types of structures occur mainly on military bases and in facilities designed for munitions testing and storage. These features are correctly included in the ground classification.

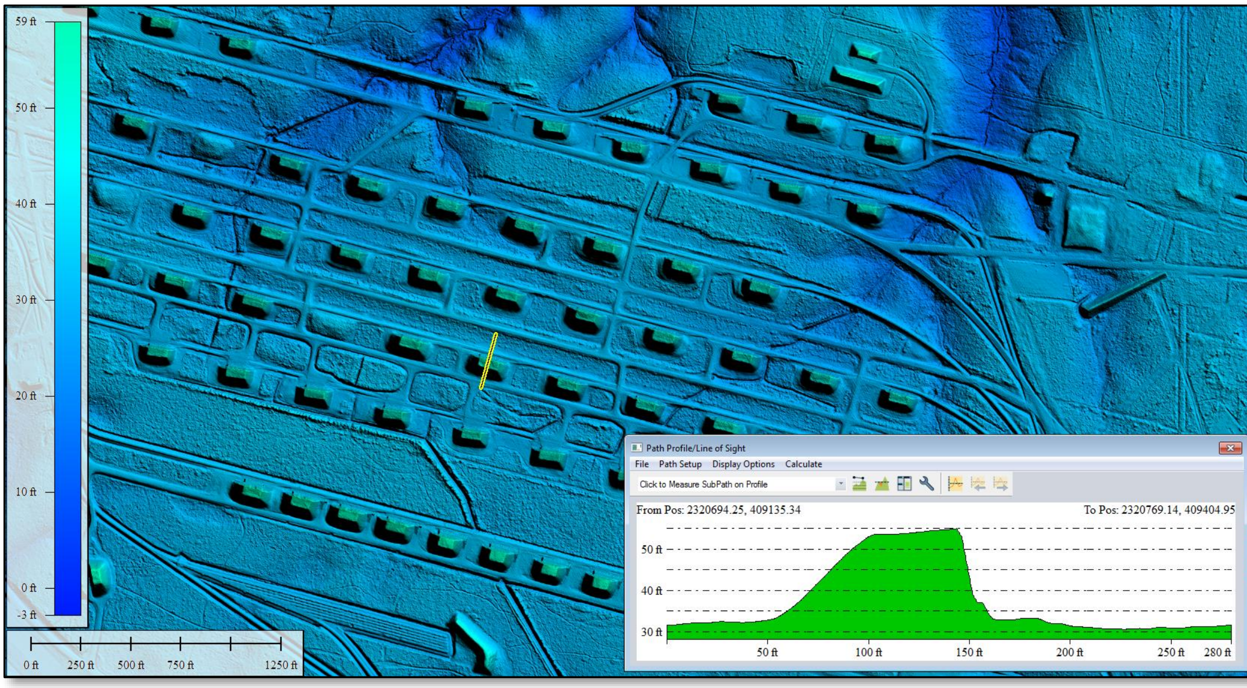

Figure 13 – Tiles 3410-02, 3420-01, 3411-04, and 3421-03. A DEM of the surface is shown in the image. These features are correctly included in the ground classification.

Marsh Areas

It is sometimes difficult to determine true ground in low wet areas; the lowest points available are used to represent ground. Marsh areas are present within the project area and were not collected with breaklines as they are not open bodies of water. As these areas are not included in the collected breaklines, marsh areas were not flattened in the final DEMs. While low points are used to determine ground in marsh areas, there is often greater variation within the low points due to wet soils that cause greater interpolation between points, and undulating or uneven ground. An example is shown below.

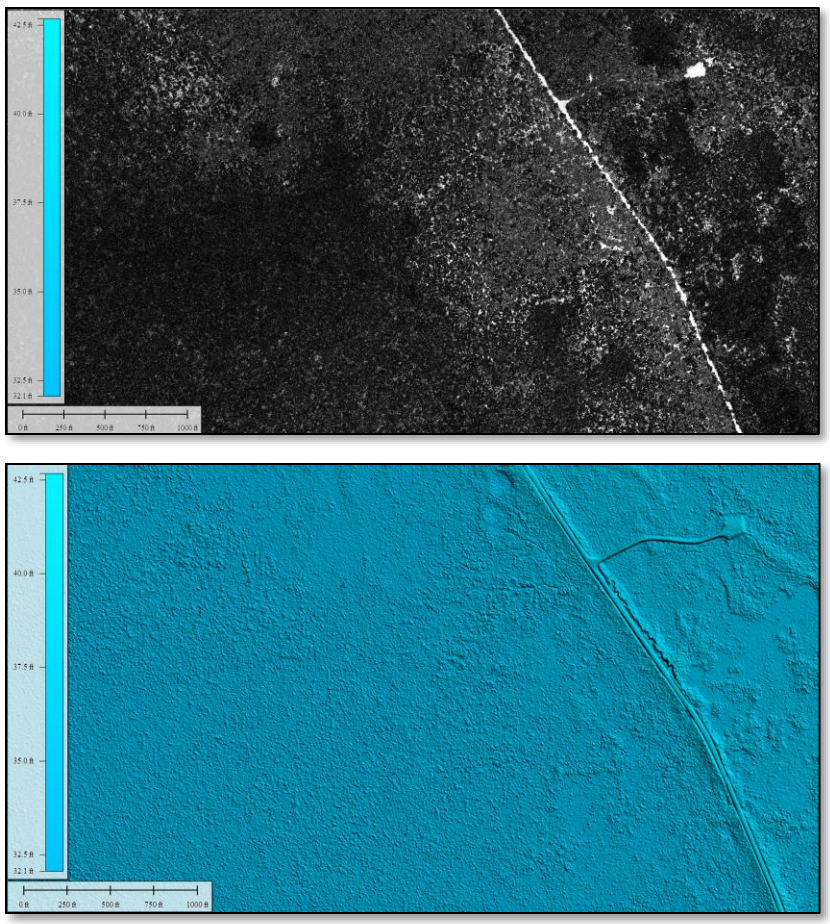

Figure 14 – Tile 3499-02. The intensity on the top shows a marsh area that was not included in the collected breaklines. The same area is shown in the DEM on the bottom. Due to wet soils and broken terrain, the point density in marsh areas is sparser than surrounding areas and there is more variation in the low points representing ground.

FORMATTING

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

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
LAS Version	1.4	Pass
Point Data Format	Format 6	Pass
Coordinate Reference System	NAD83 (2011) South Carolina, International Feet and NAVD88 (Geoid 12B), US Survey Feet in WKT Format	Pass
Global Encoder Bit	Should be set to 17 for Adjusted GPS Time	Pass
Time Stamp	Adjusted GPS Time (unique timestamps)	Pass
System ID	Should be set to the processing system/software and is set to NIIRS10 for GeoCue software	Pass
Multiple Returns	The sensor shall be able to collect multiple returns per pulse and the return numbers are recorded	Pass
Intensity	16 bit intensity values are recorded for each pulse	Pass
Classification	Required Classes include: Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 8: Model Keypoint Class 9: Water Class 10: Ignored Ground Class 13: Culverts Class 17: Bridge Decks Class 18: High Noise	Pass
Overlap and Withheld Points	Overlap (Overage) and Withheld points are set to the Overlap and Withheld bits	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates (0.001 resolution) are recorded for each pulse	Pass

Derivative Lidar Products

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

CONTOURS

One-foot contours have been created for the full project area (SC DNR deliverables only). The contour attributes include labeling as either Index or Intermediate and an elevation value. The contours are also 3D, storing the elevation value within its internal geometry. The contours have been created from the final hydro-enforced DEM. As per project specifications, these contours are generated from automated tools. While some smoothing has been applied to the contours to enhance their aesthetic quality, no manual edits or corrections have been applied to the contours.

TERRAIN

A county-wide terrain has been created and delivered within a File Geodatabase (SC DNR deliverables only). The terrain resides in the geodatabase along with all feature classes used to build the terrain. The terrain was built from all bare earth ground points and culvert points (class 2-ground, class 8-model key points, and class 13-culverts) along with all breaklines collected for this project. The terrain hydro-enforced. The project boundary is enforced in the terrain as well. One pyramid layer, in addition to the overview and full resolution layers, has been built. The pyramid layer was built using the window size definition, which defines the area of the terrain tile used in thinning elevation points by selecting one or two points from each window size.

Lidar Positional Accuracy

BACKGROUND

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

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

SURVEY VERTICAL ACCURACY CHECKPOINTS

For the vertical accuracy assessment, one hundred-twenty-six (126) check points were surveyed for the project and are located within bare earth/open terrain, grass/weeds/crops, and forested/fully grown land cover categories. Please see the separate appendix A to view the survey report which details and validates how the survey was completed for this project.

Checkpoints were evenly distributed throughout the project area so as 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) SC State Plane		NAVD88 (Geoid 12B)	LAND COVER
	Easting X (ft)	Northing Y (ft)	Elevation (ft)	
8-9-8	2338273.77	377060.99	9.88	Bare Earth
8-1-5	2332887.91	573656.40	75.13	Bare Earth
8-1-9	2327992.80	572198.13	77.03	Bare Earth
8-1-12	2327417.54	573525.50	74.02	Bare Earth
8-2-1	2348924.28	527733.62	45.45	Bare Earth
8-2-7	2343538.07	527973.51	42.40	Bare Earth
8-2-10	2342958.78	529326.77	39.87	Bare Earth
8-3-4	2355585.90	415454.75	37.08	Bare Earth
8-3-8	2356189.34	405584.05	42.24	Bare Earth
8-4-2	2349664.45	479640.60	29.58	Bare Earth
8-4-7	2358163.19	485537.28	53.40	Bare Earth
8-4-10	2362577.85	476083.51	25.39	Bare Earth
8-5-1	2436050.39	496792.05	45.44	Bare Earth
8-5-2	2435493.93	496810.76	46.29	Bare Earth
8-5-6	2440953.06	496748.16	41.69	Bare Earth
8-5-9	2438718.33	493496.27	31.60	Bare Earth
8-6-1	2394077.19	475658.14	32.88	Bare Earth
8-6-6	2402663.61	476321.90	37.00	Bare Earth
8-6-7	2402396.70	470554.49	35.92	Bare Earth
8-7-2	2257148.19	527432.40	72.89	Bare Earth
8-7-3	2257439.42	525080.10	70.17	Bare Earth
8-7-6	2259663.00	527034.99	71.20	Bare Earth
8-8-2	2263011.42	441396.48	70.29	Bare Earth
8-8-6	2258785.21	437742.98	70.43	Bare Earth
8-8-9	2255696.24	436913.69	78.31	Bare Earth
8-9-2	2330569.86	373952.35	12.29	Bare Earth
8-9-6	2337411.33	377048.80	11.57	Bare Earth
8-9-9	2338271.55	377170.81	9.40	Bare Earth
8-10-2	2326994.08	421335.32	7.26	Bare Earth
8-10-5	2327309.11	425185.44	12.22	Bare Earth
8-10-8	2328601.81	428542.67	9.26	Bare Earth
8-11-2	2302477.18	497319.92	55.97	Bare Earth
8-11-3	2304959.55	496356.23	49.75	Bare Earth
8-11-6	2308081.45	496150.02	33.98	Bare Earth
8-1-4	2332766.24	573636.24	75.88	Urban
8-1-10	2328023.76	572394.86	77.61	Urban
8-1-11	2327341.37	573538.04	74.91	Urban
8-2-9	2342949.05	529236.92	41.05	Urban
8-2-11	2344779.63	529668.88	46.15	Urban
8-2-12	2342192.85	528719.85	41.91	Urban
8-3-1	2350582.51	414295.29	35.86	Urban
8-3-7	2355885.91	405077.05	40.38	Urban
8-4-6	2358109.38	485487.93	51.84	Urban

8-4-9	2362496.31	476112.42	26.45	Urban
8-4-12	2341255.52	477357.83	54.85	Urban
8-7-5	2257285.52	525215.34	68.56	Urban
8-7-9	2257699.22	533131.84	76.98	Urban
8-7-12	2253714.14	528098.87	86.34	Urban
8-8-5	2258502.79	437789.31	70.17	Urban
8-8-7	2258748.48	439079.74	79.23	Urban
8-8-11	2256871.80	438934.48	79.90	Urban
8-9-7	2337893.97	377141.14	9.15	Urban
8-9-11	2337270.03	383296.05	10.56	Urban
8-9-12	2336782.26	376759.36	9.88	Urban
8-10-4	2327034.09	424170.54	17.07	Urban
8-10-7	2328770.79	428580.34	8.20	Urban
8-10-9	2326665.44	432943.76	11.34	Urban
8-11-1	2302261.59	497461.14	57.03	Urban
8-11-4	2305738.27	497009.37	52.27	Urban
8-11-10	2306805.25	495367.50	46.68	Urban
8-10-1	2325957.73	414638.55	8.59	Urban
8-1-2	2335854.97	573483.67	81.25	Brush
8-1-7	2326133.30	566779.15	69.53	Brush
8-2-2	2346391.43	523693.50	38.63	Brush
8-2-3	2343858.83	522140.84	40.62	Brush
8-3-3	2355311.06	414292.60	41.17	Brush
8-3-10	2352336.42	409137.79	23.44	Brush
8-4-1	2348314.52	478197.53	27.25	Brush
8-4-11	2358667.16	474599.29	19.97	Brush
8-5-3	2437685.78	496744.25	40.92	Brush
8-5-4	2438809.87	496813.17	35.68	Brush
8-6-3	2396171.90	477408.54	33.76	Brush
8-6-8	2406940.90	464689.59	34.25	Brush
8-7-1	2255555.40	527651.96	74.94	Brush
8-7-4	2257608.46	524700.39	68.59	Brush
8-8-4	2258481.73	437511.50	73.14	Brush
8-8-12	2268767.42	441155.77	78.59	Brush
8-9-4	2331426.59	372860.40	7.65	Brush
8-9-10	2340753.43	380819.52	5.31	Brush
8-10-3	2326868.84	424217.69	10.77	Brush
8-10-11	2326993.66	433436.45	10.74	Brush
8-11-7	2311937.94	500013.22	52.49	Brush
8-11-9	2310569.78	497770.09	48.34	Brush
8-1-3	2335365.89	573373.90	64.59	Forested
8-1-8	2322734.66	567598.92	79.14	Forested
8-2-4	2343929.53	522108.78	40.27	Forested
8-2-8	2342950.00	523944.54	36.89	Forested
8-3-2	2351690.43	411969.84	37.43	Forested
8-3-5	2359748.48	414446.64	40.64	Forested
8-4-5	2352812.52	482875.58	56.08	Forested
8-4-8	2362706.47	481801.62	16.48	Forested

8-5-5	2438737.49	496827.61	37.75	Forested
8-5-7	2441059.87	495450.10	39.96	Forested
8-6-4	2397988.51	478376.02	34.93	Forested
8-6-9	2402144.70	464569.24	35.34	Forested
8-7-8	2254991.34	530250.45	82.23	Forested
8-7-10	2257587.00	533103.23	74.91	Forested
8-8-8	2255858.70	436870.56	87.93	Forested
8-8-10	2258208.19	441343.53	100.34	Forested
8-9-3	2330217.84	374061.02	6.98	Forested
8-9-5	2331502.62	372827.85	7.74	Forested
8-10-12	2326348.11	433903.91	8.48	Forested
8-10-13	2327497.22	424196.19	16.16	Forested
8-11-8	2311856.32	500304.57	43.67	Forested
8-11-12	2307182.67	494044.95	38.70	Forested
8-1-1	2335636.21	573340.94	75.46	High Grass
8-1-6	2326553.46	567101.39	70.36	High Grass
8-2-5	2343101.79	525615.69	36.57	High Grass
8-2-6	2343561.67	527919.45	41.75	High Grass
8-3-6	2356010.11	405517.21	43.14	High Grass
8-3-9	2352435.37	409083.93	28.89	High Grass
8-4-3	2349423.76	479523.10	25.07	High Grass
8-4-4	2352438.76	482916.71	56.12	High Grass
8-5-8	2441222.23	494517.18	41.77	High Grass
8-5-10	2443225.08	506348.99	43.32	High Grass
8-6-2	2394827.40	476176.44	36.19	High Grass
8-6-5	2402789.11	478417.62	37.15	High Grass
8-7-7	2254960.60	530074.45	81.59	High Grass
8-7-11	2254611.89	534117.93	86.47	High Grass
8-8-1	2263698.85	443541.88	76.25	High Grass
8-8-3	2257996.02	436810.09	69.45	High Grass
8-9-1	2330607.11	374068.61	8.67	High Grass
8-10-6	2327205.15	424990.06	12.28	High Grass
8-10-10	2326492.58	432956.30	12.40	High Grass
8-11-5	2308160.90	495890.84	39.75	High Grass
8-11-11	2306761.00	494008.86	47.01	High Grass

Table 6 - South Carolina Berkeley County surveyed accuracy checkpoints

One hundred-twenty-six checkpoints were surveyed for vertical accuracy testing. While reviewing the checkpoints, Dewberry identified issues with the location of some forest checkpoints. Two checkpoints in forest areas deviated significantly from the lidar elevations. These two points (8-8-8 and 8-8-10) were deemed as unreliable since the lidar data shows a consistent ground surface *below* the survey checkpoints. If the lidar data was higher than the survey checkpoints, the issue could be caused by poor penetration of the lidar to the ground in the forested area. However, since the lidar elevations are below the survey, the lidar shows a consistent ground surface in this area and good relative accuracy with surrounding areas, it is more likely there is an issue with the survey of these two checkpoints. Since collection sketches or photos were not provided by the survey, the methodology could not be examined for the cause of the error. The points (and their magnitude of offset) are described in the table below and shown in the images below.

Points Removed from LiDAR Vertical Accuracy Testing						
Point ID	NAD83(2011) SC State Plane		NAVD88 (Geoid 12B)		DeltaZ	AbsDeltaZ
	Easting X (ft)	Northing Y (ft)	Z-Survey (ft)	Z-LiDAR (ft)		
8-8-8	2255858.70	436870.56	87.93	77.72	-10.20	10.20
8-8-10	2258208.19	441343.53	100.34	81.03	-19.32	19.32

Table 7: Checkpoints removed from vertical accuracy testing

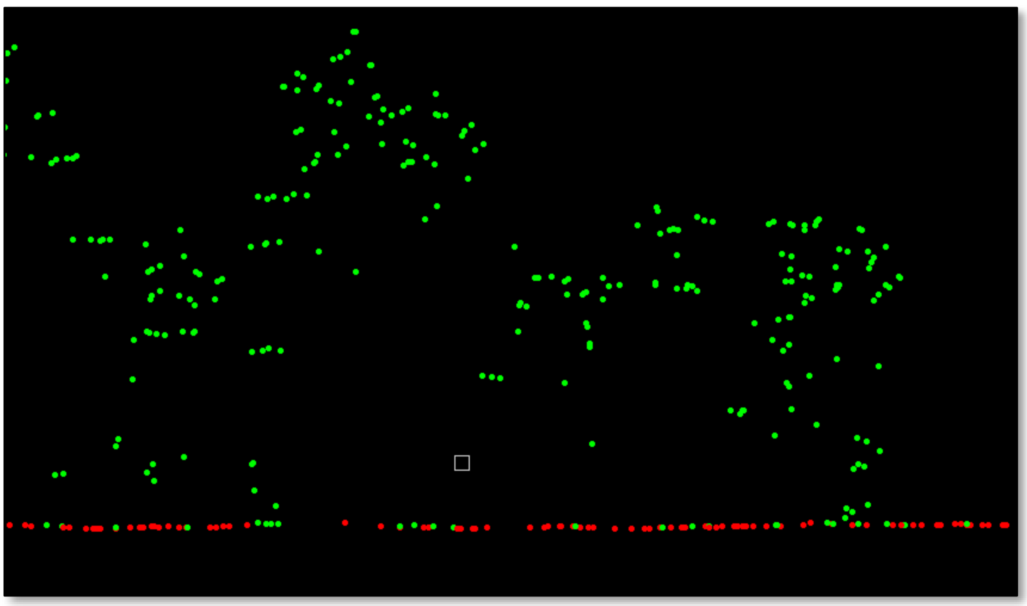

Figure 15 – Forest checkpoint 8-8-8, shown as the white box in the profile, is located in a forest stand. This checkpoint was removed from all vertical accuracy calculations due to its probable unreliability.

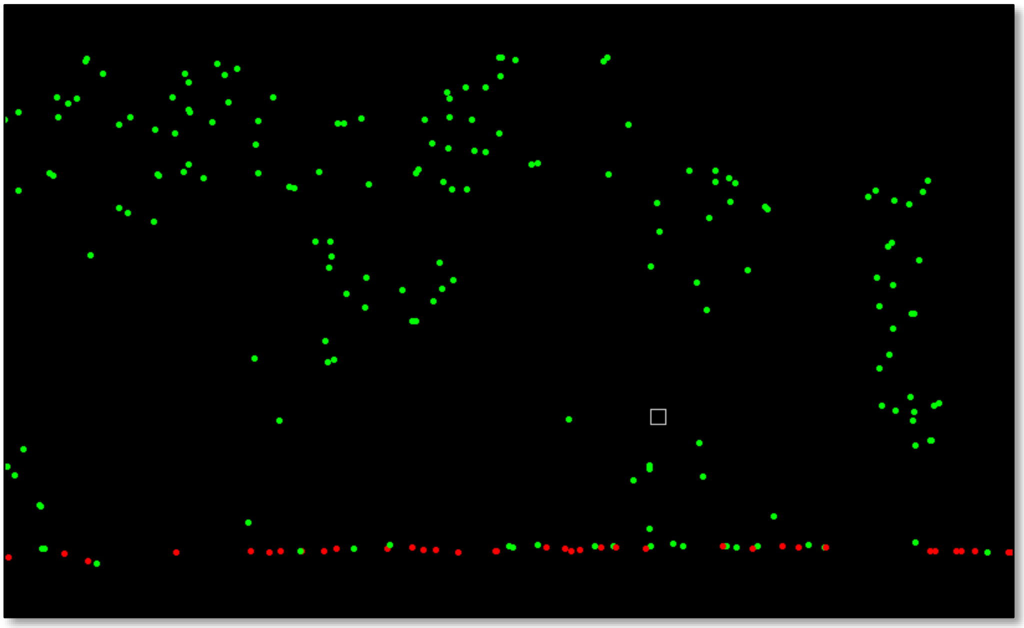

Figure 16 – Forest checkpoint 8-8-10 shown as the white box in the profile, is located in a forest stand. This checkpoint was removed from all vertical accuracy calculations due to its probable unreliability.

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

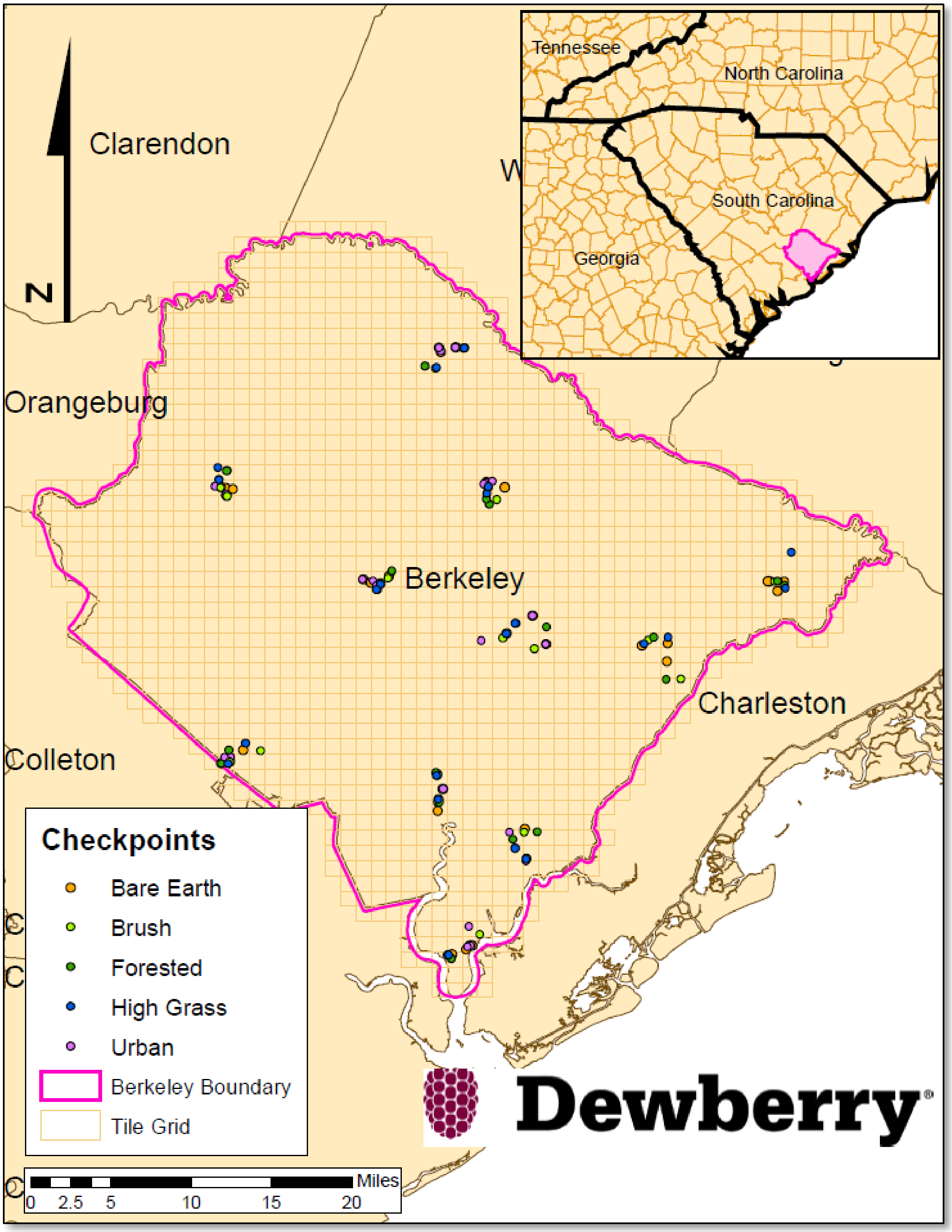

Figure 17 – Location of QA/QC Checkpoints

VERTICAL ACCURACY TEST PROCEDURES

NVA (Non-vegetated Vertical Accuracy) is determined with check points located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas, where there is a very high probability that the lidar sensor will have detected the bare-earth ground surface and where random errors are expected to follow a normal error distribution. The NVA determines how well the calibrated lidar sensor performed. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_z$) of the checkpoints x 1.9600. For the South Carolina Berkeley County project, vertical accuracy must be 0.64 ft (19.6 cm) or less based on an $RMSE_z$ of 0.33 ft (10 cm) x 1.9600.

VVA (Vegetated Vertical Accuracy) is determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas, where there is a possibility that the lidar sensor and post-processing may yield elevation errors that do not follow a normal error distribution. VVA at the 95% confidence level equals the 95^{th} percentile error for all checkpoints in all vegetated land cover categories combined. The South Carolina Berkeley County Lidar Project VVA standard is 0.96 ft (29.4 cm) based on the 95^{th} percentile. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95^{th} 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 7.

Quantitative Criteria	Measure of Acceptability
Non-Vegetated Vertical Accuracy (NVA) in open terrain and urban land cover categories using $RMSE_z$ *1.9600	0.64 ft (19.6 cm),(based on $RMSE_z$ 0.33 ft (10 cm) * 1.9600
Vegetated Vertical Accuracy (VVA) in all vegetated land cover categories combined at the 95% confidence level	0.96 ft, 29.4 cm (based on combined 95^{th} percentile)

Table 8 — Acceptance Criteria

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

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

VERTICAL ACCURACY RESULTS

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

Land Cover Category	# of Points	NVA — Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.64 ft	VVA — Vegetated Vertical Accuracy (95th Percentile) Spec=0.96 ft
NVA	60.00	0.29	
VVA	64.00		0.57

Table 9 — Tested NVA and VVA

This lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 0.33 ft (10 cm) RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ =0.15 ft (4.6 cm), equating to +/- 0.30 ft (9.1 cm) at 95% confidence level. Actual VVA accuracy was found to be +/- 0.58 ft (17.7 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 majority of lidar elevations were within +/- 0.30 ft of the checkpoints elevations, but there is one outlier where lidar and checkpoint elevations differed by over -2 ft.

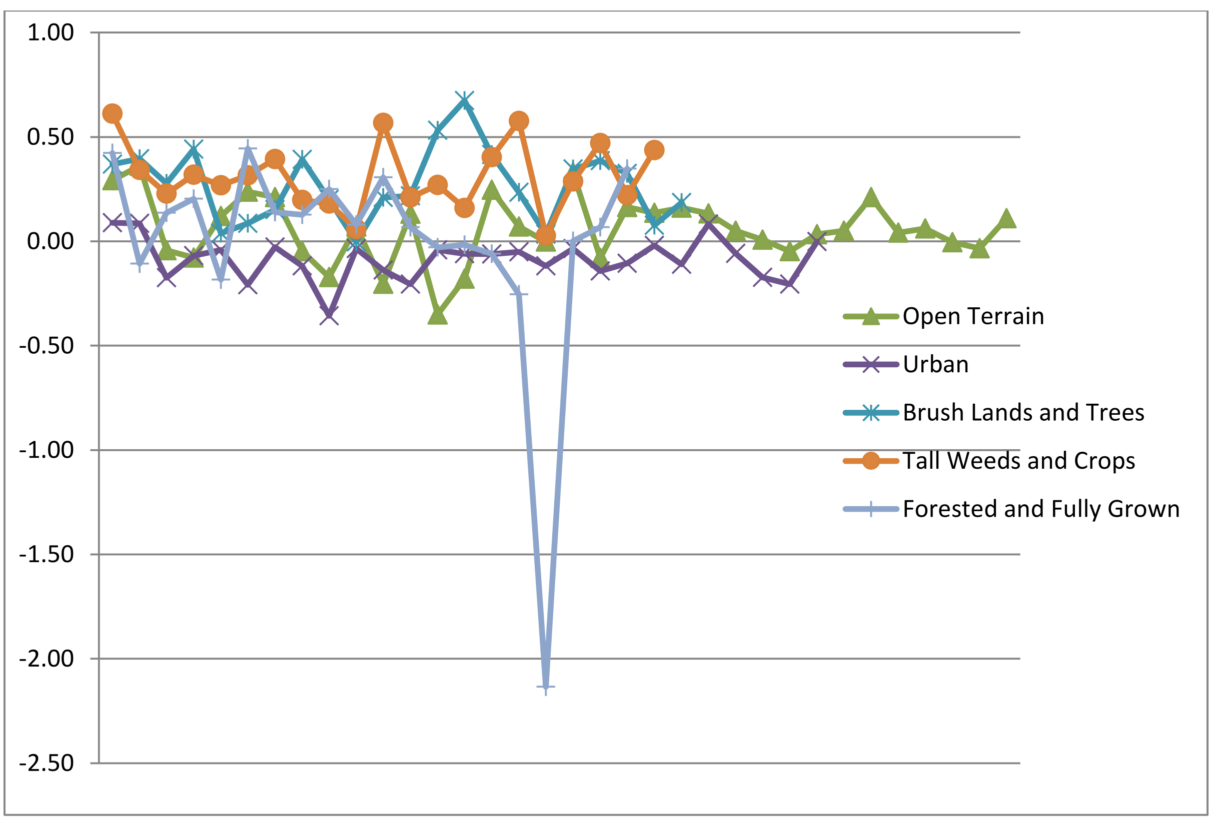

Figure 18 – Magnitude of elevation discrepancies per land cover category

Table 10 lists the 5% outliers that are larger than the VVA 95th percentile.

LiDAR 5% Outliers						
Point ID	NAD83(2011) SC State Plane		NAVD88 (Geoid 12B)		DeltaZ	AbsDeltaZ
	Easting X (ft)	Northing Y (ft)	Z-Survey (ft)	Z-LiDAR (ft)		
8-10-12	2326348.11	433903.91	8.48	6.35	-2.14	2.14
8-7-4	2257608.46	524700.39	68.59	69.26	0.67	0.67
8-8-3	2257996.02	436810.09	69.45	70.03	0.58	0.58

Table 10 — 5% Outliers

Table 11 provides overall descriptive statistics.

LiDAR Descriptive Statistics									
100 % of Totals	# of Points	RMSEz (ft) Spec=0.33 ft NVA	Mean (ft)	Median (ft)	Skew	Std Dev (ft)	Kurtosis	Min (ft)	Max (ft)
Open Terrain	33.00	0.16	0.05	0.05	-0.32	0.15	0.47	-0.35	0.36
Urban	27.00	0.13	-0.09	-0.06	-0.45	0.10	1.03	-0.36	0.09
NVA	**60.00**	**0.15**	**-0.01**	**-0.03**	**0.17**	**0.15**	**0.23**	**-0.36**	**0.36**
Tall Weeds and Crops	22.00	0.35	0.31	0.29	0.30	0.16	-0.24	0.03	0.61
Brush Lands and Trees	22.00	0.32	0.27	0.26	0.33	0.17	-0.17	0.00	0.67
Forested and Fully Grown	20.00	0.52	-0.01	0.07	-3.57	0.53	14.57	-2.14	0.45
VVA	**64.00**	**N/A**	**0.20**	**0.22**	**-4.65**	**0.35**	**30.48**	**-2.14**	**0.67**

Table 11 — Overall Descriptive Statistics

The figure below illustrates 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. Although the discrepancies vary between a low of -2.14 ft and a high of +0.67 ft, the histogram shows that the majority of the discrepancies are not skewed. The vast majority of points are within the ranges of -0.225 feet to +0.525 feet.

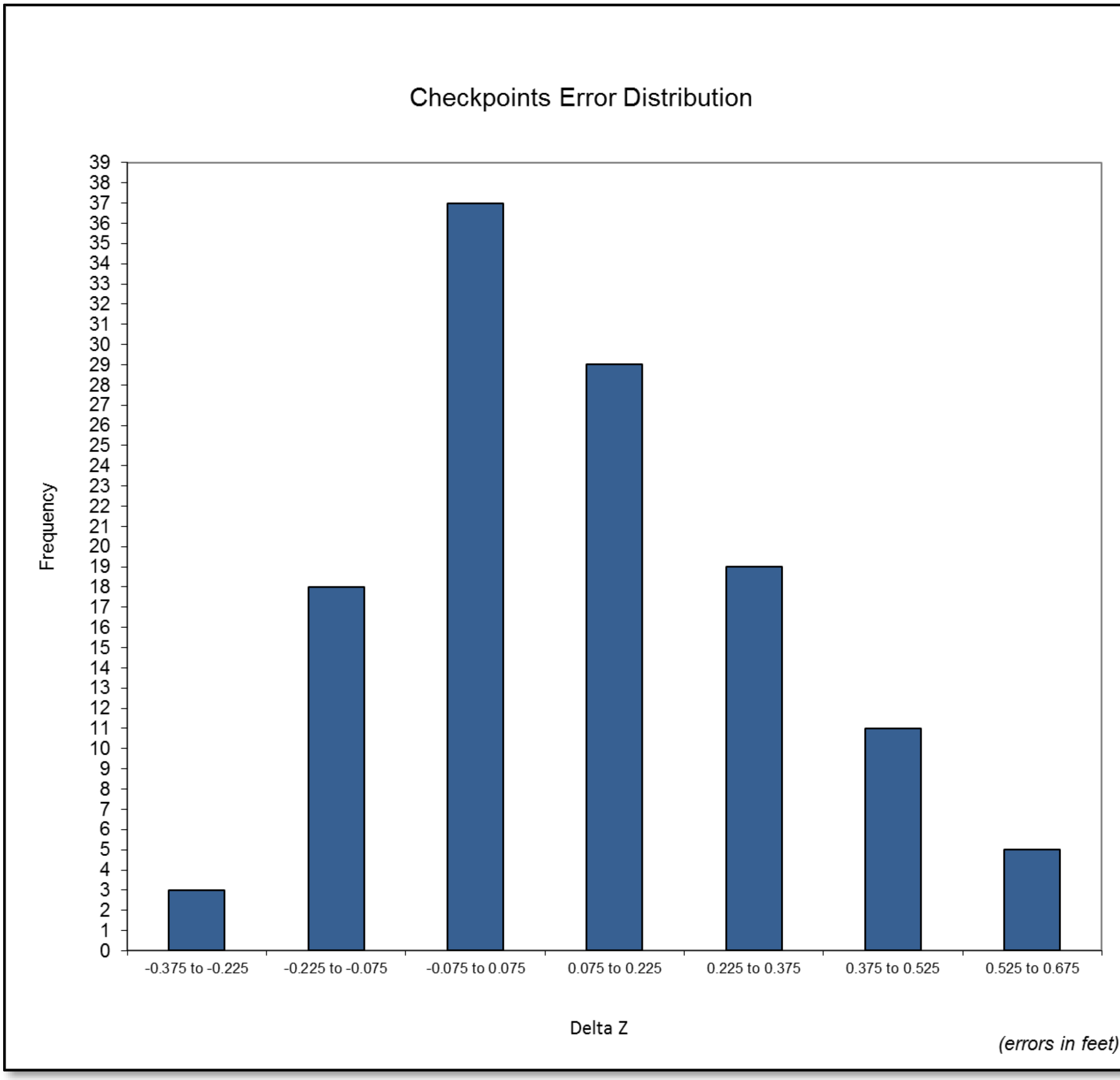

Figure 19 — Histogram of Elevation Discrepancies with errors in feet

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the South Carolina Berkeley County satisfies the project's pre-defined vertical accuracy criteria.

HORIZONTAL ACCURACY TEST PROCEDURES

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

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

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

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications and tried to locate half of the NVA checkpoints on features photo-identifiable in the intensity imagery.
2. Next, Dewberry identified the well-defined features in the intensity imagery.
3. Dewberry then computed the associated xy-value differences between the coordinates of the well-defined feature in the lidar intensity imagery and the ground truth survey checkpoints.
4. The data were analyzed 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

No checkpoints were photo-identifiable in the intensity imagery; horizontal accuracy could not be tested on this dataset.

Breakline Production & Qualitative Assessment Report

BREAKLINE PRODUCTION METHODOLOGY

Dewberry used a combination of lidargrammetry and automated techniques to collect breaklines for this project. The delineation of lakes and ponds, or other water bodies at a constant elevation, was achieved using eCognition software. Dewberry produced full point cloud intensity imagery, bare earth ground models, density models, and slope models. These files were ingested into eCognition, segmented into polygons, and training samples were created to identify water. eCognition used the training samples and defined parameters to identify water segments throughout the project area. Water segments were then reviewed for completeness. Segments identified as lakes and ponds were merged and smoothed. 3D elevations were then applied to the breakline features. Lidargrammetry was used to monotonically collect streams and rivers, or features that have gradient 3D elevations. 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 streams and rivers in accordance with the project's Data Dictionary. Flowlines were generated in ArcGIS using hydrologically conditioned elevation models. These flowlines were then manually edited in 2D ArcGIS environments to create 2D single line drains and centerlines. The single line drains and centerlines were then converted to 3D with monotonic elevations using proprietary procedures which are ArcGIS based. Hydro connectors and culvert connectors were manually collected and 3D elevations were assigned from the connecting single line drain and centerline network. USGS deliverables do not include single line drains, centerlines, hydro connectors, or culvert connectors.

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 following workflow diagram represents the steps taken by Dewberry to provide a thorough qualitative assessment of the breakline data.

Completeness and horizontal placement is verified through visual reviews against lidar intensity imagery. Automated checks are 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 is to compare 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 is expected because of the hydro-enforcement applied to the breaklines and because of the interpolated imagery used to acquire the breaklines. A given tolerance is used to validate if the elevations differ too much from the lidar.

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

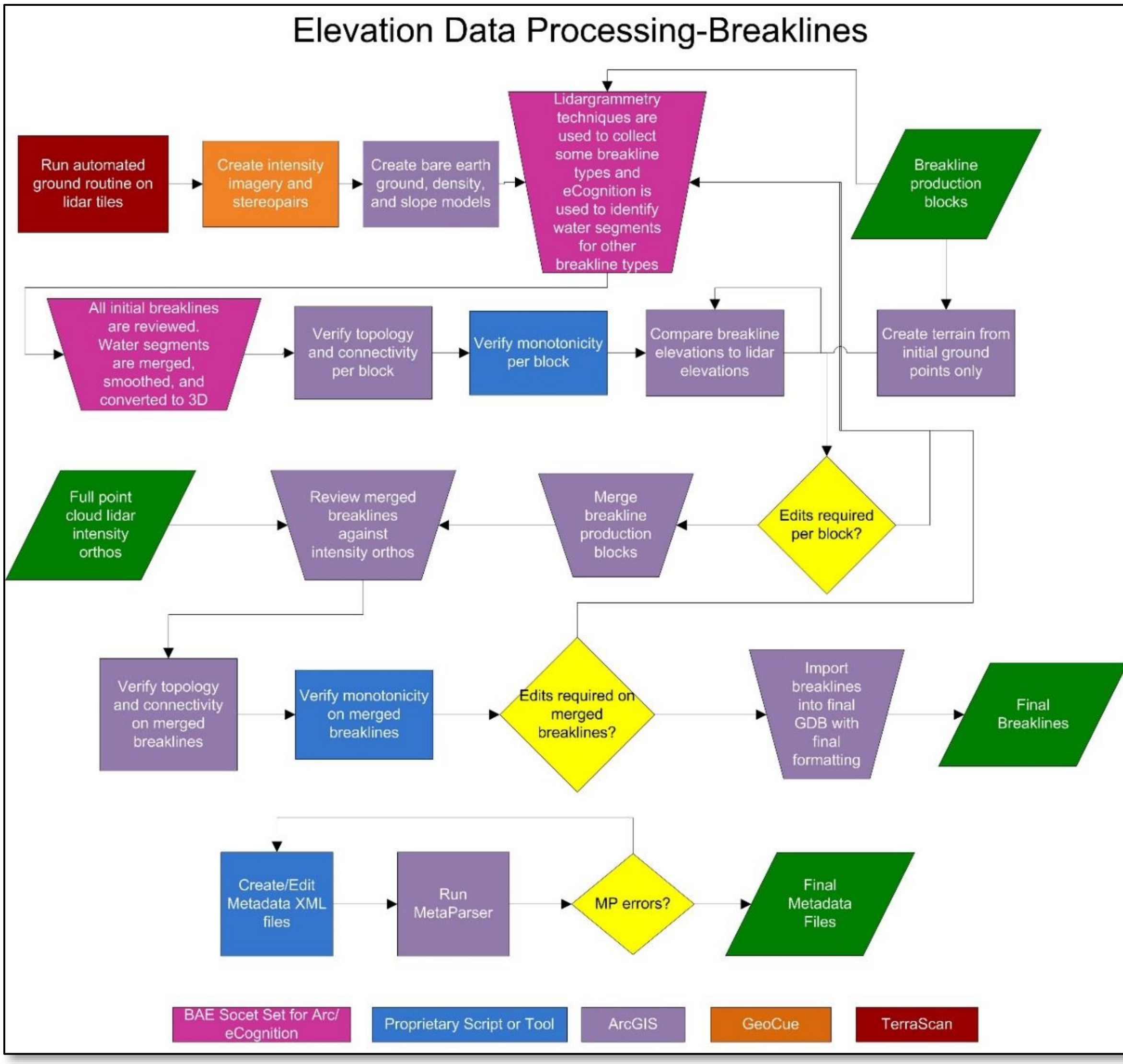

Figure 20-Breakline QA/QC workflow

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	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 10) 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 12 -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 shall be North American Datum of 1983(2011), Units in International Feet. The vertical datum shall be referenced to the North American Vertical Datum of 1988 (NAVD 88), Units in US Survey Feet. Geoid12B shall be used to convert ellipsoidal heights to orthometric heights.

Coordinate System and Projection

All data shall be projected to South Carolina State Plane, Horizontal Units in International Feet and Vertical Units in US Survey Feet.

Inland Streams and Rivers

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: STREAMS_AND_RIVERS
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will depict linear hydrographic features with a width greater than 20 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 20 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 20 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 ½ 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: Accept Default Setting
XY Tolerance: 0.003

Feature Class: PONDS_AND_LAKES
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will depict 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. <u>The compiler shall take care to ensure that the z-value remains consistent for all vertices placed on the water body.</u> 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 0.5 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.

Single Line Drains

Feature Dataset: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: Single_Line_Drains
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polyline feature class will depict linear hydrographic features with a width less than 20 feet which drain at least ½ square mile.

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
Single Line Streams	Linear hydrographic features such as streams, rivers, canals, etc. which drain areas of ½ square mileage or more but have an average width less than 20 feet.	Capture features showing single line (center of channel). Average width shall be less than 20 feet. Each vertex placed should maintain vertical integrity and show downhill flow. 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. Single line features shall break at road crossings (culverts) and connectivity shall be shown using culvert connectors. In areas where a bridge is present the single line feature shall continue through the bridge.

Stream Centerlines

Feature Dataset: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: Center_Lines
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polyline feature class will depict the centerline for linear hydrographic features with a width greater than 20 feet and will be used to show flow through lake/pond features along stream reaches which are part of the flow network.

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
Stream Centerlines	Linear feature used to represent the centerline and flow through dual line streams and rivers greater than 20 feet in width and through lake/pond features along stream reaches which are part of the flow network.	Centerlines must snap to a node along the edge of the polygon (dual line streams or lakes/ponds) and the continuing stream should connect at that same node. Centerlines should be captured for all dual line drains greater than 20 feet in width but centerlines must only be captured for lakes/ponds along stream reaches which have flow.

Culverts

Feature Dataset: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: Connector_Culvert
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polyline feature class will be collected where streams (single line drains or centerlines) cut through roads or other features.

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
Culverts	Culverts will be collected where streams (single line drains or centerlines) cut through roads or other features.	Culverts should be collected with only two vertices (start/end) and must snap to adjacent features.

Hydro Connectors

Feature Dataset: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: Connector_Hydro
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polyline feature class will be used to connect streams to the main network when it is difficult or impossible to determine where the actual channel is located.

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
Hydro Connectors	Hydro connectors will be used to connect streams to the main network when it is difficult or impossible to determine where the actual channel is located.	In areas where a stream ends and it is difficult or impossible to determine where that feature continues, a hydro connector can be used to connect that stream or drainage to the main network. This should be done at the most logical point, i.e. closest stream. Hydro connectors should also be used to pass a stream through a dam or other hydro control structure.

Beneath Bridge Breaklines

Feature Dataset: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: Bridge_Breaklines
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
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.

Bridge Decks

Feature Dataset: BREAKLINES
Feature Class: Bridge_Polygons
Feature Type: Polygon
Contains M Values: No
Contains Z Values: No
Annotation Subclass: None
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Description

This polygon feature class will depict bridge decks where bridge structures were classified to class 17.

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
Bridges	Elevated bridge decks that are classified in the lidar point cloud. Culverts should not be captured as part of this feature class.	Bridges should be collected to show the full extents of the elevated portion of the bridge deck only.

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 figure below shows the entire process necessary for bare earth DEM production, starting from the lidar swath processing.

The final bare-earth lidar points are used to create a terrain. The final 3D breaklines collected for the project are also enforced in the terrain. The terrain is then converted to raster format using natural neighbors interpolation. The DEM is reviewed for any issues requiring corrections, including remaining lidar mis-classifications, erroneous breakline elevations, poor hydro-flattening or hydro-enforcement, and processing artifacts. DEM mosaics are delivered for SC DNR deliverables and tiled DEMs are delivered for USGS deliverables.

Figure 21-DEM Production Workflow

DEM QUALITATIVE ASSESSMENT

Dewberry performed a comprehensive qualitative assessment of the bare earth DEM deliverables to ensure that all 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 project boundary or 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 and hydro-enforced features. To perform this review Dewberry creates HillShade models and overlays a partially transparent colorized elevation model to review for these issues. All corrections are completed using Dewberry's proprietary correction workflow. Upon completion of the corrections, the DEM data is loaded into Global Mapper for its second review and to verify corrections. For tiled DEM deliverables, the final tiles are again loaded into Global Mapper to ensure coverage, extents, and that the final tiles are seamless.

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 on the left shows a bridge saddle while the image below on the right shows the same bridge after bridge breaklines have been enforced.

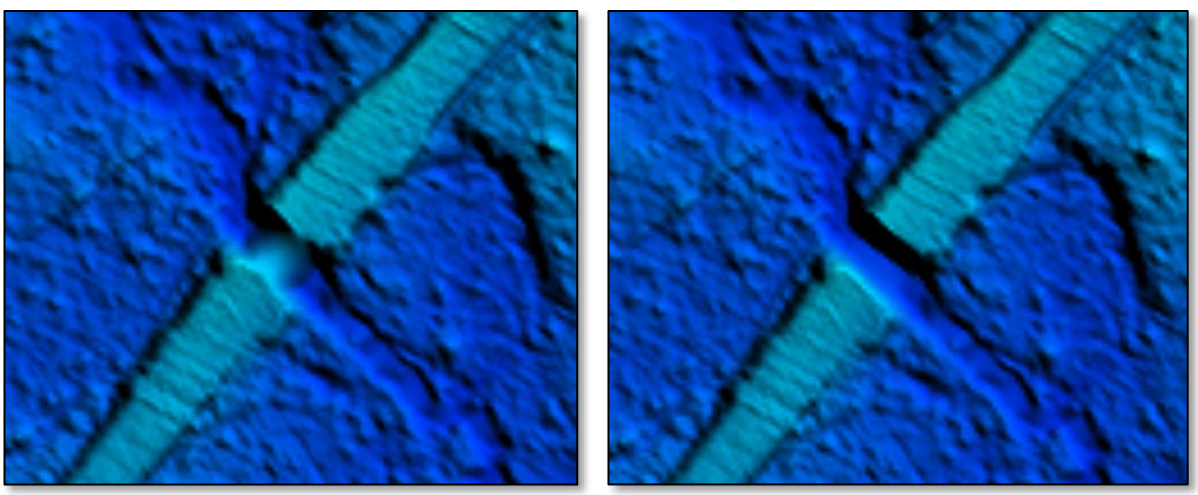

Figure 22 – Tile 3524-03. The DEM on the left shows a bridge saddle artifact while the DEM on the right shows the same location after bridge breaklines have been enforced.

DEM VERTICAL ACCURACY RESULTS

The same 124 checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products as well. 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 13 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final DEM dataset.

DEM Vertical Accuracy Results			
Land Cover Category	**# of Points**	**NVA – Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.64 ft**	**VVA – Vegetated Vertical Accuracy (95th Percentile) Spec=0.96 ft**
NVA	60.00	0.28	
VVA	64.00		0.57

Table 13 – DEM tested NVA and VVA

This DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 0.33 ft (10 cm) RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ =0.15 ft (4.6 cm), equating to +/- 0.29 ft (8.8 cm) at 95% confidence level. Actual VVA accuracy was found to be +/- 0.57 ft (17.4) cm at the 95th percentile.

Table 14 lists the 5% outliers that are larger than the VVA 95^{th} percentile.

Point ID	NAD83(2011) SC State Plane		NAVD88 (Geoid 12B)	DEM Z (ft)	Delta Z	AbsDeltaZ
	Easting X (ft)	Northing Y (ft)	Survey Z (ft)			
8-10-12	2326348.11	433903.91	8.48	6.40	-2.08	2.08
8-7-4	2257608.46	524700.39	68.59	69.26	0.68	0.68
8-1-1	2335636.21	573340.94	75.46	76.09	0.63	0.63
8-6-2	2394827.40	476176.44	36.19	36.77	0.58	0.58

Table 14– 5% Outliers

Table 15 provides overall descriptive statistics.

DEM Descriptive Statistics									
100 % of Totals	# of Points	RMSEz (ft) Spec=0.33 ft NVA	Mean (ft)	Median (ft)	Skew	Std Dev (ft)	Kurtosis	Min (ft)	Max (ft)
Open Terrain	33.00	0.16	0.05	0.06	-0.40	0.15	0.51	-0.34	0.37
Urban	27.00	0.13	-0.09	-0.06	-0.32	0.10	1.44	-0.35	0.11
NVA	60.00	0.15	-0.01	-0.02	0.16	0.15	0.13	-0.35	0.37
Tall Weeds and Crops	21.00	N/A	0.33	0.30	0.13	0.15	-0.12	0.04	0.63
Brush Lands and Trees	23.00	N/A	0.28	0.28	0.43	0.16	-0.11	0.02	0.68
Forested and Fully Grown	20.00	N/A	0.00	0.03	-3.49	0.53	14.22	-2.08	0.48
VVA	64.00	N/A	0.21	0.24	-4.61	0.35	30.01	-2.08	0.68

Table 15 — Overall Descriptive Statistics

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the South Carolina Berkeley County Lidar 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 10 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 15 -A subset of the high-level steps from Dewberry's bare earth DEM Production and QA/QC checklist performed for this project.

Appendix A: Survey Report

See separate appendix document: ***Appendix A Checkpoint Survey Report.pdf***

Appendix B: Complete List of Delivered Tiles

1590-02	2428-04	2447-04	2463-02	2475-01
1591-01	2429-01	2448-01	2463-03	2475-02
1591-02	2429-02	2448-02	2463-04	2475-03
1591-04	2429-03	2448-03	2464-01	2475-04
1592-02	2429-04	2448-04	2464-02	2476-01
1592-03	2435-01	2449-01	2464-03	2476-02
1592-04	2435-02	2449-02	2464-04	2476-03
2399-02	2435-03	2449-03	2465-01	2476-04
2399-04	2435-04	2449-04	2465-02	2477-01
2407-02	2436-01	2453-01	2465-03	2477-02
2408-02	2436-02	2453-02	2465-04	2477-03
2408-04	2436-03	2453-04	2466-01	2477-04
2409-01	2436-04	2454-01	2466-02	2478-01
2409-02	2437-01	2454-02	2466-03	2478-02
2416-02	2437-02	2454-03	2466-04	2478-03
2417-01	2437-03	2454-04	2467-01	2478-04
2417-02	2437-04	2455-01	2467-02	2479-01
2417-03	2438-01	2455-02	2467-03	2479-02
2417-04	2438-02	2455-03	2467-04	2479-03
2418-01	2438-03	2455-04	2468-01	2479-04
2418-02	2438-04	2456-01	2468-02	2482-01
2418-03	2439-01	2456-02	2468-03	2482-02
2418-04	2439-02	2456-03	2468-04	2482-03
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2419-03	2444-01	2457-02	2469-03	2483-02
2419-04	2444-02	2457-03	2469-04	2483-03
2425-02	2444-04	2457-04	2472-01	2483-04
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2426-02	2445-02	2458-02	2472-03	2484-02
2426-03	2445-03	2458-03	2472-04	2484-03
2426-04	2445-04	2458-04	2473-01	2484-04
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2427-02	2446-02	2459-02	2473-03	2485-02
2427-03	2446-03	2459-03	2473-04	2485-03
2427-04	2446-04	2459-04	2474-01	2485-04
2428-01	2447-01	2462-01	2474-02	2486-01
2428-02	2447-02	2462-02	2474-03	2486-02
2428-03	2447-03	2463-01	2474-04	2486-03

2486-04	2496-04	2520-04	2536-02	2548-02
2487-01	2497-01	2521-01	2536-03	2548-03
2487-02	2497-02	2521-02	2536-04	2548-04
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2487-04	2497-04	2521-04	2537-04	2549-04
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2494-02	2511-02	2533-04	2545-04	2556-02
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2496-03	2520-03	2536-01	2548-01	2558-03

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3327-01	3349-04	3407-02	3417-02	3427-02
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3329-02	3369-01	3409-03	3419-03	3429-03
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Appendix C: GPS Processing

See separate appendix document: ***Appendix C GPS Processing.pdf***