LiDAR Quality Assurance (QA) Report
Chesterfield County, South Carolina
March 18, 2009

Submitted to:
USGS
Prepared by:
Dewberry
Fairfax, VA

EXECUTIVE SUMMARY

Reference: USGS Contract 07CRCN0004, Task Order 07004C0009, South Carolina 16 County LiDAR, dated January 17, 2008.

This report documents Dewberry's actions to quality assure the LiDAR deliverables of Chesterfield, County, SC, produced by Dewberry's subcontractor, Fugro EarthData, under the referenced USGS task order. The LiDAR data was acquired in January, 2008 and delivered as LiDAR LAS point cloud data in five ASPRS LAS classes (class 1 = non-ground; class 2 = ground; class 8 = intelligently-thinned model key points; class 9 = water; and class 12 = overlap points not used in other classes). The LiDAR data was determined to be of high quality.

Completeness: Dewberry verified the completeness of the classified LiDAR points, intensity images, and an ESRI geodatabase containing a terrain (triangulated irregular network) and ground masspoints. Hydrographic breaklines were delivered separately by watershed. Dewberry verified that the high density masspoint data has an average point spacing less than 1.4m, that 990 tiles (each 5000 ft x 5000 ft) were delivered covering all of Chesterfield County, that all data was delivered in the correct file format and projected to the South Carolina State Plane Coordinate System in International feet, NAD83 HARN, with elevations in meters, NAVD88; and that the FGDC-complaint metadata satisfies project requirements.

Quantitative: Using checkpoints surveyed by the South Carolina Geodetic Survey, Dewberry tested the RMSEz, Fundamental Vertical Accuracy (FVA) in open terrain, Consolidated Vertical Accuracy (CVA) in all land cover categories, and Supplemental Vertical Accuracy (SVA) in each of three major land cover categories per FEMA requirements, and the accuracy easily surpassed the specified accuracy required, as shown below, when tested per FEMA, NSSDA, NDEP and ASPRS guidelines.

Criterion	Checkpoints Required	Checkpoints Used	Accuracy Specification	Results Achieved
RMSEz	60	136	18.5 cm	7.9 cm
FVA	20	42	36.3 cm	11.4 cm
CVA	60	136	36.3 cm	16.5 cm
SVA-bare earth	20	42	36.3 cm	10.9 cm
SVA-vegetated	20	51	36.3 cm	21.1 cm
SVA-urban	20	43	36.3 cm	8.7 cm

Qualitative: Dewberry visually inspected 100% of the data; no remote-sensing data voids were found and the data is free of major systematic errors. The cleanliness of the bare earth model meets expectations; minor errors were found in less than 2% of the data, including poor LiDAR penetration, small misclassifications, and inconsistent editing. All of the deliverables extend to the county boundaries where adjoining counties are not delivered; where adjoining counties are delivered there is no clipping of the tiles.

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QA REPORT

1 Introduction

The following definitions are provided to distinguish between steps taken by Dewberry, as prime contractor, to provide Quality Assurance (QA) of the LiDAR data produced by Fugro EarthData, and steps taken by Fugro EarthData, as data producer, to perform Quality Control (QC) of the data that it provides to Dewberry. Collectively, this QA/QC process ensures that the LiDAR data delivered to USGS and its client (South Carolina Department of Natural Resources) are accurate, usable, and in conformance with the deliverables specified in the Scope of Work. These definitions are taken from the DEM Quality Assessment chapter of the 2nd edition of “Digital Elevation Model Technologies and Applications: The DEM Users Manual,” published by the American Society for Photogrammetry and Remote Sensing (ASPRS), 2007:

> **Quality Assurance (QA)** — Steps taken: (1) to ensure the end client receives the quality products it pays for, consistent with the Scope of Work, and/or (2) to ensure an organization’s Quality Program works effectively. Quality Programs include quality control procedures for specific products as well as overall Quality Plans that typically mandate an organization’s communication procedures, document and data control procedures, quality audit procedures, and training programs necessary for delivery of quality products and services.
>
> **Quality Control (QC)** — Steps taken by data producers to ensure delivery of products that satisfy standards, guidelines and specifications identified in the Scope of Work. These steps typically include production flow charts with built-in procedures to ensure quality at each step of the work flow, in-process quality reviews, and/or final quality inspections prior to delivery of products to a client.

Dewberry’s role is to provide overall project management as well as quality management that include QA of the data, including a completeness validation of the LiDAR masspoints, vertical accuracy assessment and reporting, and a qualitative review of the derived bare earth surface. In addition, Dewberry provides an extensive review of other derived products such as 3D streamlines, TIN-terrain, and LiDAR intensity images.

First, the completeness verification is conducted at a project scale (files are considered as the entities) for all products. It consists of a file inventory and a validation of conformity to format, projection, and georeference specifications. At this point Dewberry also ensures that the data adequately covers the project area for all products. The LiDAR data review begins with the computation of general statistics over all fields per file, followed by an analysis of the results to identify anomalies, especially in the elevation fields and LAS class fields.

The quantitative analysis addresses the quality of the data based on absolute accuracy of a limited collection of discrete checkpoint survey measurements. Although only a small amount of points are actually tested through the quantitative assessment, 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 surrounding LiDAR measurements as acquisition conditions remain similar from one point to the next.

To fully address the LiDAR data for overall accuracy and quality, a manual qualitative review for anomalies and artifacts is conducted on each tile. This includes creating pseudo-image products such as 3-dimensional models. The QA analyst uses multiple images and overlays to find potential errors in the data as well as areas where the data meets and exceeds expectations.

Three fundamental questions are addressed during Dewberry's QA process:

- Was the data complete?
- Did the LiDAR system perform to specifications?
- Did the ground classification process yield desirable results for the intended bare-earth terrain product?

Under the referenced task order, LiDAR data was acquired for 16 counties in South Carolina (Figure 1). This report focuses on the deliverables covering Chesterfield County that are directly derived from the LiDAR. The hydrolines, derived from the LiDAR, are being delivered per watershed and thus will be discussed in a subsequent report. All quality assurance processes and results are given in the following sections.

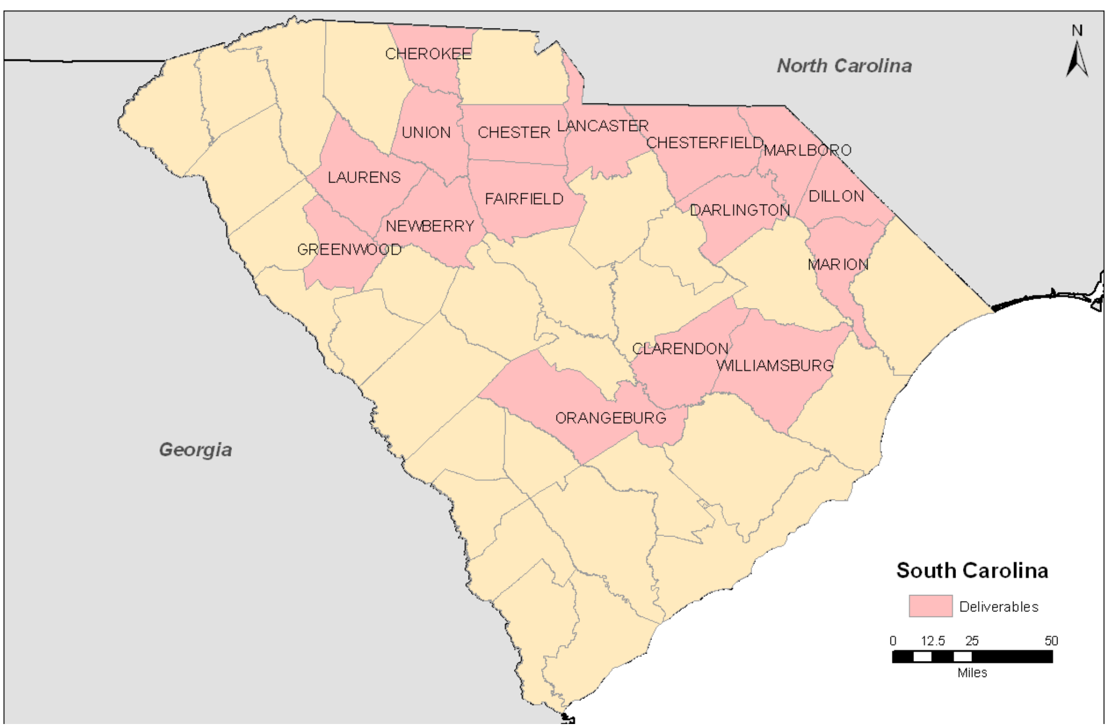

Figure 1 *– Project area; the 16 deliverable counties for the South Carolina project are shown in pink.*

2 Completeness of deliverables

Dewberry reviews the inventory of the data delivered by validating the format, projection and georeferencing. County based deliverables are listed in Table 1.

Table 1 – County Deliverables

Dataset	Format	Spatial
LiDAR	LAS	Tiled
Intensity images	GeoTiff	Tiled
Terrain (bare earth)	ESRI feature class Terrain	1 feature class
Ground masspoints	ESRI feature class multipoints	1 feature class
Boundary	ESRI feature class - polygons	3 feature classes (county/tile/LiDAR)

Clipping of the data along the county boundary was performed according to the following rules (Figure 2):

- a partial tile is delivered at the boundary with a county that is not part of the project,
- a full tile is delivered at the boundary with a county that is part of the project

LAS files and intensity images were delivered in tiles that adhere to these rules and to the State of South Carolina's 5000 ft x 5000 ft tile schema (see Figure 3). The LAS, the ground masspoint feature class, the terrain, and the intensity images extend outside the project boundary with a 50 ft buffer (Figure 4 and Figure 5) as expected.

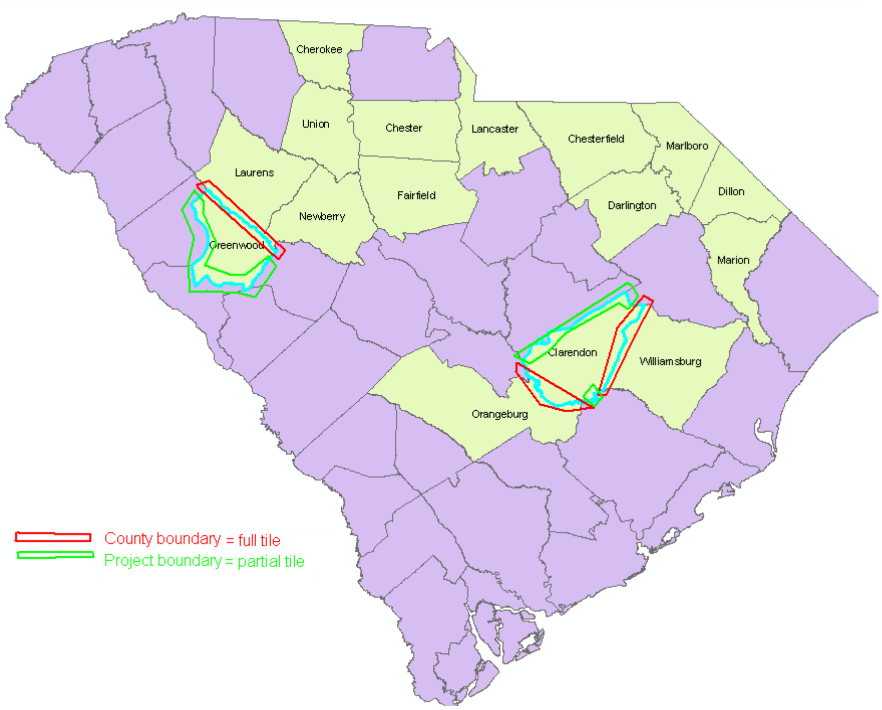

***Figure 2** – Convention used for the tile coverage: at the boundary of a county that is not part of the project, a partial tile is delivered; at the boundary of a county that is part of the project, a full tile is delivered.*

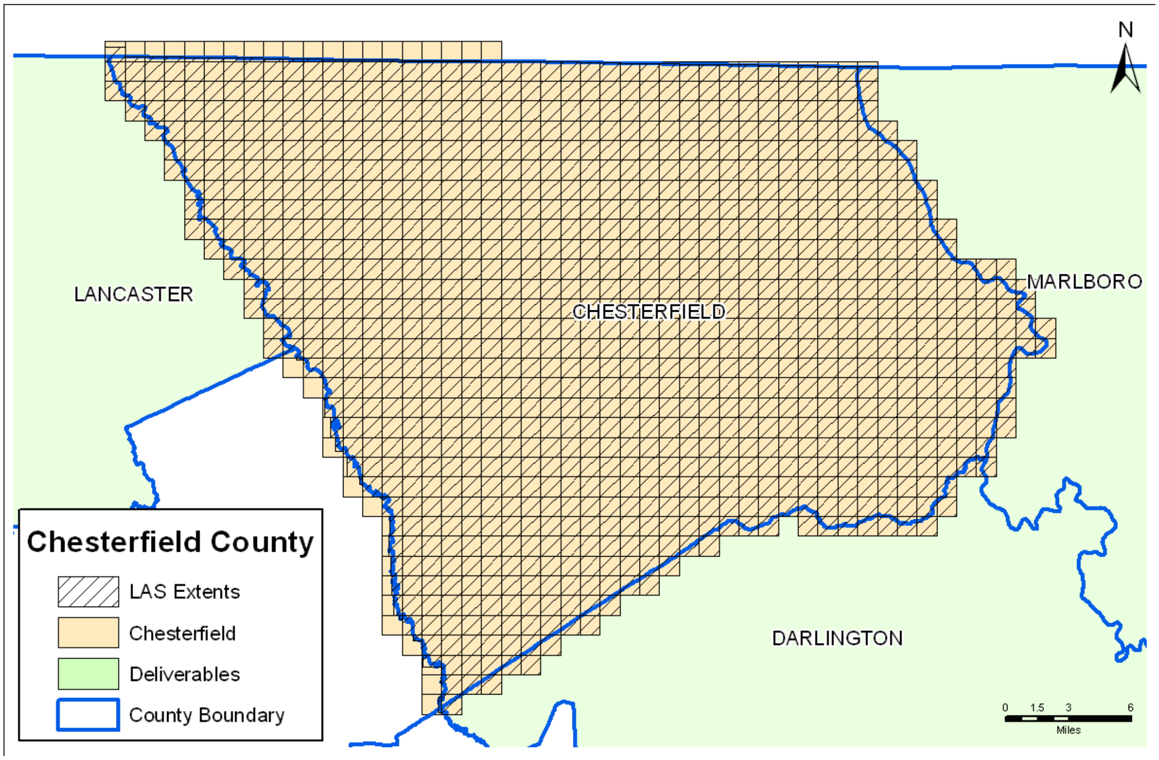

***Figure 3** – The LiDAR coverage of Chesterfield County. Neighboring deliverable counties are shown in green.*

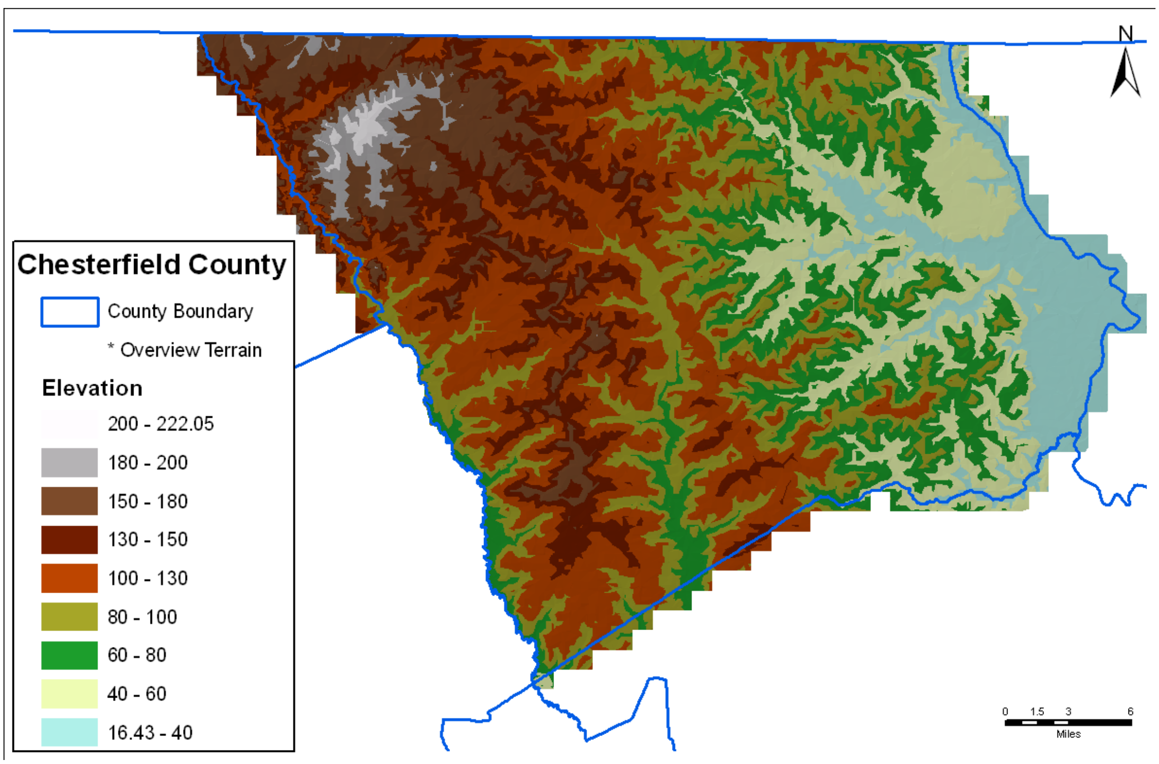

***Figure 4** – The terrain for Chesterfield has a 50 ft buffer outside of the project boundary.*

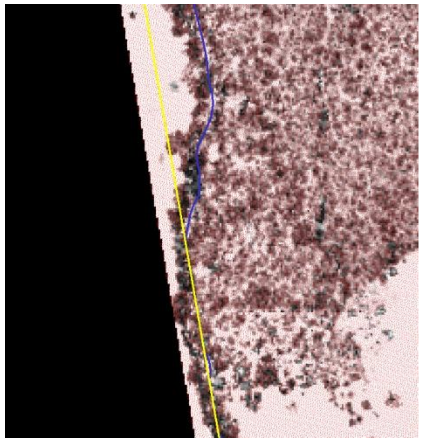

Figure 5 *- Ground masspoints (red) and intensity images extent 50 feet outside the project boundary in yellow. The LAS and terrain do the same. Hydrolines are clipped at the project boundary and the watershed boundary.*

3 QA of Intensity images

990 intensity images in GeoTiff format were delivered for Chesterfield County. An automated script was used to validate that intensity values are integers ranging between 0 and 255, that the cell size is 4 ft, and that the column and row count is 1250. 1250 multiplied by 4 (the pixel size in feet) equals 5000 feet which is the required size of the tiles: 5000 by 5000 feet. Another automated script was used to validate the header information on all of the GeoTiffs. There were no issues with these checks. An example of the header is shown in Table .

Table 2 - Intensity header

```
Output from Display Header
File Name:  E:\Chesterfield_County_112408\Intensity_Images\7149-02.tif
File Information:
 Standard : : TIFF File
 Format : : Byte integers (8 bits)
 Pixels per Line :  1250
 Number of Lines :  1250
 Samples per pixel :  1
 File bits per sample : 8
 Actual bits per sample : 8
 Untiled file
 Number of overviews :  0
 Scanning device resolution :  72  : lines/inch
 Orientation :  4  : Row major order, origin at top left
 NO scan line headers : non-scannable file
 Packet size (16-bit words) : 0
 Free vlt space (16-bit words) : 2000000000
 Free packet space (16-bit words) : 2000000000
Raster to UOR matrix:
 Unspecified or All Zero Matrix
Raster to World Matrix:
 Units: Feet
 amx[ 0]=          4, amx[ 1]=          0, amx[ 2]=     1745000
 amx[ 3]=          0, amx[ 4]=         -4, amx[ 5]=     1200000
       1745000 ,      1200000
       1750000 ,      1200000
       1750000 ,      1195000
       1745000 ,      1195000
Geotiff_Information:
   Version: 1
   Key_Revision: 1.0
   Tagged_Information:
      ModelTiepointTag (2,3):
         0            0            0
         1745000      1200000      0
      ModelPixelScaleTag (1,3):
         4            4            0
      End_Of_Tags.
   Keyed_Information:
      GTModelTypeGeoKey (Short,1): ModelTypeProjected
      GTRasterTypeGeoKey (Short,1): RasterPixelIsArea
      ProjectedCSTypeGeoKey (Short,1): Unknown-3361
      ProjLinearUnitsGeoKey (Short,1): Linear_Foot
      End_Of_Keys.
   End_Of_Geotiff.
PCS = 3361 (NAD83(HARN) / South Carolina (ft))
Projection = 15355 (SPCS83 South Carolina zone (International feet))
Projection Method: CT_LambertConfConic_2SP
   ProjFalseOriginLatGeoKey: 31.833333 ( 31d50' 0.00"N)
   ProjFalseOriginLongGeoKey: -81.000000 ( 81d 0' 0.00"W)
   ProjStdParallel1GeoKey: 34.833333 ( 34d50' 0.00"N)
   ProjStdParallel2GeoKey: 32.500000 ( 32d30' 0.00"N)
   ProjFalseEastingGeoKey: 609600.000000 m
   ProjFalseNorthingGeoKey: 0.000000 m
GCS: 4152/NAD83(HARN)
Datum: 6152/NAD83 (High Accuracy Regional Network)
Ellipsoid: 7019/GRS 1980 (6378137.00,6356752.31)
Prime Meridian: 8901/Greenwich (0.000000/  0d 0' 0.00"E)
Projection Linear Units: 9002/foot (0.304800m)
Corner Coordinates:
Upper Left    (1745000.000,1200000.000)
Lower Left    (1745000.000,1195000.000)
Upper Right   (1750000.000,1200000.000)
Lower Right   (1750000.000,1195000.000)
Center        (1747500.000,1197500.000)
```

Dewberry also visually checked the tile-matching in ArcMap. Overall, the intensity is consistent between adjacent tiles.

Tiles over the boundary between two delivered counties are delivered in full for each county. Tiles over the outside project boundary are partial; the section outside the buffered project area is filled with black pixels (value 0).

One issue with the intensity data was found in Chesterfield County. Several tiles displayed tonal changes within the tile. The sharp tonal transition seems to follow the flight line boundaries, as shown in Figure 6. This small anomaly does not significantly impact the intensity product as a whole.

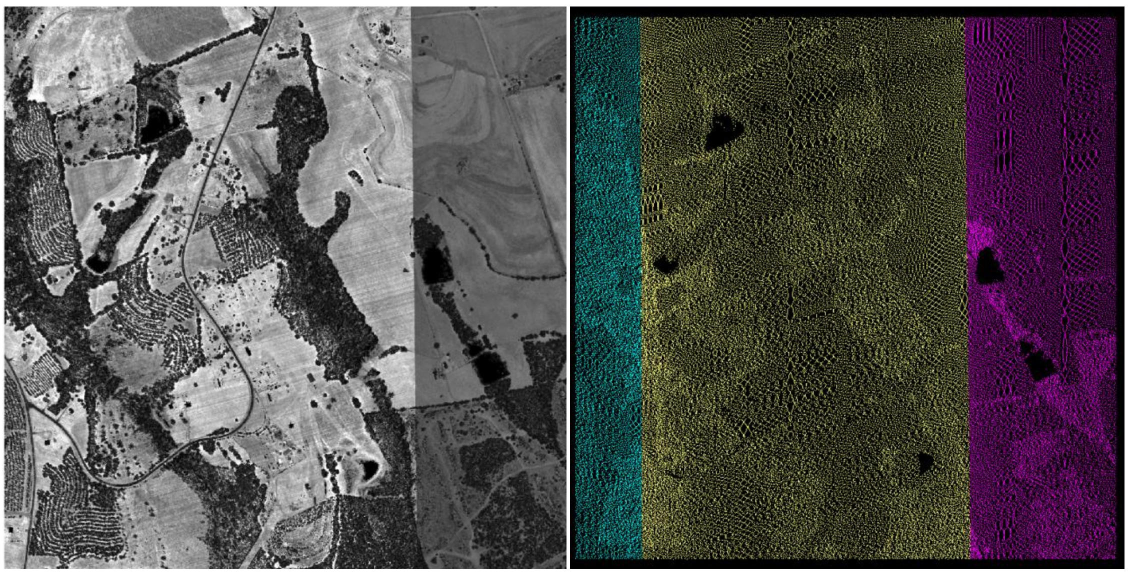

Figure 6 *- 3007-03 Tonal changes in intensity values within a tile (Left is intensity image, Right is image of LAS points colored by flight line).*

4 Metadata

Dewberry verified the metadata and all of the xml files were FGDC complaint. Metadata is delivered for the project, terrain, intensity images, and the LAS.

5 LiDAR QA

5.1 Completeness

5.1.1 LAS inventory

Dewberry received 990 LiDAR files covering the Chesterfield County area. They are in the correct format and projection:

- LAS version: 1.1
- Point data format: 1
- Projection set in the header:
  - NAD_1983_HARN_StatePlane_South_Carolina_FIPS_3900_Feet_Intl;
  - Horizontal unit: linear foot;
  - NAVD88 - Geoid03;
  - Vertical unit: meters

The point spacing matches the requirement of an average point spacing of 1.4 meters.

Each record includes the following fields:

- XYZ coordinates
- Flight line
- Intensity
- Return number, number of return, scan direction, edge of a flight line and scan angle
- Classification:
  - class 1 for non-ground,
  - class 2 for ground (must be combined with class 8 to be complete),
  - class 8 for (intelligently-thinned) model key points,
  - class 9 for water,
  - class 12 for overlap
- GPS time (this is expressed in second of the week; note that the date of collection will be given in the metadata file because the date contained in the LAS header is the file creation date according to LAS standard)

5.1.2 Statistical analysis of LAS tile content

To verify the content of the data and to validate the data integrity, a statistical analysis was performed on all the data. This process allows Dewberry to statistically review 100% of the data to identify any gross outliers. This statistical analysis consists of:

1. Extracting the header information
2. Reading the actual records and computing the number of points, minimum, maximum and mean elevation for each class. Minimum and maximum for other relevant variables are also evaluated.

Each tile was queried to extract the number of LiDAR points. With a nominal point spacing of 1.4m, the number of point per tile should be around 3.9 million. The mean over Chesterfield County is around 4.8 million which proves that the average density is more than what is required. All tiles are within the anticipated size range except for where fewer points are expected (near the external project boundary where tiles are clipped or over large rivers and lakes) as illustrated in Figure 7.

To first identify incorrect elevations, the z-minimum and z-maximum values for the ground class were reviewed. With maximum values between 80 and 225m, no noticeable anomalies were identified because this is consistent with the expected range of elevation in the county (max elevation in Chesterfield County: around 225m). Figure 8 (right) shows the spatial distribution of these elevations, following the anticipated terrain topography. Lower elevations are found near hydrographic features; see Figure 8 (left) for the Z min elevations.

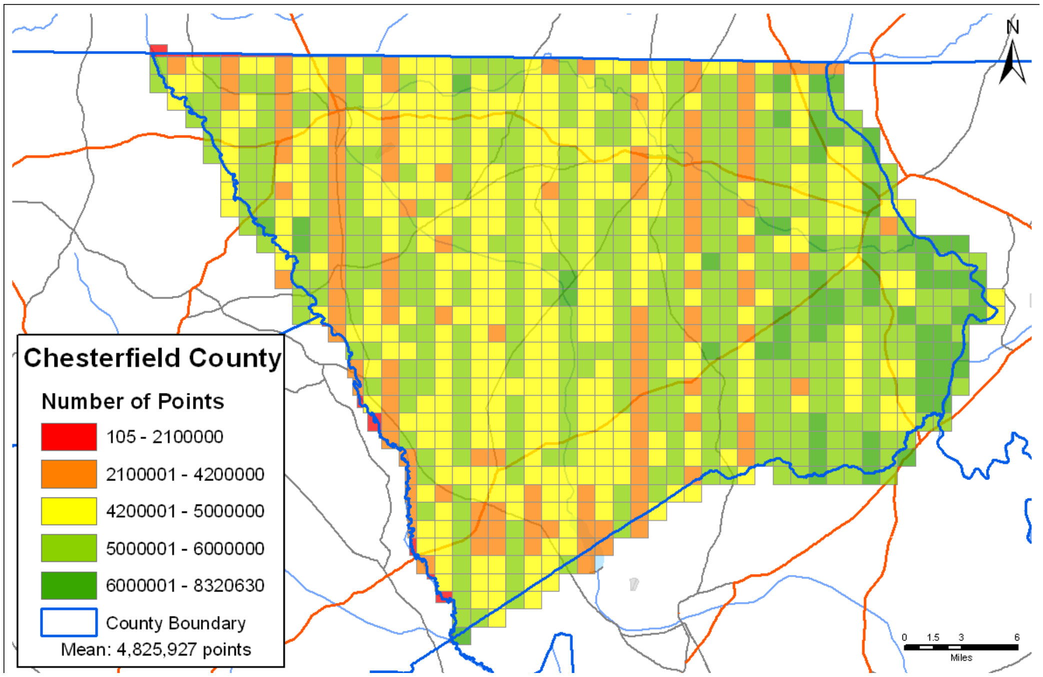

Figure 7 *– Number of points per tile. The red tiles at the border and are expected to have fewer points.*

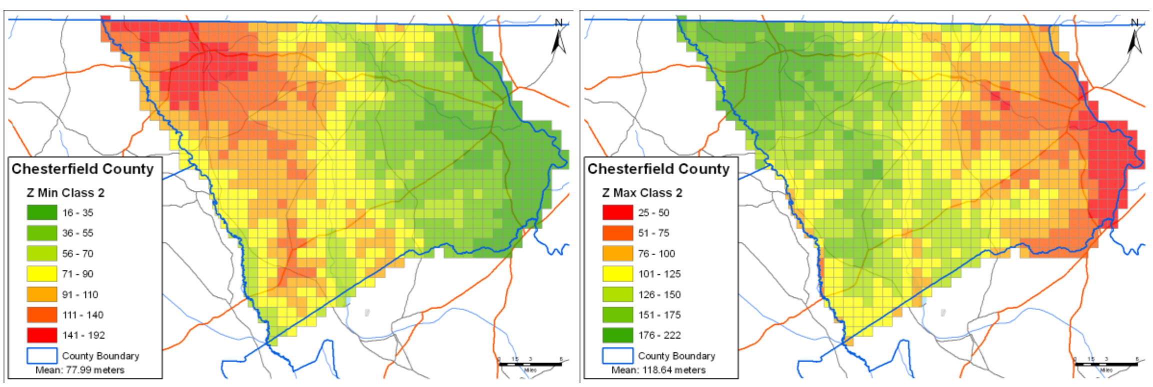

Figure 8 *– Z min and Z max elevation for ground points (class 2) per tile.*

5.2 LiDAR Quantitative Assessment

5.2.1 Checkpoint inventory

Typically for this type of data collection, a ground truth survey is conducted following the *FEMA Guidelines and Specifications for Flood Hazard Mapping Partners Appendix A: Guidance for Aerial mapping and Surveying* which is based on the NSSDA. This methodology collects a minimum of 20 points for each of the predominant land cover types (i.e. bare-earth, weeds and crop, forest, urban etc.) for a minimum of three land cover classes. By verifying the data in these different classes, the data accuracy is tested, but it also tests whether the classification of the LiDAR has been performed correctly at those test point locations. In this project the predominant land covers selected are bare-earth, mixed vegetation, and urban.

The field survey was conducted and prepared by the South Carolina Geodetic Survey in April 2008. The guidelines were to collect 60 checkpoints in 3 different land covers: 20 points in Urban Areas, 20 points in Open Terrain, and 20 points divided equally in Medium Vegetation and Forested Areas.

In reality 118 points were collected, as presented in Table 3, with 51 vegetation points instead of 20, including an additional class (bush). All the checkpoints used for the vertical assessment of the LiDAR data are available in Appendix A. Figure 9 shows the distribution of the checkpoints throughout the area. The points are grouped together in clusters. In some cases the checkpoints within a cluster are less than 100 ft apart which is not ideal but still acceptable.

Table 3 – Number of points required and acquired.

Class	Guidelines	Acquired
o - Open Terrain	20	42
b - Bush	0	17
h - High Grass	10	17
w - Woods	10	17
u - Urban	20	43
Total	**60**	**136**

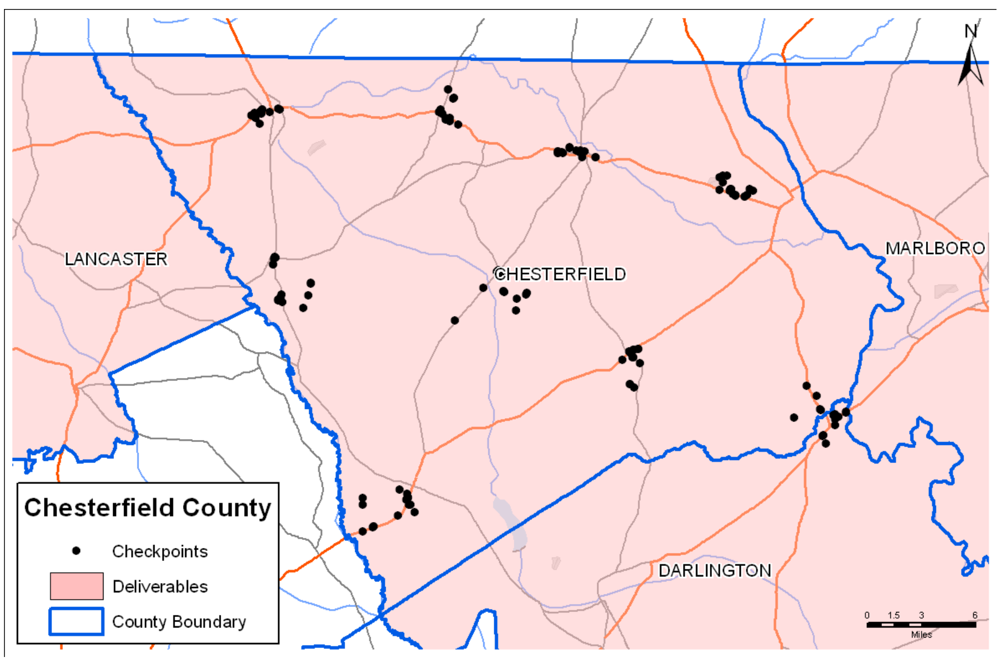

Figure 9 *– Survey checkpoints from South Carolina Geodetic Survey.*

5.2.2 Vertical Accuracy Assessment Methodologies

The first method of testing vertical accuracy used the FEMA specifications which follows the National Standard for Spatial Data Accuracy (NSSDA) procedures. The accuracy is reported at the 95% confidence level using the Root Mean Square Error (RMSE) which is valid when errors follow a normal distribution. By this method, vertical accuracy at the

95% confidence level equals RMSEz x 1.9600. This methodology measures the square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. The vertical accuracy assessment compares the measured survey checkpoint elevations with those of the TIN as generated from the bare-earth LiDAR. The X/Y locations of the survey checkpoints are overlaid on the TIN and the interpolated Z values are recorded. This interpolated Z values are then compared with the survey checkpoint Z values and this difference represents the amount of error between the measurements.

The second method of testing vertical accuracy, endorsed by the National Digital Elevation Program (NDEP) and American Society for Photogrammetry and Remote Sensing (ASPRS) uses the same (RMSE) method in open terrain only; an alternative method uses the 95th percentile to report vertical accuracy in each of the other land cover categories (defined as Supplemental Vertical Accuracy – SVA) and all land cover categories combined (defined as Consolidated Vertical Accuracy – CVA). The 95th percentile method is used when vertical errors may not follow a normal error distribution, as in vegetated terrain.

The Fundamental Vertical Accuracy (FVA) is the same for both methods; both methods utilize RMSE x 1.9600 in open terrain where there is no reason for LiDAR errors to depart from a normal error distribution.

The following tables and graphs outline the vertical accuracy and the statistics of the associated errors as computed by the different methods.

Table 4 shows the complete results of the Chesterfield County data set run through the FEMA/NSSDA process; vertical accuracy at the 95% confidence level equals the RMSE x 1.9600. By this method, the consolidated vertical accuracy equals the RMSE (0.079 m) x 1.9600, or 0.155 m (15.5 cm).

Table 4 – Final statistics for Chesterfield County using FEMA/NSSDA processes.

100 % of Totals	RMSE (m) Spec=0.185m	Mean (m)	Median (m)	Skew	Std Dev (m)	# of Points	Min (m)	Max (m)
Consolidated	0.079	0.034	0.032	0.438	0.071	136	-0.159	0.243
Open Terrain	0.058	0.016	0.003	0.301	0.057	42	-0.109	0.145
Vegetated	0.106	0.059	0.047	-0.079	0.089	51	-0.159	0.243
Urban	0.054	0.021	0.021	0.419	0.050	43	-0.053	0.160

Table 5 shows the complete results of the Chesterfield data set run through the NDEP/ASPRS process; the CVA value 0.165 m (16.5 cm). The similar results between the two methods (15.5 cm and 16.5 cm) demonstrate that the errors did approximate a normal error distribution, even in vegetation. All of the calculated statistics for Chesterfield County fall well below the specifications.

Table 5 – Final statistics for Chesterfield County using NDEP/ASPRS processes.

Land Cover Category	# of Points	FVA — Fundamental Vertical Accuracy (RMSEz x 1.9600) Spec=36.3 cm	CVA — Consolidated Vertical Accuracy (95th Percentile) Spec=36.3 cm	SVA — Supplemental Vertical Accuracy (95th Percentile) Target=36.3 cm
Consolidated	136		16.5	
Bare Earth	42	11.4		10.9
Vegetated	51			21.1
Urban	43			8.7

Figure 10 illustrates the distribution of the elevation differences between the LiDAR data and the surveyed checkpoints. The majority of delta Z values are concentrated on the positive side (LiDAR higher than the checkpoints) pointing toward a slight positive bias in the data.

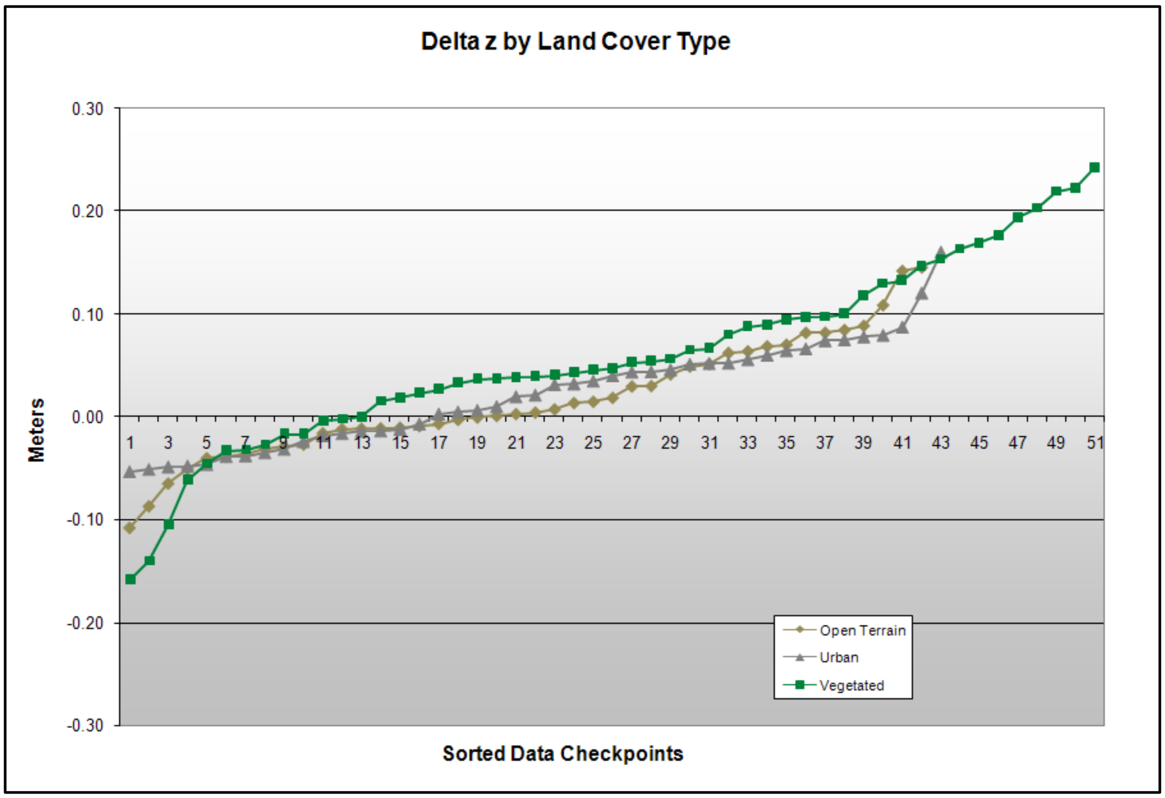

Figure 10 - *Checkpoints shown per land cover type and sorted by errors (deltaZ).*

Given the good results and the high number of checkpoints used, Dewberry is confident that the data meets the accuracy requirement despite the less ideal spatial dispersion of the checkpoints.

Compared with the 36.3 cm specification for vertical accuracy at the 95% confidence level, equivalent to 2-foot contours, the dataset passes by all methods of accuracy assessment:.

- Tested 11.4 cm meter Fundamental Vertical Accuracy at 95% confidence level in open terrain using RMSEz x 1.9600 (FEMA/NSSDA and NDEP/ASPRS methodologies).
- Tested 15.5 cm Consolidated Vertical Accuracy at 95% confidence level in all land cover categories combined using RMSEz x 1.9600 (FEMA/NSSDA methodology).
- Tested 16.5 cm Consolidated Vertical Accuracy at 95th percentile in all land cover categories combined (NDEP/ASPRS methodology).

5.3 LiDAR Qualitative Assessment

5.3.1 Protocol

The goal of Dewberry's qualitative review is to assess the continuity and the level of cleanliness of the bare earth product. Each LiDAR tile is expected to meet the following acceptance criteria:

- The point density is homogeneous and sufficient to meet the user needs;
- The ground points have been correctly classified (no manmade structures and vegetation remains, no gap except over water bodies);
- The ground surface model exhibits a correct definition (no aggressive classification, no over-smoothing, no inconsistency in the post-processing);
- No obvious anomalies due to sensor malfunction or systematic processing artifact is present (data holidays, spikes, divots, ridges between tiles, cornrows…);
- 90% or more of the artifacts have been removed, 95% of the outliers, 95% of the vegetation, and 98% of the buildings.

Dewberry analysts, experienced in evaluating LIDAR data, performed a visual inspection of the bare-earth digital elevation model (bare-earth DEM). LiDAR masspoints were first gridded with a grid distance of 2x the full point cloud resolution. Then, a triangulated irregular network (TIN) was built based on this gridded DEM and displayed as a 3D surface. A shaded relief effect was applied which enhances 3D rendering. The software used for visualization allows the user to navigate, zoom and rotate models and to display elevation information with an adaptive color coding in order to better identify anomalies.

One of the variables established when creating the models is the threshold for missing data. For each individual triangle, the point density information is stored; if it meets the threshold, the corresponding surface will be displayed in green, if not it will be displayed in red (see Figure 11). It should also be noted that if this density model is created with the ground points only, it is expected to have void areas where buildings exist or in water; vegetation can also reduce the number of points hitting the ground, resulting in more distanced points.

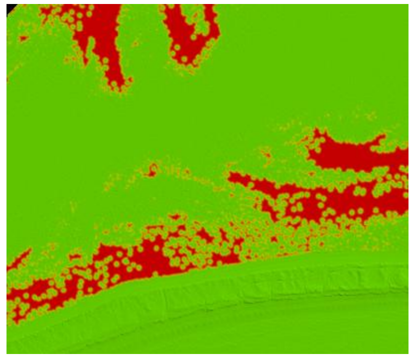

***Figure 11** – Ground model with density information (red means sparse data).*

The first step of Dewberry's qualitative workflow was to verify the point distribution by systematically loading a percentage of the tiles as masspoints colored by flight line (Figure 12) or by class (Figure 13). This particular type of display helps us visualize and better understand the scan pattern, the flight line orientation, flight coverage, and gives an additional confirmation that all classes are present and logically represent the terrain.

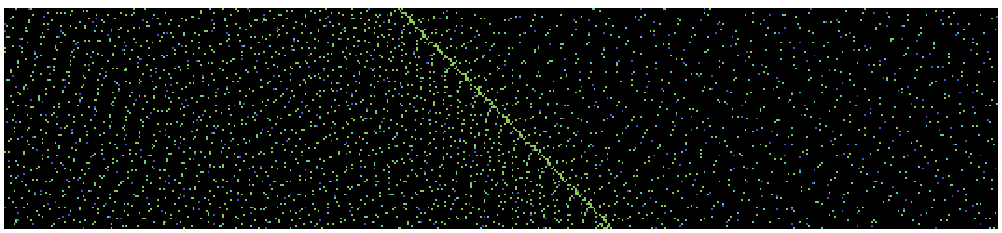

***Figure** 12 – LiDAR points colored by flight line. Detail of the point distribution. Note the variations in the scan pattern*

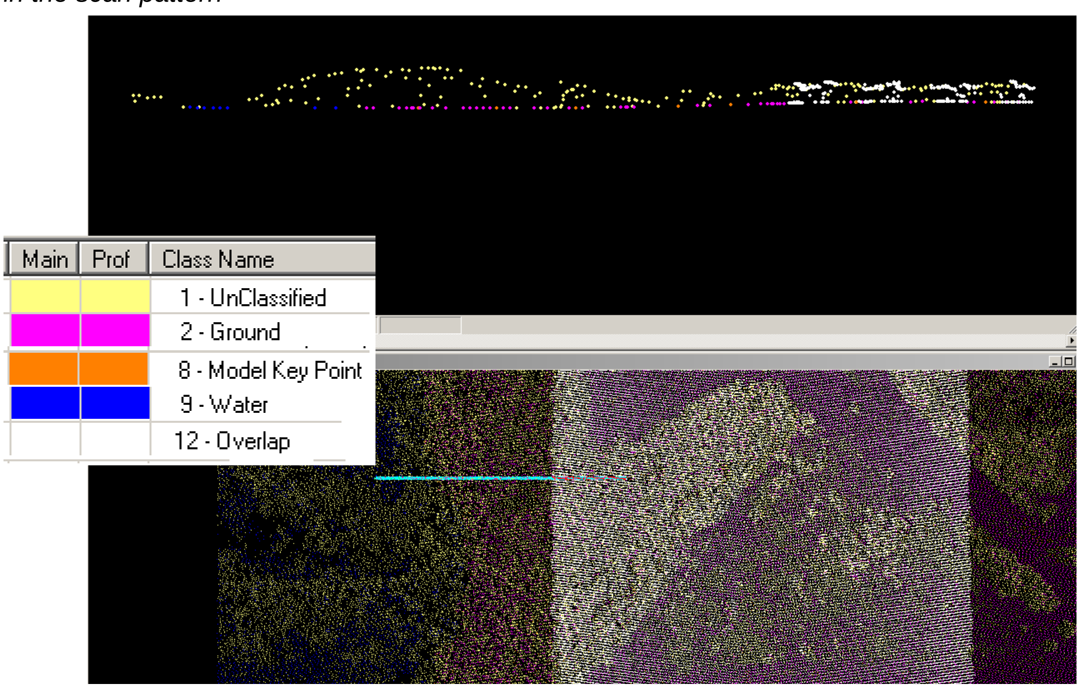

***Figure 13** - Full point cloud colored by classification.*

The second step was to verify data completeness and continuity using the bare-earth DEM with density information, displayed at a macro level. If, during this macro review of the ground models, potential artifacts or large voids are found, the digital surface model (DSM) based on the full point cloud including vegetation and buildings will be used to pinpoint the extent and the cause of the issue. Moreover, the intensity information stored in the LiDAR data can be visualized over this surface model, helping in interpretation of the terrain. Finally, if the analyst suspects a systematic error relating to data collection, a visualization of the 3D raw masspoints is performed, rather than visualizing as a surface.

Dewberry's micro-level qualitative review is the process of importing, comparing and analyzing these two later types of models (DSM with intensity and raw masspoints), along with cross section extraction, surface measurements, density evaluation.

5.3.2 Quality report

Dewberry's qualitative review consists of a micro visual inspection of all the tiles. There is no automated toolset more effective than the manual inspection by a GIS analyst to find errors in automated processing of LiDAR data. The analyst will inspect the data for processing anomalies, classification errors, and full point cloud artifacts remaining in the ground surface models.

After closely examining the dataset, the bare earth model was determined to be of high quality. The data set is very clean with nearly zero artifacts. Dewberry found very few errors in the data as outlined in the text and images below. The majority of the calls are due to minor misclassifications and poor LiDAR penetration. However, these issues are not serious enough to render the data unusable.

Inconsistent Editing

Dewberry discovered several areas of inconsistent editing within the dataset. In the example illustrated in Figure 14, it is apparent that different parameters were used to classify the bordering tiles, resulting in an abrupt and unnatural change in classification. This type of error does not have a significant effect on the usability of the data.

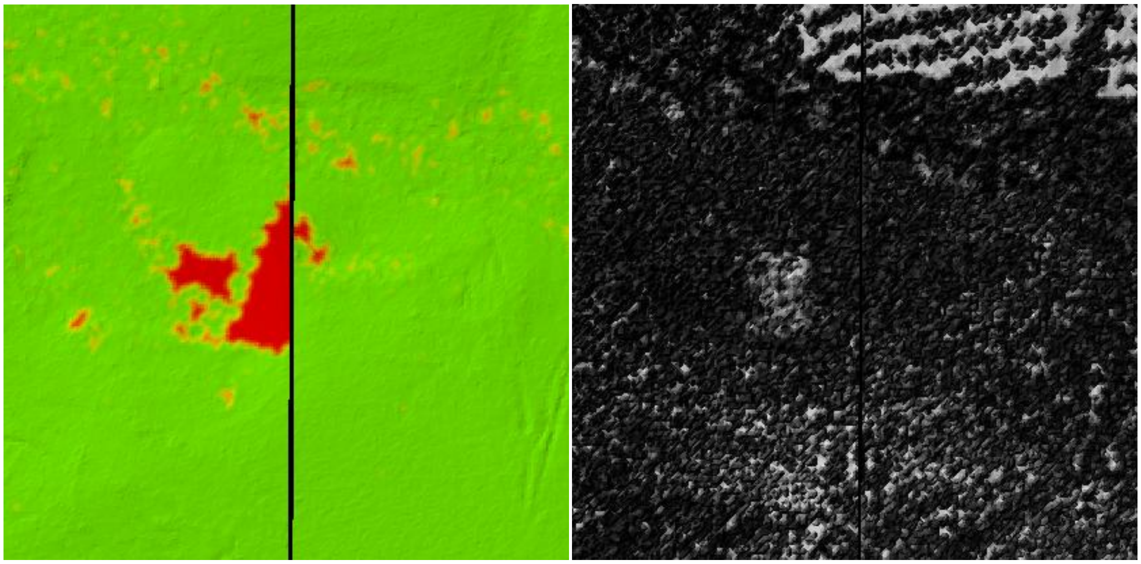

Figure 14 *– 2052-04 Inconsistent editing (L: Ground density model, R: Full point cloud intensity)*

Misclassification

One of the more common problems seen in Chesterfield County was misclassification of ground points as water. During the classification process, it appears that hydrolines were used to classify water points. At the time of acquisition however, many of these retention areas were partially dry and the LiDAR sensor was able to return ground points resulting in a good representation of the ground surface in these areas. In the left image of Figure 15, the red area signifies an absence of ground points in a water retention area. The full point cloud intensity image in the middle shows that the LiDAR sensor actually returned points as there was no water present at the time. The image on the right illustrates that these points were classified as water (colored blue).

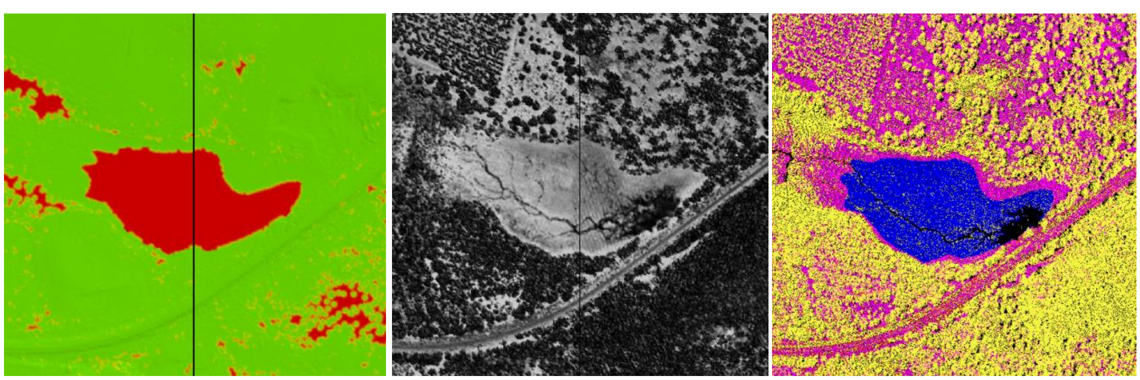

Figure 15 *– 2969-04 & 2979-03 Misclassification of ground points. Left image is ground density model and middle is full point cloud with intensity. Right image is full point cloud colored by classification, yellow is unclassified (class 1), purple is ground (class 2), and blue is water (class 9).*

A second type of misclassification found in Chesterfield County appears to be more editor error than systematic error. Figure 16 and Figure 17 display areas of points that have been accidentally placed into class 1 (unclassified). The profile image of the cross-section in Figure 17 shows that the LiDAR sensor returned ground points in this area although they were erroneously left in class 1.

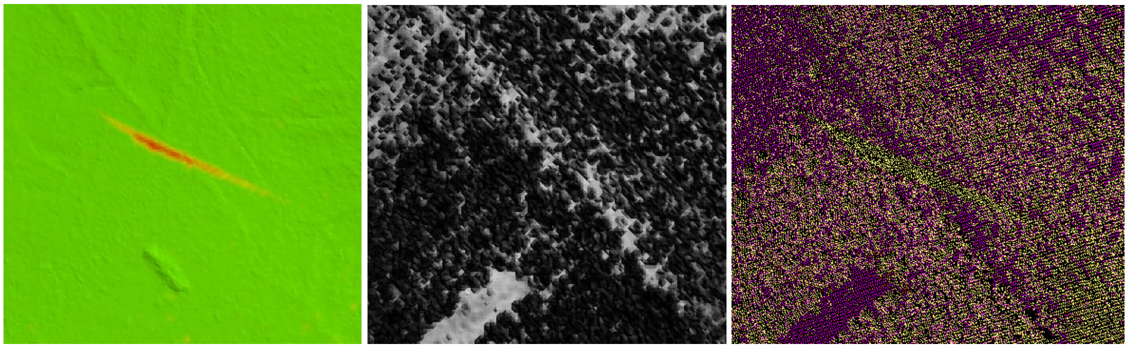

Figure 16 *– 2077-01 Misclassification of ground points. Left image is ground density model and middle is full point cloud with intensity. Right image is full point cloud colored by classification, yellow is unclassified (class 1), purple is ground (class 2), and blue is water (class 9).*

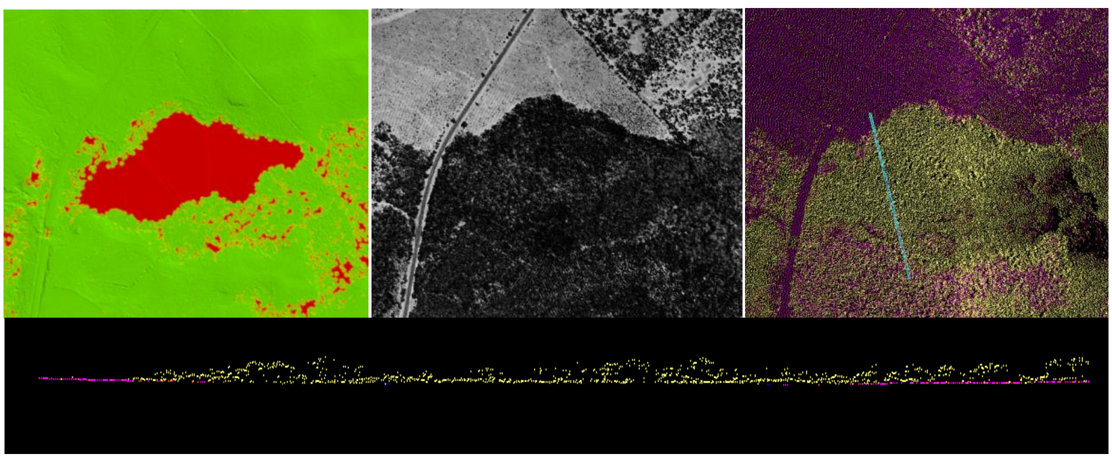

Figure 17 *– 2989-03 Misclassification of ground points. Left image is ground density model and middle is full point cloud with intensity. Right image is full point cloud colored by classification, yellow is unclassified (class 1), purple is ground (class 2), and blue is water (class 9). Bottom image is profile of cross-section.*

Poor LiDAR Penetration

Several areas were identified with patches of low density of ground points. This may be unavoidable. When the vegetation is very dense, the LiDAR may not penetrate the canopy all the way to the ground; this is illustrated in Figure 18. This type of sparse density of ground points was found throughout the dataset and causes the surface to be sometimes less accurate. Poor LiDAR penetration cannot be fixed without a re-flight, but even then, this might be inherent to the type of vegetation surveyed. While increasing the flight line overlap would provide different angles of incidence and would increase the chance of penetrating the canopy, this is more expensive, and it is possible that the density of the vegetation prevents any point from reaching the ground. Regardless, the accuracy of the data is always expected to diminish in vegetated areas, and when a few ground points are available an elevation model can be interpolated with acceptable precision, especially in flat terrain.

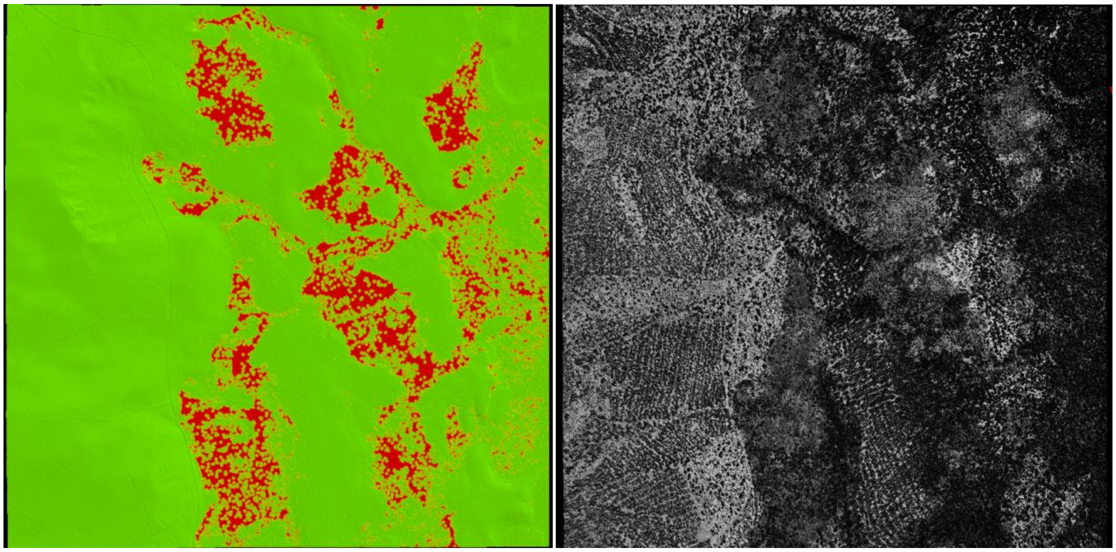

__Figure 18__ – 2042-03 Poor LiDAR penetration in vegetated area. (L: Ground density model, R: Full point cloud intensity).

Acquisition "Drop-Off"

Another anomaly detected in the data is the lack of returns on certain types of roads, buildings, runways, and parking lots, as depicted in Figure 19.

Several possible explanations for this anomaly are low gain setting or low emission power, both resulting in a non detection of a weak reflected signal. A weak reflected signal can occur on certain types of asphalt that absorb the near infrared wavelength. For the roads and buildings there is no simple fix other than a re-flight without a guarantee of success.

The user should be aware that this issue has almost no impact on the ground integrity as buildings are always removed from the ground class and road edges are left in allowing a proper definition of the terrain. Moreover, this kind of acquisition "drop-off" had a limited occurrence.

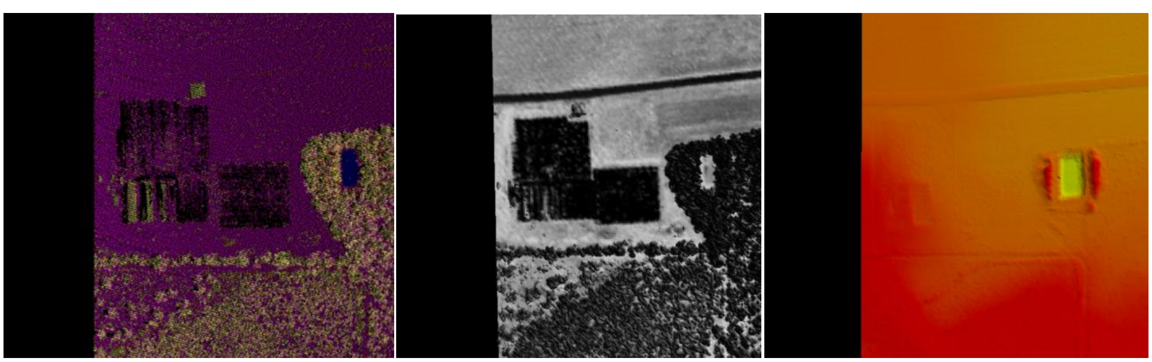

__Figure 19__ – 3928-02 Acquisition drop-off (Left: Full point cloud colored by class, Middle: Full point cloud with intensity, Right: Ground elevation model).

Conclusions

Overall the LiDAR data meets the minimum standards for absolute and relative accuracy. The level of cleanliness for the bare-earth terrain easily meets the specifications and no major anomalies were found. The user should be aware of the minor misclassification when focusing on portions of the data, but the data set as a whole is of high quality. The processing performed exceptionally well given the low relief terrain. The figures highlighted above are a sample of the minor issues that were encountered and are not representative of the majority of the data, which is of high quality. The intensity images meet specifications and the terrain and multipoint entities are correctly derived from the classified bare earth LiDAR points.

Appendix A Checkpoints

The horizontal coordinate system is South Carolina State Plane **International feet,** horizontal datum NAD83 **HARN** with **elevation in meters** (NAVD88).

The point numbering scheme uses a three digit sequence starting with the county number (SC numbers its counties in alphabetical order), a dash, followed by zone number, a dash and then a sequence number corresponding to order of collection within the zone, the land cover code was concatenated in front of the number.

pointNo	easting	northing	elevation	zLidar	DeltaZ	AbsDeltaZ
oEA38	2129352.791	1084401.141	174.016	173.94	Open Terrain	-0.0761
oea83	2067519.392	1050186.659	162.412	162.36	Open Terrain	-0.0492
o29-5-4	2126696.584	995506.950	164.880	164.83	Open Terrain	-0.0461
o29-9-1	2108821.366	1036025.172	196.618	196.59	Open Terrain	-0.0231
o29-7-14	2095286.720	1006874.232	215.630	215.61	Open Terrain	-0.0227
o29-7-10	2103011.233	1001188.524	199.857	199.84	Open Terrain	-0.0191
o29-7-11	2102465.481	1002003.998	201.126	201.13	Open Terrain	0.0061
o29-7-1	2101798.443	1002455.323	202.055	202.06	Open Terrain	0.0064
o29-9-4	2114377.428	1031243.741	184.709	184.72	Open Terrain	0.0152
o29-9-12	2104459.043	1040038.843	187.647	187.66	Open Terrain	0.017
o29-3-11	2068856.888	1099050.256	167.048	167.07	Open Terrain	0.0218
o29-3-2	2068483.340	1049614.029	165.881	165.91	Open Terrain	0.028
o29-3-16	2069007.478	1051186.444	161.330	161.36	Open Terrain	0.0315
o29-6-1	2145132.703	1039559.553	200.099	200.14	Open Terrain	0.0364
o29-8-2	2049671.901	977932.090	141.401	141.44	Open Terrain	0.0376
o29-3-15	2067170.447	1060231.882	172.567	172.62	Open Terrain	0.0489
o29-2-2	2045788.414	1133599.909	193.260	193.31	Open Terrain	0.0548
o29004av	2125802.034	987120.374	159.933	159.99	Open Terrain	0.0569
oM103	2038413.069	1165343.653	195.560	195.62	Open Terrain	0.0621
oea69	2067039.270	1055755.742	151.503	151.57	Open Terrain	0.0636
o29-2-4	2043737.848	1135981.949	191.737	191.8	Open Terrain	0.0662
oTAXAHAWAZMK2	2144367.751	1039133.591	200.358	200.43	Open Terrain	0.0676
o29-3-14	2066659.084	1059908.655	159.136	159.2	Open Terrain	0.0685
oEA16	2104611.381	1027424.861	202.187	202.26	Open Terrain	0.0749
o29-4-2	2120677.098	1080451.111	176.339	176.42	Open Terrain	0.0859
o29-7-9	2097752.494	1003525.425	208.897	208.99	Open Terrain	0.0959
oea12	2130025.446	984952.378	154.992	155.1	Open Terrain	0.1088
o19350f	2094781.318	1008430.458	218.097	218.24	Open Terrain	0.1448
u29-9-5	2114294.352	1025770.531	176.017	175.94	Urban	-0.0722
u29-9-CP1REO	2108484.033	1036299.920	195.211	195.18	Urban	-0.0356
u29-2-9	2049285.740	1127451.155	179.704	179.7	Urban	-0.0074
u29-2-3	2045643.583	1133970.572	192.740	192.73	Urban	-0.0057
u29-6-2	2145337.091	1039655.461	200.317	200.31	Urban	-0.003
u29-9-11	2110047.991	1039540.547	211.125	211.13	Urban	0.0022
u29-4-9	2119670.931	1072440.103	188.930	188.94	Urban	0.0119
u29-3-9	2069176.540	1050010.430	165.120	165.14	Urban	0.0196
u29-7-12	2098366.609	1003307.488	206.308	206.33	Urban	0.0223

u29-7-15	2095903.840	1007698.988	213.016	213.04	Urban	0.0267
u29-1-9	2036814.149	1163932.721	197.302	197.33	Urban	0.0307
u29-7-5	2097479.819	996045.706	192.769	192.8	Urban	0.0319
u29-4-6	2122349.338	1077484.632	169.126	169.17	Urban	0.0404
u29-5-5	2131076.026	983680.886	151.946	151.99	Urban	0.0411
u29-7-7	2097805.519	1003870.104	208.668	208.71	Urban	0.0418
u29-6-9	2146402.089	1038969.545	196.191	196.23	Urban	0.0438
u29-9-2	2109944.469	1034345.126	193.941	193.99	Urban	0.0474
u29-3-12	2069024.231	1049248.076	161.683	161.73	Urban	0.0495
u29-3-1	2067491.620	1050191.333	162.399	162.45	Urban	0.0544
u29-7-16	2096039.424	1003502.381	206.525	206.58	Urban	0.0571
u29-8-CP1REO	2049641.567	978033.840	141.473	141.54	Urban	0.0666
u29-3-13	2066980.270	1054002.599	136.366	136.44	Urban	0.0709
u29-7-13	2097671.335	1004803.325	208.591	208.68	Urban	0.0892
u29-3-17	2069852.178	1049221.113	162.306	162.4	Urban	0.0979
h29-5-2	2126682.981	995479.493	164.683	164.65	Vegetated	-0.029
b29-5-9	2125366.932	988349.207	161.445	161.42	Vegetated	-0.0283
h29-9-6	2105326.981	1027213.506	198.444	198.42	Vegetated	-0.0258
w29-3-6	2072346.342	1063171.443	171.224	171.22	Vegetated	-0.0002
w29-5-3	2126659.434	995384.090	164.405	164.41	Vegetated	0.0048
w29-1-8	2036840.754	1164420.286	198.343	198.35	Vegetated	0.0056
h29-4-1	2122939.324	1085337.459	177.476	177.48	Vegetated	0.008
w29-7-3	2101774.201	1002862.220	202.558	202.57	Vegetated	0.0081
w29-6-6	2146404.266	1037864.804	194.677	194.7	Vegetated	0.0186
w29-9-8	2110579.055	1038806.823	202.816	202.84	Vegetated	0.0214
h29-1-7	2036980.929	1164245.537	199.552	199.58	Vegetated	0.0242
h29-2-6	2041644.756	1135262.355	176.387	176.41	Vegetated	0.026
w29-9-7	2106060.086	1031199.770	197.900	197.93	Vegetated	0.0278
w29-1-1	2033635.555	1166970.017	181.354	181.38	Vegetated	0.0281
w29-2-5	2041712.061	1135337.619	177.002	177.03	Vegetated	0.0302
w29-3-7	2072945.578	1056921.403	145.842	145.87	Vegetated	0.0307
h29-9-3	2114224.102	1030530.691	190.288	190.32	Vegetated	0.0342
h29-6-4	2145185.515	1036581.238	189.146	189.18	Vegetated	0.0359
w29-3-4	2070704.254	1055412.611	150.436	150.48	Vegetated	0.0453
b29-7-2	2101768.247	1002759.592	202.764	202.81	Vegetated	0.0466
h29-3-8	2074802.546	1048271.908	167.153	167.21	Vegetated	0.0555
h29-6-3	2143869.777	1035722.357	188.774	188.83	Vegetated	0.0579
h29-5-1	2124635.852	994973.597	166.660	166.72	Vegetated	0.059
w29-5-6	2128399.483	990701.684	157.089	157.15	Vegetated	0.0591
b29-6-5	2145265.785	1031948.553	169.904	169.97	Vegetated	0.0612
w29-7-8	2094852.734	1008460.590	217.225	217.29	Vegetated	0.0651
w29-4-7	2119612.081	1075890.732	187.097	187.17	Vegetated	0.071
w29-2-8	2045655.250	1136408.200	185.928	186.01	Vegetated	0.0826
w29-4-8	2118912.019	1075553.269	188.034	188.12	Vegetated	0.0875
b29-2-7	2042017.928	1130543.447	174.761	174.85	Vegetated	0.0902
b29-5-8	2123150.636	992427.972	164.002	164.09	Vegetated	0.0926
h29-1-2	2031411.983	1199079.870	188.655	188.75	Vegetated	0.0977
h29-4-3	2120631.832	1080853.027	177.085	177.18	Vegetated	0.0977
b29-2-1	2046571.330	1133545.019	193.576	193.68	Vegetated	0.099

b29-3-5	2070762.253	1055184.534	148.870	148.97	Vegetated	0.1007
b29-7-6	2093679.490	996452.832	190.304	190.41	Vegetated	0.1025
hEA50	2053268.960	1124765.414	167.585	167.69	Vegetated	0.1032
hea6	2097514.558	996016.481	192.887	192.99	Vegetated	0.1042
b29-9-10	2115203.140	1033772.724	160.608	160.71	Vegetated	0.1055
b29-9-9	2114771.138	1036848.890	190.386	190.5	Vegetated	0.1104
h19345j	2076395.866	1050964.721	155.435	155.55	Vegetated	0.115
b29-1-3	2032058.445	1174590.495	190.784	190.92	Vegetated	0.1314
h29-3-3	2070561.476	1055394.956	150.428	150.57	Vegetated	0.145
b29-6-8	2154811.334	1036930.722	173.198	173.35	Vegetated	0.147