Dewberry Engineers Inc.
1000 North Ashley Drive, Suite 801
Tampa, FL 33602
813.225.1325
813.225.1385 fax
www.dewberry.com

# FL Peninsular 2018 Lidar Project- Putnam County

## Report Produced for U.S. Geological Survey

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

SUBMITTED TO:
**U.S. Geological Survey**
tnm_help@usgs.gov

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# 1. EXECUTIVE SUMMARY

The primary purpose of this project was to develop a consistent and accurate surface elevation dataset derived from high-accuracy light detection and ranging (lidar) technology for the FL Peninsular 2018 Lidar Project-Putnam County project area.

Lidar data were processed and classified according to project specifications. Detailed breaklines and bare-earth Digital Elevation Models were produced for the project area. Project components were formatted based on a tile grid with each tile covering an area 5,000 ft by 5,000 ft. A total of 39,185 tiles will be produced for the project, providing approximately 34,912 sq. miles of coverage. A total of 892 tiles were produced for Putnam County, providing approximately 799.91 sq. miles of coverage.

## 1.1 Project Team

Dewberry served as the prime contractor for the project. Dewberry and Quantum Spatial was responsible for LAS classification, all lidar products, breakline production, and digital elevation model (DEM) production. Dewberry was responsible for project management and quality assurance.

Dewberry completed the ground survey for the project and delivered surveyed checkpoints. The task was to acquire surveyed checkpoints for the project to use in independent testing of the vertical accuracy of the lidar-derived surface model and to acquire surveyed ground control points for use in calibration activities. The GPS base station coordinates used during lidar data acquisition were verified.

Airborne Imaging and Quantum Spatial completed lidar data acquisition and data calibration for the project area.

## 1.2 Project Area

The block area is shown in figure 1. Putnam County contains 892 5,000 ft by 5,000 ft tiles. The project tile grid contains 39,185 5,000 ft by 5,000 ft tiles.

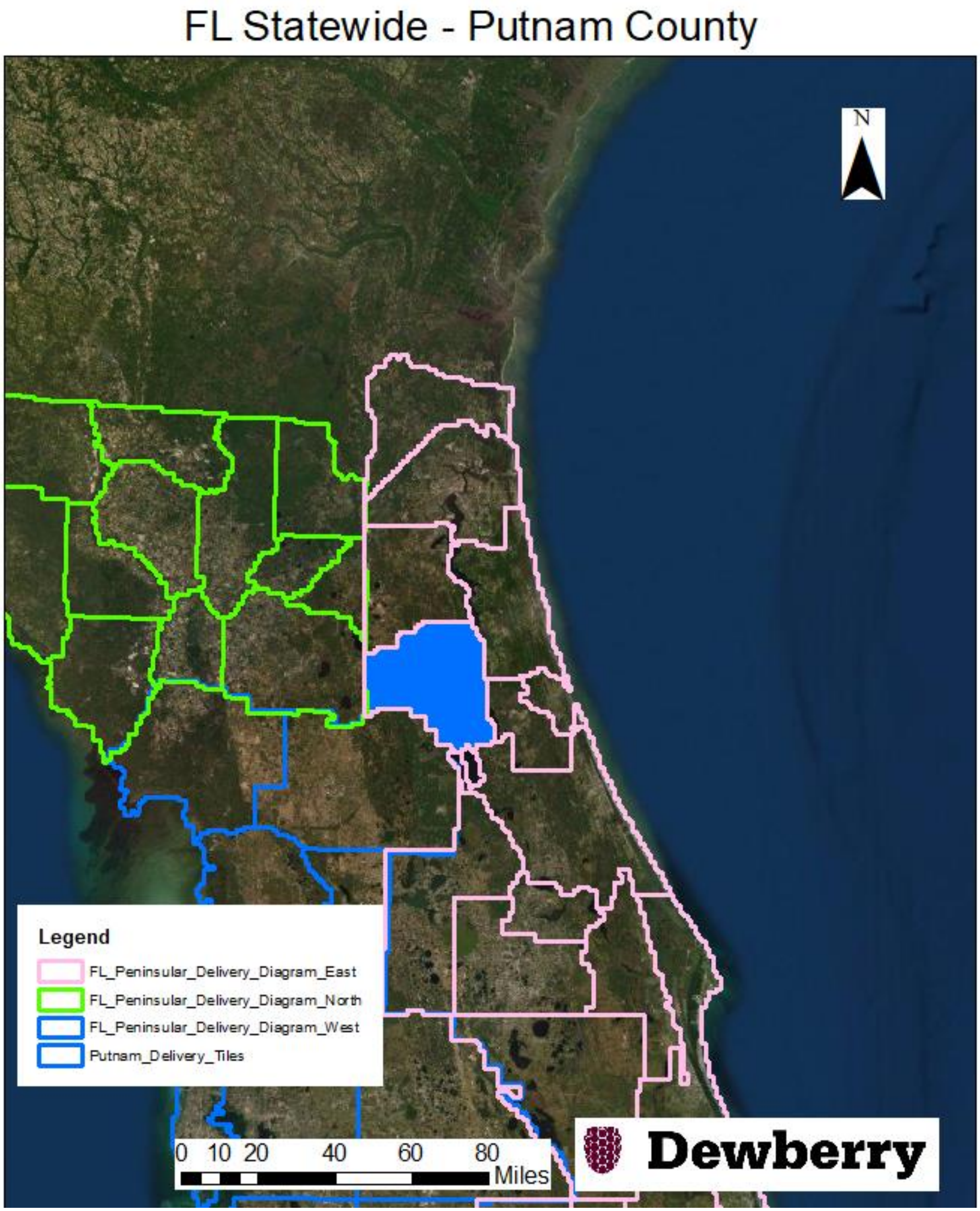


**Figure 1 - Project map and tile grid.**

## 1.3 Coordinate Reference System

Data produced for the project are delivered in the following spatial reference system:

| | |
|---|---|
| **Horizontal Datum:** | North American Datum of 1983 with the 2011 Adjustment (NAD 83 (2011)) |
| **Vertical Datum:** | North American Vertical Datum of 1988 (NAVD88) |
| **Geoid Model:** | Geoid12B |
| **Coordinate System:** | FL State Plane Zone East |
| **Horizontal Units:** | U.S. Survey Feet |
| **Vertical Units:** | U.S. Survey Feet |

## 1.4 Project Deliverables

The deliverables for the block are as follows:

1. Project Extents (Esri SHP)
2. Calibration Points (coordinates, Esri shapefile)
3. Classified Point Cloud (tiled LAS)
4. Independent Survey Checkpoint Data (report, photos, coordinates, Esri shapefiles)
5. Intensity Images (tiled, 8-bit gray scale, GeoTIFF format)
6. Swath Separation Images (tiled raster, GeoTIFF format)
7. Breakline Data (file GDB)
8. Bare Earth Surface (tiled raster DEM, GeoTIFF format)
9. Interswath Raster
10. DZ Orthos
11. Interswath Polygons
12. Intraswath Polygons
13. Metadata (XML)
14. Block Report

## 1.5 Dewberry Production Workflow Diagram

The diagram below outlines Dewberry's standard lidar production workflow.

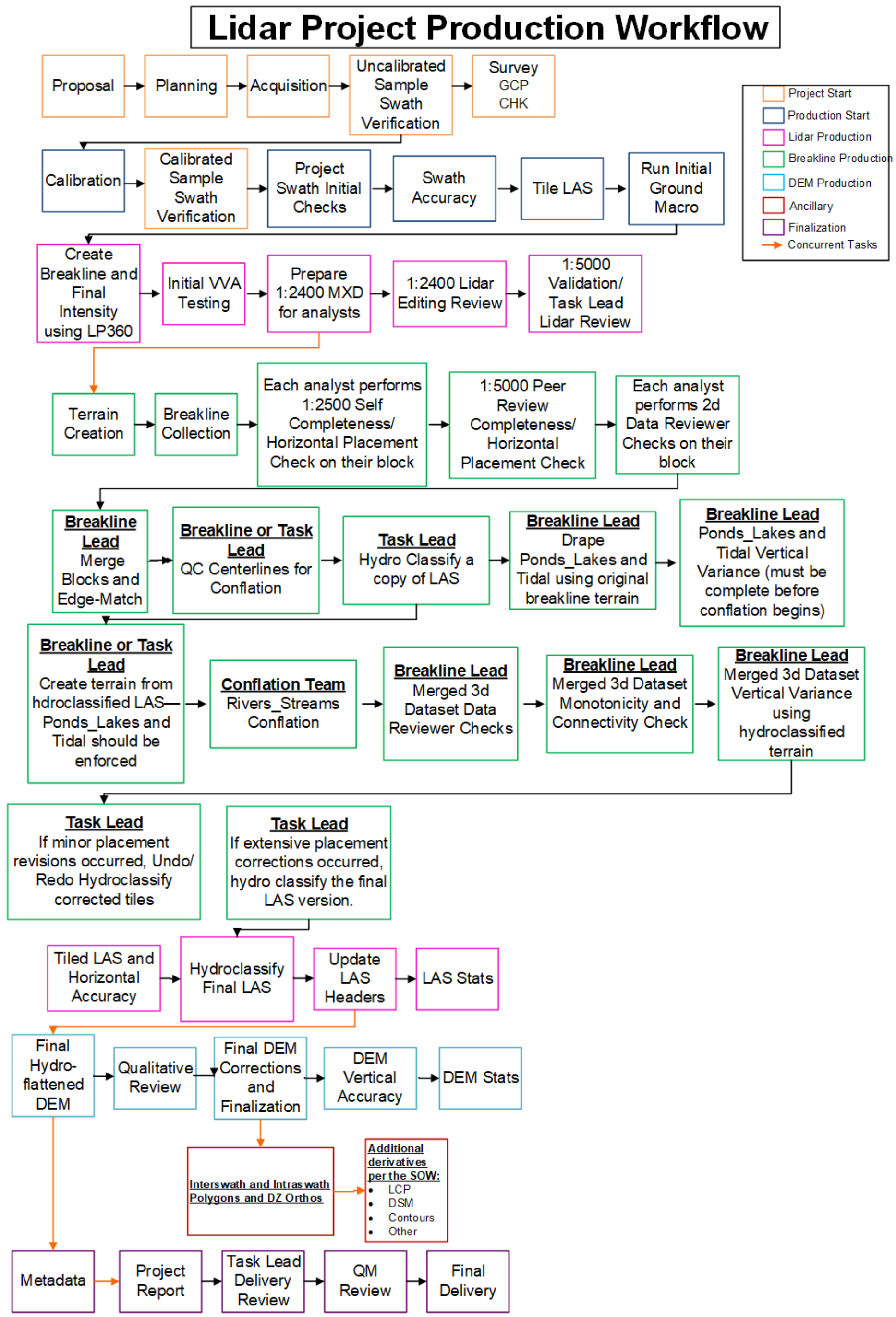


Figure 2- Dewberry's Lidar Production Workflow Diagram

# 2. LIDAR ACQUISITION REPORT- AIRBORNE IMAGING

Dewberry elected to subcontract the lidar acquisition and calibration activities to Airborne Imaging and Quantum Spatial. Airborne Imaging and Quantum Spatial were responsible for providing lidar acquisition, calibration, and delivery of lidar data files.

The lidar aerial acquisition for Putnam County was conducted between January 2, 2019 to April 25, 2019.

## 2.1 Lidar Acquisition Details

Airborne Imaging lidar sensors are calibrated at a designated site located at Red Deer, Alberta, Canada; St. Hubert, Quebec, Canada; and Provo, Utah, USA, and are periodically checked and adjusted to minimize corrections at project sites.

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, Airborne Imaging followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

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

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

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

## 2.2 Lidar System Parameters

Airborne Imaging operated a Piper PA-31 Navajo (Tail # C-GMEC) outfitted with a Riegl VQ-15601i lidar system during data collection. Table 1 details the lidar system parameters used during acquisition for this project.

**Table 1. Airborne Imaging lidar system parameters.**

| Parameter | Value |
|---|---|
| System | Riegl VQ-1560i |
| Altitude (m above ground level) | 1300 |
| Nominal flight speed (kts) | 160 |
| Scanner pulse rate (kHz) | 2000 |
| Scan frequency (Hz) | 375 |
| Pulse duration of the scanner (ns) | 3 |

| | |
|---|---|
| Pulse width of the scanner (m) | 0.9 |
| Central wavelength of the sensor laser (nm) | 1064 |
| Multiple pulses in the air | Yes |
| Beam divergence (mrad) | 0.25 |
| Swath width (m) | 1500 |
| Nominal swath width on the ground (m) | 1456 |
| Swath overlap (%) | 20 |
| Total sensor scan angle (degrees) | 60 |
| Computed down track spacing per beam (m) | 0.43 |
| Computed cross track Spacing per beam (m) | 0.38 |
| Nominal pulse spacing (NPS) (single swath) (m) | 0.31 |
| Nominal Pulse Density (NPD) (single swath) (points per sq m) | 10.7 |
| Aggregate NPS (m) (if NPS was designed to be met through single coverage, ANPS and NPS will be equal) | 0.31 |
| Aggregate NPD (m) (if NPD was designed to be met through single coverage, ANPD and NPD will be equal) | 10.7 |
| Maximum Number of Returns per Pulse | 7 |

## 2.3 Acquisition Status Report and Flight Lines

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 course, position, pitch, roll, and yaw of the aircraft. The sensor operator monitored the lidar sensor, the position dilution of precision (PDOP), and performed the first quality control review during acquisition. The flight crew 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 3 shows the combined flight line trajectories.

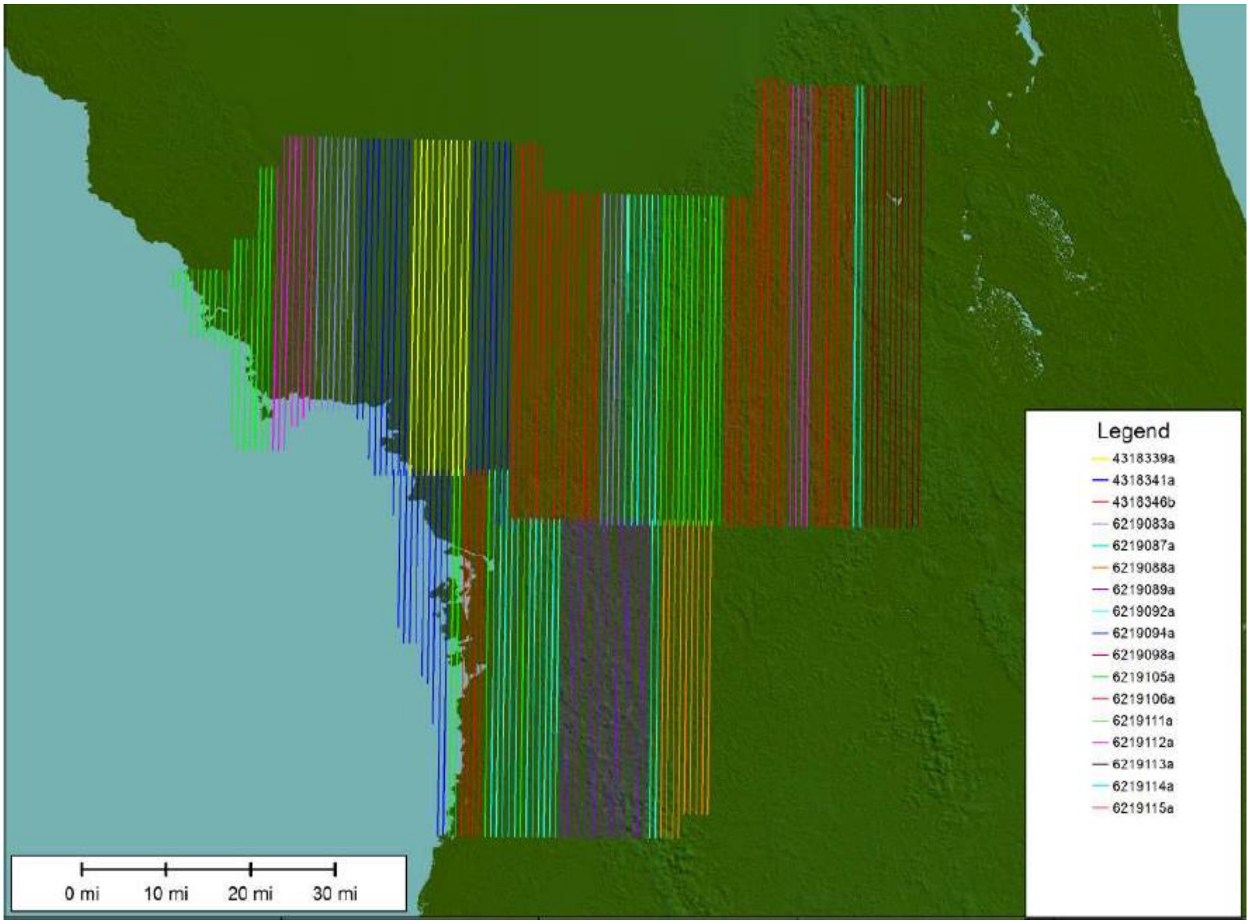


**Figure 3 - Trajectories of flight lines flown by Airborne Imaging.**

## 2.4 Acquisition Static Control

Fifteen Florida Department of Transportation (FDOT) FPRN active control points were used to control the lidar acquisition for the FL Peninsular lidar project area. The coordinates of all base stations used are provided in Table 2. All control and calibration points are also provided in shapefile format as part of is delivery.

**Table 2. Base stations used to control lidar acquisition.**

| Name | NAD83(2011) FL State Plane West, ft | | NAD83(2011), ft | NAVD88 Geoid12B, ft |
|---|---|---|---|---|
| | Easting (X) | Northing (Y) | Ellipsoid Height | Orthometric Height |
| BKVL | 510418.02 | 1505238.06 | -16.49 | 70.12 |
| DUNN | 537666.49 | 1719074.72 | -20.81 | 69.87 |
| FLBR | 450759.31 | 1856432.11 | -14.03 | 76.77 |
| FLCK | 327059.73 | 1746402.47 | -56.81 | 33.06 |
| FLDC | 595768.58 | 1465759.38 | 41.62 | 128.55 |
| FLEM | 422824.51 | 1438944.74 | -53.27 | 30.61 |
| FLHS | 471328.88 | 1624471.48 | -63.88 | 25.03 |

| Name | NAD83(2011) FL State Plane West, ft | | NAD83(2011), ft | NAVD88 Geoid12B, ft |
|---|---|---|---|---|
| | Easting (X) | Northing (Y) | Ellipsoid Height | Orthometric Height |
| FLWD | 597601.29 | 1632096.54 | -27.85 | 61.68 |
| GNVL | 568252.49 | 1946043.11 | 78.53 | 170.06 |
| INGS | 459341.67 | 1705768.25 | -46.4 | 43.51 |
| OCLA | 622901.54 | 1762408.74 | 58.14 | 149.61 |
| XCTY | 304094.98 | 1927424.32 | -45.33 | 45.71 |
| FLEU | 757116.23 | 1640545.49 | 35.42 | 125.9 |
| PLTK | 755340.83 | 1937646.25 | -58.92 | 34.13 |
| FLBF | 368132.76 | 2047198.56 | -43.54 | 47.97 |

## 2.5 Airborne Kinematic Control

Airborne GNSS data was processed using the Applanix POSPac MMS software suite and Novatel’s GrafNav software. Flights were flown with a minimum of six satellites in view (13° above the horizon) and with a PDOP of better than four. Distances from at least one base station to aircraft were kept to a maximum of 40 km (25 miles). For all flights, the GNSS data can be classified as excellent, with GNSS residuals of 3 cm average or better but no larger than 10 cm being recorded.

GPS processing reports for each mission are included in the Appendix A attachment.

## 2.6 Generation and Calibration of Raw Lidar Data

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

Subsequently the mission points were output using 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 was verified within Microstation/TerraScan for calibration errors. If a calibration error greater than specification was observed, the appropriate roll, pitch and scanner scale corrections were calculated. The point data were then regenerated with the new calibration values and validated internally again to ensure that the errors were fully addressed.

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

Figure 4 - Lidar swath output showing complete coverage.

### 2.6.1 Boresight and Relative accuracy

The initial points for each mission calibration were inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the lidar unit or GPS. Roll, pitch and scanner scale were optimized during the calibration process until relative accuracy requirements were met (Figure 5).

Relative accuracy and internal quality were checked using at least 3 regularly spaced QC blocks in which points from all lines were loaded and inspected. Vertical differences between ground surfaces of each line were displayed. Color scale was adjusted to flag errors that were not within project specifications (Figure 6). Cross sections were visually inspected across each block to validate point to point, flight line to flight line, and mission to mission agreement.

The following relative accuracy specifications were used for this project:

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

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

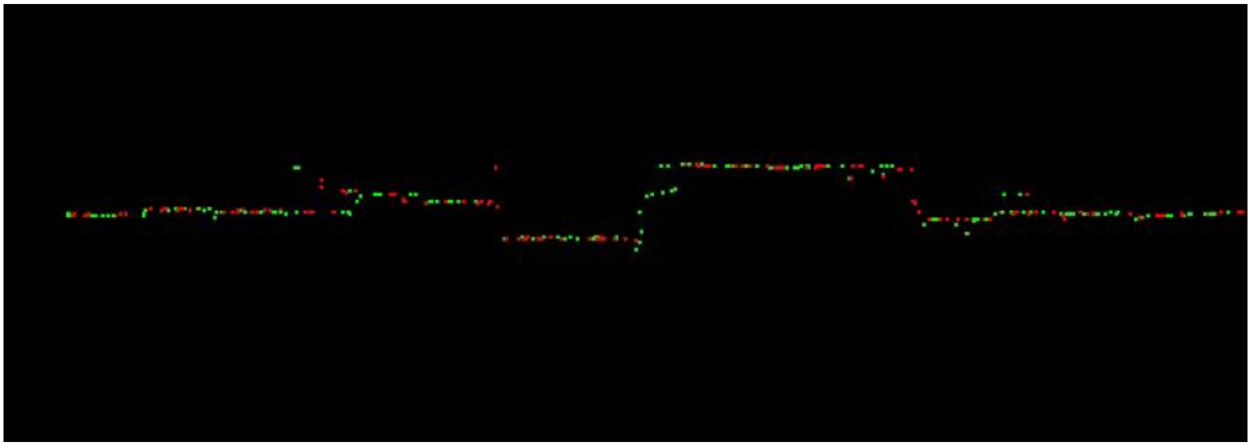

**Figure 5 - Profile views showing results of roll and pitch adjustments.**

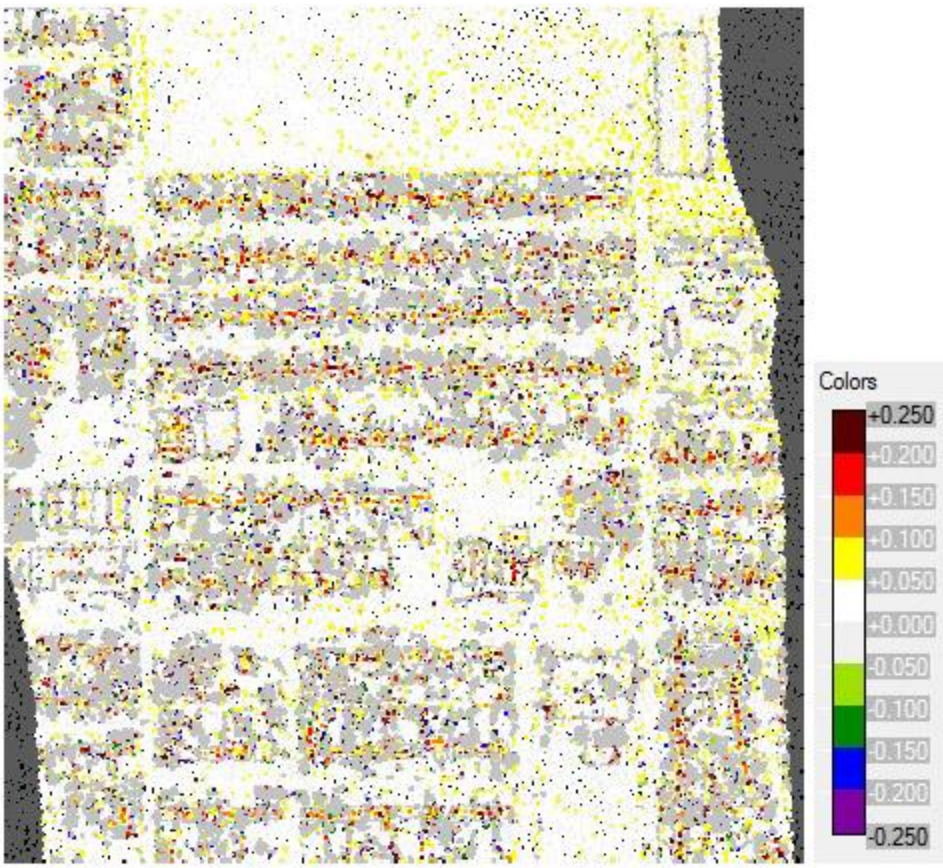


**Figure 6 - QC block colored by vertical difference between swaths to check accuracy at swath edges.**

## 2.7 Final Calibration Verification

A preliminary RMSEz error check was performed by Airborne Imaging at this stage of the project life cycle in the raw Lidar dataset against GNSS static and kinematic data and compared to RMSEz project specifications. The Lidar data was examined in non-vegetated, flat areas away from breaks. Lidar ground points for each flight line generated by an automatic classification routine were used. Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met Non-Vegetated Vertical Accuracy (NVA) requirements (RMSEz ≤ 10 cm and Accuracy at the 95% confidence level ≤ 19.6 cm) when compared to kinematic GNSS checkpoints.

The following summary shows the results comparing the final calibrated Lidar data to NVA ground check points provided by Airborne Imaging.

**Table 3. Ground control points (GCPs) vertical accuracy results.**

| 100 % of Totals | # of Points | RMSEz (ft) NVA Spec=0.33 ft | NVA- Non-vegetated Vertical Accuracy ((RMSEz x 1.9600) Spec=0.64 ft | Mean (ft) | Std Dev (ft) | Min (ft) | Max (ft) |
|---|---|---|---|---|---|---|---|
| GCP | 62 | 0.03 | 0.06 | 0.04 | 0.04 | -0.07 | 0.15 |

# 3. LIDAR ACQUISITION REPORT- QUANTUM SPATIAL

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

The lidar aerial acquisition for Putnam County was conducted between January 2, 2019 to April 25, 2019.

## 3.1 Lidar Acquisition Details

Quantum Spatial planned 720 passes for passes for the project area as a series of parallel flight lines with cross flight lines 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, Quantum Spatial followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

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

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

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

## 3.2 Lidar System Parameters

Quantum Spatial operated three Cessna Grand Caravans (Tail # N704MD, N208NR, N604MD) and two Cessna T206 Turbo Stationair (Tail#N916WC, N917WC) outfitted with Leica ALS80 lidar systems during data collection. Table 4 details the lidar system parameters used during acquisition for this project.

**Table 4- Quantum Spatial lidar system parameters.**

| Parameter | Value |
|---|---|
| System | Leica ALS80 |
| Altitude (m above ground level) | 1400 |
| Nominal flight speed (kts) | 150 |
| Scanner pulse rate (kHz) | 586 |
| Scan frequency (Hz) | 52 |
| Pulse duration of the scanner (ns) | 2.5 |
| Pulse width of the scanner (m) | 0.31 |
| Central wavelength of the sensor laser (nm) | 1064 |
| Multiple pulses in the air | Yes |
| Beam divergence (mrad) | 0.22 |
| Swath width (m) | 1019 |
| Nominal swath width on the ground (m) | 1018 |
| Swath overlap (%) | 60 |
| Total sensor scan angle (degrees) | 40 |
| Computed down track spacing per beam (m) | 0.74 |
| Computed cross track Spacing per beam (m) | 0.53 |
| Nominal pulse spacing (NPS) (single swath) (m) | 0.316 |
| Nominal Pulse Density (NPD) (single swath) (points per sq m) | 10 |
| Aggregate NPS (m) (if NPS was designed to be met through single coverage, ANPS and NPS will be equal) | 0.309 |
| Aggregate NPD (m) (if NPD was designed to be met through single coverage, ANPD and NPD will be equal) | 10.47 |
| Maximum Number of Returns per Pulse | 7 |

## 3.3 Acquisition Status Report and Flight Lines

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 course, position, pitch, roll, and yaw of the aircraft. The sensor operator monitored the lidar sensor, the position dilution of precision (PDOP), and performed the first quality control review during acquisition. The flight crew 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.

## 3.4 Acquisition Static Control

Quantum Spatial utilized FPRN and USGS CORS for the FL Peninsular lidar project area. The coordinates of all base stations used are provided in Table 5. All control and calibration points are also provided in shapefile format as part of is delivery.

**Table 5- Base stations used to control lidar acquisition.**

| Name | NAD83(2011) FL State Plane East, ft | | NAD83(2011), ft | NAVD88 Geoid12B, ft |
|---|---|---|---|---|
| | Easting (X) | Northing (Y) | Ellipsoid Height | Orthometric Height |
| PLTK | 437738.25 | 1938161.29 | -17.94 | 10.44 |
| DLND | 572080.63 | 1716876.59 | 0.28 | 28.38 |

| Name | NAD83(2011) FL State Plane North, ft | | NAD83(2011), ft | NAVD88 Geoid12B, ft |
|---|---|---|---|---|
| | Easting (X) | Northing (Y) | Ellipsoid Height | Orthometric Height |
| GNVL | 2674388.15 | 256559.51 | 23.95 | 51.82 |

## 3.5 Airborne Kinematic Control

Airborne GNSS data was processed using the Applanix POSPac MMS software suite and Novatel's GrafNav software. Flights were flown with a minimum of six satellites in view (13° above the horizon) and with a PDOP of better than four. Distances from at least one base station to aircraft were kept to a maximum of 40 km (25 miles). For all flights, the GNSS data can be classified as excellent, with GNSS residuals of 3 cm average or better but no larger than 10 cm being recorded.

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

## 3.6 Generation and Calibration of Raw Lidar Data

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

Subsequently the mission points were output using Leica software initially with default values from Leica or the last mission calibrated for the system. The initial point generation for each mission calibration was verified within Microstation/TerraScan for calibration errors. If a calibration error greater than specification was observed, the appropriate roll, pitch and scanner scale corrections were calculated. The point data were then regenerated with the new calibration values and validated internally again to ensure that the errors were fully addressed.

Data collected by the lidar unit was reviewed for completeness, acceptable density, and to make sure all data were captured without errors or corrupted values. All GPS, aircraft trajectory, mission information, and ground control files were reviewed and logged. A supplementary coverage check was carried out (Figure 7) to ensure that there were no unreported gaps in data coverage.

**Figure 7- Lidar swath output showing complete coverage.**

### 3.6.1 Boresight and Relative accuracy

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

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

The following relative accuracy specifications were used for this project:

- ≤ 6 cm maximum difference within individual swaths (intra-swath); and

- ≤ 8 cm RMSDz between adjacent and overlapping swaths (inter-swath).

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

## 3.7 Final Calibration Verification

A preliminary RMSEz error check was performed by Quantum Spatial at this stage of the project life cycle in the raw Lidar dataset against GNSS static and kinematic data and compared to RMSEz project specifications. The Lidar data was examined in non-vegetated, flat areas away from breaks. Lidar ground points for each flight line generated by an automatic classification routine were used. Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met Non-Vegetated Vertical Accuracy (NVA) requirements (RMSEz ≤ 10 cm and Accuracy at the 95% confidence level ≤ 19.6 cm) when compared to kinematic GNSS checkpoints.

# 4. LIDAR PRODUCTION & QUALITATIVE ASSESSMENT

## 4.1 Initial Processing

Following receipt of the calibrated swath data from the acquisition provider, Dewberry performed vertical accuracy validation of the swath data, inter-swath relative accuracy validation, intra-swath relative accuracy validation, verification of horizontal alignment between swaths, and confirmation of point density and spatial distribution. This initial assessment allowed Dewberry to determine whether the data was suitable for full-scale production.

### 4.1.1 Post Calibration Lidar Review

The table below identifies requirements verified by Dewberry prior to tiling the swath data, running initial ground macros, and starting manual classification.

**Table 6. Post calibration and initial processing data verification steps.**

| Requirement | Description of Deliverables | Additional Comments |
| --- | --- | --- |
| Non-vegetated vertical accuracy (NVA) of the swath data meet required specifications of 19.6 cm at the 95% confidence level based on RMSEz (10 cm) x 1.96 | The swath NVA was tested and passed specifications. | None |
| The NPD/NPS (or Aggregate NPD/Aggregate NPS) meets required specification of 8 ppsm or 0.35 m NPS. The NPD (ANPD) is calculated from first return points only. | The average calculated (A)NPD of this project is 8 ppsm. Density raster visualization also passed specifications. | None |
| Spatial Distribution requires 90% of the project grid, calculated with cell sizes of 2*NPS, to contain at least one lidar point. This is calculated from first return points only. | 98% of cells (2*NPS cell size) had at least 1 lidar point within the cell. | None |
| Within swath (Intra-swath or hard surface repeatability) relative accuracy must meet ≤ 6 cm maximum difference | Within swath relative accuracy passed specification. | None |

| Requirement | Description of Deliverables | Additional Comments |
|---|---|---|
| Between swath (Inter-swath or swath overlap) relative accuracy must meet 8 cm RMSDz/16 cm maximum difference. These thresholds are tested in open, flat terrain. | Between swath relative accuracy passed specification, calculated from single return lidar points. | None |
| Horizontal Calibration-There should not be horizontal offsets (or vertical offsets) between overlapping swaths that would negatively impact the accuracy of the data or the overall usability of the data. Assessments made on rooftops or other hard planar surfaces where available. | Horizontal calibration met project requirements. | None |
| Ground Penetration-The missions were planned appropriately to meet project density requirements and achieve as much ground penetration beneath vegetation as possible | Ground penetration beneath vegetation was acceptable. | None |
| Sensor Anomalies-The sensor should perform as expected without anomalies that negatively impact the usability of the data, including issues such as excessive sensor noise and intensity gain or range-walk issues | No sensor anomalies were present. | None |
| Edge of Flight line bits-These fields must show a minimum value of 0 and maximum value of 1 for each swath acquired, regardless of which type of sensor is used | Edge of Flight line bits were populated correctly | None |
| Scan Direction bits-These fields must show a minimum value of 0 and maximum value of 1 for each swath acquired with sensors using oscillating (back-and-forth) mirror scan mechanism. These fields should show a minimum and maximum of 0 for each swath acquired with Riegl sensors as these sensors use rotating mirrors. | Scan Direction bits were populated correctly | None |
| Swaths are in LAS v1.4 formatting | Swaths were in LAS v1.4 as required by the project. | None |
| All swaths must have File Source IDs assigned (these should equal the Point Source ID or the flight line number) | File Source IDs were correctly assigned | None |

| Requirement | Description of Deliverables | Additional Comments |
|---|---|---|
| GPS timestamps must be in Adjusted GPS time format and Global Encoding field must also indicate Adjusted GPS timestamps | GPS timestamps were Adjusted GPS time and Global Encoding field were correctly set to 17 | None |
| Intensity values must be 16-bit, with values ranging between 0-65,535 | Intensity values were 16-bit | None |
| Point Source IDs must be populated, and swath Point Source IDs should match the File Source IDs | Point Source IDs were assigned and match the File Source IDs | None |

## 4.2 Data Classification and Editing

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data were confirmed, Dewberry utilized proprietary and TerraScan software for processing. The acquired 3D laser point clouds were tiled according to the project tile grid using proprietary software. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine classified any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. Points along flight line edges that were geometrically unusable were flagged as withheld and classified to a separate class so that they would be excluded from the initial ground algorithm. After points that could negatively affect the ground were removed from class 1, the ground layer was extracted from this remaining point cloud using an iterative surface model.

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

After the initial automated ground routine, each tile was imported into TerraScan and a surface model was created to examine the ground classification. Dewberry analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing. Dewberry analysts employed 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points were removed from the ground classification. Bridge decks were classified to class 17 and bridge saddle breaklines were used where necessary. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilized breaklines to automatically classify hydro features. The water classification routine selected ground points within the breakline polygons and automatically classified them as class 9, water. During this water classification routine, points that were within 1 NPS distance or less of the hydrographic feature boundaries were moved to class 20, ignored ground, to avoid hydro-flattening artifacts along the edges of hydro features.

The withheld bit was set on the withheld points previously identified in TerraScan before the ground classification routine was performed.

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

### 4.2.1 Qualitative Review

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

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

**Table 7. Post calibration and initial processing data verification steps.**

| Category | Editing Guideline | Additional Comments |
|---|---|---|
| No Data Voids | The SOW for the project defines unacceptable data voids as voids greater than 4 x $ANPS^2$, or 1.96 $m^2$, that are not related to water bodies or other areas of low near-infrared reflectivity and are not appropriately filled by data from an adjacent swath. The LAS files were used to produce density grids based on Class 2 (ground) points for review. | No unacceptable voids were identified in this dataset |
| Artifacts | Artifacts in the point cloud are typically caused by misclassification of points in vegetation or man-made structures as ground. Low-lying vegetation and buildings are difficult for automated grounding algorithms to differentiate and often must be manually removed from the ground class. Dewberry identified these features during lidar editing and reclassified them to Class 1 (unassigned). Artifacts up to 0.3 m above the true ground surface may have been left as Class 2 because they do not negatively impact the usability of the dataset. | None |

| Category | Editing Guideline | Additional Comments |
|---|---|---|
| Bridge Saddles | The DEM surface models are created from TINs or terrains. TIN and terrain models create continuous surfaces from the input points, interpolating surfaces beneath bridges where no lidar data was acquired. The surface model in these areas tend to be less detailed. Bridge saddles may be created where the surface interpolates between high and low ground points. Dewberry identifies problems arising from bridge removal and resolves them by reclassifying misclassified ground points to class 1 and/or adding bridge saddle breaklines where applicable due to interpolation. | None |
| Culverts and Bridges | It is Dewberry's standard operating procedure to leave culverts in the bare earth surface model and remove bridges from the model. In instances where it is difficult to determine whether the feature was a culvert or bridge, Dewberry errs on the side of culverts, especially if the feature is on a secondary or tertiary road. | None |
| In-Ground Structures | In-ground structures typically occur on military bases and at facilities designed for munitions testing and storage. When present, Dewberry identifies these structures in the project and includes them in the ground classification. | No in-ground structures present in this dataset |
| Dirt Mounds | Irregularities in the natural ground, including dirt piles and boulders, are common and may be misinterpreted as artifacts that should be removed. To verify their inclusion in the ground class, Dewberry checked the features for any points above or below the surface that might indicate vegetation or lidar penetration and reviews ancillary layers in these locations as well. Whenever determined to be natural or ground features, Dewberry edits the features to class 2 (ground) | No dirt mounds or other irregularities in the natural ground were present in this dataset |

| Category | Editing Guideline | Additional Comments |
|---|---|---|
| Irrigated Agricultural Areas | Per project specifications, Dewberry collected all areas of standing water greater than or equal to 2 acres, including areas of standing water within agricultural areas and not within wetland or defined waterbody, hydrographic, or tidal boundaries. Areas of standing water that did not meet the 2 acre size criteria were not collected. | Standing water within agricultural areas not present in the data |
| Wetland/Marsh Areas | Vegetated areas within wetlands/marsh areas are not considered water bodies and are not hydroflattened in the final DEMs. However, it is sometimes difficult to determine true ground in low wet areas due to low reflectivity. In these areas, the lowest points available are used to represent ground, resulting in a sparse and variable ground surface. Open water within wetland/marsh areas greater than or equal to 2 acres is collected as a waterbody. | No marshes present in the data |
| Flight Line Ridges | Flight line ridges occur when there is a difference in elevation between adjacent flight lines or swaths. If ridges are visible in the final DEMs, Dewberry ensures that any ridges remaining after editing and QA/QC are within project relative accuracy specifications. | No flight line ridges are present in the data |
| Temporal Changes | If temporal differences are present in the dataset, the offsets are identified with a shapefile. | If temporal offsets are present in the data, the areas are outlined in the temporal.shp |
| Low NIR Reflectivity | Some materials, such as asphalt, tars, and other petroleum-based products, have low NIR reflectivity. Large-scale applications of these products, including roadways and roofing, may have diminished to absent lidar returns. USGS LBS allow for this characteristic of lidar but if low NIR reflectivity is causing voids in the final bare earth surface, these locations are identified with a shapefile. | No Low NIR Reflectivity is present in the data |
| Laser Shadowing | Shadows in the LAS can be caused when solid features like trees or | No Laser Shadowing is present in the data |

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

### 4.2.2 Formatting Review

After the final QA/QC was performed and all corrections were applied to the dataset, all lidar files were updated to the final format requirements and the final formatting, header information, point data records, and variable length records were verified using proprietary tools. The table below lists the primary lidar header fields that are updated and verified.

Table 8. Classified lidar formatting parameters.

| Parameter | Project Specification | Pass/Fail |
|---|---|---|
| LAS Version | 1.4 | Pass |
| Point Data Record Format | 6 | Pass |
| Horizontal Coordinate Reference System | NAD83 (2011) FL State Plane Zone East in WKT format | Pass |
| Vertical Coordinate Reference System | NAVD88 (Geoid 12B), feet in WKT format | Pass |
| Global Encoder Bit | 17 for adjusted GPS time | Pass |
| Time Stamp | Adjusted GPS time (unique timestamps) | Pass |
| System ID | Sensor used to acquire data | Pass |

| Parameter | Project Specification | Pass/Fail |
|---|---|---|
| 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 recorded for each pulse | Pass |
| Classification | Class 1: Unclassified<br>Class 2: Ground<br>Class 6: Buildings<br>Class 7: Low Noise<br>Class 9: Water<br>Class 17: Bridge Decks<br>Class 18: High Noise<br>Class 20: Ignored Ground<br>Class 22: Temporal | Pass |
| Withheld Points | Withheld bits set | Pass |
| Scan Angle | Recorded for each pulse | Pass |
| XYZ Coordinates | Recorded for each pulse | Pass |

### 4.2.3 Synthetic Points

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

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

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

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

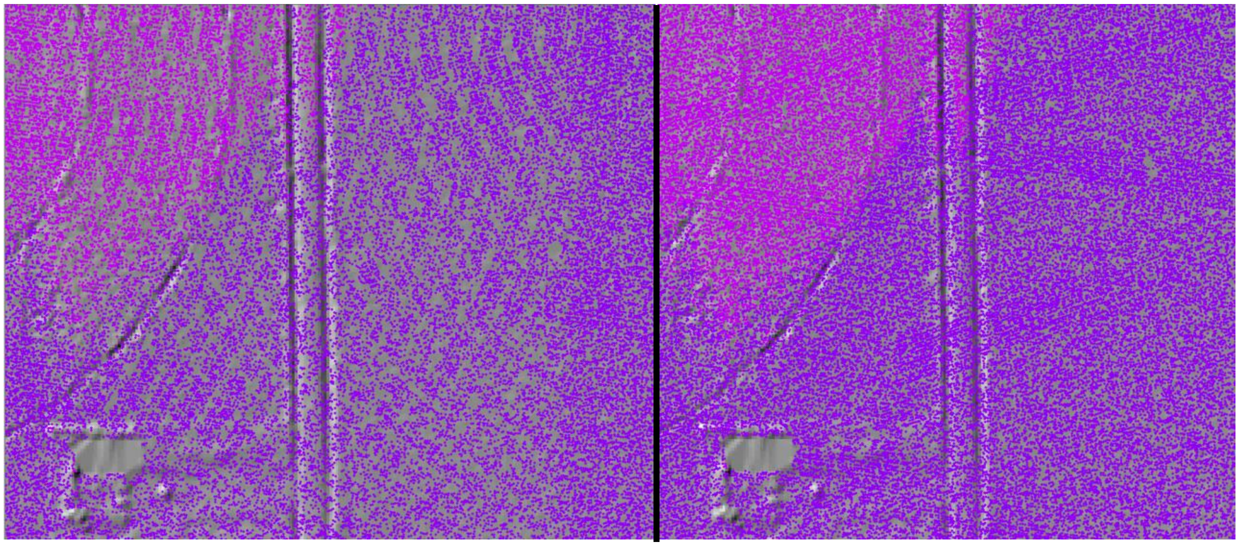

**Figure 8 – The left image shows ground classified without synthetic points. The right image shows ground classified with synthetic points. Both images are overlaid on a hillshade of the example area.**

# 5. BREAKLINE PRODUCTION & QUALITATIVE ASSESSMENT

## 5.1 Breakline Production Methodology

Breaklines were manually digitized within an Esri software environment, using full point cloud intensity imagery, bare earth terrains and DEMs, the lidar point cloud, and ancillary ortho imagery where appropriate.

When data characteristics are suitable, Dewberry may use eCognition software to generate initial, automated water polygons, which are then manually reviewed and refined where necessary.

Breakline features with static or semi-static elevations (ponds and lakes, bridge saddles, and soft feature breaklines) were converted to 3D breaklines within the Esri environment where breaklines were draped on terrains or the las point cloud. Subsequent processing was done on ponds/lakes to identify the minimum z-values within these features and re-applied that minimum elevation to all vertices of the breakline feature.

Linear hydrographic features show downhill flow and maintain monotonicity. These breaklines underwent conflation by using a combination of Esri and LP360 software. Centerlines were draped on terrains, enforced for monotonicity, and those elevations were then assigned to the bank lines for the final river/stream z-values.

Tidal breaklines may have been converted to 3D using either method, dependent on the variables within each dataset.

### 5.1.1 Breakline Collection Requirements

The table below outlines breakline collection requirements for this dataset.

**Table 9. Breakline collection requirements.**

| Parameter | Project Specification | Additional Comments |
|---|---|---|
| Ponds and Lakes | Breaklines are collected in all inland ponds and lakes ~2 acres or greater. These features are flat and level water bodies at a single elevation for each vertex along the bank. | None |
| Hydrographic Features | Breaklines are collected for all streams and rivers 8 ft nominal width or wider as dual line drains and single line drains for features <8 ft in nominal width but greater than 0.5 mi in length. The dual line drain features are flat and level bank to bank, gradient will follow the surrounding terrain and the water surface will be at or below the surrounding terrain. Streams/river channels will break at culvert locations however not at elevated bridge locations. | None |
| Coastal Feature | Breaklines are collected as polygon features depicting water bodies such as oceans, seas, gulfs, bays, inlets, salt marshes, very large lakes, etc. Includes any significant water body that is affected by tidal variations. Tidal variations over the course of collection, and between different collections, can result in discontinuities along shorelines. This is considered normal and should be retained. Variations in water surface elevation resulting from tidal variations during collection should not be removed or adjusted. Features should be captured as a dual line with one line on each bank. Each vertex placed shall maintain vertical integrity. Parallel points on opposite banks of the tidal waters must be captured at the same elevation to ensure flatness of the water feature. The entire water surface edge is at or below the immediate surrounding terrain. | None |

| | | |
|---|---|---|
| Islands | Donuts will exist where there are islands greater than 1 acre in size within a hydro feature. | None |
| Bridge Saddle Breaklines | Bridge Saddle Breaklines are collected where bridge abutments were interpolated after bridge removal causing saddle artifacts. | None |
| Soft Features | Soft Feature Breaklines are collected where additional enforcement of the modeled bare earth terrain was required, typically on hydrographic control structures or vertical waterfalls, due to large vertical elevation differences within a short linear distance on a hydrographic features. | None |
| Connectors | A CONNECTOR will be collected where a hydrographic feature is collected on either side of the road. The connector must snap to the adjoining hydrological features. | None |

## 5.2 Breakline Qualitative Assessment

Dewberry performed both manual and automated checks on the collected breaklines. Breaklines underwent peer reviews, breakline lead reviews (senior level analysts), and final reviews by an independent QA/QC team. The table below outlines high level steps verified for every breakline dataset.

**Table 10. Breakline verification steps.**

| Parameter | Requirement | Pass/Fail |
|---|---|---|
| Collection | Collect breaklines according to project specifications using lidar-derived data, including intensity imagery, bare earth ground models, density models, slope models, and terrains. | Pass |
| Placement | Place the breakline inside or seaward of the shoreline by 1-2 x NPS in areas of heavy vegetation or where the exact shoreline is hard to delineate. | Pass |
| Completeness | Perform a completeness check, breakline variance check, and all automated checks on each block before designating that block complete. | Pass |

| | | |
|---|---|---|
| Merged Dataset | Merge completed production blocks. Ensure correct horizontal and vertical snapping between all production blocks. Confirm correct horizontal placement of breaklines. | Pass |
| Merged Dataset Completeness Check | Check entire dataset for features that were not captured but that meet baseline specifications or other metrics for capture. Features should be collected consistently across tile boundaries. | Pass |
| Edge Match | Ensure breaklines are correctly edge-matched to adjoining datasets. Check completion type, attribute coding, and horizontal placement. | Pass |
| Vertical Consistency | Waterbodies shall maintain a constant elevation at all vertices<br><br>Vertices should not have excessive min or max z-values when compared to adjacent vertices<br><br>Intersecting features should maintain connectivity in X, Y, Z planes<br><br>Dual line streams shall have the same elevation at any given cross-section of the stream | Pass |
| Vertical Variance | Using a terrain created from lidar ground (class 2, 8, and 20 as applicable) and water points (class 9) to compare breakline Z values to interpolated lidar elevations to ensure there are no unacceptable discrepancies. | Pass |
| Monotonicity | Dual line streams generally maintain a consistent down-hill flow and collected in the direction of flow – some natural exceptions are allowed | Pass |
| Topology | Features must not overlap or have gaps<br><br>Features must not have unnecessary dangles or boundaries | Pass |
| Hydro-classification | The water classification routine selected ground points within the breakline polygons and automatically classified them as class 9, water. During this water classification routine, points that were within 1 NPS distance or less of the hydrographic feature boundaries were moved to class 20, ignored ground, to avoid hydroflattening artifacts along the edges of hydro features. | Pass |
| Hydro-flattening | Perform hydro-flattening and hydro-enforcement checks. Tidal waters should preserve as much ground as possible and can be non-monotonic. | Pass |

# 6. DEM PRODUCTION & QUALITATIVE ASSESSMENT

## 6.1 DEM Production Methodology

Dewberry utilized LP360 to generate DEM products and both ArcGIS and Global Mapper for QA/QC.

The final classified lidar points in all bare earth classes were loaded into LP360 along with the final 3D breaklines and the project tile grid. A raster was generated from the lidar data with breaklines enforced and clipped to the project tile grid. The DEM was reviewed for any issues requiring corrections, including remaining lidar misclassifications, erroneous breakline elevations, incorrect or incomplete hydro-flattening or hydro-enforcement, and processing artifacts. The formatting of the DEM tiles was verified before the tiles were loaded into Global Mapper to ensure that there was no missing or corrupt data and that the DEMs matched seamlessly across tile boundaries. A final qualitative review was then conducted by an independent review department within Dewberry.

## 6.2 DEM Qualitative Assessment

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

The table below outlines high level steps verified for every DEM dataset.

**Table 11. DEM verification steps.**

| Parameter | Requirement | Pass/Fail |
|---|---|---|
| Digital Elevation Model (DEM) of bare-earth w/ breaklines | DEM of bare-earth terrain surface (2.5') is created from lidar ground points and breaklines. DEMs are tiled without overlaps or gaps, show no edge artifact or mismatch, DEM deliverables are .tif format | Pass |
| DEM Compression | DEMs are not compressed | Pass |
| DEM NoData | Areas outside survey boundary are coded as NoData. Internal voids (e.g., open water areas) are coded as NoData | Pass |
| Hydro-flattening | Ensure DEMs were hydro-flattened or hydro-enforced as required by project specifications | Pass |
| Monotonicity | Verify monotonicity of all linear hydrographic features | Pass |
| Breakline Elevations | Ensure adherence of breaklines to bare-earth surface elevations, i.e., no floating or digging hydrographic feature | Pass |

| | | |
|---|---|---|
| Bridge Removal | Verify removal of bridges from bare-earth DEMs and no saddles present | Pass |
| DEM Artifacts | Correct any issues in the lidar classification that were visually expressed in the DEMs. Reprocess the DEMs following lidar corrections. | Pass |
| DEM Tiles | Split the DEMs into tiles according to the project tiling scheme | Pass |
| DEM Formatting | Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression is not applied to the tiled DEMs | Pass |
| DEM Extents | Load all tiled DEMs into Global Mapper and verify complete coverage within the (buffered) project boundary and verify that no tiles are corrupt | Pass |

# 7. DERIVATIVE LIDAR PRODUCTS

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

## 7.1 Interswath Raster

Interswath raster representing interswath alignment have been delivered. This raster was created from the last return of all points except points classified as noise or flagged as withheld. The images are in .TIFF format.

## 7.2 Swath Separation Images

Swath separation images representing interswath alignment have been delivered. These images were created from the last return of all points except points classified as noise or flagged as withheld. The images are in .TIFF format. The swath separation images are symbolized by the following ranges:

- 0-8 cm: **Green**
- 8-16 cm: **Yellow**
- >16 cm: **Red**

## 7.3 Interswath and Intraswath Polygons

### 7.3.1 Interswath Accuracy

The Interswath accuracy, or overlap consistency, measures the variation in the lidar data within the swath overlap. Interswath accuracy measures the quality of the calibration or boresight adjustment of the data in each lift. Per USGS specifications, overlap consistency was assessed at multiple locations within overlap in non-vegetated areas of only single returns. As with precision, the interswath consistency was reported by way of a polygon shapefile delineating the sample areas checked and attributed with the following and using the cells within each polygon as sample values:

- Minimum difference in the sample area (numeric)
- Maximum difference in the sample area (numeric)
- RMSDz (Root Mean Square Difference in the vertical/z direction) of the sample area (numeric). Intraswath Accuracy

The intraswath accuracy, or the precision of lidar, measures variations on a surface expected to be flat and without variation. Precision is evaluated to confirm that the lidar system is performing properly and without gross internal error that may not be otherwise apparent. To measure the precision of a lidar dataset, level or flat surfaces were assessed. Swath data were assessed using only first returns in non-vegetated areas.

Precision was reported by way of a polygon shapefile delineating the sample areas checked and attributed with the following and using the cells within each polygon as sample values:

- Minimum slope-corrected range (numeric)
- Maximum slope-corrected range (numeric)
- RMSDz of the slope-corrected range (numeric).

# 8. LIDAR QUALITATIVE ASSESSMENT

## 8.1 Intensity Range Correction

Intensity values are determined by the strength of the return pulse and is influenced by a number of factors, including the reflectivity of the target. Low reflectivity targets, like road surfaces, typically appear as darker pixels in the intensity imagery. Higher reflective surfaces like paint stripes or wet surfaces result in higher intensity return and will have brighter pixels in the intensity imagery.

Brightness at nadir in the intensity imagery and related depressions in the DEM are present in this dataset. The issues are located within areas of wetland marsh. Marshes are defined as areas of low flat ground that are typically always wet and soft. The wetlands may not appear visibly “wet” in the DEM, intensity imagery, or aerial imagery but water is present at or above the soil level causing saturated or waterlogged soil for a sufficient period of the year.

While water or wet surfaces typically absorbs most of the NIR wavelength, lidar pulses at or near nadir have a higher probability of returning some energy to the lidar sensor whereas lidar pulses at larger incident angles will be more likely to scatter and reflect in the opposite direction of the incident angle. This can result in water features, especially larger water features, showing a “striping” pattern of light and dark in the intensity imagery.

Due to ranging differences in bright and dark targets due to range walk, these ranging errors are corrected during initial processing of sensor data. However once the maximum receiver threshold is reached there is a phenomenon known as “time over threshold” that occurs. This occurs in extremely reflective environments, and the received values are brighter than the receivers dynamic (or static) range. The end result is that the target is known to be “very bright” but it is unknown the magnitude of brightness over the threshold, or the timing of the waveform curve over that threshold. Primarily due to the inability to fit a gaussian pulse correctly to the return it has an inherent ranging error that cannot be corrected any larger than the maximum correction for bright targets.

For these areas that are a result of time over threshold errors, there is not a known “brightness” of the target return that can be used for a correction. In the case of flat areas with consistent intensity (e.g. runway paint stripes), the error can be corrected based on the geometric offset between the planar data since intensity is assumed to be constant in the error area. Unfortunately in the Florida project examples, it is visible that there is an “arc” to the offset points. This is likely due to the fact that the intensity is still changing as the reflectance angle approaches its maximum. Due to this non-linear nature and the true return intensity value being unknown creates a situation that cannot be directly or simply corrected without additional sensor and return modeling.