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GEOSPATIAL SERVICES

LiDAR MAPPING REPORT

UTAH 3DEP – WEST DESERT NORTH BLOCK 2A AERIAL SURVEY

PRJ_ID: 224853
WU_ID: 300368
WU_Name: UT_WestEast_5_B22

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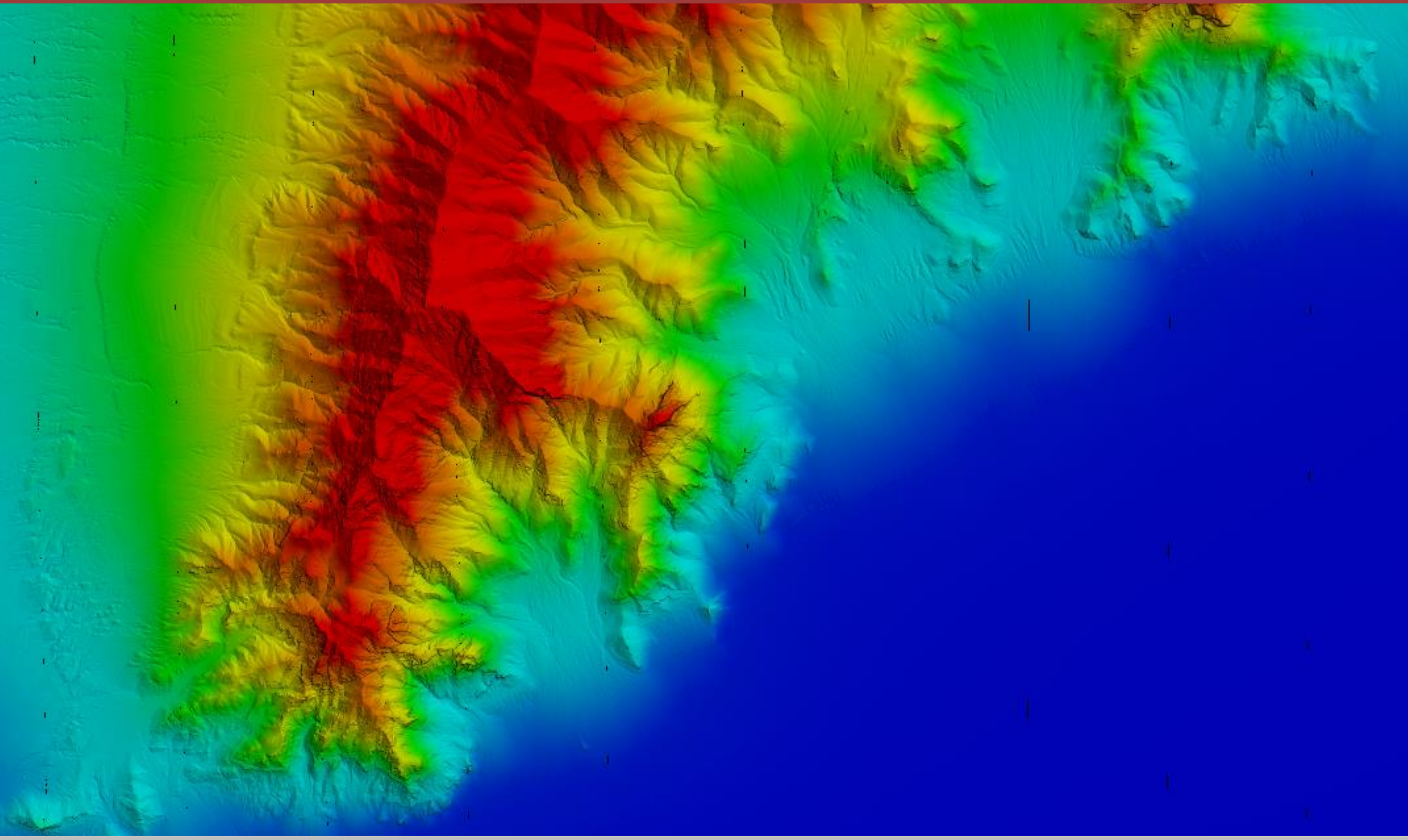

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ATTACHMENTS

Appendix A: GPS Processing Reports

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 Utah West East B22 – West Desert North WUID 300368 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 1,000 m by 1,000 m. A total of 33,429 tiles were produced for the project, providing approximately 12,471 sq. miles of coverage. A total of 4,738 tiles were produced for WUID 300368, providing approximately 1,729 sq. miles of coverage.

1.1 Project Team

Aero-Graphics served as the prime contractor for the project. In addition to project management, the Aero-Graphics Team was responsible for LAS classification, all LiDAR products, breakline production, digital elevation model (DEM) production, and quality assurance.

Aero-Graphics' professional land surveyor identified, targeted, and surveyed ground control points for use in data calibration as well as QC check points in vegetated and non-vegetated land cover classification as an independent test of accuracy for this project. A combination of precise GPS surveying methods, including static and RTK observations were used to establish the 3D position of ground control points and QC check points.

The Aero-Graphics Team completed LiDAR data acquisition and data calibration for the project area.

1.2 Project Area

The block area is shown in figure 1. WUID 300368 contains 4,738 1,000 m by 1,000 m tiles.

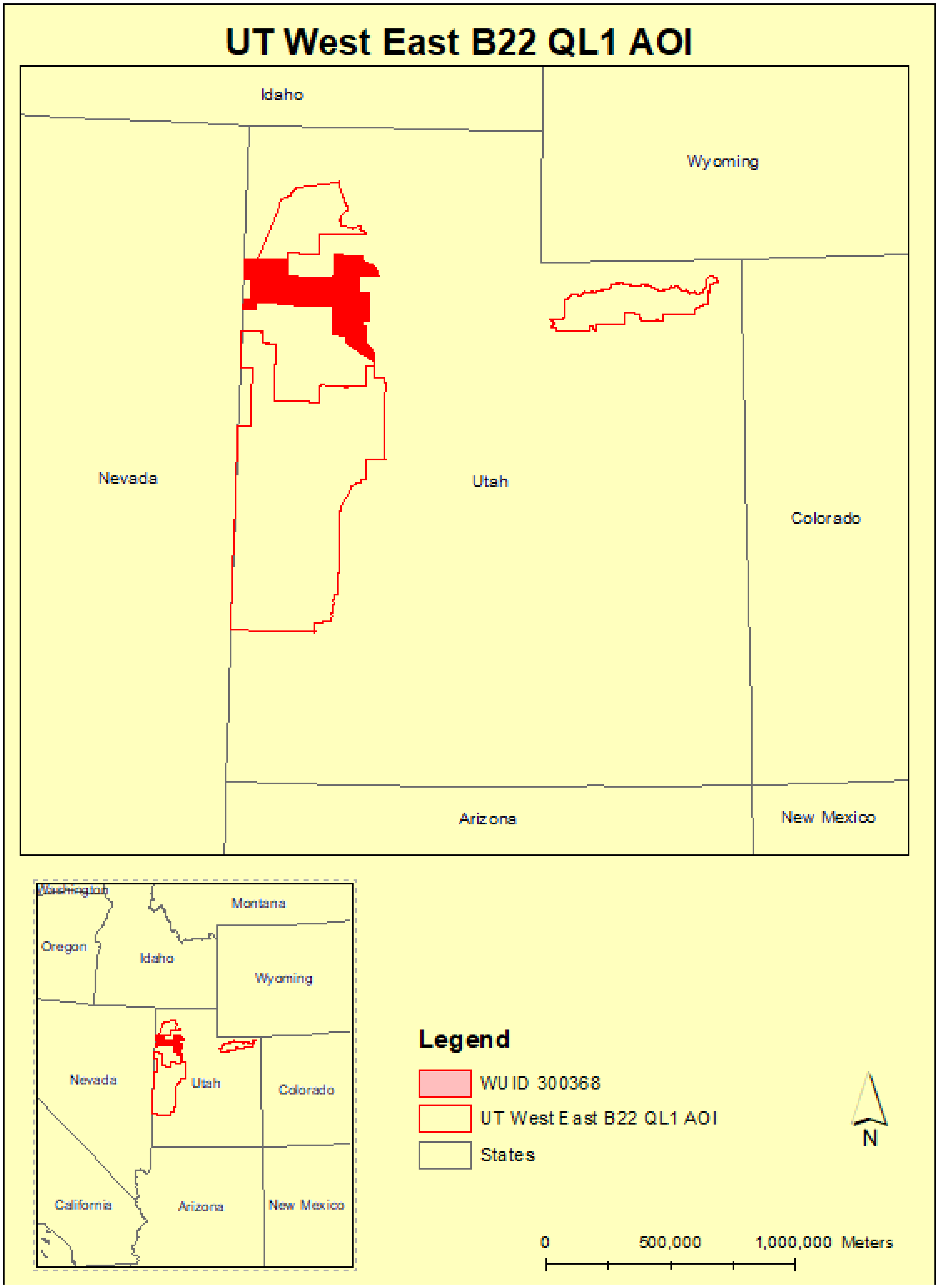


Figure 1. Project map and tile grid.

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: Geoid18
Coordinate System: UTM Zone 12
Horizontal Units: Meters
Vertical Units: Meters

1.4 Project Deliverables

The deliverables for the block are as follows:

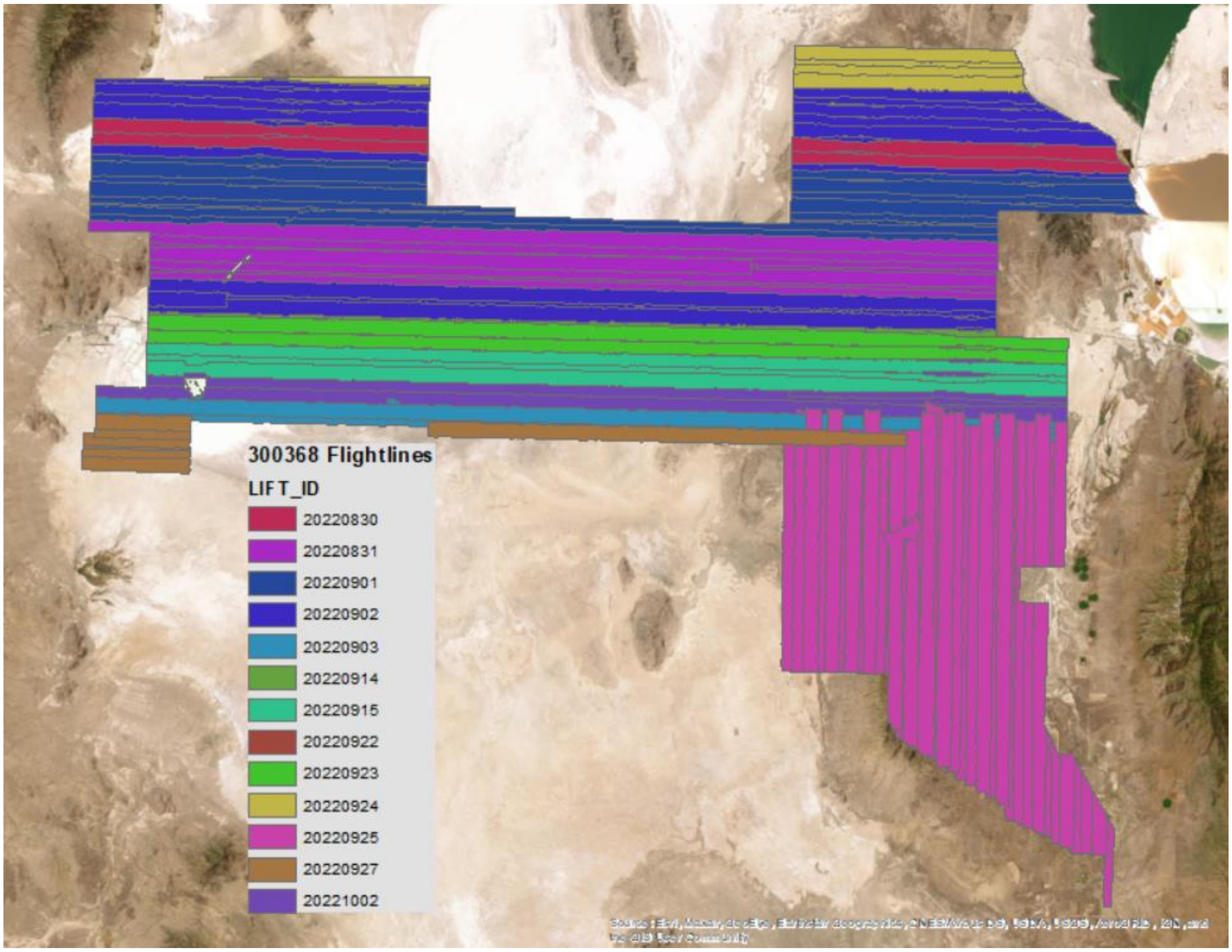
1. Project Tile Grid (Esri SHP)
2. Classified Point Cloud (tiled LAS)
3. Intensity Images (tiled, 8-bit gray scale, GeoTIFF format)
4. Breakline Data (file GDB)
5. Bare Earth Surface (tiled raster DEM, COG format)
6. Swath Separation Images
7. Digital Surface Model (tiled raster DSM, COG format)
8. Metadata (XML)
9. Flightline Extents GDB
10. Maximum Surface Height Rasters (tiled raster MSHRs, GeoTIFF format)
11. Low Confidence Polygons (Esri SHP)

2. LIDAR ACQUISITION REPORT

The Aero-Graphics Team was responsible for providing LiDAR acquisition, calibration, and delivery of LiDAR data files.

2.1 Acquisition Extents

Figure 3 shows flightline vectors by lift.



Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 3. WUID 300368 swaths

2.2 Acquisition Summary

Acquisition began on August 13, 2022. Early in the acquisition effort the VQ-1560II-S LiDAR sensor experienced a failure of its second, of two, channels. To compensate for this, the acquisition blocks were replanned to accommodate single channel collection and still reliably meet the requirements for QL1 data. Additionally, a second sensor was mobilized to the project. A Riegl VQ-1560i topographic LiDAR system began flying on August 26, 2022, and collected data until October 4, 2022. On October 5, 2022, the single channel VQ-1560II-S was replaced with a standard dual channel VQ-1560II-S sensor which completed the project on October 13, 2022.

Prior to beginning acquisition, the Aero-Graphics Team began coordination for access to restricted airspace within the project boundaries, as well as for permission to overfly Department of Defense (DOD) lands. These included the areas surrounding the Utah Test and Training Range (UTTR), a facility that operates under the Department of Defense (DOD). The UTTR is a military testing and training area located in Utah’s West Desert, approximately 80 miles west of Salt Lake City, whose airspace is restricted to authorized personnel only and classified as a No-Fly Zone (NFZ) by the DOD. Due to factors concerning military security and safety, the

Team’s pilots used their discretion to determine the closest permissible flying limits near the NFZs. No civilian air traffic is allowed to enter NFZs, therefore the pilot had to leave ample time to turn the plane around and not drift into these zones, which did not allow the pilot to come right up to the NFZ boundaries. Additionally, the data within these NFZs are restricted and cannot be used. The collection and use of high-resolution data of these facilities may compromise the security of the area, whether the data is intentionally distributed or not. To avoid this, the sensor operator had to turn the sensor off an appropriate distance away from the NFZs in order ensure these restricted data were not collected. Due to these factors, voids exist between the originally planned project boundary and the NFZs that are unable to be filled with LiDAR data.

2.3 Sensor Calibration and Boresight

Prior to the West Desert North Acquisition, the Aero-Graphics Team completed a sensor boresight on 04/28/2022 and another boresight on the second sensor on 08/30/2022. The boresights consisted of multiple opposing lines in an E-W direction as well as multiple opposing lines in a N-S direction. The swaths have a large overlap (>60%) with neighbors. The trajectory (.sbet) was processed using Applanix PosPac and raw swath data (.las) was produced using Riegl RiProcess. The boresight was calibrated and then analyzed. All deemed necessary corrections are then applied to the senor orientation internal files.

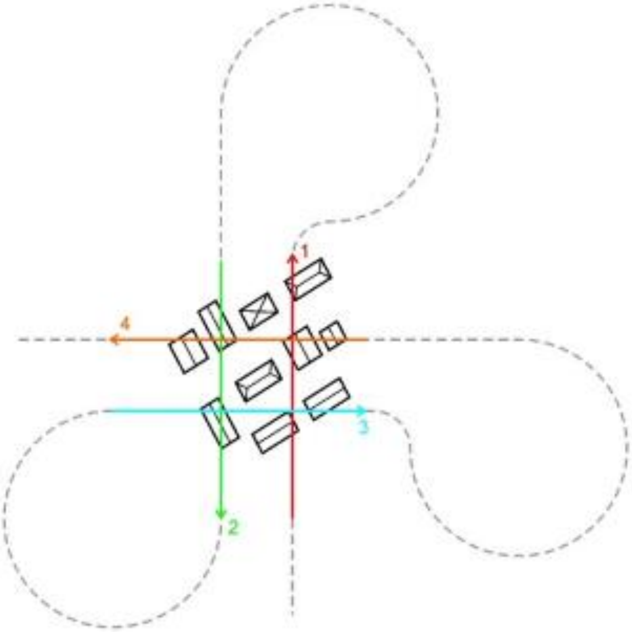


Figure 4. A typical calibration and boresight flight plan where above ground features are acquired from all four cardinal directions, any offsets of the above ground features between overlapping and other directional flight lines is analyzed, and corrections are applied as necessary to ensure proper configuration of the sensor.

2.4 LiDAR Acquisition and Processing Details

Table 1 outlines LiDAR acquisition details, including the project spatial reference system, and processing software used for this project.

Table 1. LiDAR acquisition details

Parameter	Value
Number of Flight lines	115
Approximate Area	1,729 sq. miles
Acquisition Dates	August 30, 2022 – October 2, 2022
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	Geoid18
Coordinate Reference System	UTM Zone 12
Horizontal Units	Meters
Vertical Units	Meters
Kinematic Solution Processing Software:	Applanix Pospac
Point Cloud Generation Software	Riegl RiProcess

2.5 LiDAR System Parameters

The Aero-Graphics Team operated a Cessna T303 (Tail # N978NC) outfitted with a Riegl VQ-1560II-S LiDAR system during data collection. Table 2 details the LiDAR system parameters used during acquisition for this project.

Table 2. The Aero-Graphics Team's LiDAR system parameters.

Parameter	Value
System	Riegl VQ-1560II-S
Altitude (m above ground level)	1690
Nominal flight speed (kts)	160
Scanner pulse rate (kHz)	3386
Scan frequency (Hz)	396
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)	0.17
Nominal swath width on the ground (m)	1894
Swath overlap (%)	55
Total sensor scan angle (degrees)	58.5
Nominal pulse spacing (NPS) (single swath) (m)	0.29

Nominal Pulse Density (NPD) (single swath) (points per sq m)	12
Aggregate NPS (m) (if NPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.29
Aggregate NPD (m) (if NPD was designed to be met through single coverage, ANPD and NPD will be equal)	12
Maximum Number of Returns per Pulse	9

2.6 Acquisition Static Control

No static control was used during this acquisition. An Applanix PosPac PP-RTX solution was used which doesn't require single base stations or CORS.

2.7 ABGNSS-Inertial Processing

ABGNSS-Inertial processing was performed using the software identified in Table 1. The reference frame used for this processing does not always match the project spatial reference system and is shown in Table 3.

Appendix A contains additional mission GPS and IMU processing covering:

- Pospac graphics and processing
- Graphics of any reference stations used for differential correction
- Graphics of processing interface to show trajectory data and labeled reference stations for each lift (only graphics of trajectory when precise point position is used).
- Graphics of processed plots for each mission/flight/lift to include:
    1. Forward/reverse separation of trajectory
    2. Estimated accuracy of trajectory
    3. Any additional plots used in the analyses of trajectory quality

Table 3. Spatial reference system used for ABGNSS-Inertial processing

Parameter	Value
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	Geoid18
Coordinate Reference System	UTM Zone 12
Horizontal Units	Meters
Vertical Units	Meters

2.8 Calibration Process (Project Mission Calibration)

LiDAR mission flight trajectories were combined with raw point files in Riegl RiProcess. The initial points (.las) for each mission calibration were inspected for flight line errors, spatial distribution, data voids, density, or issues with the LiDAR sensor. If a calibration error greater than specification was observed within the mission, the necessary roll, pitch, and scanner scale corrections were calculated, and corrections were applied to each individual swath using the BayesMap StripAlign software. In addition, all GPS, aircraft trajectory, mission information, and ground control files were reviewed and logged into a database. The missions with the new calibration values were regenerated and validated internally once again to ensure quality.

The methodology and assessment for the spatial distribution, density, and sensor anomaly reviews are outlined further in the Post Calibration LiDAR Review table.

2.9 Final Calibration Verification

AGI surveyed 39 ground control points (GCPs) in flat, non-vegetated areas to test the accuracy of the calibrated swath data. GCPs were in open, non-vegetated terrain. To assess the accuracy of calibration, the heights of the ground control points were compared with a surface derived from the calibrated swath LiDAR. A full list of GCPs used for accuracy testing is included in the GCP Survey Report provided with project deliverables.

Table 4. Summary of calibrated swath vertical accuracy tested with ground control points.

Land Cover Type	# of Points	$RMSE_z$ (m)	NVA (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Ground Control Points (GCPs)	**39**	0.046	0.090	-0.024	0.012	-0.421	0.045	-0.102	0.107	-0.108

3. LIDAR PRODUCTION & QUALITATIVE ASSESSMENT

3.1 Initial Processing

Following receipt of the calibrated swath data from the acquisition provider, the Aero-Graphics Team 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 the Team to determine whether the data was suitable for full-scale production.

The methodology and assessment for the absolute and relative accuracy, density, and spatial distribution reviews performed are outlined further in the Post Calibration LiDAR Review table.

3.1.1 Post Calibration LiDAR Review

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

Table 5. Post calibration and initial processing data verification steps.

Methodology and Requirement	Description of Deliverables	Additional Comments
Using proprietary software, it was determined the 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
Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing density mean statistics output by proprietary tool, the project area was determined to meet the required specification of 8 ppsm or 0.35 m NPS. A visual review of a 1-square meter density grid is also performed to confirm most 1-square meter cells satisfies the project requirements. Density is also viewed/analyzed by representative 1-square kilometer areas (to account for the irregular spacing of LiDAR point clouds) to confirm density passes with no issues.	The average calculated (A)NPD of this project is 26.33 ppsm. Density raster visualization also passed specifications.	None
The spatial distribution of points must be uniform and free of clustering. This specification is tested by creating a grid with cell sizes equal to the design NPS*2. Proprietary tools are then used to calculate the number of first return points of each swath within each grid cell. At least 90% of the cells must contain 1 LiDAR point, excluding acceptable void areas such as water or low NIR reflectivity features, i.e. some asphalt and roof composition materials. This project passes spatial distribution requirements, as shown in the image below.	99.3% 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	Within swath relative accuracy passed specification.	None

Methodology and Requirement	Description of Deliverables	Additional Comments
meet ≤ 6 cm maximum difference. The Team verifies the intra-swath or within swath relative accuracy by using proprietary scripting to output intra-swath raster's. Proprietary scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. The Team performs a visual review of planar surfaces and ensures the data passes specification.		
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. The Team verifies the inter-swath or between swath relative accuracy by using proprietary scripting to output inter-swath raster's and LP360 generated Swath Separation Images which are both reviewed visually at multiple stages of production to ensure the data passes specification.	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	Edge of Flight line bits were populated correctly	None

Methodology and Requirement	Description of Deliverables	Additional Comments
acquired, regardless of which type of sensor is used		
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
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

3.2 Data Classification and Editing

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data were confirmed, the Aero-Graphics Team 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. The Team's 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. The Team's 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 0.35 meter 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 software.

3.2.1 Qualitative Review

The Aero-Graphics Team'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 the Team's standard editing and review guidelines for specific types of features, land covers, and LiDAR characteristics.

Table 6. LiDAR editing and review guidelines.

Category	Editing Guideline	Additional Comments
No Data Voids	The SOW for the project defines unacceptable data voids as voids greater than 4 x ANPS^2, or 1.96 m^2, that are not related to water bodies or other areas of low near-infrared reflectivity and are not appropriately filled by data from an adjacent swath.	No unacceptable voids were identified in this dataset

Category	Editing Guideline	Additional Comments
	The LAS files were used to produce density grids based on Class 2 (ground) points for review.	
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. The Team 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
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. The Team 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 the Team’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, the Team errs on the side of culverts, especially if the feature is on a secondary or tertiary road.	None

Category	Editing Guideline	Additional Comments
In-Ground Structures	In-ground structures typically occur on military bases and at facilities designed for munitions testing and storage. When present, the Team 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, the Team 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, the Team edits the features to class 2 (ground)	No dirt mounds or other irregularities in the natural ground were present in this dataset
Irrigated Agricultural Areas	Per project specifications, the Team 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

Category	Editing Guideline	Additional Comments
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, the Team ensures that any ridges remaining after editing and QA/QC are within project relative accuracy specifications.	No flight line ridges are present in the data
Temporal Changes	If temporal differences are present in the dataset, the offsets are identified with a shapefile.	No temporal offsets are present in the data
Low NIR Reflectivity	Some materials, such as asphalt, tars, and other petroleum-based products, have low NIR reflectivity. Large-scale applications of these products, including roadways and roofing, may have diminished to absent LiDAR returns. USGS LBS allow for this characteristic of LiDAR but if low NIR 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 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	No Laser Shadowing is present in the data

Category	Editing Guideline	Additional Comments
	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.	
Vertical Cliff Faces	Overhanging ground points near the tops of cliffs and mesas were left as Class 1 – Unclassified. Ground points in the same pixel with large differences in vertical elevations will average the elevation for that single pixel and cause the overall terrain to be mis-represented. In order to model the most accurate terrain delineation, the Team classifies ground points above and below the extremely vertical cliff faces.	Vertical cliff faces exist in this dataset and are classified accordingly.

3.2.2 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 7. 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) UTM Zone 12, meters in WKT format	Pass
Vertical Coordinate Reference System	NAVD88 (Geoid 18), meters 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
Multiple Returns	The sensor shall be able to collect multiple returns per pulse and the return numbers are recorded	Pass

Parameter	Project Specification	Pass/Fail
Intensity	16-bit intensity values recorded for each pulse	Pass
Classification	Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 9: Water Class 17: Bridge Decks Class 18: High Noise Class 20: Ignored Ground	Pass
Withheld Points	Withheld bits set for geometrically unreliable points and for noise points in classes 7 and 18	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Recorded for each pulse	Pass

3.3 Positional Accuracy Validation

3.3.1 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 and boresight adjustment of the data in each lift. The Aero-Graphics Team reviews the overlap consistency of the LiDAR dataset during multiple stages of production. Each review is performed by an initial reviewer and then reviewed by a second reviewer to verify the overlap consistency meets expectations. After calibration, the Aero-Graphics Team uses a proprietary software to generate a point statistics interswath raster. The interswath raster is reviewed for any systematic interswath errors that should be considered of concern. If issues are identified they will be corrected by the calibration team. The interswath rasters are symbolized by the following ranges:

- +/- 0-8 cm: **Green**
- +/- 8-16 cm: **Yellow**
- +/- 16 cm: **Red**

Once the initial ground macro has been run on the dataset, the Team uses LP360 to generate swath separation images. The swath separation images are generated using the same settings as the final deliverable swath separation images outlined in 6.1 Swath Separation Images (SSIs) and in accordance with USGS LiDAR Base Specification v2022 Rev A. If the LiDAR dataset is heavily vegetated, the Team will generate swath separation images using the last return of ground points only to better confirm no offsets are present in the bare earth DEM. If issues are identified, dependent on the cause of the issue, it will be corrected by recalibrating the affected data or classifying the impacting points to withheld.

Lastly, the final deliverable swath separation images are generated using LP360. A final review is performed by the final product producer and then verified by a member of the quality management team prior to sending to USGS.

3.3.2 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. The Aero-Graphics Team reviews the precision of the LiDAR dataset during multiple stages of production. Each review is performed by an initial reviewer and then reviewed by a second reviewer to verify the precision of the LiDAR meets expectations. The Aero-Graphics Team performs an intraswath accuracy review for each mission within 1-2 days of collection. The precision of the LiDAR dataset is then reviewed before calibration on the LiDAR dataset to ensure no systematic errors.

The Aero-Graphics Team uses a proprietary software to generate point statistics intraswath rasters. Swath data in non-overlap areas were assessed using only first returns in non-vegetated areas. To measure the precision of a LiDAR dataset, level or flat surfaces were assessed. If the LiDAR dataset is located in areas with sloped or steep terrain, a slope raster will be used in conjunction with the intraswath raster to ensure only level or flat surfaces are being assessed. The intraswath raster is reviewed for any systematic intraswath errors that should be considered of concern.

The intraswath rasters are symbolized by the following ranges:

- 0-6 cm: **Green**
- >6 cm: **Red**

4. BREAKLINE PRODUCTION & QUALITATIVE ASSESSMENT

4.1 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, the Aero-Graphics Team 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.

4.1.1 Breakline Collection Requirements

The table below outlines breakline collection requirements for this dataset.

Table 8. Breakline collection requirements

Parameter	Project Specification	Additional Comments
Ponds and Lakes	Breaklines are collected in all inland ponds and lakes ~2 acres or greater.	None

	These features are flat and level water bodies at a single elevation for each vertex along the bank.	
Rivers and Streams	Breaklines are collected for all streams and rivers ~100' nominal width or wider. These 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.	Rivers and streams were not present in this dataset, so no breaklines were collected.
Tidal	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.	No tidally influenced features are in this dataset so no tidal breaklines were collected.
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 feature.	Soft features were not applicable to this dataset so no soft feature breaklines were collected.

4.2 Breakline Qualitative Assessment

The Aero-Graphics Team 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 9 – 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	Pass

	Vertices should not have excessive min or max z-values when compared to adjacent vertices Intersecting features should maintain connectivity in X, Y, Z planes Dual line streams shall have the same elevation at any given cross-section of the stream	
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	N/A
Topology	Features must not overlap or have gaps 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

5. DEM PRODUCTION & QUALITATIVE ASSESSMENT

5.1 DEM Production Methodology

The Aero-Graphics Team utilized LP360 to generate DEMs. LP360 uses TIN (Triangulated Irregular Network) as the interpolated surface method. A TIN divides a surface into a set of contiguous, non-overlapping, Delaunay triangles. The height of each triangle vertex interpolates together to construct the surface. The Aero-Graphics Team utilized 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 the Team.

5.2 DEM Qualitative Assessment

The Aero-Graphics Team 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. The Team 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. The Teams swath extents were flown much shorter than originally planned due to the DOD no fly zone. During acquisition, the pilot was not given approval to fly the full length of the planned trajectory. In addition, the locations at the extreme tail of the swath are areas where the sensor tail only has coverage from a single channel collect. During the ground macro routine, the classification algorithm classified all points along the plane thus resulting in a noticeable corn row pattern of points all in the same scan direction pattern. With the use of all points at the very end of swaths, a non-significant buffer distance of the trajectory due to DOD restrictions, and single channel collects, the ground classification shows visible patterns in the DEM. Low confidence polygons that delineate these areas were delivered. Upon correction of any outstanding issues, the DEM data was loaded into Global Mapper for its second review and to verify corrections.

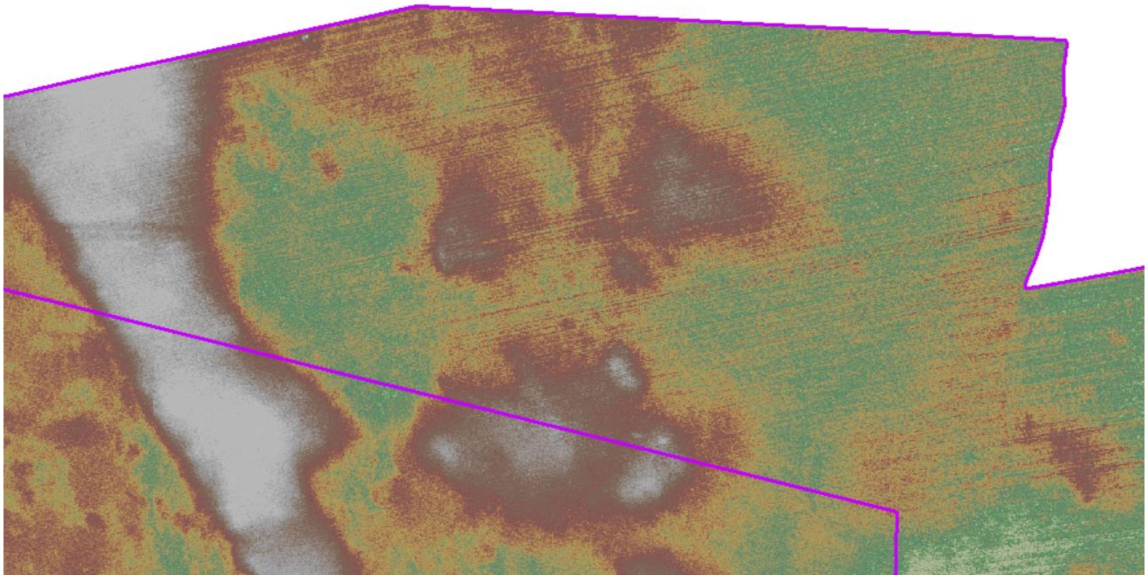


Figure 5. The image above is an example of the corn rowing pattern visible in the bare earth DEM and the low confidence polygons (purple) outlining these areas adjacent to the DoD No Fly Zones.

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

Table 10. DEM verification steps.

Parameter	Requirement	Pass/Fail
Digital Elevation Model (DEM) of bare-earth w/ breaklines	DEM of bare-earth terrain surface (0.5m) 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 (-999999)	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	N/A
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

6. DERIVATIVE LIDAR PRODUCTS

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

6.1 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**
- 16-24 cm: **Orange**
- >24: **Red**

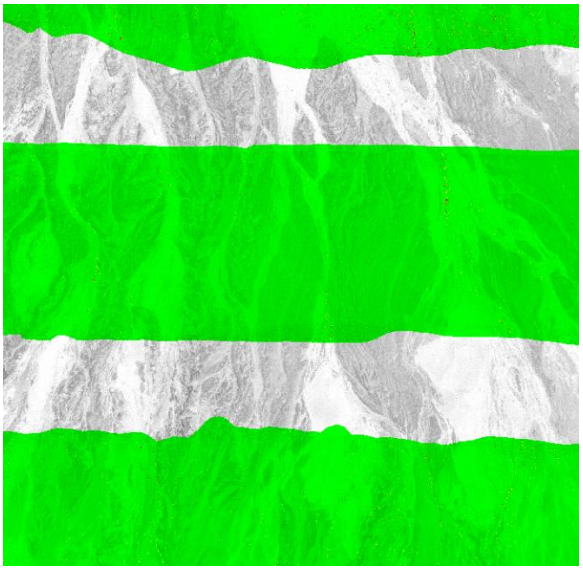


Figure 6. The image above is an example of a Swath Separation Image for the Block 2A area.

6.2 Intensity Images

The intensity imagery was created from the point cloud intensity values of first returns from all point classes except for noise (classes 7 and 18) and points flagged as withheld were used to create the raster. The review of the intensity imagery included looking for anomalous intensity values, voids, and processing artifacts.

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 reflective surfaces like paint stripes or wet surfaces result in higher intensity return and will have brighter pixels in the intensity imagery.

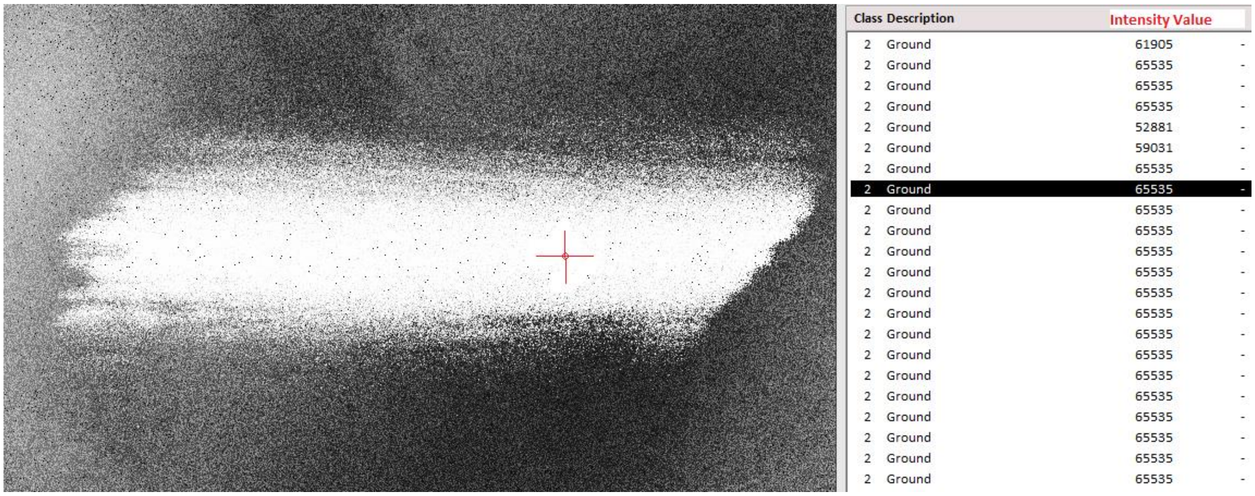
Although the areas observed are not directly over bodies of water, the terrain where the issues are present are located within areas of saturated ground. The areas may not appear visibly “wet” in the DEM, intensity imagery, or aerial imagery but water is present at or above the soil level causing saturated 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’s 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.

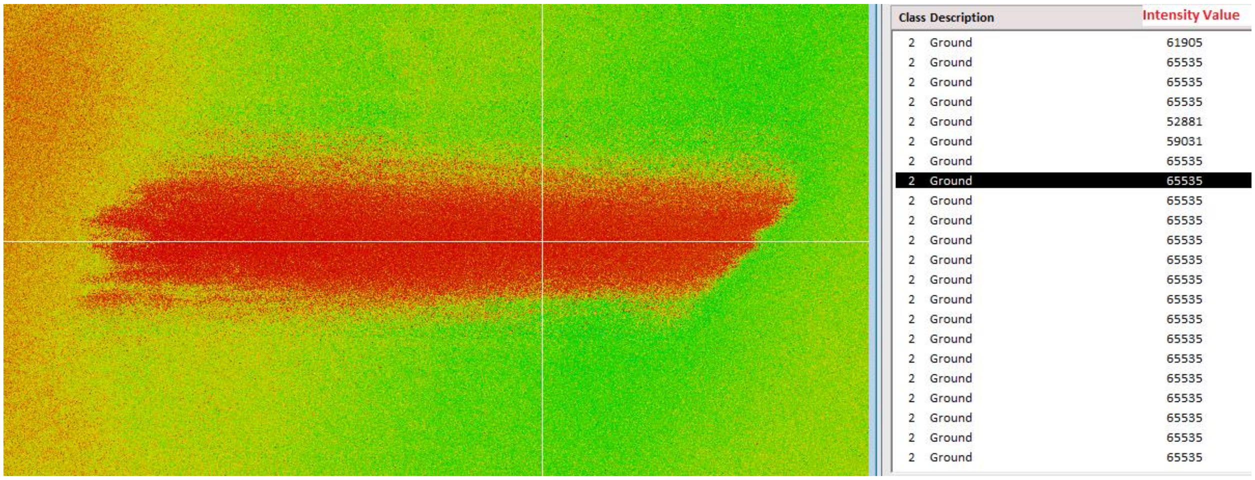
For these areas, that are a result of time over threshold errors, there is not a known “brightness” of the target return that can be used for a correction. In the case of flat areas with consistent intensity (e.g. runway paint stripes), the error can be corrected based on the geometric offset between the planar data since intensity is assumed to be constant in the error area. Unfortunately, in the UT West Desert 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.

The images below show the intensity value for the identified LAS point that appears bright white at nadir. The LAS point has an intensity value of 65,535.



Class Description		Intensity Value	
2	Ground	61905	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	52881	-
2	Ground	59031	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-
2	Ground	65535	-

Figure 7. The image above shows the ground points displayed by intensity and highlights one of the points with an intensity value of 65,535.



Class Description		Intensity Value
2	Ground	61905
2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	52881
2	Ground	59031
2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	65535
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2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	65535
2	Ground	65535

Figure 8. The image above shows the bare earth DEM and highlights one of the points with an intensity value of 65,535.

Due to the incredibly flat terrain in these areas of the UT West Desert LiDAR project, any slight offset in LiDAR elevation is going to show a much larger difference in the DEM. The DEM in these areas is showing slightly raised ground which can not be corrected by manual efforts. Ground only swath separation images show that the ground offset in these areas are within the specifications for a QL1 LiDAR project.

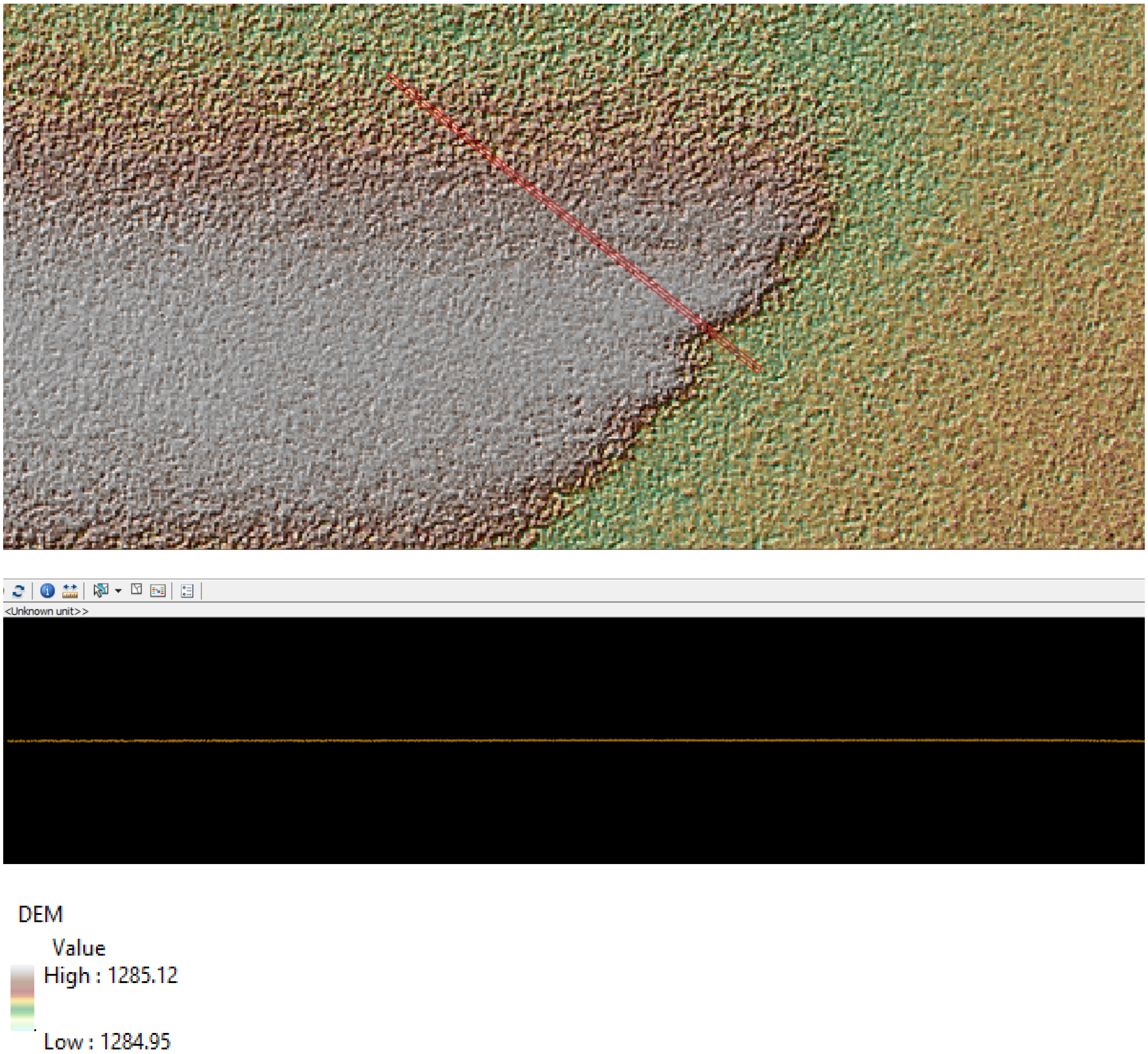
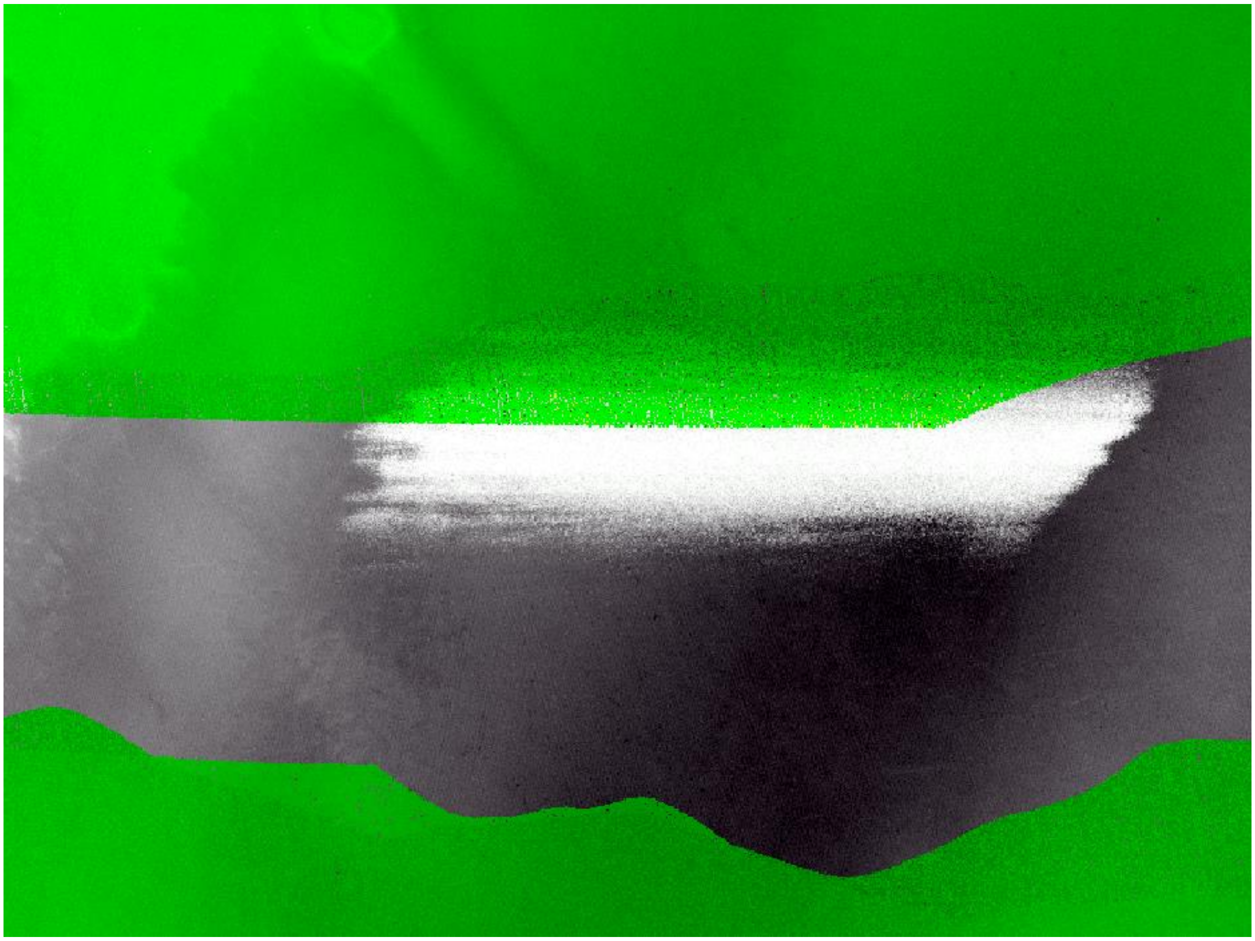


Figure 9. The images above show the bare earth DEM, an LAS profile showing minimal ground change, and the min and max values of the DEM. Due to the flat terrain, slight changes in elevation are exaggerated when zoomed in.



- 0-8 cm: **Green**
- 8-16 cm: **Yellow**
- 16-24 cm: **Orange**
- >24: **Red**

Figure 10. The images above show the ground only swath separation images and symbology. These areas are within the QL1 specification.

6.3 Maximum Surface Height Rasters (MSHRs)

MSHRs are delivered as tiled GeoTIFFs (32-bit, floating point), with the tile size and naming convention matching the project tile grid, tiled point cloud, and tiled DEM deliverables. MSHRs are provided as proof of performance that the Team's withheld bit flag has been properly set on all points, including noise, which are not deemed valid returns, and which should be excluded from all derivative product development. All points, all returns, excluding points flagged as withheld, are used to produce MSHRs. The rasters are produced with a binning method in which the highest elevation of all LiDAR points intersecting each pixel is applied as the pixel elevation in the resulting raster. Final MSHRs are formatted using GDAL software version 2.4.0, spatially defined to match the project CRS, and the cell size equals 2x the deliverable DEM cell size (unless LiDAR density at the defined DEM cell size is insufficient for MSHR analysis and then a larger cell size for the MSHRs may be used). Prior to delivery, all MSHRs are reviewed for complete coverage, correct formatting, and any remaining point cloud misclassifications specifically in regard to the use of the withheld bit.

6.4 Flightline Extents GDB

Flightline extents are delivered as polygons in an Esri GDB, delineating actual coverage of each swath used in the project deliverables. The Aero-Graphics Team delivered this GDB using USGS's provided template so that each polygon contains the following attributes:

- Lift/Mission ID (unique per lift/mission)
- Point Source ID (unique per swath)
- Type of Swath (project, cross-tie, fill-in, calibration, or other)
- Start time in adjusted GPS seconds
- End time in adjusted GPS seconds

Prior to delivery, a final flightline GDB is created from the final, tiled point cloud deliverables to ensure all correct swaths are represented in the flightline GDB. The flightline GDB is then reviewed for complete coverage and correct formatting.

6.5 DSM

The creation of first return DSMs followed a similar workflow to the bare-earth DEMs, except that the first returns from all point classes except for noise (classes 7 and 18) and points flagged as withheld were used to create the raster and breaklines were not used to hydro-flatten or hydro-enforce the surface. The review of the DSMs included looking for spikes, divots, noise points not properly classified to the noise classes, other LiDAR misclassifications, and processing artifacts.