Lidar Mapping Report for the U.S. Geological Survey

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Work Unit ID: 300364

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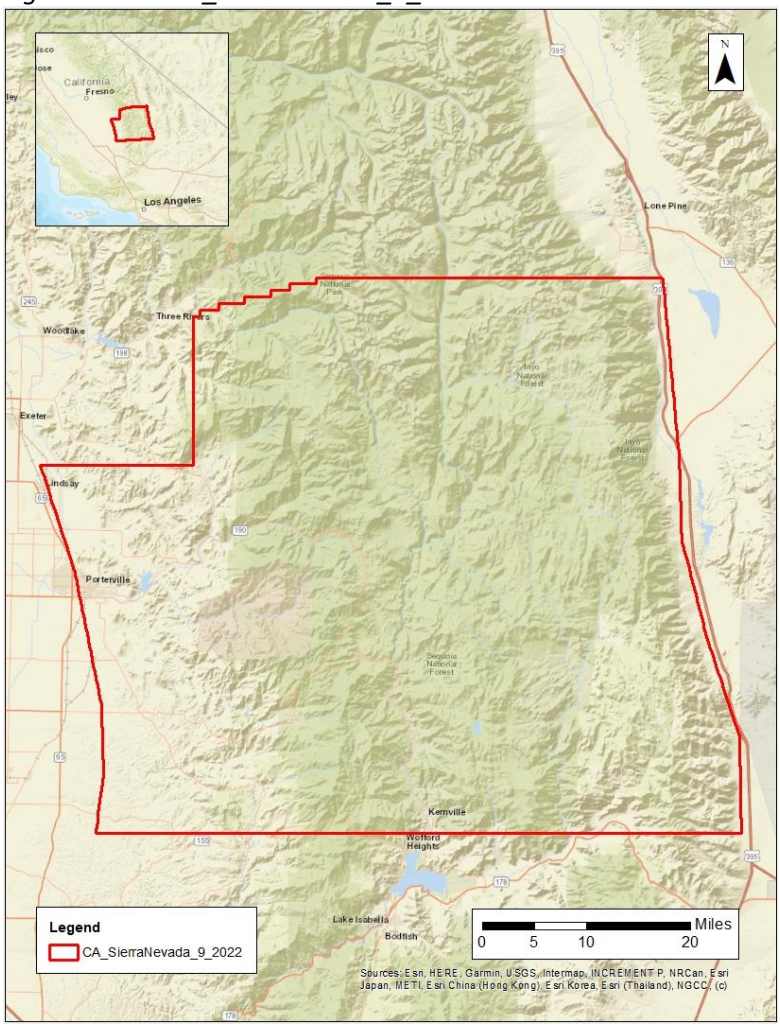
1. Overview

1.1. Description

CA_SierraNevada_9_2022, WU300364 is part of Task order 140G0222F0176.
This Lidar Mapping Report will cover the acquisition, processing, and derivative products of Work Unit 300364. Lidar data was collected to an aggregate nominal pulse spacing (ANPS) of ≤0.35-meters and 8-points per square meter (ppsm) covering approximately 2,944.498 square miles in California to meet USGS Quality Level 1 standards. NV5 produced the Maximum Surface Height Raster. The rest of this work unit was acquired and processed by NV5 GPSC4 team member Woolpert, under supervision by NV5.

Figure 1.1.1 – CA_SierraNevada_9_2022



1.2. Purpose

This project will support the 3DEP mission, the Natural Resources Conservation Service (NRCS) high-resolution elevation enterprise, and many state and local agencies.

1.3. Specifications

Data and reporting for this task order were acquired and produced to meet the "*USGS Lidar Base Specification* v2022 Revision A", and the American Society of Photogrammetry and Remote Sensing (ASPRS) "*Positional Accuracy Standards for Digital Geospatial Data (Edition 1, Version 1.0)*".

1.4. Spatial Reference

Geospatial data products were produced using the following spatial data reference system:

- Horizontal Datum: NAD83 (2011)
- Horizontal Projection: UTM 11
- Horizontal Units: Meters
- Horizontal EPSG Code: 6340
- Vertical Datum: NAVD88
- Geoid Model: 18
- Vertical Units: Meters
- Height Type: Orthometric

1.5. Task Order Deliverables

All data products produced as part of this task order are listed below. All tiled deliverables had a tile size of 1,000-meters x 1,000-meters. CA_SierraNevada_9_2022 contains a total of 7,709 tiles.

Lidar Data

- Classified lidar point cloud data in compressed LAZ format:
    - Class 1 – Default / Processed, but not Classified
    - Class 2 – Bare Earth Ground
    - Class 7 – Low Noise
    - Class 9 – Water
    - Class 17 – Bridge Decks
    - Class 18 – High Noise
    - Class 20 – Ignored Ground
- Breaklines used for hydro-flattening:
    - Rivers 30.5-meters / 100-feet and greater in width as PolylineZ features in Esri geodatabase format
    - Waterbodies greater than 2-acres as PolylineZ feature classes in Esri geodatabase format
    - Bridges used in DEM generation as PointZ feature classes in Esri .shp format
- Hydro-flattened bare earth digital elevation model (DEM): 0.5-meter pixel size, 32-bit floating-point with no bridges or overpass structures, in GeoTIFF format
- Intensity imagery: 0.5-meter pixel size, 8-bit, 256 gray-scale (linear rescaling from 16-bit intensity) in GeoTIFF format

1.5.1. Spatial Metadata

- Tile index: Esri .shp format
- Swath polygons: Georeferenced, polygonal representation of the detailed extents of each lidar swath as polygon feature class in an Esri file geodatabase format
- Maximum surface height (maximum height separation) rasters: 1.0-meter pixel size, 32-bit floating-point, GeoTIFF format
- Swath separation images: 1.0-meter pixel size, GeoTIFF format.

1.6. Flight Planning

Acquisition was planned based on the specifications listed below:

- Resolution: 8 points per square meter, with 0.35-meter nominal point spacing
- Overlap: At contractor's discretion, but enough to ensure there are no data gaps between usable portions of the swath and to ensure the aggregate nominal point density (ANPD) is achieved
- Acquisition Window: June/August 2022
- Acquisition Conditions:
    - Daytime Acquisition
    - Leaf-on conditions
    - No snow is on the ground
    - Rivers are within their channels at or below their normal levels
    - Sky is sufficiently clear of clouds, smoke, and atmospheric haze.
- Control: Airborne Global Positioning System (ABGPS) and Inertial Measurement Unit (IMU) data to be used along with differentially-corrected GPS ground control points.
- Data Voids are not allowed except:
    - Where caused by waterbodies
    - Where caused by areas of low near infra-red (NIR) reflectivity (i.e. asphalt, composition roofing)
    - Where caused by lidar shadowing from buildings or other features
      Where appropriately filled-in by another swath

1.7. Lidar Sensor Information

Aerial lidar data was acquired using the Leica Terrain Mapper lidar sensor system[1].

1.7.1. Sensor Specifications

- Operating Altitude: 300 – 5,500-m AGL at 10% reflective target
- Maximum Measurement Rate: 2000-kHz
- Scan Angle: 20°-40°
- Scan Width: Up to 70% of flight altitude
- Scan Frequency: Programmable up to 125-Hz (7,500 RPM), 250 scan lines per second
- Number of Returns: 15

[1] Source: Leica TerrainMapper Data Sheet. https://leica-geosystems.com/en-US/products/airborne-systems/topographic-lidar-sensors/leica-terrainmapper

- Number of intensity measurements: 15
- Pulse Mode(s): Up to 35 pulses in air

1.7.2. Laser Specifications

- Laser Beam Divergence: 0.25-mrad (1/e)
- Laser Classification: Class 4 laser product

1.7.3. Accuracy

- Range Resolution: < 1 cm RMS
- Elevation Accuracy: < 5-cm 1 σ
- Horizontal Accuracy: < 13-cm 1 σ

1.7.4. Physical Specifications

- Scanner size: 37 W x 68 L x 26 H-cm
    - Scanner weight: 47-kg
    - Control Electronics size: 45 W x 47 D x 25 H-cm
    - Control Electronics weight: 33-kg
    - Scanner operating temperature: 0 – 40°C cabin-side temperature
    - Control Electronics operating temperature: 0 – 40°C
- Flight Management: Leica FlightPro
- Power Consumption: 922-W @ 22.0 – 30.3-VDC

1.8. Planned Flight Specifications

Flight plans were created using Leica Mission Pro v.12.5 software. Aerial lidar data was acquired for this project using the following lidar sensor systems:

- Terrain Mapper – serial number 90515, last calibrated June 27, 2019
- Terrain Mapper – serial number 91513, last calibrated February 25, 2019
- Terrain Mapper – serial number 90511, last calibrated July 3, 2019

The following settings for Leica Terrain Mapper – serial number 90515, Leica Terrain Mapper – serial number 91513, and Leica Terrain Mapper – serial number 90511 were used:

- Maximum Number of Returns: 15
- Nominal Point Spacing: 0.35-m
- Nominal Point Density: 8 ppsm
- Flying Height Above Ground Level: 2,000-m
- Flight Speed: 160-knots
- Scan Angle: 40°
- Scan Rate Used: 150-Hz
- Pulse Rate Used: 1600-kHz
- Multi-Pulse in Air: Enabled
- Overlap: Minimum 25%

1.9. Timeline

Lidar data was collected from June 19, 2022, through August 31, 2022. A total of 476 individual flight lines were collected. Flight logs are contained in Attachment 2: Flight Logs.

1.10. GNSS and IMU Equipment

Prior to mobilizing to the project site, flight crews coordinated with required air traffic control personnel to ensure airspace access. Crews were on-site, operating a Global Navigation Satellite System (GNSS) Base Station for airborne GPS support.

Flight navigation during acquisition was performed using Integrated Geospatial Innovations' CCNS (Computer Controlled Navigation System). The pilots are skilled at maintaining their planned trajectory, while holding the aircraft steady and level. If atmospheric conditions were such that the trajectory, ground speed, roll, pitch and/or heading could not be properly maintained, the mission was aborted until suitable conditions occur.

Base stations were set by acquisition staff to support the aerial data acquisition. Table 2.5.2 lists the Station ID and coordinates for all base stations operated during acquisition. GPS/IMU graphics are contained in Attachment 3: GPS IMU Images.

Figure 2.5.1. Flight Coverage by Lift

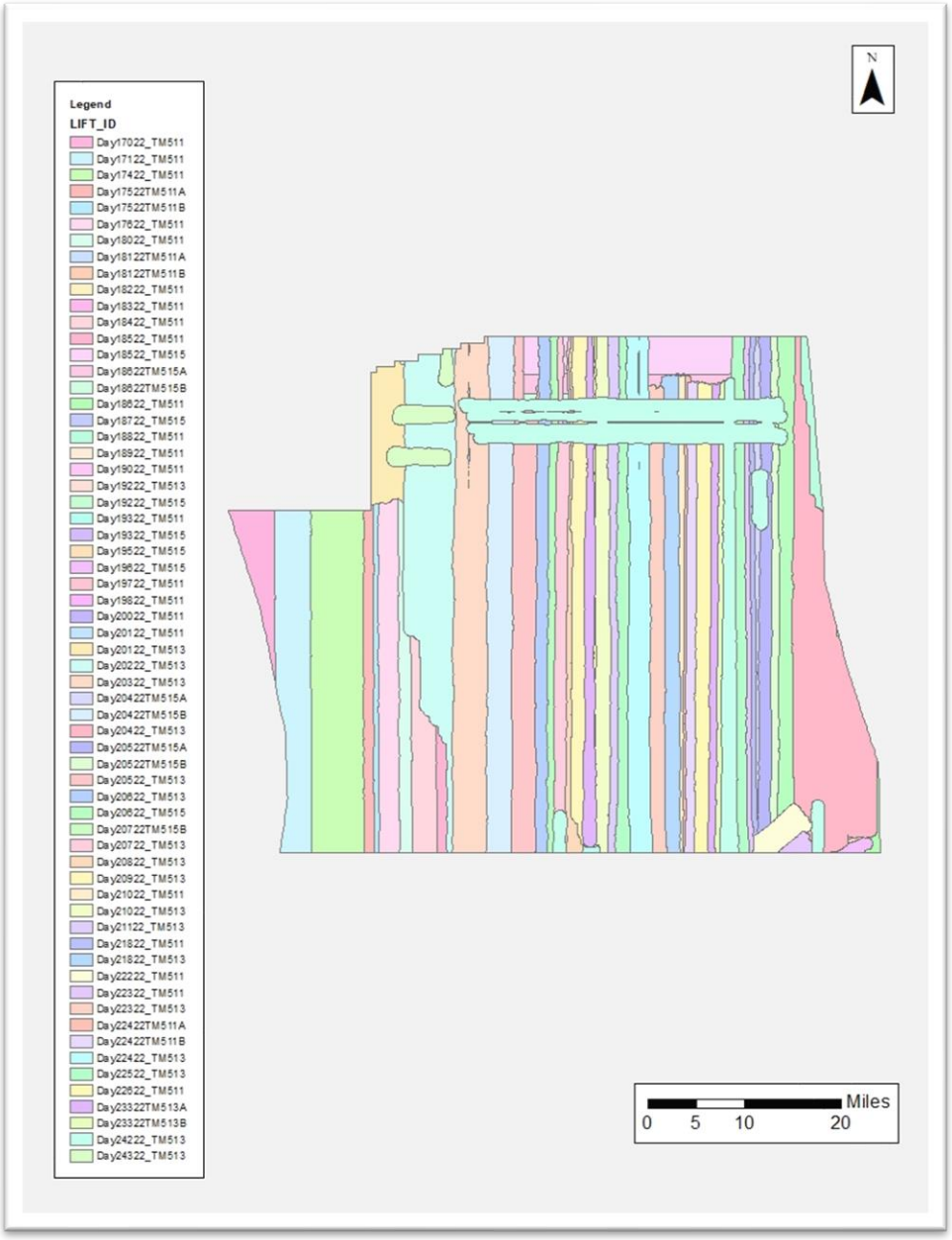


Table 2.5.2. GNSS Base Stations

Station Name	Longitude (DMS)	Latitude (DMS)	Ellipsoid Height L1 Phase Center (M)
P558_CORS	35°08'18.96637"	-118°36'41.90683"	1412.201
P567_CORS	35°25'15.39395"	-118°45'12.82643"	707.071
P572_CORS	36°35'07.84359"	-118°57'16.49421"	1168.037
P056_CORS	36°01'38.76146"	-119°03'46.28389"	102.113
PO56_CORS	36°01'38.76146"	-119°03'46.28389"	102.113
P567_CORS	35°25'15.39395"	-118°45'12.82643"	707.071
P467_CORS	36°34'12.71246"	-118°05'26.19300"	1380.864

1.11. Acquisition Quality Assurance

Woolpert developed a quality assurance and validation plan to ensure the acquired lidar data meets the USGS Lidar Base Specification. For quality assurance purposes, the lidar data was processed immediately following acquisition to verify the coverage has appropriate density, distribution, and no unacceptable data voids. Accompanying GPS data was post processed using differential and Kalman filter algorithms to derive a best estimate of trajectory. The quality of the solution was verified to be consistent with the accuracy requirements of the task order. Any required re-flights were scheduled at the earliest opportunity.

The spatial distribution of the geometrically usable first return lidar points was reviewed for density requirements. The first returns were also reviewed for regular and uniform point distribution - verifying the lidar data was spaced so that 90% of the cells in a 2*NPS grid placed over the data contain at least one lidar point. The Nominal Point Spacing (NPS) assessment was conducted against single swath, first return data located within the geometrically usable center portion (typically ~90%) of each swath. Additionally, the data was reviewed for unacceptable data voids –no area greater than or equal to $(4 \times ANPS)^2$ exhibited data coverage gaps. An initial quality control process was performed after each flight to review data coverage, airborne GPS data, and the trajectory solution.

2. Processing

2.1. Processing Summary

Once the lidar data passed initial QC, the dataset was corrected for aircraft orientation and movement. This process used airborne inertial, orientation, and GPS data collected during acquisition along with ground-based GPS data. The data was subject to geometric calibration that further corrected each laser point. This calibrated dataset was used to create the LAS point cloud. LAS point data was initially classified into “ground” and “non-ground”, then further refined using the classes specified by the task order. Breaklines were drawn to denote hydrological features. After the hydro-flattening process, the final deliverable products were created.

2.2. GPS-IMU Trajectory Processing

Kinematic corrections for the aircraft position were resolved using aircraft GPS and static ground GPS (1-Hz) for each geodetic control (base station) for three subsystems: inertial measurement unit (IMU), sensor orientation information, and airborne GPS data.

Post-processing of the IMU system data and aircraft position with attitude data was completed to compute an optimally accurate and blended navigation solution based on Kalman filtering technology, or the smoothed best estimate of trajectory (SBET).

For more information, see the GPS/IMU graphics in Attachment 3: GPS IMU Images. Software used included POSPac Software v. 5.3, IPAS Pro v.1.35., and Novatel Inertial Explorer v8.60.6129.

2.2.1. Trajectory Quality

The GNSS trajectory and high-quality IMU data are key factors in determining the overall positional accuracy of the final sensor data. Within the trajectory processing, there are many factors that affect the overall quality, but the most indicative are the combined separation, the estimated positional accuracy, and the Positional Dilution of Precision (PDOP).

2.2.2. Combination Separation

Combined separation is a measure of the difference between the forward-run and the backward-run solution of the trajectory. The Kalman filter was processed in both directions to remove the combined directional anomalies. In general, when these two solutions match closely, an optimally accurate and reliable solution is achieved. The data for this task order was processed with a goal to maintain a combined separation difference of less than 10-cm.

2.2.3. Estimated Positional Accuracy

Estimated positional accuracy plots the standard deviations of the east, north, and vertical directions along a time scale of the trajectory. It illustrates loss of satellite lock issues, as well as issues arising from long baselines, noise, and/or other atmospheric interference.

2.2.4. PDOP

The PDOP measures the precision of the GPS solution in regard to the geometry of the satellites acquired and used for the solution. Lidar data for this task order was processed with a goal to maintain an average PDOP value below 3.0. Brief periods of PDOP over 3.0 are acceptable due to the calibration and control process if other metrics are within specification.

2.3. Geometric Calibration

After the initial phase was complete, a formal reduction process was performed on the lidar data. Laser point position was calculated by associating the SBET position to each laser point return time, scan angle, intensity, etc. Raw laser point cloud data was created for the whole project area in LAS format. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Statistical reports were generated for comparison and used to make the necessary adjustments to remove any residual systematic error.

For more information, see the Sensor Calibration Report(s) in Attachment 1: Sensor Calibration Reports. Software used included proprietary software, TerraMatch v20, and Leica CloudPro 1.2.4.

2.4. Relative Accuracy: Interswath (Overlap) Consistency

This project required the interswath accuracy to meet ≤ 8-cm RMSDz. Accuracy was assessed in accordance with "*USGS Base Specification v2022, Revision A*".

The interswath (overlap) consistency was calculated using 18 sample locations in nonvegetated areas of swath overlap with only single returns. The achieved interswath accuracy is RMSDz= 0.012 meters.

2.5. Relative Accuracy: Intraswath Precision

This project required the intraswath accuracy to meet ≤ 6-cm RMSDz. Accuracy was assessed in accordance with the "*USGS Base Specification v2022, Revision A*".

The intraswath precision was calculated using 8 sample locations in flat/open terrain against single swath and first-return points only. The achieved intraswath accuracy is RMSDz= 0.048 meters.

2.6. Lidar Data Classification

LAS data was initially classified as ground and non-ground points "first and only" as well as "last of many" lidar returns. Additional filters were created to meet the task order classification specifications. Statistical absolute accuracy was assessed by direct comparisons of ground classified points to ground RTK survey data. Based on the statistical analysis, the lidar data was then adjusted to reduce the vertical bias when compared to the survey ground control of higher accuracy.

The bare-earth (Class 2 - Ground) lidar points were subject to a manual quality control step to verify the quality of the Digital Elevation Model (DEM) as well as a peer-based review. This included a review of the DEM surface to remove artifacts and ensure topographic quality. After the bare-earth surface was finalized, it was used to generate all hydro-breaklines through a semi-automated process.

All Ground (Class 2) lidar data inside of the Lake Pond and Double Line Drain hydrological flattening breaklines were then classified to Water (Class 9) using TerraScan/LP360 algorithms. A buffer of 0.7-meters was also used around each hydro-flattened feature to classify these Ground (Class 2) points to Ignored Ground (Class 20). All Lake Pond Island and Double Line Drain Island features were checked to ensure that the Ground (Class 2) points were reclassified to the correct classification after the automated classification was completed.

All data was manually reviewed and any remaining artifacts were removed. Industry-standard LAS files were then created. Final statistical analysis was performed per tile on the LAS files classes to verify final classification metrics and full LAS header information. Those classes include:

- Class 1: Processed, but Unclassified
- Class 2: Bare Earth
- Class 7: Low Noise
- Class 9: Water
- Class 17: Bridge Deck
- Class 18: High Noise
- Class 20: Ignored Ground

Classified LAS files were evaluated through a series of manual quality control steps as well as a peer-based review to eliminate remaining artifacts from the Ground class. This included a review of the DEM surface to

remove artifacts and ensure topographic quality. Software used included proprietary software, GeoCue LP360, TerraScan v20, and Global Mapper v20.

2.7. Hydrologic Flattening

The lidar task order required compilation of breaklines defining the following types of waterbody features:

- Lakes, reservoirs, and ponds:
  - Minimum of 2-acres or greater
  - Compiled as closed polylines collected at a constant elevation
- Rivers and streams:
  - Nominal width of 30.5-meters / 100-feet
  - Compiled in direction of flow, with both sides maintaining an equal elevation gradient

Woolpert used the following steps to hydrologically flatten the waterbodies and for gradient hydrologic flattening of the double line streams within the existing lidar data:

1. Newly acquired lidar data was used to manually compile the hydrologic features in a 2D environment using the lidar intensity and bare earth surface. Open Source imagery was used as reference as necessary.
2. An integrated software approach combined the lidar data and 2D breaklines. This process “draped” the 2D breaklines onto the 3D lidar surface model to assign an elevation. A monotonic process was performed to ensure the streams flowed consistently in a downhill gradient. A secondary step within the program verified an equally matching elevation of both stream edges. The breaklines that characterize the closed waterbodies were draped onto the 3D lidar surface and assigned a constant elevation at or just below ground elevation.
3. All classified ground points inside the hydrologic feature polylines were reclassified to Water (Class 9).
4. All classified Ground points were reclassified from within a buffer along the hydrologic feature breaklines to Buffered Ground (Class 20). The buffer distance was approximately the task order designed Nominal Pulse Spacing distance.
5. Breaklines used for bridge removal during the hydrologic flattening were included with the hydrologic breakline geodatabase deliverable. These breaklines produce a more aesthetically pleasing DEM appearance.
6. The lidar ground points and breaklines were used to generate a DEM.
7. Quality control was performed by reviewing the hydrologically flattened DEM and hydrologic breakline features. An approach combining commercial off the shelf software and proprietary methods reviewed the overall connectivity of the hydrologic breaklines.

Breaklines defining waterbodies greater than 2-acres were provided as a PolylinesZ feature class. All lake breaklines compiled as part of the flattening process were provided in an Esri file geodatabase. Breaklines used for DEM generation were provided as PointZ features in Esri shapefile format.

Software used included TerraScan v20, TerraModeler v20, Esri ArcMap v10.7, and GeoCue LP360.

TerraScan was used to add the hydrologic breakline vertices and export the lattice models.

2.8. Digital Elevation Model

TerraScan was used to add the hydrologic breakline vertices and export the lattice models. Ground lidar points in conjunction with the hydro breaklines and bridge breaklines were used to create 0.5-meter hydro-flattened bare-earth raster DEM files. Automated routines in ArcMap generated a 32-bit floating point raster GeoTIFF file

for each tile. 7,709 files were produced and clipped to the data extent. Each surface was checked for surface anomalies or incorrect elevations found within the surface.

Software used included TerraScan v20, GDAL 2.4.0, Esri ArcMap v10.7, and Global Mapper v20.

2.9. Intensity Imagery

Lidar intensity data derived from the acquired lidar data was linearly rescaled from 16-bit intensity and provided as 0.5-meter pixel, 8-bit, 256 gray scale GeoTIFF files. 7,709 files were produced and clipped to the data extent.

Software used included TerraScan v20 and Esri ArcMap v10.7.

2.10. Swath Separation Image

The swath separation image was generated to visualize the DZ between the overlapping areas of the flight lines. To generate this surface a point insertion method was applied as the primary algorithm. All returns for point classes, except Classes 7 and 18, were used in the calculation for each cell. GSD and color ramp values were dependent on the Quality Level and point spacing for the project. The GSD for the surface was no more than four (4) times the NPS of the lidar data rounded to an appropriate whole number.

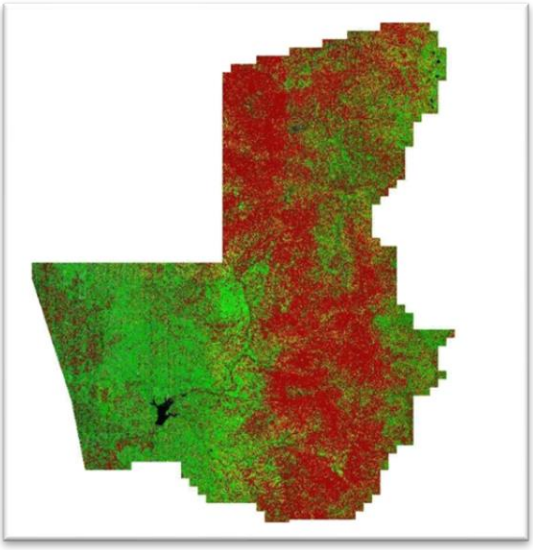
Intensity values were modulated to 50% to ensure that there is no oversaturation of intensities values throughout the surface. After all calculations and surfaces were made, 7,709 files were produced and clipped to the data extent.

Software used was GeoCue LP360.

The color ramp for the swath separation image is as follows:

- Less than 8-cm: Green
- 8 to 16-cm: Yellow
- Greater than 16-cm: Red

Figure 3.10.1 Swath Separation Image - Sample



This raster is a proof of performance check that the withheld bit flag was used properly in the point cloud. The raster is generated as a GeoTIFF and visually reviewed for anomalies that might indicate improperly classified noise. Any issues encountered are then corrected in the point cloud and a new/updated raster is generated.

Software used included TerraScan v23, Add LP360 v2022 and Esri ArcMap v10.7

2.11. Maximum Surface Height Raster

Maximum Surface Height rasters (topographic) represent a lidar-derived product illustrating natural and built-up features. NV5 generated Maximum Surface Height rasters using their proprietary software to take all valid classified lidar points, excluding those flagged with a withheld bit, and create a raster on a tile-by-tile basis. A 32-bit floating point GeoTIFF was generated for each tile with a pixel size of 1-meter. NV5 Geospatial's proprietary software was used to write appropriate horizontal and vertical projection information as well as applicable header values into the file during product generation. Each maximum surface height raster is reviewed in ESRI ArcMap to check for any anomalies and to ensure a seamless dataset. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the DEMs against what is required before final delivery.

2.12. Metadata

FGDC CSDGM/USGS MetaParser-compliant metadata was produced in XML format. The metadata includes a complete description of the task order client information, contractor information, project purpose, lidar acquisition and ground survey collection parameters, lidar acquisition and ground survey collection dates, spatial reference system information, data processing including acquisition quality assurance procedures, GPS and base station processing, geometric calibration, lidar classification, hydrologic flattening, intensity imagery development, and final product development.

Other metadata deliverables included:

- Tile index
- Georeferenced, polygonal representation of the detailed extents of each acquired lidar swath
- Swath separation images in GeoTIFF format
- Maximum height separation rasters in GeoTIFF format

3. Accuracy

3.1. Horizontal Accuracy

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 0.15 cm RMSEx / RMSEy.

Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 0.509 (m) at a 95% confidence level

3.2. Classified Point Cloud

The LAS data set was produced to meet ASPRS Positional Accuracy Standard for Digital Geospatial Data (2014) fora 10-cm RMSEz Vertical Accuracy Class.

3.3. Digital Elevation Model

The Bear-Earth DEM data set was produced to meet ASPRS Positional Accuracy Standard for Digital Geospatial Data (2014) for a 10-cm RMSEz Vertical Accuracy Class.

Table 3.3.1 NVA Accuracy Results

Parameter	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM
Sample	**45 points**	**45 points**
95% Confidence (1.96*RMSE)	0.169 m	0.167 m
Average	0.006 m	0.007 m
Median	0.006 m	0.005 m
RMSE	0.086 m	0.085 m
Standard Deviation (1σ)	0.087 m	0.086 m

Table 3.3.2 VVA Accuracy Results

Parameter	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
Sample	**43 points**	**43 points**
95th Percentile	0.484 m	0.472 m
Average	0.127 m	0.125 m
Median	0.124 m	0.123 m
RMSE	0.202 m	0.199 m
Standard Deviation (1σ)	0.159 m	0.157 m

3.4. Point Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns greater than 1 from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water, and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas, the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface. Low confidence polygons were used to denote areas of low coverage and small sections of tiles with no valid LAS points. These areas were under trees or beneath steep cliffs, which provided a challenge to lidar acquisition.

The density of ground-classified lidar returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of lidar data for the project was 23.8 points/m^2 while the average ground classified density was 10.08 points/m^2.