Lidar Mapping Report for the U.S. Geological Survey

Contractor: Woolpert Inc.
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Project Name: MT Lincoln D24
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WU Name: MT Lincoln 1 D24
Work Unit ID: 300864

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Table of Contents

1. Overview

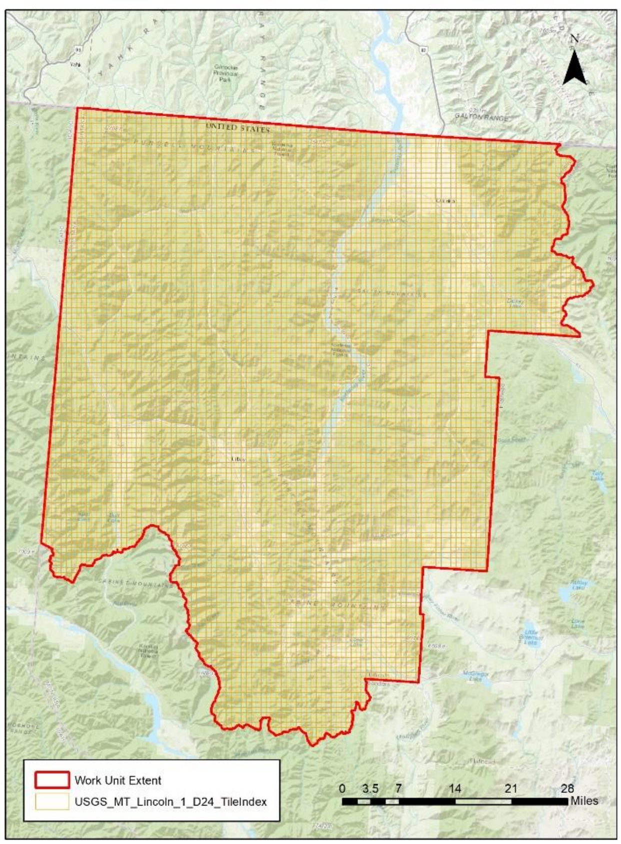
1.1. Description

MT Lincoln D24 (Task Order 140G0224F0248), was contracted to support the 3DEP mission and the needs of other federal, state, and local agencies.

This Lidar Mapping Report will cover the acquisition, processing, and derivative products of MT Lincoln D24, Work Unit 300864. Lidar data was collected to an aggregate nominal pulse spacing (ANPS) of ≤ 0.35-meters and 8-points per square meter (ppsm) covering approximately 3,693 square miles of Lincoln County, Montana to meet USGS Quality Level 1 standards. In addition to high density lidar data acquisition, new ground control survey data was collected to support lidar data production and accuracy.

Data and reporting for this work unit were acquired and produced to meet the U.S. Geological *Survey "National Geospatial Program Lidar Base Specification 2024, Revision A"*, and the American Society of Photogrammetry and Remote Sensing (ASPRS) "Positional Accuracy Standards for Digital Geospatial Data, EDITION 2, VERSION 2.0.

Figure 1.1.1 – MT_Lincoln_1_D24



1.2. Deliverables

The data deliverables for this work unit are listed below.

- Esri file geodatabase of the flight line index with georeferenced, polygonal extents detailing the actual coverage of each of the lidar swaths
- Tile Index in Esri .shp format
- Tiled classified lidar data (all returns point clouds) in LAZ 1.4 format
- Tiled bare earth DEMs generated at a 0.5-meter pixel spacing in 32-bit floating point Cloud-Optimized GeoTIFF format. Bridges and overpass structures will not be included in the bare earth model
- Hydrobreakline geopackage containing all breaklines used to generate the DEM
- Tiled Swath Separation Images (SSI) generated at 1.0-meter pixel spacing in GeoTIFF format
- Tiled Maximum Surface Height Rasters (MSHR) generated at 1.0-meter pixel spacing in GeoTIFF format
- Tiled raster DSMs generated at a 0.5-meter pixel spacing in 32-bit floating point Cloud-Optimized GeoTIFF format
- Tiled Intensity Images at a 0.5-meter pixel spacing GeoTIFF format
- Low Confidence Polygons
- Temporal Polygons
- Snow Polygons
- Lidar Mapping Report
- Product level FGDC compliant metadata in XML format for the following deliverables:
    - Classified lidar data
    - Bare earth DEM
    - Hydrobreakline geopackage
    - Swath separation images
    - Maximum surface height raster
    - DSM
    - Intensity

All tiled deliverables have a tile size of 1,000 x 1,000 meters. The delivery tiles conform to the Montana State Tiling Scheme, provided by the state of Montana. The tiled datasets contain 9,849 tiles. Due to open water there is no tiled LAZ, INT, SSI or MSHR product for the following tiles: 178495, 178496, 184543, 185540, 185541.

1.3. Spatial Reference

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

- Horizontal Datum: NAD83 (2011)
- Horizontal Projection: Montana State Plane (FIPS 2500)
- Horizontal Units: Meters
- Horizontal EPSG Code: 6514
- Vertical Datum: NAVD88
- Geoid Model: 18
- Vertical Units: Meters
- Height Type: Orthometric

2. Lidar Data Acquisition

2.1. Planning and Acquisition

Prior to mobilizing to the project site, flight crews coordinated with required air traffic control personnel to ensure airspace access. Lidar data was collected from July 21, 2024 – October 11, 2024. The following sensors were used:

- TerrainMapper – serial number 91515, last calibrated June 27, 2019
- TerrainMapper – serial number 91513, last calibrated February 25, 2019
- TerrainMapper – serial number 91511, last calibrated July 3, 2019

A total of 530 individual flight lines were collected. The calibration report and flight logs are contained in Attachment 1: Sensor Calibration Reports and Attachment 2: Flight Logs.

Flight plans were created using Leica Mission Pro v.12.5 software. Acquisition was planned based on the specifications listed below. The planned settings are listed, but please note that flight height and scan rate may vary between flights.

- Maximum number of returns per pulse: 15
- Nominal post spacing (in meters): 0.35-meters
- Nominal pulse density: 8-ppsm
- Aggregate Nominal Pulse Spacing: 0.35-meters
- Aggregate Nominal Pulse Density: 8-ppsm
- Flying Height for collection: 2,133-meters
- Nominal Flight Speed for collection: 150-knots
- Total Sensor Scan Angle: 40-degrees
- Scan Frequency of scanner: 150-hetrz
- Pulse Rate of scanner: 1,650-kilohertz
- Pulse Duration of scanner: 5-nanoseconds
- Pulse Width: 0.53-meters
- Central Wavelength of the sensor laser: 1,064-nanometers
- Multiple Pulses In Air: 1 (yes)
- Beam Divergence: 0.25-milliradians
- Swath Width on the ground: 1,553-meters
- Nominal Swath Overlap: 25%

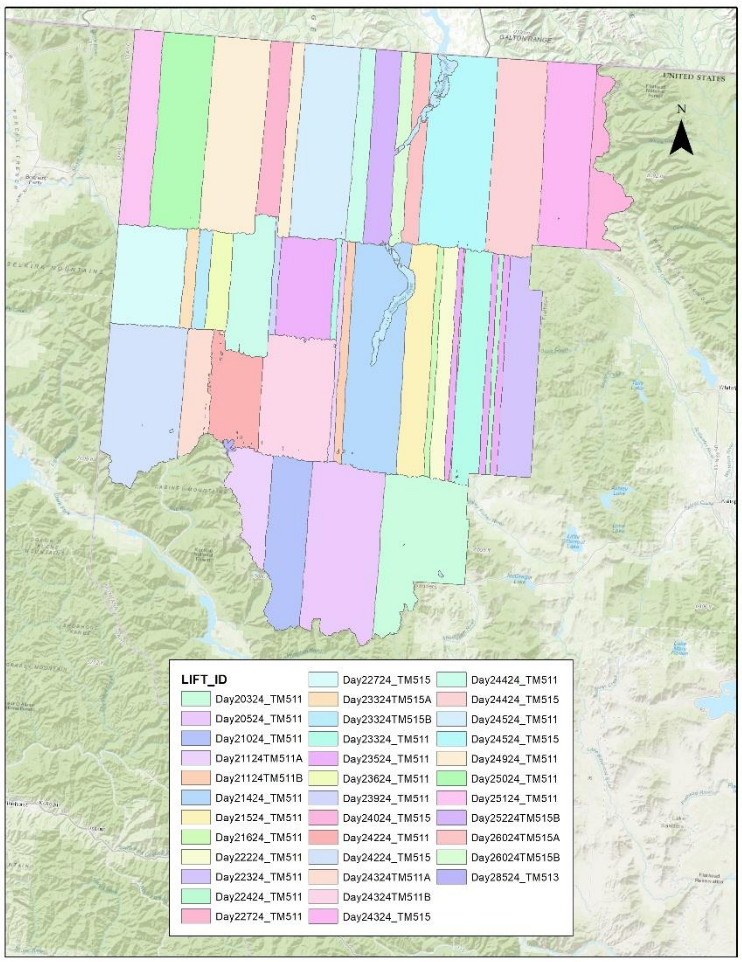
Data was collected based on the criteria listed below:

- Acquisition Conditions:
    - As early as possible to avoid potential snow in fall.
    - Leaf-off conditions.
    - Period of annual minimal water level.
    - Sky is sufficiently clear of clouds, smoke, and atmospheric haze.
- Control: Airborne Global Positioning System (ABGNSS) and Inertial Measurement Unit (IMU) data to be used along with differentially corrected GNSS 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, terrain, or other features.
    - Where appropriately filled-in by another swath.

Georeferenced, polygonal representation of the detailed extents of each lidar swath as polygon feature class in an Esri file geodatabase format as shown below.

Figure 2.1.1 - Flight Coverage by Lift



2.2. GNSS and IMU Equipment

Flight navigation during acquisition was performed by 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.

2.3. GNSS-IMU Trajectory Processing

The dataset was corrected for aircraft orientation and movement. This process used airborne inertial, orientation, and GNSS data collected during acquisition along with ground-based GNSS data. The airborne GNSS positions (collected at 1/2-second intervals) were post-processed using Novatel's Inertial Explorer software. A smoothed best estimate of trajectory (SBET) was developed by combining the corrected GNSS positions with 1/500 -second inertial measurement unit (IMU) data, which tracked the plane's roll, pitch, and yaw throughout the flight.

While generating the SBET, several factors are looked at including combined separation, the estimated positional accuracy, and the Positional Dilution of Precision (PDOP).

A Kalman filter was processed in both directions to remove the combined directional anomalies. The data for this task order was processed with a goal to maintain a combined separation difference of less than 10-cm. Estimated positional accuracy plots the standard deviations of the east, north, and vertical directions along a time scale of the trajectory. The plots were reviewed for accuracy better than 5-cm. 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.

GNSS/IMU graphics are contained in Attachment 3: GNSS IMU Images.

2.4. Acquisition Quality Assurance

Woolpert developed a quality assurance and validation plan to ensure the acquired lidar data meets the USGS Lidar Base Specification. During the initial quality check, the lidar data was processed immediately following acquisition to verify the coverage has appropriate density, distribution, and no unacceptable data voids.

The spatial distribution of the geometrically usable first return lidar points was reviewed for density by verifying the points 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. The data coverage was reviewed for unacceptable data voids to determine no area greater than or equal to $(4 \times ANPS)^2$ exhibited data coverage gaps.

Accompanying GNSS data was post processed 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.

3. Lidar Data Processing

3.1. 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 GNSS data collected during acquisition along with ground-based GNSS 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.

3.2. Boresight and Geometric Calibration

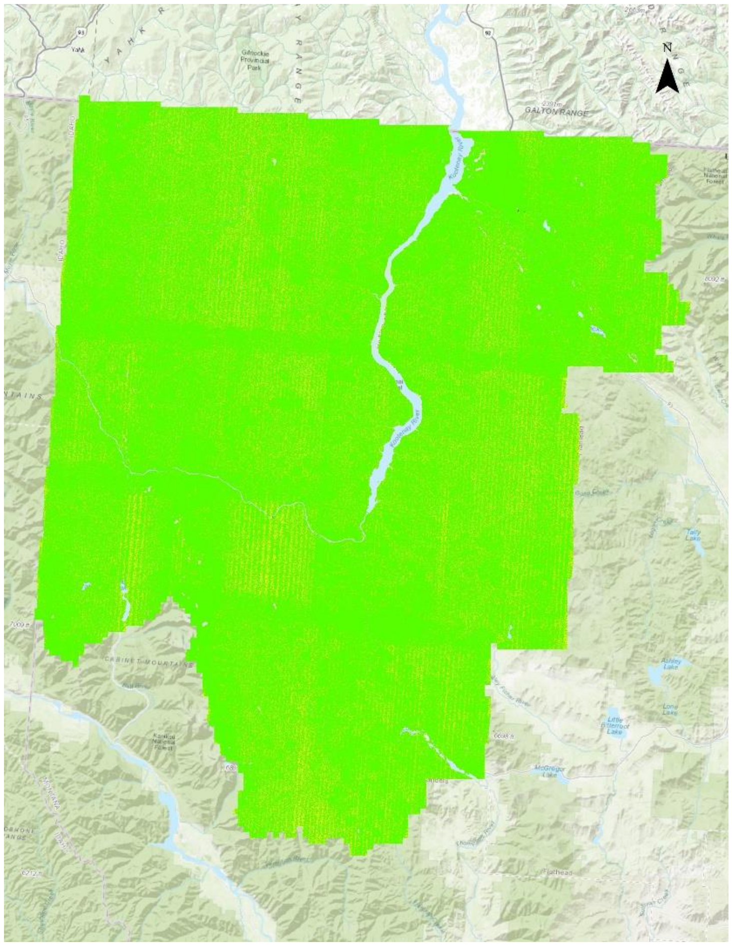
After the initial phase was complete, a formal reduction process was performed. Boresight calibrations (omega, phi, kappa) are performed, and a block adjustment is made to ensure relative accuracy. The laser point position was then calculated by associating the SBET position to each laser point return time, scan angle, intensity, etc. Raw laser point cloud data was created for the whole project area in LAS format with each point containing the corresponding scan angle, return number (echo), intensity, and x, y, and z information. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GNSS/IMU drift to test the relative calibration. Calibrations were performed on ground classified points from paired flight lines. Every flight line was used for relative accuracy calibration. 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, LAStools 240220, LP360, TerraSolid v24, and Global Mapper v25.

3.3. Density

This project required the aggregate nominal pulse spacing and density to meet the QL1 requirements of ≤0.35 (m) and ≥8.0 (pts/m2) respectively. The density was assessed by creating a raster with a cell size equal to 1 (m) that contained a count of all the points that fell within each cell. This evaluation was performed against all returns. The overall density of the project met the required specifications.

Figure 3.3.1 – Density Raster



3.4. 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. In determining ground classification, steps were utilized to classify points to low noise in order to derive the best ground model. Not all points that theoretically could be bare earth get classified to ground class at the risk of impacting the surface model in the form of pits or spikes. 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 TerraSolid/LP360 algorithms. A buffer of 0.35-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.

Sensor noise was reviewed using the normalized digital surface points that exceeded the average canopy height for this project overlayed on the maximum surface height raster's (MSHRs). A manual review was performed to also look for noise patterns falling below this threshold. All noise points were classified as Class 7 or Class 18 and flagged as withheld.

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 – 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
- Class 21 – Snow
- Class 22 – Temporal Exclusion

Classified LAZ 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. The LAS were generated in point record format 6 and delivered in LAZ 1.4 format.

Software used included proprietary software, LAStools 240220, LP360, TerraSolid v24, and Global Mapper v25.

3.5. Hydrologic Flattening and Breakline Geopackage

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 polygons 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:

- 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.
- 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.

- All classified ground points inside the hydrologic feature polygons were reclassified to Water (Class 9).
- All classified Ground points were reclassified from within a buffer along the hydrologic feature breaklines to Buffered/Ignored Ground (Class 20). The buffer distance was approximately the task order designed Nominal Pulse Spacing distance.
- Breaklines used for bridge removal during the hydrologic flattening were included with the hydrologic breakline geopackage deliverable. These breaklines produce a more aesthetically pleasing DEM appearance.
- The lidar ground points and breaklines were used to generate a DEM.
- 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.

All hydro breaklines compiled as part of the flattening process as well as bridge breaklines were provided in a breakline geopackage. These breaklines were used for DEM generation were provided as Polygon and Polyline features respectively. Also included in breakline geopackage are centerlines used to elevate stream polygons.

The centerlines included in the geopackage were generated using the following process:

- For each stream with a distinct flow, 2D centerlines are extracted. The centerline is placed in the middle of stream and as close to parallel as possible to adjacent banks of stream. This will sometimes require centerline to be drawn over islands to maintain parallel relationship of centerline and stream banks. Points within islands are ignored for the process of centerline processing.
- The centerline is densified to adequately capture varying changes in slope. Proprietary software will then elevate each vertex of centerline based on lowest surrounding surface. This is achieved by finding the closest group of ground returns and taking the lowest ground return to assign its z value to corresponding centerline vertex.
- The centerline is then checked to confirm the direction of centerline is pointing downstream and downstream constraint (Arc Hydro Tools) is then applied to the centerline to ensure monotonicity.
- All centerlines are checked for elevation agreement at stream junctions as well as any connection to waterbody features.
- LP360 is then used to conflate z values of centerline to corresponding vertices of stream polygon and the stream is checked to be at or below adjacent shoreline.
- After placement of stream is determined to be acceptable, a temporary surface is constructed using the stream breaklines only.
- Stream islands are then dropped onto this surface to achieve agreement with stream breaklines.

Software used included TerraSolid v24, Esri ArcMap v10.8, LP360, GDAL 3.8.1 and LAStools 240220.

3.6. Digital Elevation Model (DEM)

TerraSolid was used to add the hydrologic breakline vertices and export the lattice models using triangulated model-z interpolation method. 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. Each surface was checked for surface anomalies or incorrect elevations found within the surface.

Software used included TerraSolid v24, GDAL 3.8.1, Esri ArcMap v10.8, Global Mapper v25, and LAStools 240220.

3.7. Digital Surface Model (DSM)

The method used to create the 0.5-meter resolution DSM consisted of isolating any first return point and processing into a gridded format. Following QAQC process completion, a gridded raster file was created on a per tile basis. The task order projection information was applied to the final raster dataset. Prior to delivery, all raster files were visually reviewed to ensure coverage and validated using automated processes to ensure proper formatting.

Software used included TerraSolid v24, GDAL 3.8.1, Esri ArcMap v10.8, Global Mapper v25, and LAStools 240220.

3.8. 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.

Software used included Software used was LAStools 240220 v24, and Esri ArcMap v10.8.

3.9. Swath Separation Image (SSI)

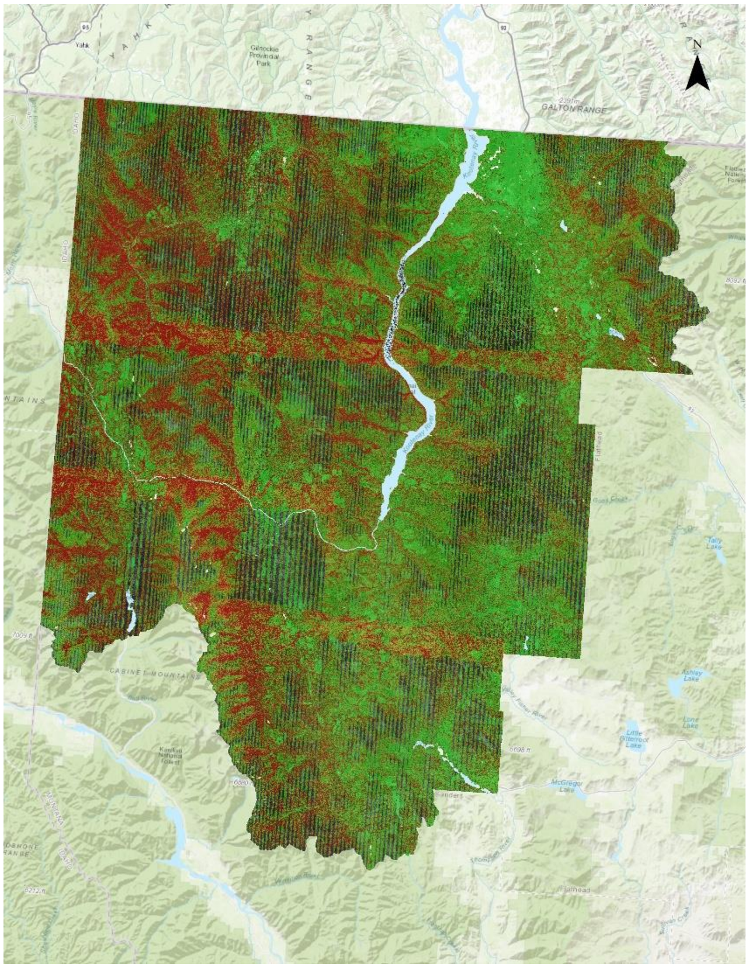
The Swath Separation Image (SSI) was generated to visualize the DZ between the overlapping areas of the flight lines. The SSI is generated with a point insertion gridding method from lidar last return points, excluding points classified as noise and/or flagged as withheld. For non-excluded last return points that fall within a given cell, the point with the lowest Z value from each flight line is selected; the separation value for that cell is then computed as the maximal vertical distance (dZ) between the selected points. A GeoTIFF was generated, and the color ramp is based on a QL1 data product. Intensity values were modulated to 50% to ensure that there is no oversaturation of intensities values throughout the surface. The GSD for the raster is 1 meter, which is two times the DEM post spacing.

Software used was LAStools 240220.

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

- Less than 8-cm: Green
- 8 to 16-cm: Yellow
- 16 to 24-cm: Orange
- Greater than 24-cm: Red

Figure 3.9.1 - Swath Separation Images

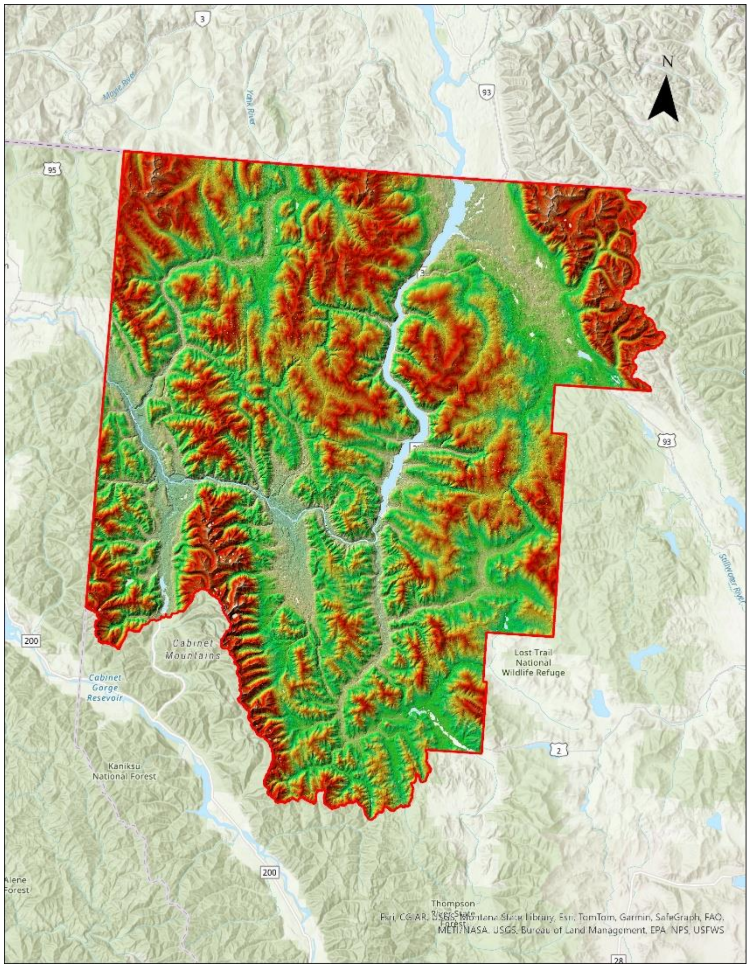


3.10. Maximum Surface Height Rasters (MSHR)

The Maximum Surface Height Rasters are a proof of performance check using all lidar returns excluding points flagged as withheld to show that the withheld bit flag was used properly in the point cloud. The MSHRs are generated as a 32-bit floating-point GeoTIFF with each pixel being generated as highest-hit elevation and is visually reviewed for anomalies that might indicate improperly classified noise. NODATA values are assigned -999999. Any issues encountered are then corrected in the point cloud and a new/updated raster is generated. The GSD for the raster is 1 meter, which is two times the DEM post spacing.

Software used included LAStools 240220.

Figure 3.10.1 - Maximum Height Surface Raster



The method used to create the DSM consisted of isolating any first return point and processing into a gridded format. Following QAQC process completion, a gridded raster file was created on a per tile basis. The task order projection information was applied to the final raster dataset. Prior to delivery, all raster files were visually reviewed to ensure coverage and validated using automated processes to ensure proper formatting.

3.11. Snow Polygon

The snow polygons were generated to identify areas where Class 21 was used to generate DEM surface. The snow polygons have been provided as a shapefile.

3.12. Temporal Polygon

The temporal polygons were generated in areas where snow melt or earth moving occurred across acquisition dates. The temporal polygons have been provided as a shapefile.

3.13. Low Confidence Polygon

Low confidence polygons were generated for 4216 areas totaling 64.1 square miles where sensor drop-out resulted in single swath areas and diminished point density.

Figure 3.13.1 - SSI Image tiles 137530 and 137531

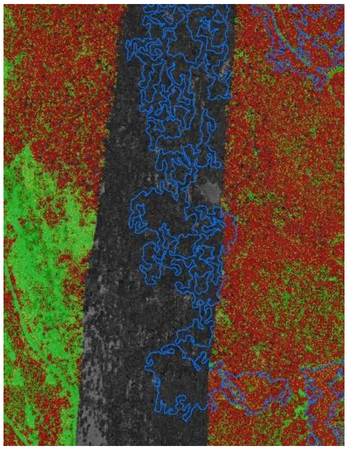
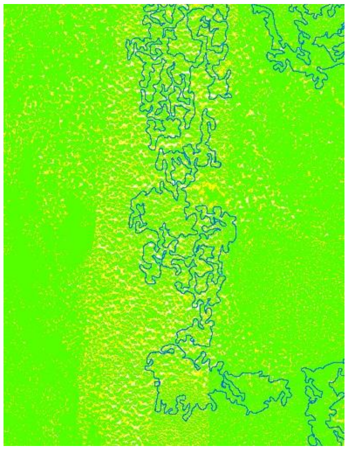


Figure 3.12.2 - Density Image tiles 137530 and 137531. Yellow pixels represent density of 1-7.99 ppsm. Green pixels represent density 8.0 and above ppsm.



3.14. 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, GNSS and base station processing, geometric calibration, lidar classification, hydrologic flattening, and final product development. Product level metadata was created for the following deliverables:

- Classified LAS
- Bare Earth DEM
- Hydro Geopackage
- DSM
- SSI
- MSHR
- Intensity

4. Accuracy

4.1. 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 v2024, Revision A".

The interswath precision was calculated using 8 sample locations in flat/open terrain against overlapping swaths and first-return points only. The achieved interswath accuracy is RMSDz= 2.1-cm.

4.2. 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 v2024, 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= 1.8-cm.

4.3. Horizontal Accuracy

This data set was calculated using the formula provided in section 7.6 of the "ASPRS Positional Accuracy Standard for Digital Geospatial Data Edition 2, Version 2 of 2024". The calculated horizontal positional accuracy was found to be RMSEH = 20.0-cm.

4.4. Classified Point Cloud

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

4.5. Digital Elevation Model

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