Dewberry

MT_HighlineCompletion Wibaux_2021_D21

Report Produced for U.S. Geological Survey

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1. EXECUTIVE SUMMARY

The primary purpose of this project was to develop a consistent and accurate surface elevation dataset derived from high-accuracy light detection and ranging (lidar) technology for the MT Highline Completion Wibaux 2021 D21 project area. This project will support United States Fish and Wildlife Service (USFWS), Natural Resources Conservation Service (NRCS), and the 3DEP mission.

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 24,678 tiles were produced for the project, providing approximately 9,248 sq. miles of coverage. Originally, the project contained 24,766 tiles. However, 88 raster files were not delivered due to the tiles being smaller than one pixel. The project tile grid and DPA were updated to remove these tiles.

1.1 Project Team

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

Dewberry and Aero-Graphics completed the ground survey for the project and delivered surveyed checkpoints. Ground control points and checkpoints were surveyed for the project. Ground control points were used in calibration activities and checkpoints were used in independent testing of the vertical accuracy of the lidar-derived surface model.

Aero-Graphics and Eagle Mapping completed lidar data acquisition and data calibration for the project area.

1.2 Project Area

The project area is shown in Figure 1. The project tile grid contains 24,678 1,000 m by 1,000 m tiles.

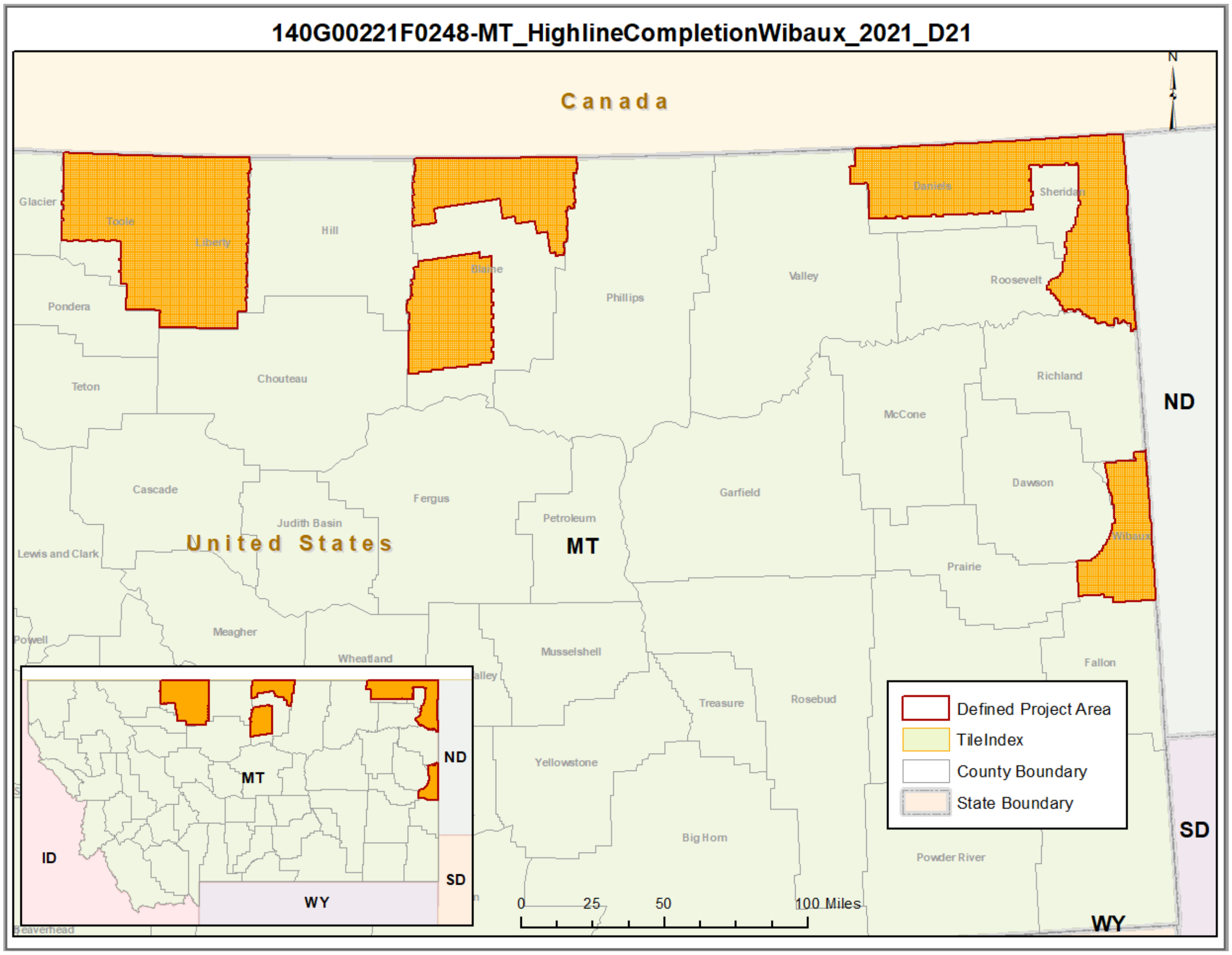


Figure 1. Project map and tile grid.

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: StatePlane Montana FIPS 2500
Horizontal Units: Meters
Vertical Units: Meters

1.4 Project Deliverables

The deliverables for the project are as follows:

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

1.5 Dewberry Production Workflow Diagram

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

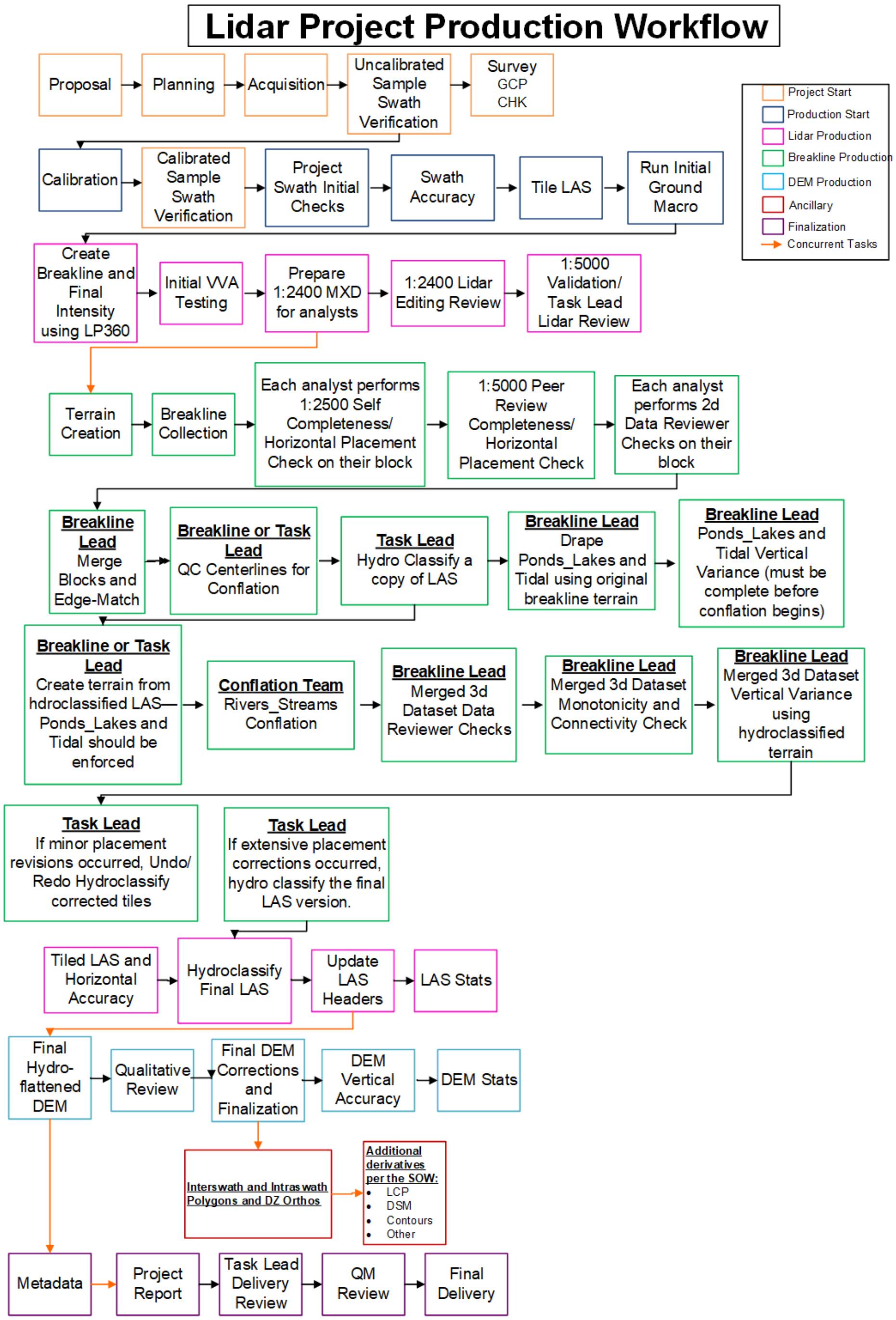


Figure 2. Dewberry's Lidar Production Workflow Diagram

2. LIDAR ACQUISITION REPORT

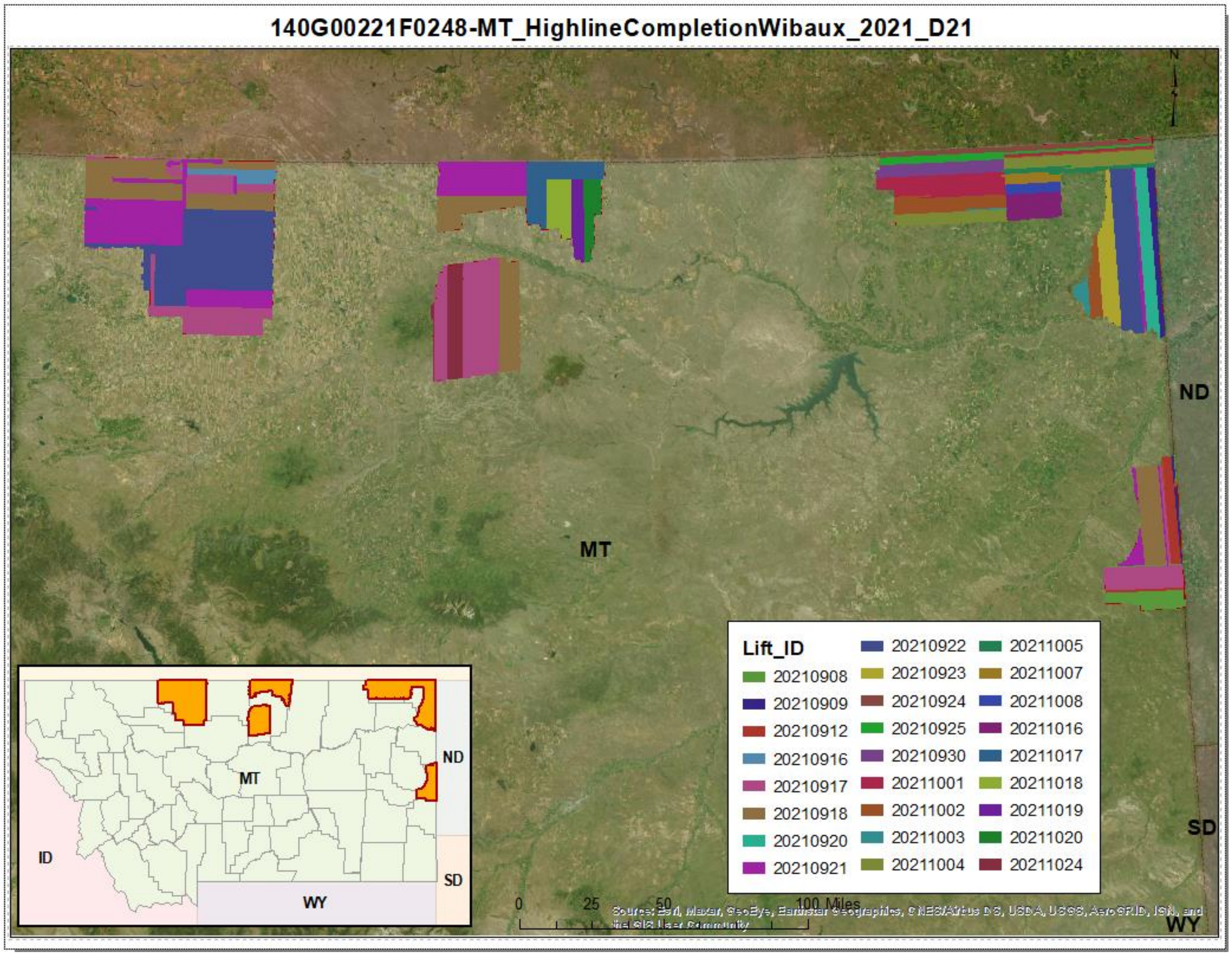
2.1 Acquisition Summary

Dewberry elected to subcontract the lidar acquisition activities to Aero-Graphics, Inc. (AGI) and Eagle Mapping (Eagle). Acquisition providers AGI and Eagle were responsible for lidar acquisition, raw data conversion from sensors and delivery of lidar data files to Dewberry for this work unit. Acquisition provider AGI acquired QL2 lidar data using an Optech Galaxy PRIME lidar sensor and Eagle acquired QL2 lidar data using Riegl VQ1560ii and Riegl LMS Q1560 lidar sensors for this work unit by monitoring suitable ground and weather conditions according to 3DEP lidar base specifications.

Acquisition providers planned a total of 598 passes over the project area for Quality Level 2 data acquisition as a series of parallel flight lines with cross flight lines for the purposes of quality control. AGI planned 371 passes and Eagle planned 227 passes over the defined project area. The flight plan included zigzag flight line collection to compensate for the drift commonly associated with onboard inertial measurement unit (IMU) systems. To reduce potential errors in the data attributable to flight planning, Acquisition Providers followed FEMA's Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix A: Guidance for Aerial Mapping and Survey. The guidance includes the following minimum criteria:

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

AGI and Eagle monitored weather and atmospheric conditions and conducted lidar missions only when no conditions existed below the sensor that would affect the collection of data. Acquisition partners accessed reliable weather sites and indicators (webcams) to establish the highest probability for successful data acquisition. Acquisition for the entire project was performed from September 08, 2021 through October 24, 2021. Some re-flights were performed due to turbulence, ground fog and/or smoke that occurred along a given swath.



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

Figure 3. Project swaths

2.2 Sensor Calibration and Boresight

Prior to the acquisition, sensor boresight calibrations were performed by acquisition providers at their respective base locations. AGI completed sensor boresight on 09/24/19 in Salt Lake City, UT and Eagle completed sensor boresight on 02/28/2020. Boresight 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 Applanix PosPac and raw swath data (.las) was produced using respective sensor software suite. The boresight was calibrated and then analyzed. All deemed necessary corrections are then applied to the senor orientation internal files.

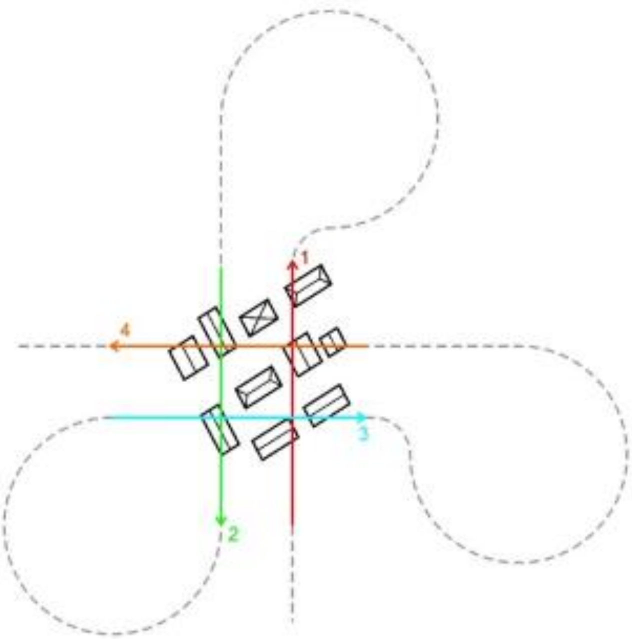


Figure 4. A typical calibration and boresight flight plan where above ground features are acquired from all four cardinal directions, any offsets of the above ground features between overlapping and other directional flight lines is analyzed, and corrections are applied as necessary to ensure proper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

2.3 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	598
Approximate Area	9.249 sq. miles
Acquisition Dates	September 8, 2021-October 24, 2021
Horizontal Datum	North American Datum of 1983 (NAD83_2011)
Vertical Datum	North American Vertical Datum of 1988 (NAVD88)
Geoid Model	Geoid18
Coordinate Reference System	StatePlane Montana
Horizontal Units	Meters
Vertical Units	Meters
Kinematic Solution Processing Software:	POSPac MMS GNSS Inertial software
Point Cloud Generation Software	Riegl's RiProcess Software, Optech LMS Software
Calibration Software	BayesMap Strip Align

2.4 Lidar System parameters

Aero-Graphics operated a Cessna 206 (Tail # N27DV) outfitted with an Optech Galaxy Prime lidar system during the collection of the study area. Eagle Mapping utilized Riegl LMS-Q1560 and VQ-1560ii dual-channel Lidar systems for acquisition of the lidar data with two aircrafts. These systems were installed in Piper Navajo aircraft operated by Peregrine Aerial Surveys out of Abbotsford, BC, Canada. Tables 2 outlines Aero-Graphics' and Eagle Mapping's system parameters for Lidar acquisition on this project.

Table 2. Lidar system parameters

Parameter	Value	Value	Value
System	Optech Galaxy Prime	Riegl LMS Q1560	Riegl VQ-1560ii
Altitude (m above ground level)	1250	1700	2000
Nominal flight speed (kts)	120	150	150
Scanner pulse rate (kHz)	550	800	1000
Scan frequency (Hz)	84.1	200	204
Pulse duration of the scanner (ns)	3	3	3
Pulse width of the scanner (m)	0.4	0.8994	0.8994
Central wavelength of the sensor laser (nm)	1064	1024	2241
Multiple pulses in the air	Yes	Yes	Yes
Beam divergence (mrad)	0.25 mrad (1/e)	<0.25	<0.25
Swath width (m)	1064	1905	2241
Nominal swath width on the ground (m)	873	1848	2174
Swath overlap (%)	20	>25%	>25%
Total sensor scan angle (degrees)	39	58.52	58.52
Computed down track spacing per beam (m)	0.33	0.74	0.71
Computed cross track Spacing per beam (m)	0.37	0.74	0.72
Nominal pulse spacing (NPS) (single swath) (m)	0.33	0.54	0.51
Nominal Pulse Density (NPD) (single swath) (points per sq m)	8.2	3.5	3.8
Aggregate NPS (m) (if NPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.37	0.54	0.51
Aggregate NPD (m) (if NPD was designed to be met through single coverage, ANPD and NPD will be equal)	8.2	3.5	3.8
Maximum Number of Returns per Pulse	8	Unlimited	Unlimited

2.5 Acquisition Static Control

The project area consists of limited number of operational CORS base stations operating at 1 Hz and many areas are not accessible by road to set up base stations. As a result, base stations were not setup to meet the

20-mile baseline requirement. Instead, Trimble PP-RTX solution for GPS/IMU data post-processing approach was utilized during the lidar acquisition and adjustment of trajectories due to the lack of CORS network. PP-RTX uses Applanix POSPac MMS software leveraging near real- time atmospheric models from Trimble's extensive worldwide network of continuously operating base stations to produce highly accurate trajectories. Detailed parameters information is provided in Appendices A and B: GPS Processing Reports.

2.6 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.

Appendices A and B contain 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 (NAD83)
Vertical Datum	North American Vertical Datum of 1988 (NAVD88)
Geoid Model	Geoid18
Coordinate Reference System	StatePlane_Montana_FIPS_2500
Horizontal Units	Meters
Vertical Units	Meters

2.7 Final Calibration Verification

Aero-Graphics and Dewberry surveyed 121 ground control points (GCPs) in flat, non-vegetated areas to test the accuracy of the calibrated swath data. GCPs were located 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.

One ground control point (GCP-35) was removed from the calibrated swath vertical accuracy testing due to noise in the raw swath dataset. When testing calibrated swath data, the unclassified swath data has not been classified to remove vegetation, structures, and other above ground features from the ground classification. While GCP-35 is in open terrain, the noise beneath the ground class is modeled by the lidar point cloud. These low points caused erroneous high values during the swath vertical accuracy testing, so these points were removed from the final calculations. Table 4, below, provides the coordinates for this checkpoint and the vertical accuracy results from the calibrated swath data. Figure 5, below, shows a cross section of the lidar point in LP360.

Table 4. Ground control point removed from calibrated swath vertical accuracy testing.

Point ID	State Plane Montana NAD83(2011), m		NAVD88 Geoid18, m		Delta Z (m)
	Easting X (m)	Northing Y (m)	Survey Z (m)	Lidar Z (m)	
GCP-35	494260.671	464637.282	962.867	959.749	-3.118

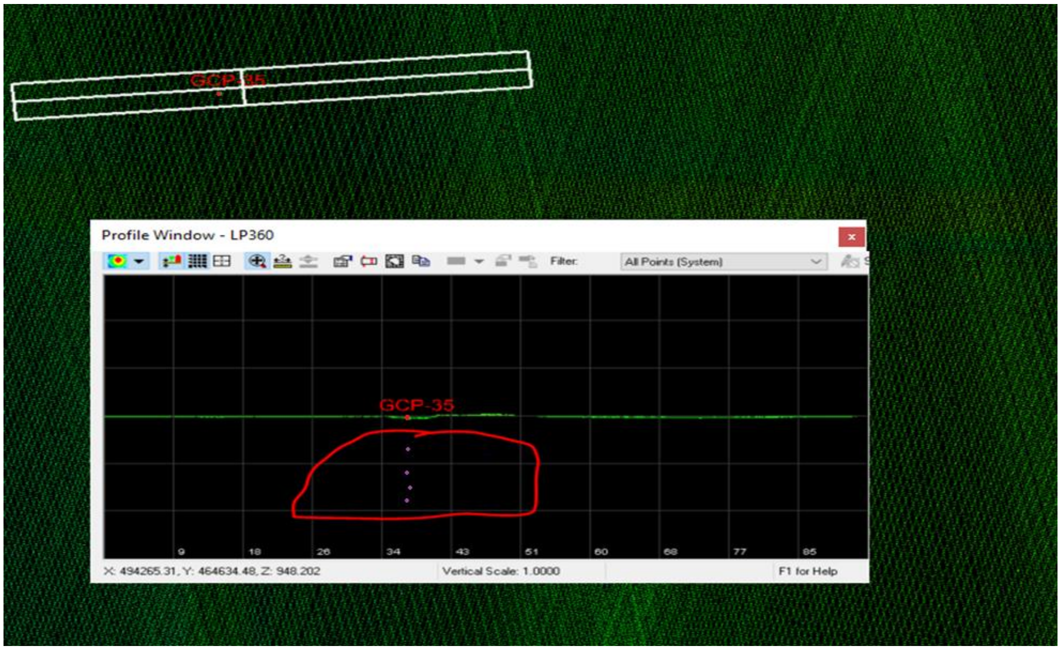


Figure 5. Ground control point GCP-35, shown as the red dot in the above image. This point was removed from calibrated swath vertical accuracy testing because noise, pink and circled in red, is causing a drop in the delta Z value.

Table 5.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)	121	0.047	0.093	0.005	-0.002	1.22	0.047	-0.092	0.247	4.868

3. LIDAR PROCESSING & QUALITATIVE ASSESSMENT

3.1 Initial Processing

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

3.1.1 Post Calibration Lidar Review

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

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

Requirement	Description of Deliverables	Additional Comments
Non-vegetated vertical accuracy (NVA) of the swath data meet required specifications of 19.6 cm at the 95% confidence level based on RMSEz (10 cm) x 1.96	The swath NVA was tested and passed specifications.	None
The NPD/NPS (or Aggregate NPD/Aggregate NPS) meets required specification of 2 ppsm or 0.7 m NPS. The NPD (ANPD) is calculated from first return points only.	The average calculated (A)NPD of this project is 8.24 ppsm. Density raster visualization also passed specifications.	None
Spatial Distribution requires 90% of the project grid, calculated with cell sizes of 2*NPS, to contain at least one lidar point. This is calculated from first return points only.	98% of cells (2*NPS cell size) had at least 1 lidar point within the cell.	None
Within swath (Intra-swath or hard surface repeatability) relative accuracy must meet ≤ 6 cm maximum difference	Within swath relative accuracy passed specification.	None
Between swath (Inter-swath or swath overlap) relative accuracy must meet 8 cm RMSDz/16 cm maximum difference.	Between swath relative accuracy passed specification, calculated from single return lidar points.	None

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

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

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

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

The withheld bit was set on the withheld points previously identified in TerraScan before the ground classification routine was performed. The withheld bit was set on points classified as noise (classes 7 and 18) after manual clean-up.

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

3.2.1 Qualitative Review

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

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

Table 7. 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. The LAS files were used to produce density grids based on Class 2 (ground) points for review.	No unacceptable voids were identified in this dataset
Artifacts	Artifacts in the point cloud are typically caused by misclassification of points in vegetation or man-made structures as ground. Low-lying vegetation and buildings are difficult for automated grounding algorithms to differentiate and often must be manually removed from the ground class. Dewberry identified these features during lidar editing and reclassified them to Class 1 (unassigned). Artifacts up to 0.3 m above the true ground surface may have been left as Class 2 because they do not negatively impact the usability of the dataset.	None

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

Category	Editing Guideline	Additional Comments
	features, Dewberry edits the features to class 2 (ground)	
Irrigated Agricultural Areas	Per project specifications, Dewberry collected all areas of standing water greater than or equal to 0.8 hectare, 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 0.8 hectare size criteria were not collected.	Standing water within agricultural areas not present in the data
Wetland/Marsh Areas	Vegetated areas within wetlands/marsh areas are not considered water bodies and are not hydroflattened in the final DEMs. However, it is sometimes difficult to determine true ground in low wet areas due to low reflectivity. In these areas, the lowest points available are used to represent ground, resulting in a sparse and variable ground surface. Open water within wetland/marsh areas greater than or equal to 2 acres is collected as a waterbody.	No marshes present in the data
Flight Line Ridges	Flight line ridges occur when there is a difference in elevation between adjacent flight lines or swaths. If ridges are visible in the final DEMs, Dewberry ensures that any ridges remaining after editing and QA/QC are within project relative accuracy specifications.	No flight line ridges are present in the data
Temporal Changes	If temporal differences are present in the dataset, the offsets are identified with a shapefile.	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	No Low NIR Reflectivity is present in the data

Category	Editing Guideline	Additional Comments
	surface, these locations are identified with a shapefile.	
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 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.	No Laser Shadowing is present in the data

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 8. Classified lidar formatting parameters

Parameter	Project Specification	Pass/Fail
LAS Version	1.4	Pass
Point Data Record Format	6	Pass

Parameter	Project Specification	Pass/Fail
Horizontal Coordinate Reference System	NAD83 (2011) StatePlane Montana FIPS 2500, meters in WKT format	Pass
Vertical Coordinate Reference System	NAVD88 (Geoid18), 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
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 Class 22: Temporal	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

3.2.3 Synthetic Points

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

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

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

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

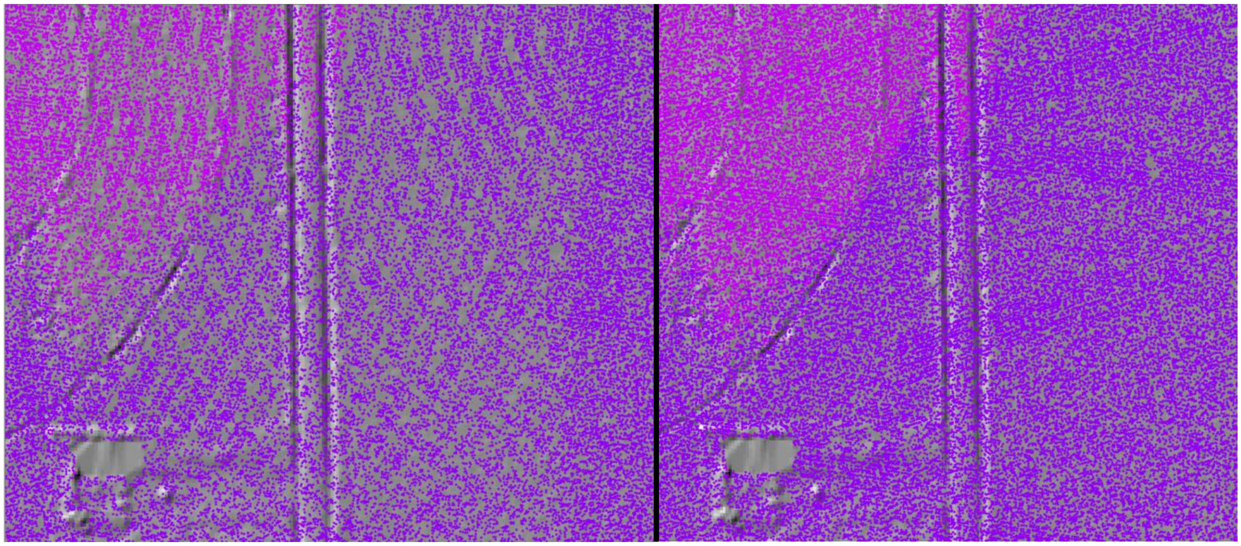


Figure 6. The left image shows ground classified without synthetic points. The right image shows ground classified with synthetic points. Both images are overlaid on a hillshade of the example area.

4. LIDAR POSITIONAL ACCURACY

4.1 Background

Dewberry quantitatively tested the dataset by testing the vertical accuracy of the lidar. The vertical accuracy is tested by comparing the discreet measurement of the survey checkpoints to that of the interpolated value within the three closest lidar points that constitute the vertices of a three-dimensional triangular face of the TIN. Therefore, the result is that only a small sample of the lidar data is tested. However, there is an increased level of confidence with lidar data due to the relative accuracy (see sections 7.1 and 7.2). This relative accuracy in turn is based on how well one lidar point "fits" in comparison to the next contiguous lidar measurement and is verified as part of the initial processing. If the relative accuracy of a dataset is within specifications and the dataset passes vertical accuracy requirements at the location of survey checkpoints, the vertical accuracy results can be applied to the whole dataset with high confidence due to the passing relative accuracy. For accuracy testing, Dewberry typically uses proprietary software, which utilizes both Esri and lastools software within its workflow, to test the swath lidar vertical accuracy and classified lidar vertical accuracy.

Horizontal accuracy testing was not required for this project.

4.2 Surveyed Vertical Accuracy Checkpoints

The MT Highline Completion Wibaux lidar project encompasses approximately 9,249 square miles within the state of Montana covering five different AOIs. The figure below shows the five AOIs with checkpoints that were collected. A complete list of survey checkpoints is contained in the project survey report, which is included as a project deliverable.

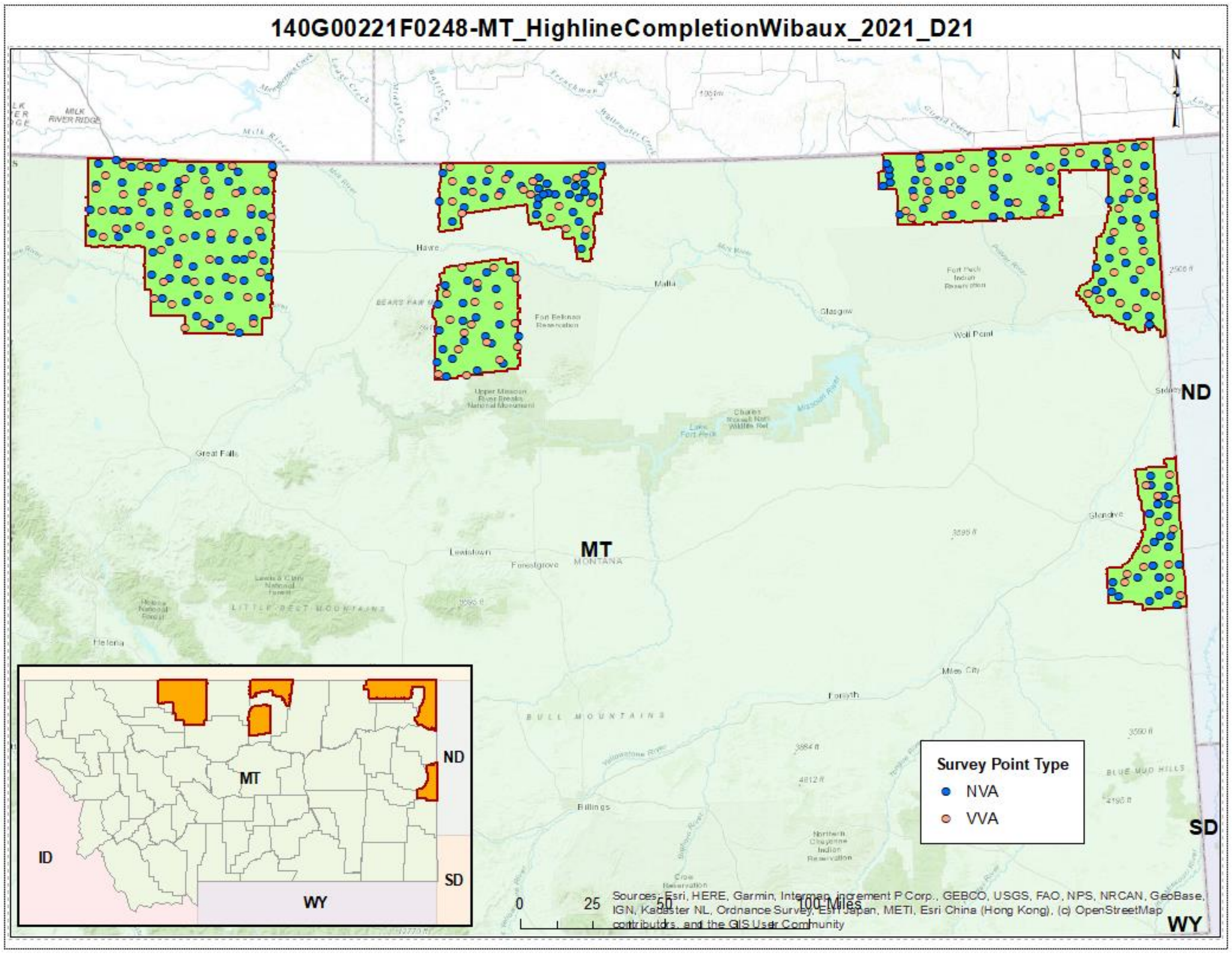


Figure 7. Project map showing five different AOIs outlined and checkpoints in each AOI displayed.

4.3 Vertical Accuracy Test Procedures

NVA (Non-vegetated Vertical Accuracy) reflects the calibration and performance of the lidar sensor. NVA was determined with checkpoints located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas. In these locations it is likely that the lidar sensor detected the bare-earth ground surface and random errors are expected to follow a normal error distribution. Assuming a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_Z$) of the checkpoints x 1.9600.

VVA (Vegetated Vertical Accuracy) was determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas. In these locations there is a possibility that the lidar sensor and post-processing may yield elevation errors that do not follow a normal error distribution. VVA at the 95% confidence level equals the 95th percentile error for all checkpoints in all vegetated land cover categories combined. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the VVA.

The relevant testing criteria are summarized in the table below.

Table 9. Vertical accuracy acceptance criteria

Land Cover Type	Quantitative Criteria	Measure of Acceptability
NVA	Accuracy in open terrain and urban land cover categories using RMSEz *1.9600	19.6 cm (RMSE$_z$ 10 cm)
VVA	Accuracy in vegetated land cover categories combined at the 95th percentile	30 cm

4.4 Final Swath Vertical Accuracy Assessment

Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to additional processing. Dewberry tested the vertical accuracy of the swath data using the non-vegetated (open terrain and urban) independent survey checkpoints. The vertical accuracy is tested by comparing survey checkpoints in non-vegetated terrain to a triangulated irregular network (TIN) that is created from the raw swath points. Only checkpoints in non-vegetated terrain can be tested against raw swath data because the data has not undergone classification techniques to remove vegetation, buildings, and other artifacts from the ground surface. Checkpoints are always compared to interpolated surfaces from the lidar point cloud because it is unlikely that a survey checkpoint will be located at the location of a discrete lidar point. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy. The table below summarizes the swath project accuracy specification, the amount of NVA points tested, and the final tested swath accuracy results.

Table 10. Tested NVA and descriptive statistics from unclassified lidar swaths

100 % of Totals	# of Points	RMSEz (m) NVA	NVA (m) Spec=0.196	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	199	0.068	0.133	-0.011	-0.005	-5.086	0.067	37.925	-0.544	0.094

Two checkpoints (N314 and NVA-72) were removed from the raw swath vertical accuracy testing due to noise in the raw swath dataset. Only non-vegetated terrain checkpoints are used to test the unclassified swath data because the unclassified swath data has not been classified to remove vegetation, structures, and other above ground features from the ground classification. While N314 and NVA-72 are in open terrain, the noise beneath the ground class is modeled by the lidar point cloud. These low points caused erroneous high values during the swath vertical accuracy testing, so these points were removed from the final calculations. Once the data underwent the classification process, the noise was removed from the final ground classification and these points could be used in the final vertical accuracy testing for the fully classified lidar data. Table 11, below, provides the coordinates for these checkpoints and the vertical accuracy results from the unclassified swath data. Table 12, below, provides the usable vertical accuracy results of these checkpoints from the fully classified lidar. The differences in the tables show how above ground features can cause erroneous vertical accuracy results in the unclassified swath data. Figure 8, below, shows a cross section of the lidar point cloud and the location of the checkpoint via imagery. Figure 9, below, shows a cross section of the lidar point in MicroStation.

Table 11. Checkpoints removed from unclassified swath vertical accuracy testing

Point ID	State Plane Montana NAD83(2011), m		NAVD88 Geoid18, m		Delta Z (m)
	Easting X (m)	Northing Y (m)	Survey Z (m)	Lidar Z (m)	
N314	1013176.506	304330.774	851.969	825.086	-26.883
NVA-72	614072.355	503967.252	792.192	786.606	-5.586

Table 12. Final tested vertical accuracy post ground classification

Point ID	State Plane Montana NAD83(2011), m		NAVD88 Geoid 18, m		Delta Z (m)
	Easting X (m)	Northing Y (m)	Survey Z (m)	Lidar Z (m)	
N314	1013176.506	304330.774	851.969	851.931	-0.038
NVA-72	614072.355	503967.252	792.192	792.160	-0.032

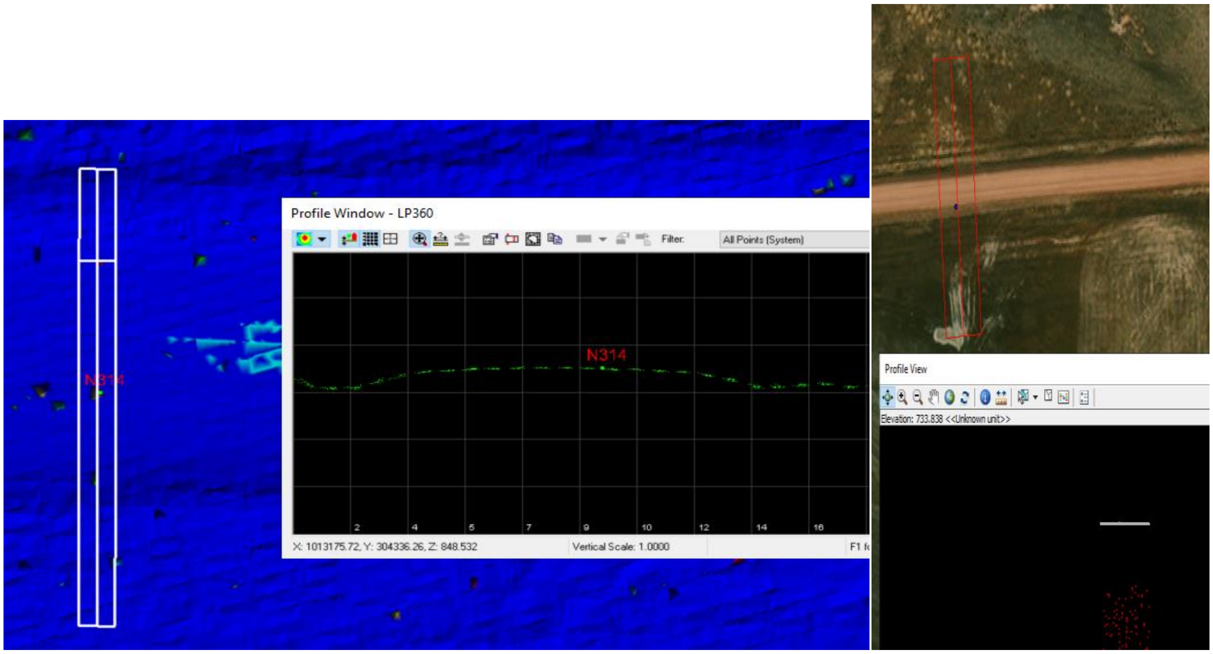


Figure 8. Open Terrain checkpoint N314, shown as the green dot in the above image, is located on the edge of a road. This point was removed from raw swath vertical accuracy testing because noise was causing the drop in the delta Z value.

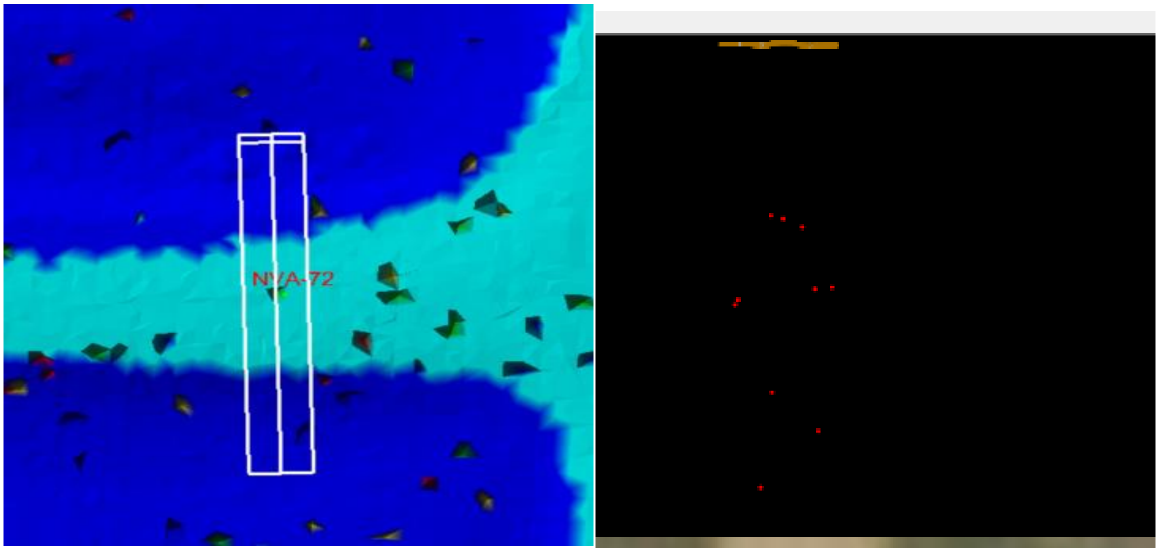


Figure 9. Open Terrain checkpoint NVA-72, shown in the left image, this point was removed from raw swath vertical accuracy testing because noise was causing the drop in the delta Z value.

4.5 Classified Lidar Vertical Accuracy Results

The table below summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar LAS files.

Table 13. Tested NVA and VVA for the classified lidar

Land Cover Type	# of Points	NVA (m)	VVA (m)
Project Specification	**315**	**0.196**	**0.300**
NVA	201	0.068	-
VVA	136	-	0.054

This classified lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSE$_z$ vertical accuracy class. Actual NVA accuracy was found to be RMSE$_z$ = 6.8 cm, equating to ± 13.3 cm at 95% confidence level. Actual VVA accuracy was found to be ± 12.1 cm at the 95th percentile. The 5% outliers are listed in Table 14. Descriptive statistics for both sets of checkpoints are presented in Table 15.

Table 14. VVA 5% outliers

Point ID	UTM Zone 16N NAD83(2011), m		NAVD88 Geoid18, m		Delta Z (m)
	Easting X (m)	Northing Y (m)	Survey Z (m)	Lidar Z (m)	
VVA-6	469445.046	519071.130	1191.994	1192.140	+0.146
VVA-9	498644.686	512788.531	1044.702	1044.840	+0.138
VVA-36	496107.363	477474.776	983.302	983.433	+0.131
VVA-37	500706.424	467712.510	973.811	973.961	+0.150
VVA-43	471531.614	452133.339	935.424	935.562	+0.138
VVA-51	628145.045	524805.077	853.183	853.323	+0.140
V209	891398.375	530987.305	825.452	825.574	+0.122

Table 15. Classified lidar vertical accuracy descriptive statistics

Land Cover Type	# of Points	RMSE$_z$ (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	201	0.068	-0.012	-0.006	-5.110	0.067	-0.544	0.094	38.320
VVA	136	-	0.024	0.021	0.362	0.049	-0.106	0.150	0.227

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for MT Highline Completion Wibaux satisfies the vertical accuracy requirements.

4.6 Horizontal Accuracy Test Procedures

Horizontal accuracy testing requires well-defined checkpoints that can be visually identified in the dataset. Elevation datasets, including lidar datasets, do not always contain well-defined checkpoints suitable for horizontal accuracy assessment. Dewberry reviewed all NVA checkpoints to determine which, if any, of these checkpoints were located on photo-identifiable features in the intensity imagery. This subset of checkpoints was used for horizontal accuracy testing.

The horizontal accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed X, Y, and Z coordinates for discrete checkpoints in accordance with project specifications. Dewberry targeted half of the NVA checkpoints for location on features that would photo-identifiable in the intensity imagery.
2. Following initial processing, Dewberry located the photo-identifiable features in the intensity imagery, utilizing Esri software.
3. Dewberry computed the differences in X and Y values between the surveyed coordinates and the lidar coordinates of the photo-identifiable feature.
4. Horizontal accuracy was assessed based on these data using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. The results are provided in the following section.

4.7 Horizontal Accuracy Results

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called Accuracy_r) is computed by the formula RMSE_r * 1.7308 or RMSE_{xy} * 2.448.

This dataset was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSE_x/RMSE_y horizontal accuracy class which equates to a positional horizontal accuracy of ± 1 meter at the 95% confidence level.

5. BREAKLINE PROCESSING & QUALITATIVE ASSESSMENT

5.1 Breakline Production Methodology

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

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 lidar point cloud. Subsequent processing was done on ponds/lakes to identify the minimum z-values within these features and re-applied that minimum elevation to all vertices of the breakline feature.

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

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

5.1.1 Breakline Collection Requirements

The table below outlines breakline collection requirements for this dataset.

Table 9. Breakline collection requirements

Parameter	Project Specification	Additional Comments
Ponds and Lakes	Breaklines are collected in all inland ponds and lakes ~0.8 hectare or greater. These features are flat and level water bodies at a single elevation for each vertex along the bank.	None
Rivers and Streams	Breaklines are collected for all streams and rivers ~30 m 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.	None
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

Parameter	Project Specification	Additional Comments
Bridge Saddle Breaklines	Bridge Saddle Breaklines are collected where bridge abutments were interpolated after bridge removal causing saddle artifacts.	None
Soft Features	Soft Feature Breaklines are collected where additional enforcement of the modeled bare earth terrain was required, typically on hydrographic control structures or vertical waterfalls, due to large vertical elevation differences within a short linear distance on a hydrographic features.	Soft features were not applicable to this dataset so no soft feature breaklines were collected.

5.2 Breakline Qualitative Assessment

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

Table 10. Breakline verification steps.

Parameter	Requirement	Pass/Fail
Collection	Collect breaklines according to project specifications using lidar-derived data, including intensity imagery, bare earth ground models, density models, slope models, and terrains.	Pass
Placement	Place the breakline inside or seaward of the shoreline by 1-2 x NPS in areas of heavy vegetation or where the exact shoreline is hard to delineate.	Pass
Completeness	Perform a completeness check, breakline variance check, and all automated checks on each block before designating that block complete.	Pass
Merged Dataset	Merge completed production blocks. Ensure correct horizontal and vertical snapping between all production blocks. Confirm correct horizontal placement of breaklines.	Pass
Merged Dataset Completeness Check	Check entire dataset for features that were not captured but that meet baseline specifications or other metrics for capture. Features should be collected consistently across tile boundaries.	Pass

Parameter	Requirement	Pass/Fail
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 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	Pass
Vertical Variance	Using a terrain created from lidar ground (class 2, 8, and 20 as applicable) and water points (class 9) to compare breakline Z values to interpolated lidar elevations to ensure there are no unacceptable discrepancies.	Pass
Monotonicity	Dual line streams generally maintain a consistent down-hill flow and collected in the direction of flow – some natural exceptions are allowed	Pass
Topology	Features must not overlap or have gaps Features must not have unnecessary dangles or boundaries	Pass
Hydro-classification	The water classification routine selected ground points within the breakline polygons and automatically classified them as class 9, water. During this water classification routine, points that were within 1 NPS distance or less of the hydrographic feature boundaries were moved to class 20, ignored ground, to avoid hydroflattening artifacts along the edges of hydro features.	Pass
Hydro-flattening	Perform hydro-flattening and hydro-enforcement checks. Tidal waters should preserve as much ground as possible and can be non-monotonic.	Pass

6. DEM PROCESSING & QUALITATIVE ASSESSMENT

6.1 DEM Production Methodology

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

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

6.2 DEM Qualitative Assessment

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

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

Table 11. DEM verification steps.

Parameter	Requirement	Pass/Fail
Digital Elevation Model (DEM) of bare-earth w/ breaklines	DEM of bare-earth terrain surface (1m) 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	Pass
Breakline Elevations	Ensure adherence of breaklines to bare-earth surface elevations, i.e., no floating or digging hydrographic feature	Pass
Bridge Removal	Verify removal of bridges from bare-earth DEMs and no saddles present	Pass

Parameter	Requirement	Pass/Fail
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. GDAL version 2.4.0 used for all DEM formatting.	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

6.3 DEM Vertical Accuracy Results

The same 337 checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by averaging several lidar points within each pixel, which may result in slightly different elevation values at each survey checkpoint when compared to the linearly interpolated TIN created from the source LAS. The vertical accuracy of the DEM was tested by comparing the elevation of a given surveyed checkpoint with the elevation of the horizontally coincident pixel in the DEM. Dewberry used Esri software to test the DEM vertical accuracy.

Table 12. DEM vertical accuracy results

Land Cover Category	# of Points	NVA (m)	VVA (m)
Project Specification	**160**	**0.196**	**0.300**
NVA	201	0.041	-
VVA	136	-	0.059

This DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10.0 cm RMSEz vertical accuracy class. Actual NVA accuracy was found to be $RMSE_z$ = 4.1 cm, equating to ± 8.0 cm at 95% confidence level. Actual VVA accuracy was found to be ± 9.4 cm at the 95th percentile.

Table 13 lists the 5% outliers that are larger than the VVA 95th percentile.

Table 13. DEM VVA 5% outliers

Point ID	UTM Zone 16N NAD83(2011), m		NAVD88 Geoid18, m		Delta Z, m
	Easting (X)	Northing (Y)	Survey Z	Lidar Z	
VVA-6	469445.046	519071.130	1191.994	1192.223	+0.229
VVA-9	498644.686	512788.531	1044.702	1044.845	+0.143
VVA-36	496107.363	477474.776	983.302	983.415	+0.113
VVA-37	500706.424	467712.510	973.811	973.960	+0.149
VVA-43	471531.614	452133.339	935.424	935.560	+0.136
V237	962292.299	455203.601	711.698	711.836	+0.138
VVA-51	528145.045	524805.077	853.183	853.331	+0.148

Table 14 provides overall descriptive statistics.

Table 14. DEM vertical accuracy descriptive statistics

Land Cover Type	# of Points	RMSE $_z$ (m)	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
NVA	201	0.041	-0.006	-0.009	-0.864	0.041	-0.238	0.094	4.714
VVA	136	-	0.029	0.026	0.639	0.051	-0.088	0.229	1.146

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for MT Highline Completion Wibaux satisfies the project's pre-defined vertical accuracy criteria.

7. DERIVATIVE LIDAR PRODUCTS

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

7.1 Swath Separation Images (SSIs)

Dewberry verified inter-swath or between swath relative accuracy of the dataset by generating swath separation images in conjunction with interswath polygons. Color-coding is used to help visualize elevation differences between overlapping swaths. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values.

The swath separation images are symbolized by the following ranges:

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

Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across one raster pixel) are expected to appear yellow or red in the SSIs. Flat, open areas are expected to be green in the SSIs. Large or continuous sections of yellow or red pixels following flight line patterns and not the terrain or vegetation can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data.

Dewberry generated swath separation images using LP360 software. These images were created from the last return of all points except points classified as noise and/or flagged as withheld. Point Insertion was used as the Surface Method and the cell size was set to 2x the deliverable DEM cell size. The three interval bins used are bulleted above and the parameter to “Modulate source differences by Intensity” was set to 50%. The output GeoTIFF rasters are tiled to the project tile grid, clipped to the master DPA, and formatted (including defining the CRS which matches the project CRS) using GDAL software, version 2.4.0.

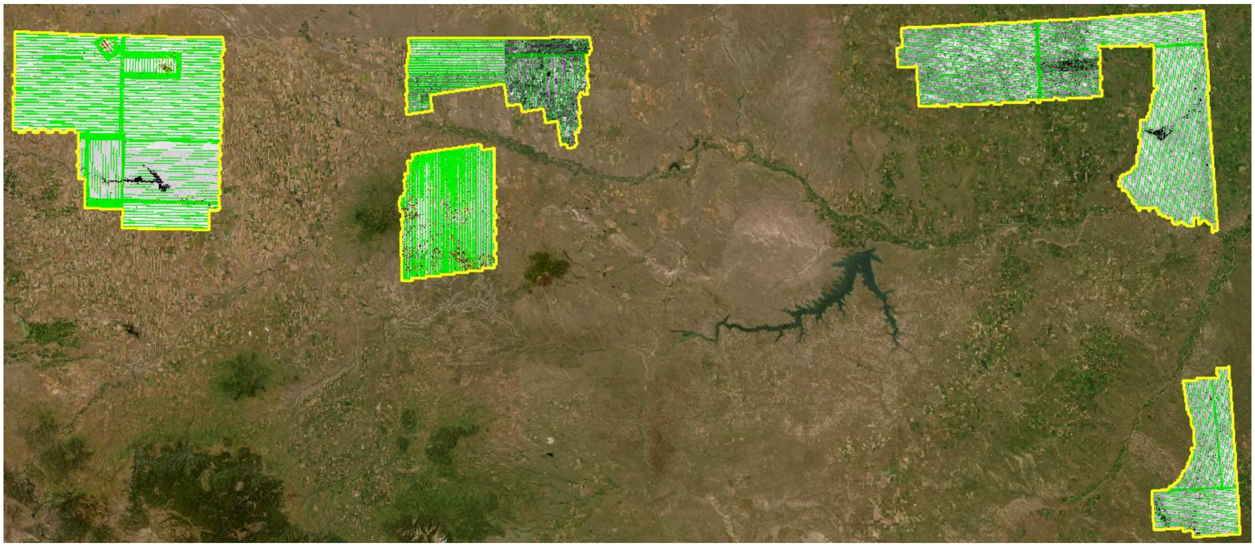


Figure 10. Swath Separation Image (SSIs) generated for the MT Highline Completion Wibaux project.

7.2 Interswath and Intraswath Polygons

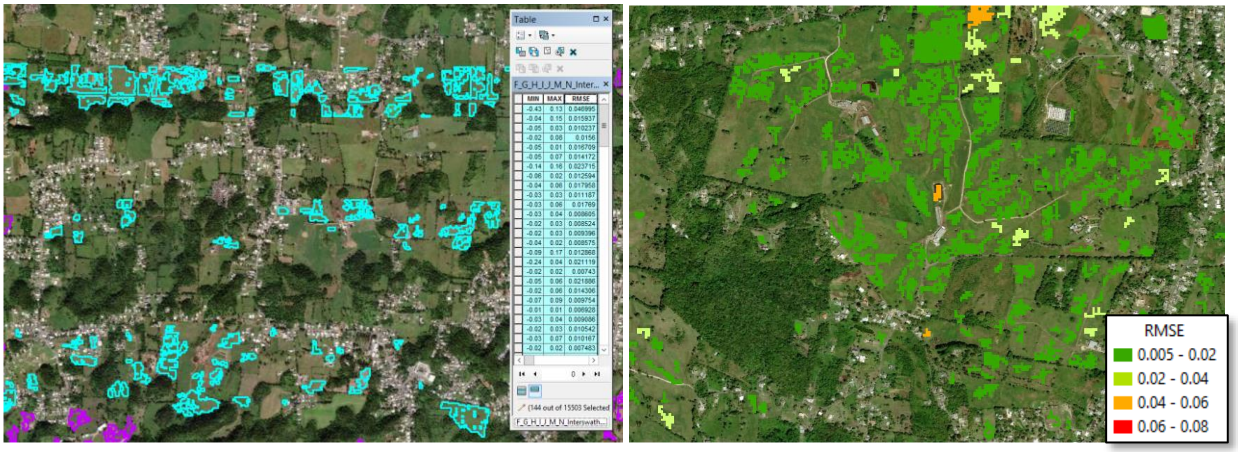
7.2.1 Interswath Accuracy

The Interswath accuracy, or overlap consistency, measures the variation in the lidar data within the swath overlap. Interswath accuracy measures the quality of the calibration or boresight adjustment of the data in each lift. Per USGS specifications, overlap consistency was assessed at multiple locations within overlap in non-vegetated areas of only single returns and on slopes less than 10 degrees. As with precision, the interswath consistency was reported by way of a polygon shapefile delineating the sample areas checked and attributed with the following and using the cells within each polygon as sample values:

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

Dewberry has developed a relatively robust process for generating these interswath polygons across the entire dataset. The current specification does not explicitly state the amount of areas to be tested. Dewberry therefore ensures that the assessment is as detailed as possible by creating test polygons for all overlap areas. The test areas are generated such that they are on slopes less than 10 degrees and not in vegetated areas. The generated polygons are then attributed with the min/max/RMSDz statistics. Polygons that intersect large waterbodies are removed from the final results, as these are not reliable test locations.

The result of the process is a shapefile of test polygons with their test values, distributed in all of the overlapping areas across the project area. These polygons are then reviewed for any systematic interswath errors that should be considered of concern.



MIN	MAX	RMSE
-0.43	0.13	0.046995
-0.04	0.15	0.015937
-0.05	0.03	0.010237
-0.02	0.08	0.0156
-0.05	0.01	0.016709
-0.05	0.07	0.014172
-0.14	0.16	0.023715
-0.06	0.02	0.012594
-0.04	0.06	0.017958
-0.03	0.03	0.011187
-0.03	0.06	0.01769
-0.03	0.04	0.008605
-0.02	0.03	0.008524
-0.02	0.03	0.009396
-0.04	0.02	0.008575
-0.09	0.17	0.012868
-0.24	0.04	0.021119
-0.02	0.02	0.00743
-0.05	0.06	0.021886
-0.02	0.06	0.014306
-0.07	0.09	0.009754
-0.01	0.01	0.006928
-0.03	0.04	0.009086
-0.02	0.03	0.010542
-0.03	0.07	0.010167
-0.02	0.02	0.007483

(144 out of 15503 Selected)

F_G_H_I_J_M_N_Interswath...

Figure 11. Left: Example interswath polygons and example statistics. Right: Example interswath polygons colored by RMSDz values.

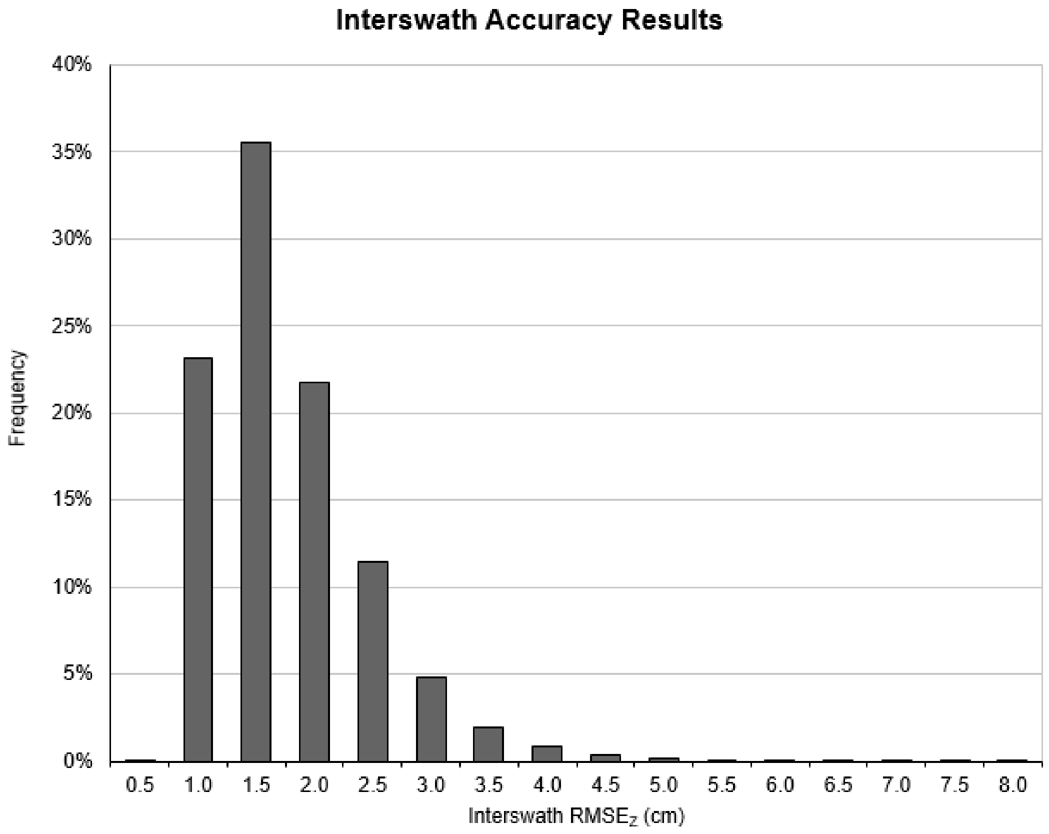


Figure 12. Frequency distribution of interswath RMSDz results for the MT Highline Completion Wibaux project.

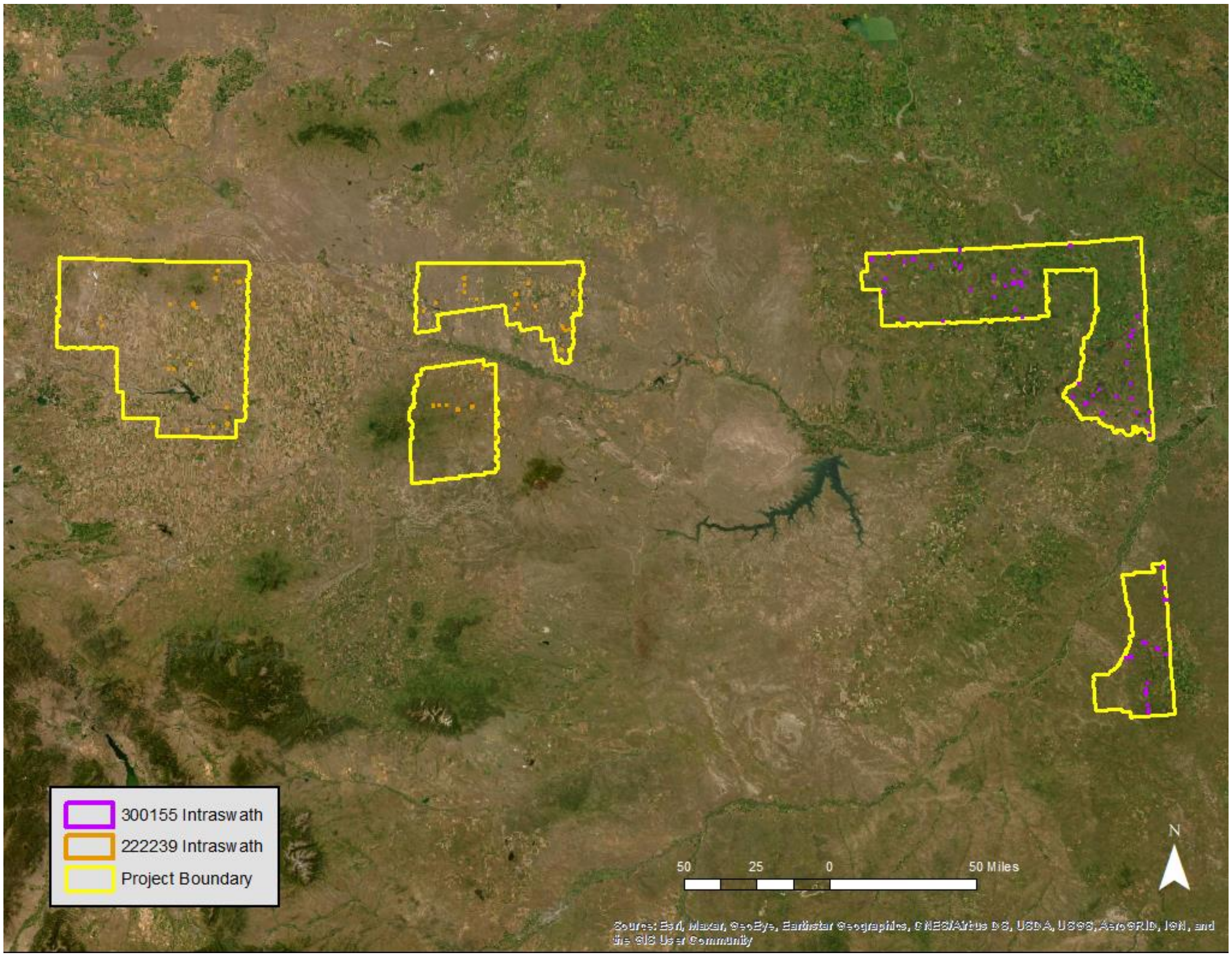
7.2.2 Intraswath Accuracy

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. To measure the precision of a lidar dataset, level or flat surfaces were assessed. Swath data in non-overlap areas were assessed using only first returns in non-vegetated areas.

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

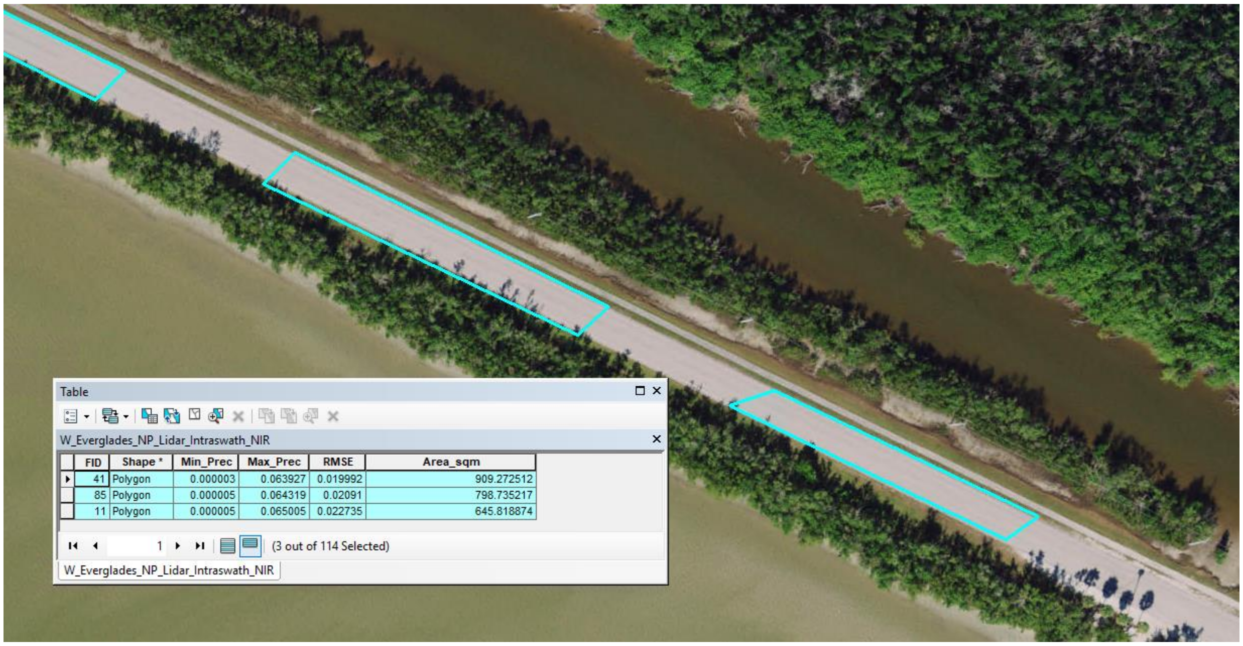
- Minimum slope-corrected range (numeric)
- Maximum slope-corrected range (numeric)
- RMSDz of the slope-corrected range (numeric).

Dewberry manually created intraswath polygons where hard surfaces exist within the project area. The intraswath polygon distribution is illustrated in Figure 13. The statistics outlined above were then generated per polygon and each polygon was reviewed for acceptability, issues, and trends.



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

Figure 13. Intraswath polygons used to test intraswath vertical accuracy.



	FID	Shape *	Min_Prec	Max_Prec	RMSE	Area_sqm
▸	41	Polygon	0.000003	0.063927	0.019992	909.272512
	85	Polygon	0.000005	0.064319	0.02091	798.735217
	11	Polygon	0.000005	0.065005	0.022735	645.818874

(3 out of 114 Selected)

Figure 14. Example test polygon for intraswath testing, and its results.

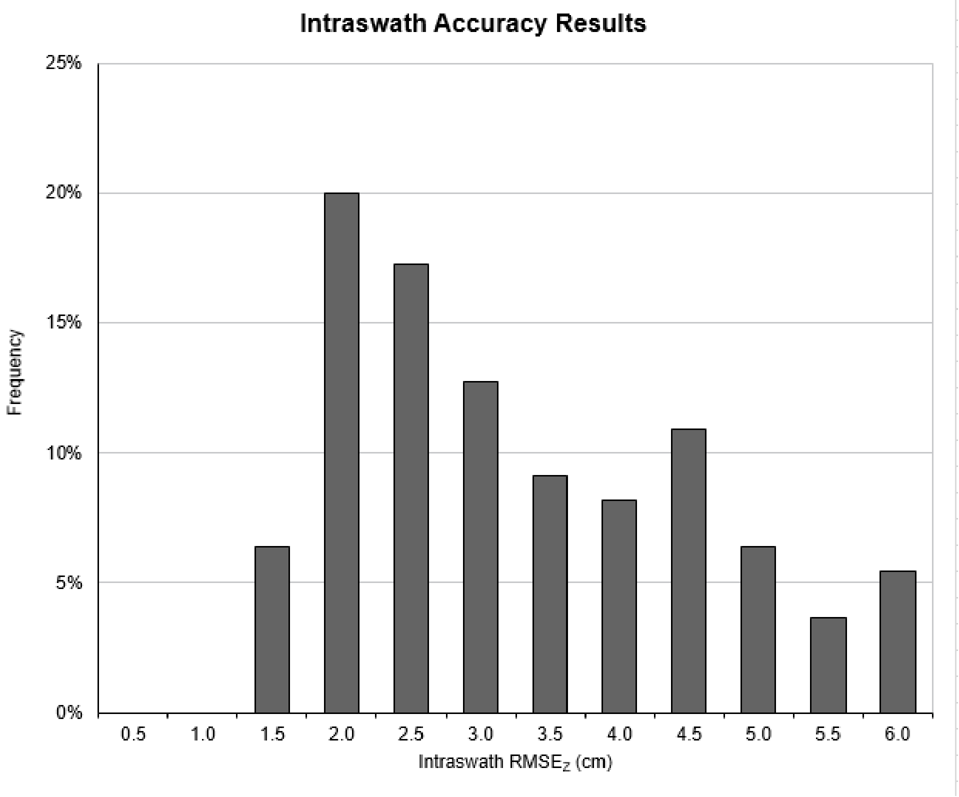


Figure 15. Frequency distribution of intraswath RMSDz results for the MT Highline Completion Wibaux project.

7.3 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 Dewberry'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 regarding the use of the withheld bit.

7.4 Flightline Extents GDB

Flightline extents are delivered as polygons in an Esri GDB, delineating actual coverage of each swath used in the project deliverables. Dewberry 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.