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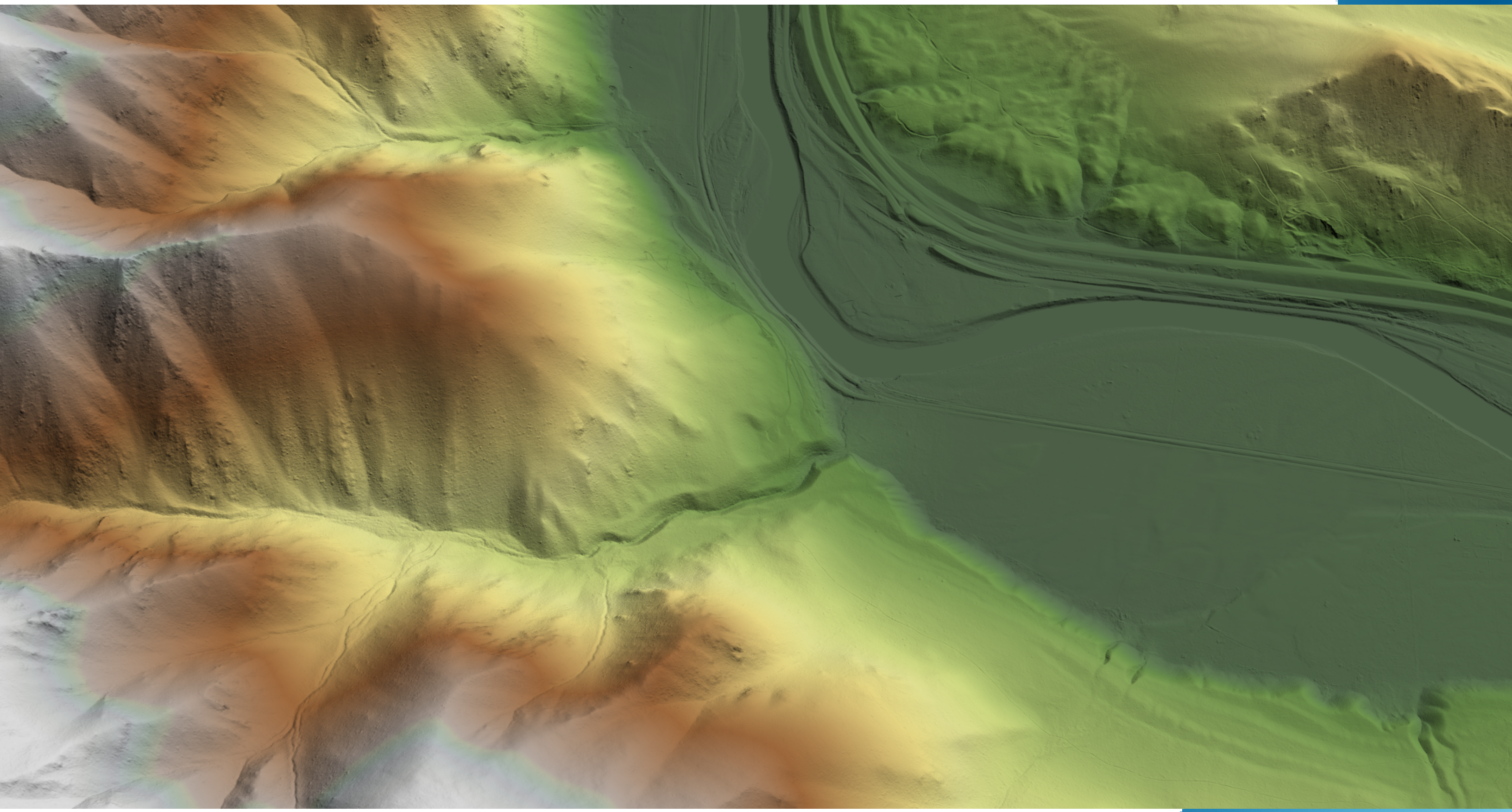

40220 MT Phase4 B22 LIDAR PROCESSING REPORT

Project ID: 231442
Work Unit: 231439

2023

Submitted: July 10, 2023

Prepared for:

USGS
science for a changing world

Prepared by:

NV5 GEOSPATIAL

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1. Summary / Scope

1.1. Summary

This report contains a summary of the 40220 MT Phase4 B22, Work Unit 231439 lidar acquisition task order, issued by USGS under their Contract 140G0221D0016 on August 13, 2021. This Work Unit yielded a project area covering 1,231 square miles over Montana at Quality Level 2. The intent of this document is only to provide specific validation information for the data acquisition/collection, processing, and production of deliverables completed as specified in the task order.

1.2. Scope

Aerial topographic lidar was acquired using state of the art technology along with the necessary surveyed ground control points (GCPs) and airborne GPS and inertial navigation systems. The aerial data collection was designed with the following specifications listed in Table 1 below.

Table 1. Originally Planned Lidar Specifications

Average Point Density	Flight Altitude (AGL)	Field of View	Minimum Side Overlap	RMSEz
2 pts / m2	3,050 m	58.5°	30%	≤ 10 cm

1.3. Coverage

The Work Unit boundary covers 1,231 square miles over Montana. Project extents are shown in Figure 1.

1.4. Duration

Lidar data was acquired from August 19, 2022 to August 30, 2022 in 4 total lifts. See “Section: 2.4. Time Period” for more details.

1.5. Issues

Some areas have snow present and the snow has been classified accordingly.

40220 MT Phase4 B22 Work Unit 231439 Projected Coordinate System: Stateplane Montana FIPS 2500 Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID 18) Units: Meters	
Lidar Point Cloud	Classified Point Cloud in .LAS 1.4 format
Rasters	• 1-meter Hydro-flattened Bare Earth Digital Elevation Model (DEM) in GeoTIFF format • 1-meter Intensity images in GeoTIFF format
Vectors	Shapefiles (*.shp) • Project Boundary • Lidar Tile Index • Calibration and QC Checkpoints (NVA/VVA) • Contours • Continuous Hydro-flattened Breaklines
Reports	Reports in PDF format • Focus on Delivery • Focus on Accuracy • Survey Report • Processing Report
Metadata	XML Files (*.xml) • Breaklines • Classified Point Cloud • DEM • Intensity Imagery • Contours

40220 MT Phase4 B22
Work Unit 231439 Boundary

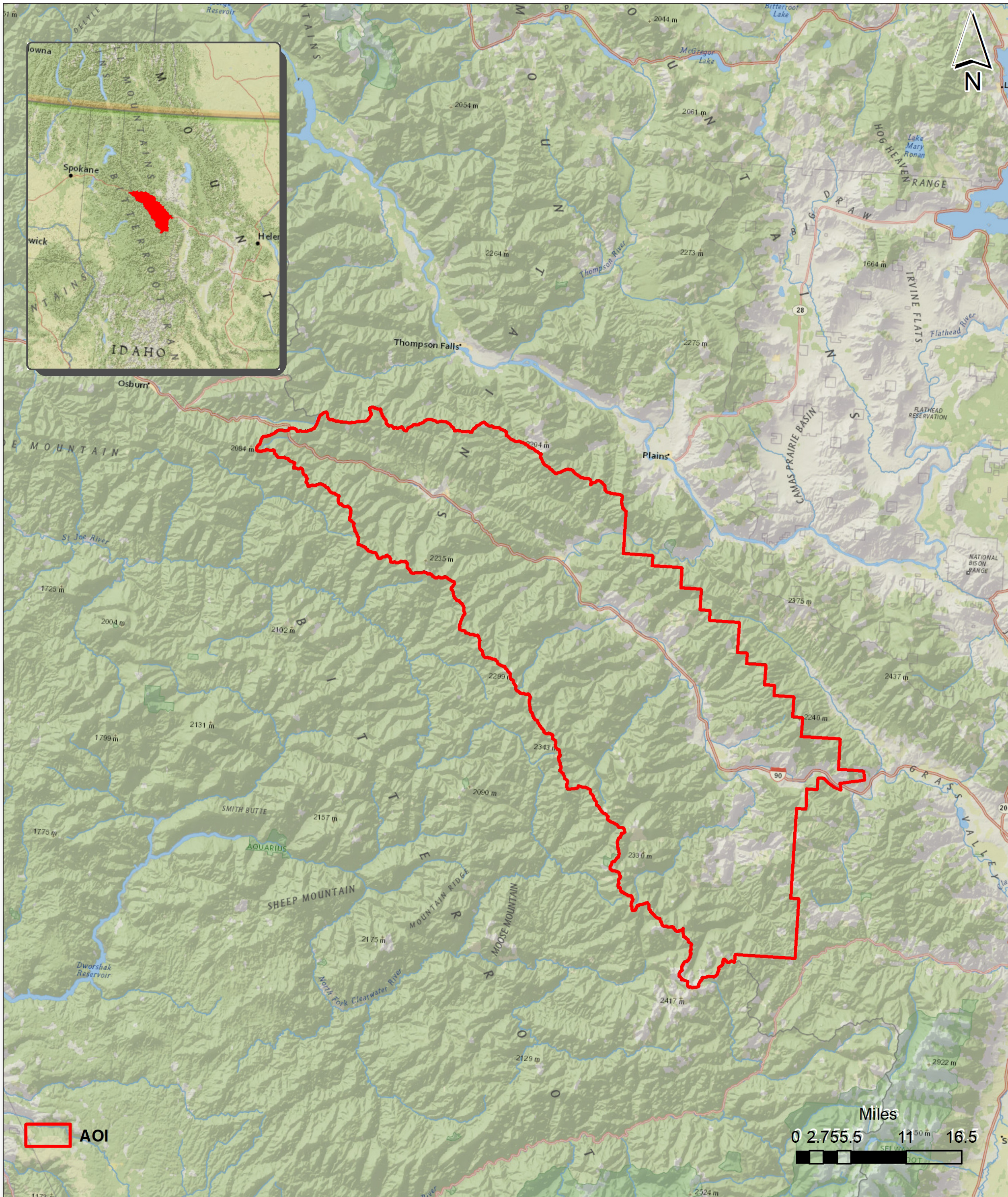


Figure 1. Work Unit Boundary

2. Planning / Equipment

2.1. Flight Planning

Flight planning was based on the unique project requirements and characteristics of the project site. The basis of planning included: required accuracies, type of development, amount / type of vegetation within project area, required data posting, and potential altitude restrictions for flights in project vicinity.

Detailed project flight planning calculations were performed for the project using RiPARAMETER planning software.

2.2. Lidar Sensor

NV5 Geospatial utilized Riegl VQ1560ii lidar sensors (Figure 2), serial number 3061, for data acquisition.

The Riegl 1560II system is a dual channel waveform processing airborne scanning system. It has a laser pulse repetition rate of up to 4 MHz resulting in up to 2.66 million measurements per second. The system utilizes a Multi-Pulse in the Air option (MPIA) and an integrated IMU/GNSS unit.

A brief summary of the aerial acquisition parameters for the project are shown in the lidar System Specifications in Table 2.

Table 2. Lidar System Specifications

		Riegl VQ1560ii (SN3061)
Terrain and Aircraft Scanner	Flying Height	3,050 m
	Recommended Ground Speed	145 kts
Scanner	Field of View	58.5°
	Scan Rate Setting Used	2 x 130 lps
Laser	Laser Pulse Rate Used	2 x 780 kHz
	Multi Pulse in Air Mode	yes
Coverage	Full Swath Width	3,416 m
	Line Spacing	0.56 m
Point Spacing and Density	Average Point Spacing	0.722 m
	Average Point Density	2 pts / m^2

Figure 2. Riegl VQ1560ii Lidar Sensor

2.3. Aircraft

All flights for the project were accomplished through the use of customized aircraft. Plane type and tail numbers are listed below.

Lidar Collection Planes

- Cessna Caravan (single-turboprop), Tail Number(s): N704MD

These aircraft provided an ideal, stable aerial base for lidar acquisition. These aerial platforms have relatively fast cruise speeds, which are beneficial for project mobilization / demobilization while maintaining relatively slow stall speeds, proving ideal for collection of high-density, consistent data posting using a state-of-the-art Riegl lidar system. Some of NV5 Geospatial's operating aircraft can be seen in Figure 3 below.

Figure 3. Some of NV5 Geospatial's Aircraft

2.4. Time Period

Project specific flights were conducted between August 19, 2022 and August 30, 2022. Four aircraft lifts were completed. Accomplished lifts are listed below.

Lift	Start UTC	End UTC
07192022A (SN3061,N704MD)	7/19/2022 5:31:21 PM	7/19/2022 7:57:06 PM
07282022A (SN3061,N704MD)	7/28/2022 1:51:17 PM	7/28/2022 6:08:33 PM
07292022A (SN3061,N704MD)	7/29/2022 2:24:10 PM	7/29/2022 5:54:25 PM
07302022A (SN3061,N704MD)	7/30/2022 2:30:29 PM	7/30/2022 4:36:55 PM

3. Processing Summary

3.1. Flight Logs

Flight logs were completed by Lidar sensor technicians for each mission during acquisition. These logs depict a variety of information, including:

- Job / Project #
- Flight Date / Lift Number
- FOV (Field of View)
- Scan Rate (HZ)
- Pulse Rate Frequency (Hz)
- Ground Speed
- Altitude
- Base Station
- PDOP avoidance times
- Flight Line #
- Flight Line Start and Stop Times
- Flight Line Altitude (AMSL)
- Heading
- Speed
- Returns
- Crab

Notes: (Visibility, winds, ride, weather, temperature, dew point, pressure, etc). Project specific flight logs for each sortie are available in Appendix A.

3.2. Lidar Processing

Applanix + POSPac software was used for post-processing of airborne GPS and inertial data (IMU), which is critical to the positioning and orientation of the lidar sensor during all flights. Applanix POSPac combines aircraft raw trajectory data with stationary GPS base station data yielding a "Smoothed Best Estimate Trajectory" (SBET) necessary for additional post processing software to develop the resulting geo-referenced point cloud from the lidar missions.

During the sensor trajectory processing (combining GPS & IMU datasets) certain statistical graphs and tables are generated within the Applanix POSPac processing environment which are commonly used as indicators of processing stability and accuracy. This data for analysis include: max horizontal / vertical GPS variance, separation plot, altitude plot, PDOP plot, base station baseline length, processing mode, number of satellite vehicles, and mission trajectory.

Point clouds were created using the RiPROCESS software. The generated point cloud is the mathematical three dimensional composite of all returns from all laser pulses as determined from the aerial mission. The point cloud is imported into GeoCue distributive processing software. Imported data is tiled and then calibrated using TerraMatch and proprietary software. Using TerraScan, the vertical accuracy of the surveyed ground control is tested and any bias is removed from the data. TerraScan and TerraModeler software packages are then used for automated data classification and manual cleanup. The data are manually reviewed and any remaining artifacts removed using functionality provided by TerraScan and TerraModeler.

DEMs and Intensity Images are then generated using proprietary software. In the bare earth surface model, above-ground features are excluded from the data set. Global Mapper is used as a final check of the bare earth dataset.

Finally, proprietary software is used to perform statistical analysis of the LAS files.

Software	Version
Applanix + POSPac	8.6
RiPROCESS	1.8.6
GeoCue	2020.1.22.1
Global Mapper	19.1;20.1
TerraModeler	21.008
TerraScan	21.016
TerraMatch	21.007

3.3. LAS Classification Scheme

The classification classes are determined by Lidar Base Specification 2021, Revision A and are an industry standard for the classification of lidar point clouds. All data starts the process as Class 1 (Unclassified), and then through automated classification routines, the classifications are determined using TerraScan macro processing.

The classes used in the dataset are as follows and have the following descriptions:

Table 3. LAS Classifications

	Classification Name	Description
1	Processed, but Unclassified	Laser returns that are not included in the ground class, or any other project classification
2	Bare earth	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7	Low Noise	Laser returns that are often associated with scattering from reflective surfaces, or artificial points below the ground surface
9	Water	Laser returns that are found inside of hydro features
17	Bridge Deck	Laser returns falling on bridge decks
18	High Noise	Laser returns that are often associated with birds or artificial points above the ground surface
20	Ignored Ground	Ground points that fall within the given threshold of a collected hydro feature.
21	Snow	Ground points that fall on snow, where identifiable

3.4. Classified LAS Processing

The bare earth surface is then manually reviewed to ensure correct classification on the Class 2 (Ground) points. After the bare- earth surface is finalized; it is then used to generate all hydro-breaklines through heads-up digitization.

All ground (ASPRS Class 2) lidar data inside of the Lake Pond and Double Line Drain hydro flattening breaklines were then classified to water (ASPRS Class 9) using proprietary tools. A buffer of 3 feet/1 meter was also used around each hydro flattened feature to classify these ground (ASPRS Class 2) points to Ignored ground (ASPRS Class 20). All Lake Pond Island and Double Line Drain Island features were checked to ensure that the ground (ASPRS Class 2) points were reclassified to the correct classification after the automated classification was completed.

Any noise that was identified either through manual review or automated routines was classified to the appropriate class (ASPRS Class 7 and/or ASPRS Class 18) followed by flagging with the withheld bit.

All data was manually reviewed and any remaining artifacts removed using functionality provided by TerraScan and TerraModeler. Global Mapper is used as a final check of the bare earth dataset. GeoCue was then used to create the deliverable industry-standard LAS files for all point cloud data. NV5 Geospatial's proprietary software was used to perform final statistical analysis of the classes in the LAS files, on a per tile level to verify final classification metrics and full LAS header information.

3.5. Hydro-Flattened Breakline Processing

Using heads-up digitization, all Lake-Ponds, Double Line Drains, and Islands are manually collected that are within the project size specification. This includes Lake-Ponds greater than 2 acres in size, Double Line Drains with greater than a 100 foot nominal width, and Islands greater than 1 acre in size within a collected hydro feature. Lidar intensity imagery and bare-earth surface models are used to ensure appropriate and complete collection of these features.

Elevation values are assigned to all collected hydro features via NV5 Geospatial's proprietary software. This software sets Lake-Ponds to an appropriate, single elevation to allow for the generation of hydro-flattened digital elevation models (DEM). Double Line Drain elevations are assigned based on lidar elevations and surrounding terrain feature to ensure all breaklines match the lidar within acceptable tolerances. Some deviation is expected between breakline and lidar elevations due to monotonicity, connectivity, and flattening rules that are enforced on the breaklines. Once completeness, horizontal placement, and vertical variances are reviewed, all breaklines are evaluated for topological consistency and data integrity using a combination of proprietary tools and manual review of hydro-flattened DEMs.

Breaklines are combined into one seamless shapefile, clipped to the project boundary, and imported into an Esri file geodatabase for delivery.

3.6. Hydro-Flattened Raster DEM Processing

Hydro-Flattened DEMs (topographic) represent a lidar-derived product illustrating the grounded terrain and associated breaklines (as described above) in raster form. NV5 Geospatial's proprietary software was used to take all input sources (bare earth lidar points, bridge and hydro breaklines, etc.) and create a Triangulated Irregular Network (TIN) on a tile-by-tile basis. Data extending past the tile edge is incorporated in this process so that proper triangulation can occur. From the TIN, linear interpolation is used to calculate the cell values for the raster product. The raster product is then clipped back to the tile edge so that no overlapping cells remain across the project area. A 32-bit floating point GeoTIFF DEM was generated for each tile with a pixel size of 1-meter. NV5 Geospatial's proprietary software was used to write appropriate horizontal and vertical projection information as well as applicable header values into the file during product generation. Each DEM is reviewed in Global Mapper to check for any surface anomalies and to ensure a seamless dataset. NV5 Geospatial ensures there are no void or no-data values (-999999) in each derived DEM. This is achieved by using propriety software checking all cell values that fall within the project boundary. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the DEMs against what is required before final delivery.

3.7. Intensity Image Processing

Intensity images represent reflectivity values collected by the lidar sensor during acquisition. Proprietary software generates intensity images using first returns and excluding those flagged with a withheld bit. Intensity images are linearly scaled to a value range specific to the project area to standardize the images and reduce differences between individual tiles. Appropriate horizontal projection information as well as applicable header values are written during product generation.

3.8. Swath Separation Raster Processing

Swath Separation Images are rasters that represent the interswath alignment between flight lines and provide a qualitative evaluation of the positional quality of the point cloud. NV5 Geospatial proprietary software generated 1-meter raster images in GeoTIFF format using last returns, excluding points flagged with the withheld bit, and using a point-in-cell algorithm. Images are generated with a 75% intensity opacity and (4) absolute 8-cm intervals, see below for interval coloring. Intensity images are linearly scaled to a value range specific to the project area to standardize the images and reduce differences between individual tiles. Appropriate horizontal projection information as well as applicable header values are written to the file during product generation. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the images against what is required before final delivery.

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

3.9. Maximum Surface Height Raster Processing

Maximum Surface Height rasters (topographic) represent a lidar-derived product illustrating natural and built-up features. NV5 Geospatial's proprietary software was used to take all first-return classified lidar points, excluding those flagged with a withheld bit, and create a raster on a tile-by-tile basis. Data extending past the tile edge is incorporated in this process so that proper gridding can occur. The raster product is then clipped back to the tile edge so that no overlapping cells remain across the project area. A 32-bit floating point GeoTIFF was generated for each tile with a pixel size of 1-meter. NV5 Geospatial's proprietary software was used to write appropriate horizontal and vertical projection information as well as applicable header values into the file during product generation. Each maximum surface height raster is reviewed in Global Mapper to check for any anomalies and to ensure a seamless dataset. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the DEMs against what is required before final delivery.

3.10. Contour Processing

Automated routines within TerraScan and TerraModeler generate an educated, thinned subset of bare earth points (ASPRS Class 8, Model Key). Model Key points and hydro-flattened breaklines were used to generate a terrain surface from which 1-foot contours could be generated. Using proprietary software, all tiled contour shapefiles were combined into one, continuous dataset within an Esri File Geodatabase. All lines have their elevations as their attributes and there are no spot elevations or depressions on separate layers.,

40220 MT Phase4 B22
Work Unit 231439 Tile Layout

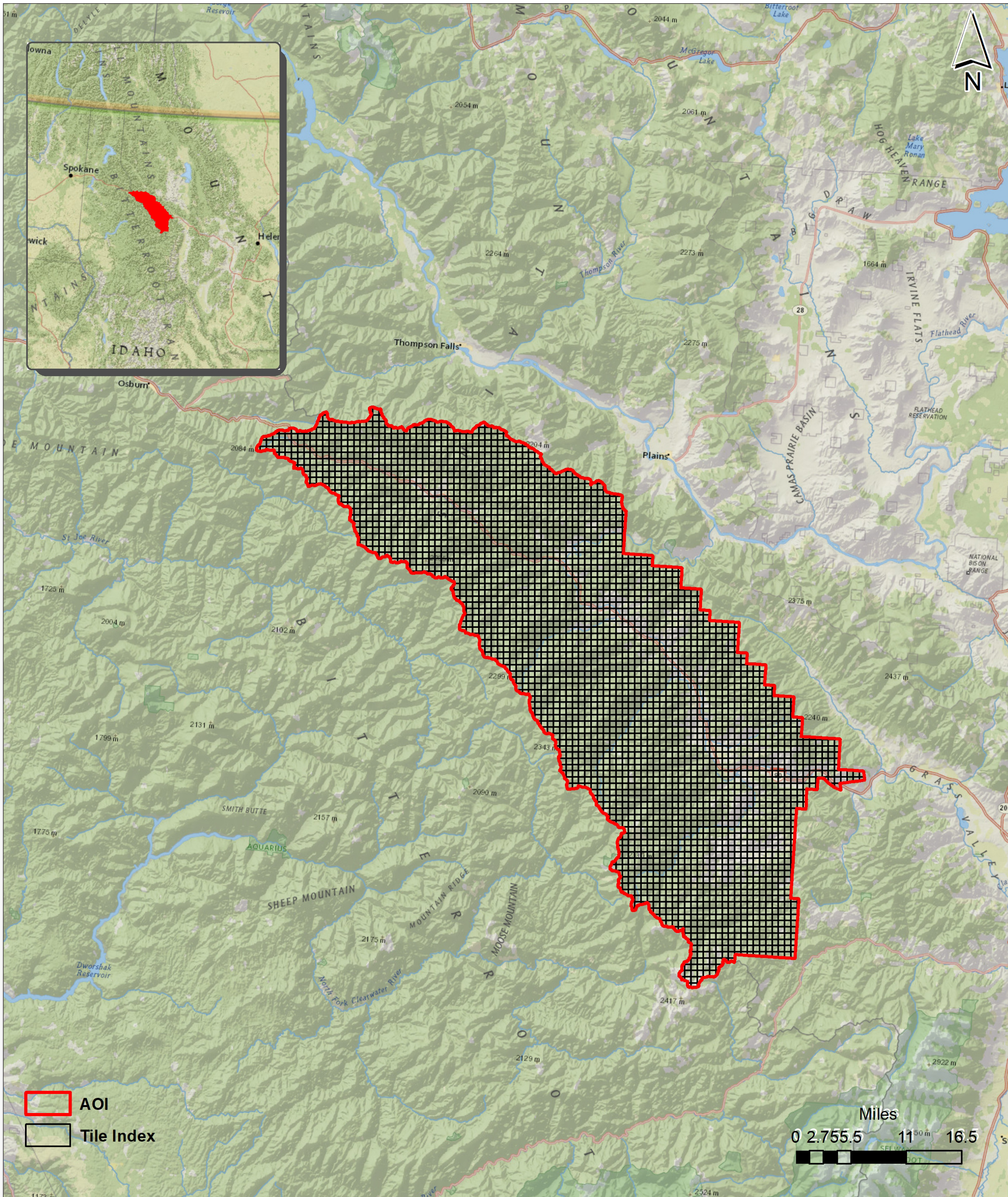


Figure 4. Lidar Tile Layout

4. Project Coverage Verification

A proprietary tool (FOCUS on Flight) produces grid-based polygons of each flightline, depicting exactly where lidar points exist. These swath polygons are reviewed against the project boundary to verify adequate project coverage. Please refer to Figure 5.

40220 MT Phase4 B22
Work Unit 231439 Lidar Coverage

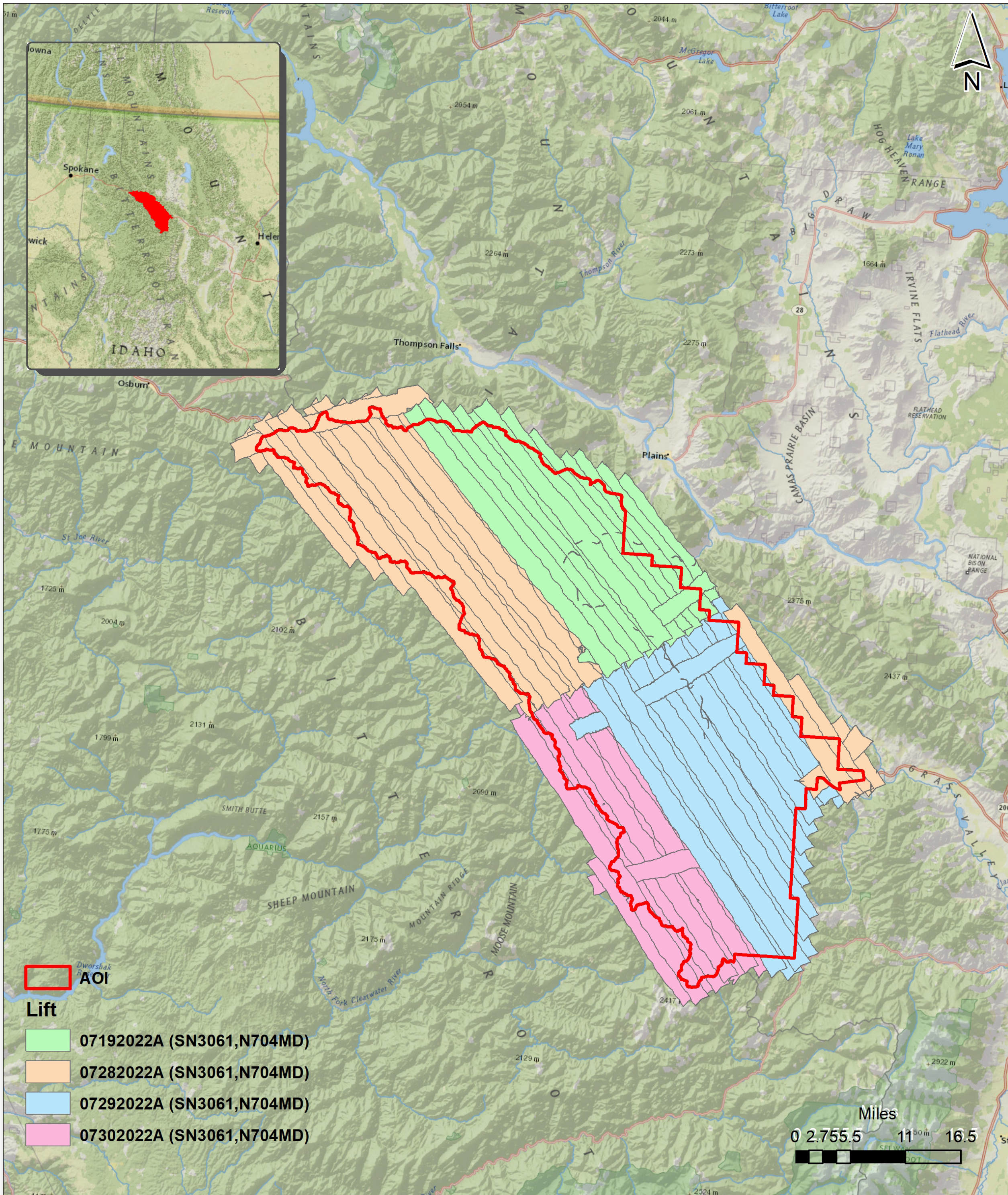


Figure 5. Lidar Coverage

5. Geometric Accuracy

5.1. Horizontal Accuracy

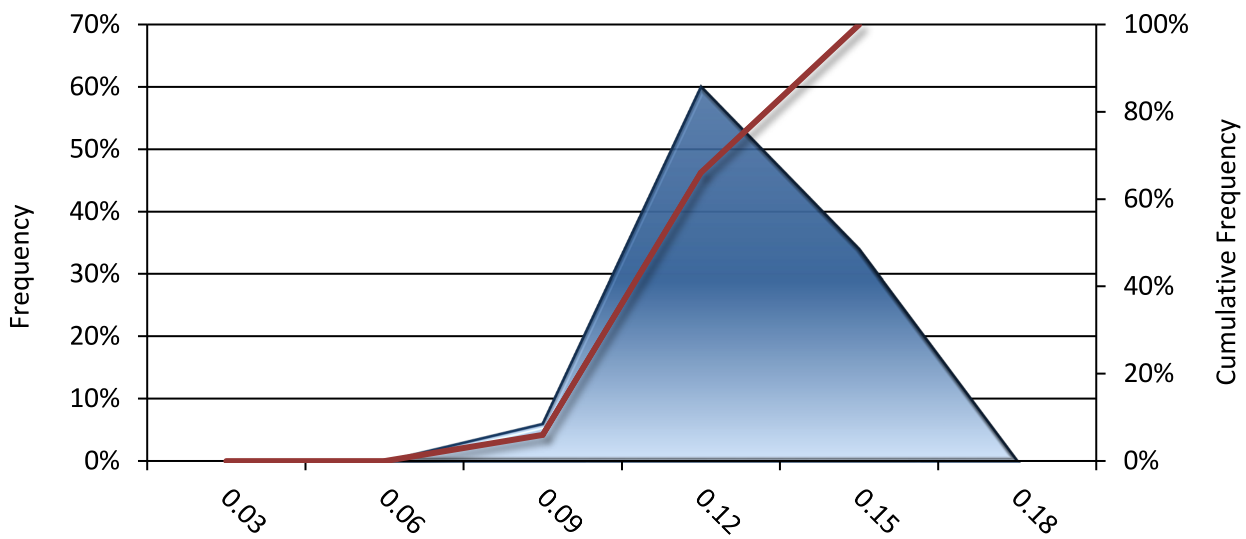
Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95% of the time. Based on a flying altitude of 3,050 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.019 meters, this project was compiled to meet 0.33 meter horizontal accuracy at the 95% confidence level. A summary is shown below.

Horizontal Accuracy	
$RMSE_r$	0.63 ft
	0.19 m
ACC_r	1.09 ft
	0.33 m

5.2. Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the 40220 MT Phase4 B22 project was 0.034 feet (0.011 meters). A summary is shown below.

Relative Vertical Accuracy	
Sample	50 flight line surfaces
Average	0.11 ft
	0.034 m
Median	0.117 ft
	0.036 m
RMSE	0.114 ft
	0.035 m
Standard Deviation (1σ)	0.012 ft
	0.004 m
1.96σ	0.023 ft
	0.007 m



Montana Phase 4, Montana Relative Vertical Accuracy (ft)
Total Compared Points (n = 4,253,152,719)

Project Report Appendices

The following section contains the appendices as listed in the 40220 MT Phase4 B22 Lidar Project Report.

Appendix A

Flight Logs

Project	947122-R040220.00	MT_Statewide_Phase4
Flightplan	MT_Statewide4_1560iiS_QL2_200	

Mission Name	S2223061_20220719_F1	**Mission Notes**
Mission Date	7/19/2022	One lift for MT Statewide QL2. We had a ride along (Kevin) with us today, but no secondary oxygen cannula so we target the lowest altitude lines around 12500'. We completed one lift with no issues other than the long mob to these lines.
Aircraft	N704MD	
Pilot	Tony Kainz	
Co-Pilot		
Operator	Spencer Beck	
Co-Operator		
Vendor	NV5 Geospatial	
Base Airport	KBZN	
Departure (Local Time)	10:17:00 AM	
Arrival (Local Time)	2:57:00 PM	

Line	Heading	Start Time (UTC)	Stop Time (UTC)	Speed (kt)	Notes
00751	NW	17:31:21	17:37:10	136.7	
00750	SE	17:39:21	17:46:29	137.4	
00749	NW	17:48:02	17:55:57	137.3	
00748	SE	17:57:40	18:05:49	138.8	
00747	NW	18:07:23	18:16:54	137.3	
00746	SE	18:19:46	18:30:32	137.5	
00745	NW	18:32:38	18:44:06	135.8	
00744	SE	18:45:15	18:56:45	135.6	
00743	NW	18:58:02	19:09:44	136.3	
00742	SE	19:11:37	19:23:40	138.8	
00741	NW	19:25:13	19:37:44	136.7	
00740	SE	19:39:15	19:51:41	138.1	

Project	947122-R040220.00	MT_Statewide_Phase4
Flightplan	MT_Statewide4_1560iiS_QL2_200	

Mission Name	S2223061_20220728_F1	**Mission Notes**
Mission Date	7/28/2022	Wanted an earlier start today, but the FBO was understaffed and it took over an hour for them to get us O2.
Aircraft	N704MD	No turbulence today with good conditions for acq. Clouds forced us out the the AOI.
Pilot	Creston Saul	
Co-Pilot		
Operator	Stephanie Cohee	
Co-Operator		
Vendor	NV5 Geospatial	
Base Airport	KMSO	
Departure (Local Time)	7:30:00 AM	
Arrival (Local Time)	12:20:00 PM	

Line	Heading	Start Time (UTC)	Stop Time (UTC)	Speed (kt)	Notes
00739	NW	13:51:16	14:03:15	144.9	
00738	SE	14:06:40	14:20:33	136.2	
00737	NW	14:23:09	14:36:45	138.4	
00736	SE	14:38:47	14:52:19	137.9	
00735	NW	14:54:57	15:08:47	137.9	
00734	SE	15:11:39	15:26:10	136.4	
00733	NW	15:28:07	15:42:25	137.7	
00732	SE	15:44:40	15:58:34	140.2	
00731	NW	16:00:45	16:14:51	137.5	
00730	SE	16:16:54	16:24:51	142.6	
00729	NW	16:27:10	16:34:33	137.2	
00728	SE	16:39:00	16:45:10	139.9	
00727	NW	16:52:12	16:53:41	134.2	xline 165520 record014
00726	E	16:55:20	17:02:32	144.2	
00248	SE	17:26:06	17:28:54	144.2	
00247	NW	17:31:50	17:36:48	140.3	
00246	SE	17:42:27	17:50:56	136.6	xline 180551 record018
00243	NE	18:05:51	18:08:33	146.9	

Project	947122-R040220.00	MT_Statewide_Phase4
Flightplan	MT_Statewide4_1560iiS_QL2_200	

Mission Name	S2223061_20220729_F1	**Mission Notes**
Mission Date	7/29/2022	We started on prioritized lines NE corner of AOI. We worked there until clouds moved in and then scouted E, but all of the lines were in clouds, still have snow conditions or in a TFR.
Aircraft	N704MD	
Pilot	Creston Saul	
Co-Pilot		
Operator	Stephanie Cohee	
Co-Operator		
Vendor	NV5 Geospatial	
Base Airport	KMSO	
Departure (Local Time)	6:30:00 AM	
Arrival (Local Time)	12:44:00 PM	

Line	Heading	Start Time (UTC)	Stop Time (UTC)	Speed (kt)	Notes
00245	SE	14:22:09	14:32:51	143.7	misfire at start of line
00244	NW	14:36:07	14:46:33	121.9	
00243	SE	14:48:23	14:56:52	148.8	
00242	NW	15:00:02	15:10:36	125.5	
00241	SE	15:13:04	15:22:29	145.7	
00240	NW	15:25:41	15:36:56	128.7	
00239	SE	15:39:08	15:50:08	139.0	
00238	NW	15:52:49	16:05:09	130.4	
00237	SE	16:07:24	16:19:28	145.9	
00236	NW	16:21:48	16:36:01	130.2	
00235	SE	16:38:07	16:51:28	145.2	
00234	NW	16:53:37	17:08:25	133.6	
00233	SE	17:10:28	17:24:14	144.0	
00232	NW	17:26:31	17:40:41	137.4	xline 174701 record015
00232	NE	17:47:01	17:54:25	141.4	

Project	947122-R040220.00	MT_Statewide_Phase4
Flightplan	MT_Statewide4_1560iiS_QL2_200	

Mission Name	S2223061_20220730_F1	**Mission Notes**
Mission Date	7/30/2022	Successful acq of priority lines. once finished with those we moved E of Missoula and acquired until turbulence was to much.
Aircraft	N704MD	
Pilot	Creston Saul	
Co-Pilot		
Operator	Stephanie Cohee	
Co-Operator		
Vendor	NV5 Geospatial	
Base Airport	KMSO	
Departure (Local Time)	7:59:00 AM	
Arrival (Local Time)	1:54:00 PM	

Line	Heading	Start Time (UTC)	Stop Time (UTC)	Speed (kt)	Notes
00231	SE	14:30:28	14:44:17	137.6	
00230	NW	14:46:30	15:01:08	127.3	
00229	SE	15:03:13	15:16:47	137.3	
00228	NW	15:18:51	15:33:13	129.5	
00227	SE	15:35:52	15:49:24	137.8	
00226	NW	15:51:22	16:05:54	128.2	
00225	SE	16:07:48	16:20:20	139.2	
00224	NW	16:22:46	16:29:33	131.0	xline 163235 record09
00223	E	16:32:35	16:36:56	144.9	
00249	SE	17:09:40	17:11:44	140.0	
00250	NW	17:14:12	17:17:24	125.5	
00251	SE	17:20:29	17:24:18	143.4	
00252	NW	17:26:55	17:32:13	125.2	
00253	SE	17:35:35	17:41:29	137.2	
00254	NW	17:44:01	17:51:27	125.5	
00255	SE	17:54:15	18:01:48	140.2	
00256	NW	18:03:48	18:12:51	124.3	
00257	SE	18:15:18	18:24:06	138.0	
00258	NW	18:26:28	18:36:07	129.4	moderate turbulence
00259	SE	18:38:59	18:48:46	136.1	Refly 11-15 statute miles FNE due to loss of density from turbulence.
00260	NW	18:50:56	19:01:37	126.2	moderate turbulence
00261	SE	19:04:15	19:14:33	138.6	Refly 0-21 statute miles FNE due to loss of density from turbulence. xline 192000 record023
00262	SW	19:20:00	19:27:13	137.5	