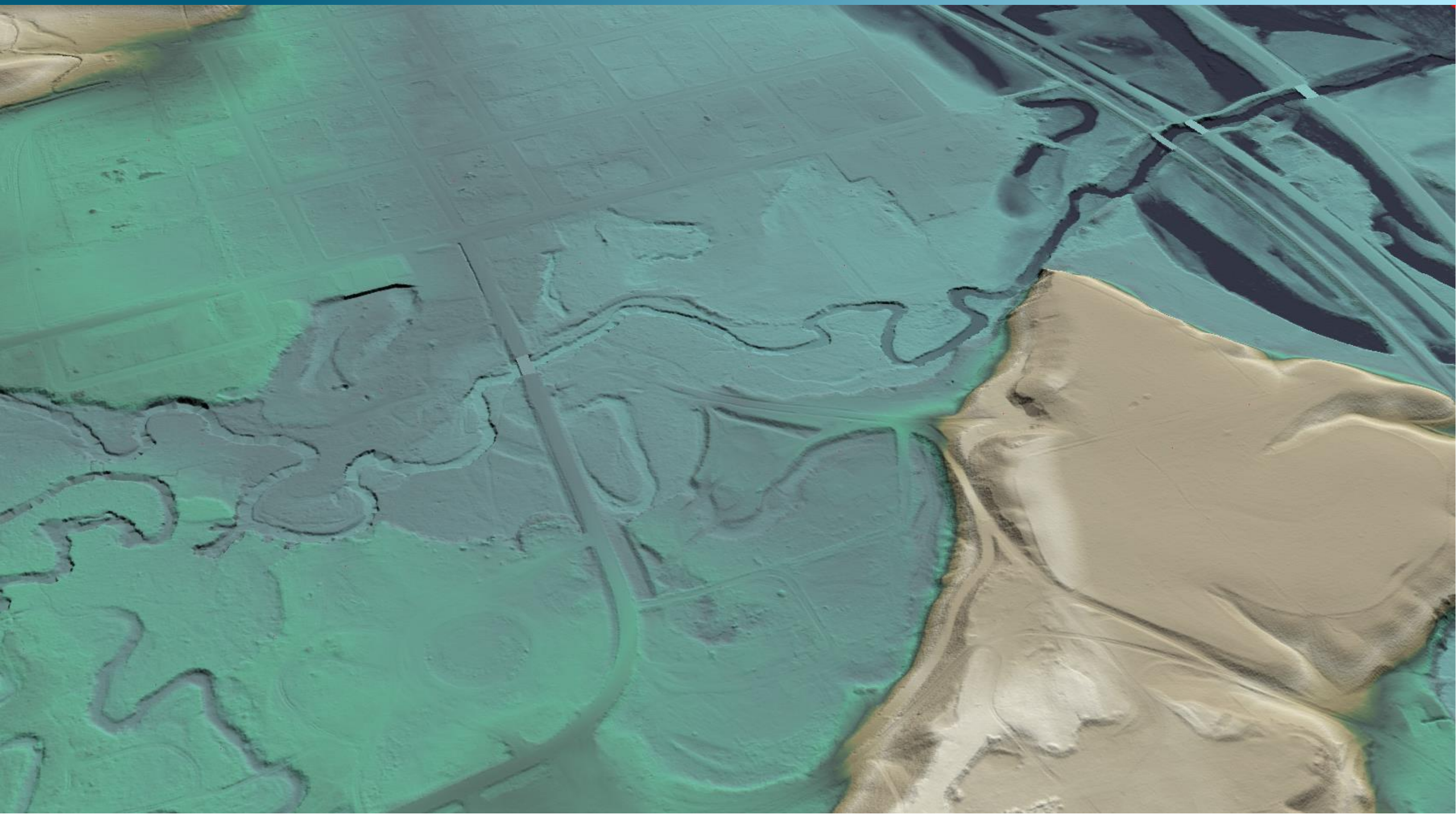
July 30, 2021



Lodge Grass, Montana

Lidar Technical Data Report

Prepared For:

The Montana Department of Natural Resources & Conservation

Katie Shank
Montana Department of Natural Resources & Conservation
701 Beverly Avenue
Missoula, MT 59801
PH: 406-444-6664
EM: Katherine.shank@mt.gov

Prepared By:

NV5 GEOSPATIAL powered by QUANTUM SPATIAL

NV5 Geospatial Corvallis
1100 NE Circle Blvd, Ste. 126
Corvallis, OR 97330
PH: 541-752-1204

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Cover Photo: A view looking North over the town of Lodge Grass with Lodge Grass Creek shown cutting across from left to right. The image was created from the lidar bare earth model colored by elevation.

INTRODUCTION

This photo taken by the Morrison-Maierle, Inc. survey team shows ground survey equipment set in the field within the Lodge Grass Lidar site in Big Horn County, Montana.

In May 2021, NV5 Geospatial (NV5) was contracted by the Montana Department of Natural Resources and Conservation (MTDNRC) to collect QL1 Light Detection and Ranging (lidar) data in the spring of 2021 for the Lodge Grass site in Montana. Data were collected to aid MTDNRC in assessing the topographic and geophysical properties of the study area and to support MTDNRC's objective of obtaining new, high resolution LiDAR-derived topographic data. This lidar-derived data would aid in floodplain mapping being carried out by MTDNRC and the Federal Emergency Management Agency (FEMA).

This report accompanies the delivered lidar data, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including lidar accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to MTDNRC is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the Lodge Grass site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Lodge Grass, Montana	6,178	6,680	05/19/2021	QL1 Lidar

Deliverable Products

Table 2: Products delivered to MTDNRC for the Lodge Grass site

Lodge Grass Lidar Products Projection: Montana State Plane Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Units: Meters	
Points	LAS v 1.4 • All Classified Returns • Raw Calibrated Swaths
Rasters	1.0 Meter GeoTiffs • Hydroflattened Bare Earth Models (DEM) • Highest Hit Digital Surface Models (DSM) Space Delimited ASCII Files (*.asc) • Hydroflattened Bare Earth Models (DEM) 0.5 Meter GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • Tile Index • Flightline Index • Ground Survey Points • 3D Building FootprintsTotal Area Flown ESRI Geodatabases (*.gdb) • 1.0 Foot Contours • 3D Water's Edge Breaklines Space Delimited ASCII Files • 3D Water's Edge Breaklines

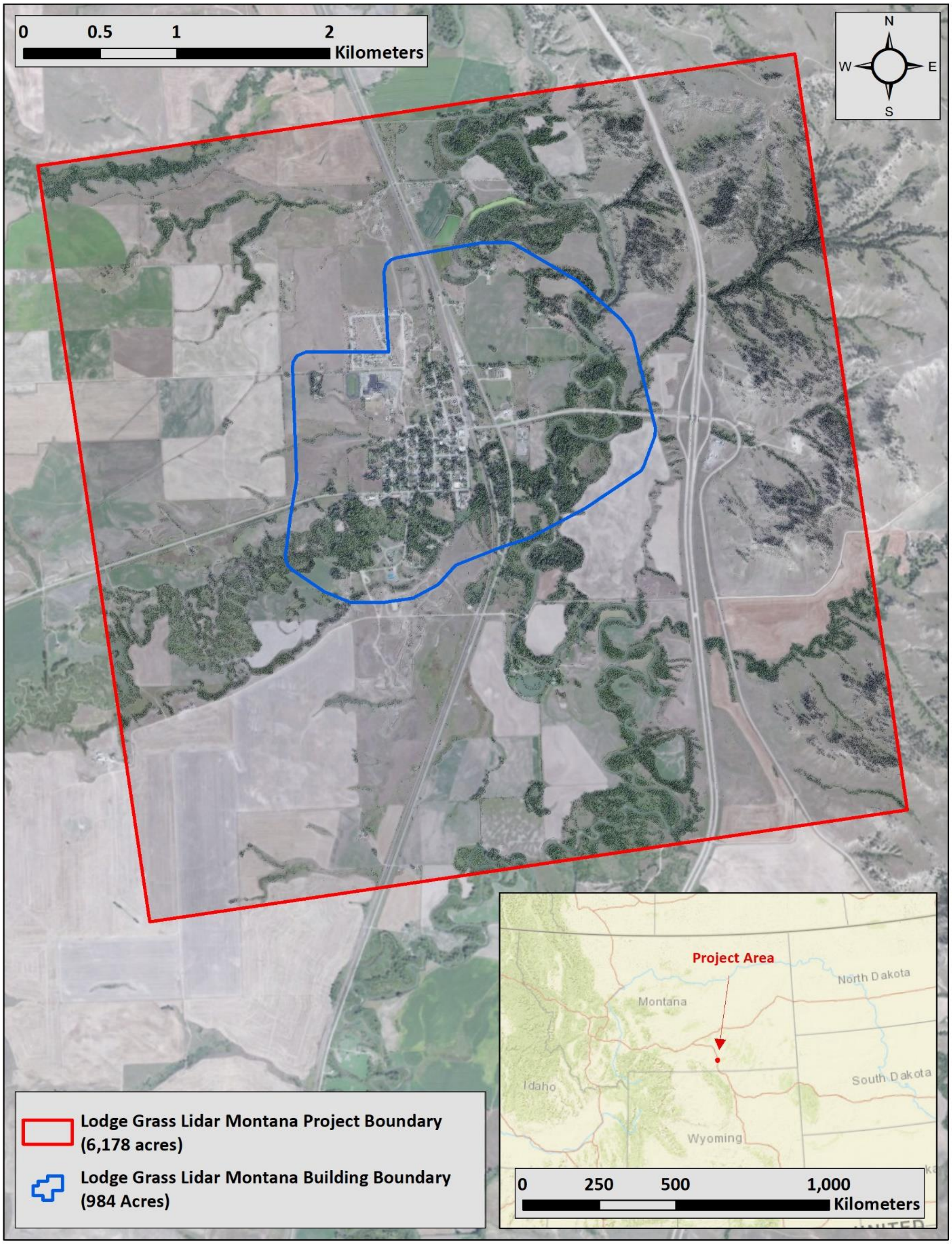


Figure 1: Location map of the Lodge Grass site in Montana

ACQUISITION

NV5 Geospatial's Cessna Caravan

Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Lodge Grass lidar study area at the QL1 point density of ≥8.0 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Boresight Calibration Flights

Prior to any data collection flights on a project, all NV5 Geospatial aircraft and sensor pairings undergo a boresight calibration flight to ensure that installed equipment is functioning properly, and the lever arms are refined. In a boresight calibration flight, flight-lines are flown in a cross-hatch pattern to check for any inter- and intra-swath offsets or system misalignments. Conducted boresight calibration flights for the Lodge Grass lidar data collection are detailed in Table 3 below.

Table 3: Boresight Calibration Flight Summary

Lidar Boresight Calibration Flight Summary for Lodge Grass, Montana Aircraft & Sensors					
Aircraft Name	Aircraft #	Sensor Name	Sensor Type	Boresight Flight Date	Boresight Flight Location
Cessna Caravan 208B	N-208JA	SN3546	Riegl VQ-1560ii	05/10/2021	Sheboygan, WI

Airborne Lidar Survey

The lidar survey was accomplished using a Riegl VQ-1560ii system mounted in a Cessna Caravan. Table 4 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Lodge Grass project area. The Riegl VQ-1560ii laser system can record unlimited range measurements (returns) per pulse, however a maximum of 15 returns can be stored due to LAS v1.4 file limitations. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the lidar sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 4: Lidar specifications and survey settings

Lidar Survey Settings & Specifications	
Quality Level	QL1
Acquisition Dates	May 19, 2021
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ-1560ii
Maximum Returns	15
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	1,998 m
Survey speed	145 knots
Field of View	58.5°
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	700 kHz
Pulse Length	3 ns
Laser Pulse Footprint Diameter	35.9 cm
Central Wavelength	1,064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.18 mrad
Swath Width	2,237 m
Swath Overlap	50 %
Intensity	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
	Horizontal Accuracy RMSE ≤ 30 cm
	Relative Accuracy ≤ 6 cm

Riegl VQ-1560ii

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the lidar data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

Figure 2: Flightline Index Map

Ground Survey


Morrison-Maierle-Established Monument

Ground control surveys, including base station occupation, and ground survey point collection (GSPs) were conducted by Morrison-Maierle, Inc. to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data. For a complete report on the collection of all survey points, see the attached MT DNRC Lodge Grass Survey Report.pdf.

Base Stations

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted by Morrison-Maierle, Inc. to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data.

Table 5: Base station positions for the Lodge Grass acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
1000	45° 19’ 4.52125”	-107° 22’ 03.95945”	1033.714
1001	45° 18’ 32.60514”	-107° 22’ 06.84057”	1015.112
1002	45° 18’ 34.81176”	-107° 22’ 06.26735”	1015.078

Ground survey points were collected by Morrison-Maierle and provided to NV5 Geospatial to be used in lidar calibration and post-processing, with some points withheld from calibration for accuracy assessment. Morrison-Maierle provided ground control point data for lidar calibration, in addition to non-vegetated (NVA) and vegetated (VVA) check point data for accuracy assessment.

Land Cover Class

In addition to ground survey points, land cover class check points were collected by Morrison-Maierle Inc. throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 6, see Lidar Accuracy Assessments, page 21).

Table 6: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrub	SH		Areas dominated by woody and herbaceous species of shrubs	VVA
Tall Grass	TG		Herbaceous grasslands in advanced stages of growth	VVA
Deciduous Forest	FR		Forested areas dominated by trees	VVA
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA

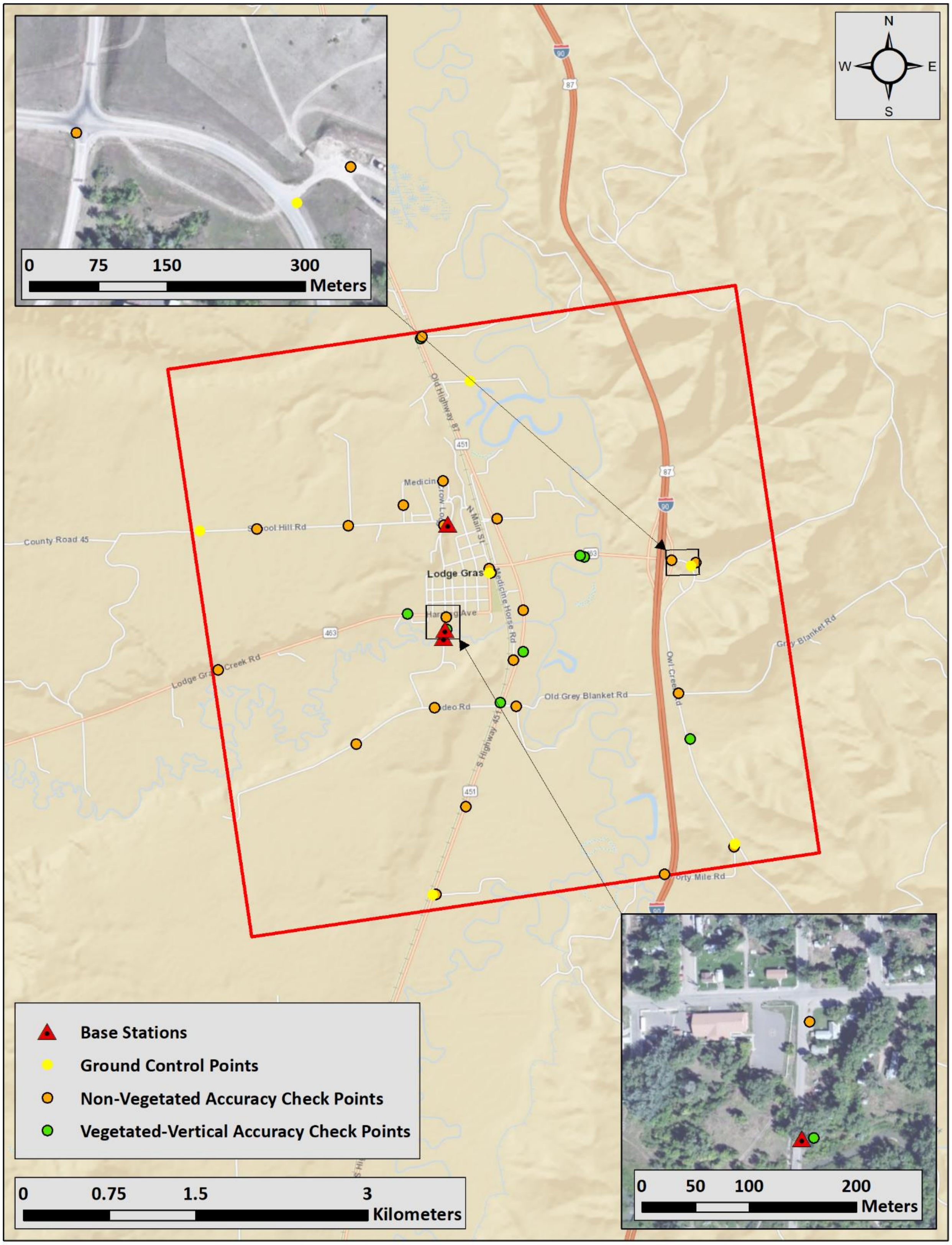
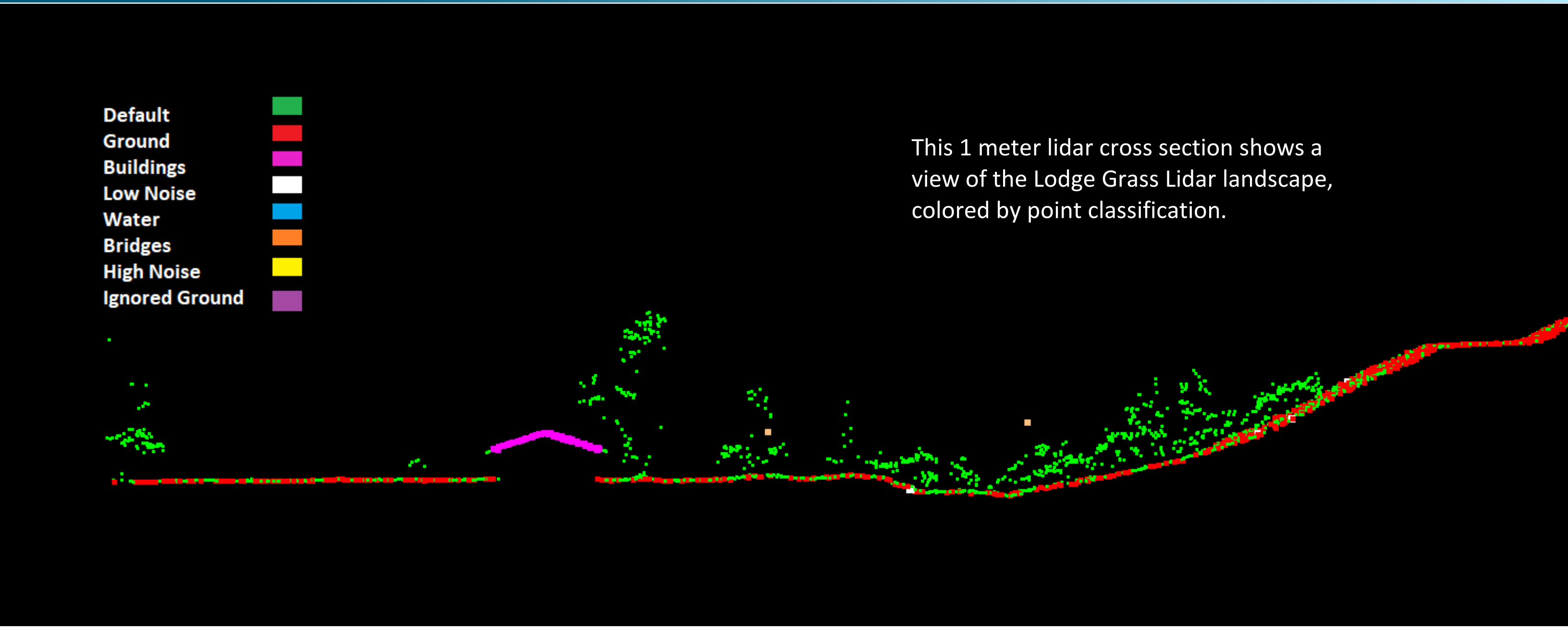


Figure 3: Ground survey location map



Lidar Data

Upon completion of data acquisition, NV5 Geospatial processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and lidar point classification (Table 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8.

Table 7: ASPRS LAS classification standards applied to the Lodge Grass dataset

Classification Number	Classification Name	Classification Description
1	Default	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1W	Edge Clip	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
6	Buildings	Permanent structures such as buildings greater than 100 square feet.
7 - W	Low Noise/Withheld	Laser returns that are often associated with artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	Bridge decks
18 -W	High Noise/Withheld	Laser returns that are often associated with birds, scattering from reflective surfaces.
20	Ignored Ground	Ground points proximate to water’s edge breaklines; ignored for correct model creation

Table 8: lidar processing workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.3
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	POSPac MMS v.8.3 RiProcess v.1.8.5
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19.005
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.19.002
Classify resulting data to ground and other client designated ASPRS classifications (Table 7). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.003 Las Monkey 2.6.3 (NV5 Geospatial proprietary)
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as GeoTIFFs at a 1.0 meter pixel resolution.	LAS Product Creator 3.0 (NV5 Geospatial proprietary)
Correct intensity values for variability and export intensity images as Cloud Optimized GeoTIFFs at a 0.5 meter pixel resolution.	LAS Product Creator 3.0 (NV5 Geospatial proprietary)
Generate contour lines from classified contour keypoints. Export all contours as polyline shapefiles. Generate final building footprint from classified Lidar point cloud.	TerraScan v.19 TerraModeler v.19 ArcMap v. 10.3.1

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Water bodies within the Lodge Grass Lidar project area were flattened to a consistent water level. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 30 meters, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed via manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were manually digitized to define the water's edge.

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered lidar returns to create the final breaklines. Lakes were assigned a consistent elevation for an entire polygon.

Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 4).

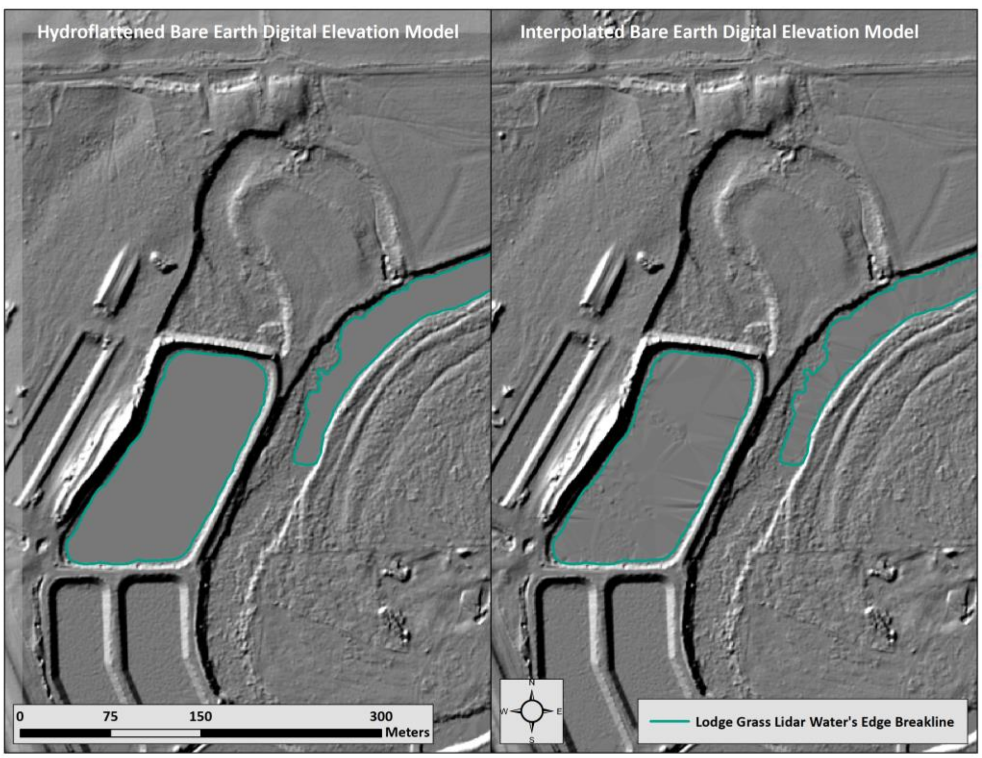


Figure 4: Example of hydroflattening in the Lodge Grass Lidar dataset

Contours

Contour generation from lidar point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. Model key points were selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature. Generation of model key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the model key points at even elevation increments (Figure 5).

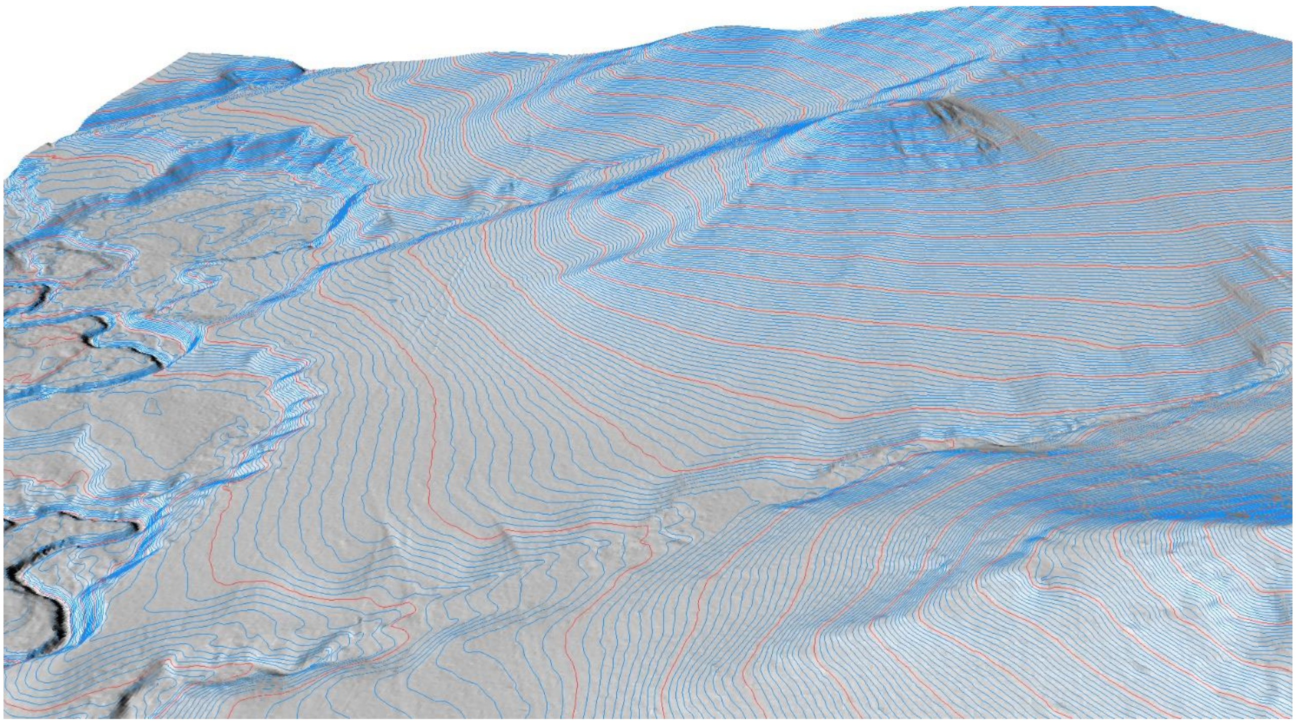


Figure 5: Contours draped over the Lodge Grass bare earth elevation model. Blue contours represent minor intervals (1 foot) confidence while the red contours represent major intervals (10 feet).

Buildings

Building classification was performed through a combination of automated algorithms and manual classification. Typically, manual editing of the building classification was necessary where dense canopy was immediately proximate to features. All non-mobile structures such as houses, barns, silos and sheds greater than 100 square feet were classified into the building category. Once classification was complete, automated routines were used generate the 3D polygon shapefile representing building footprints. A total of 513 buildings were classed in the Lodge Grass lidar data (Figure 6).

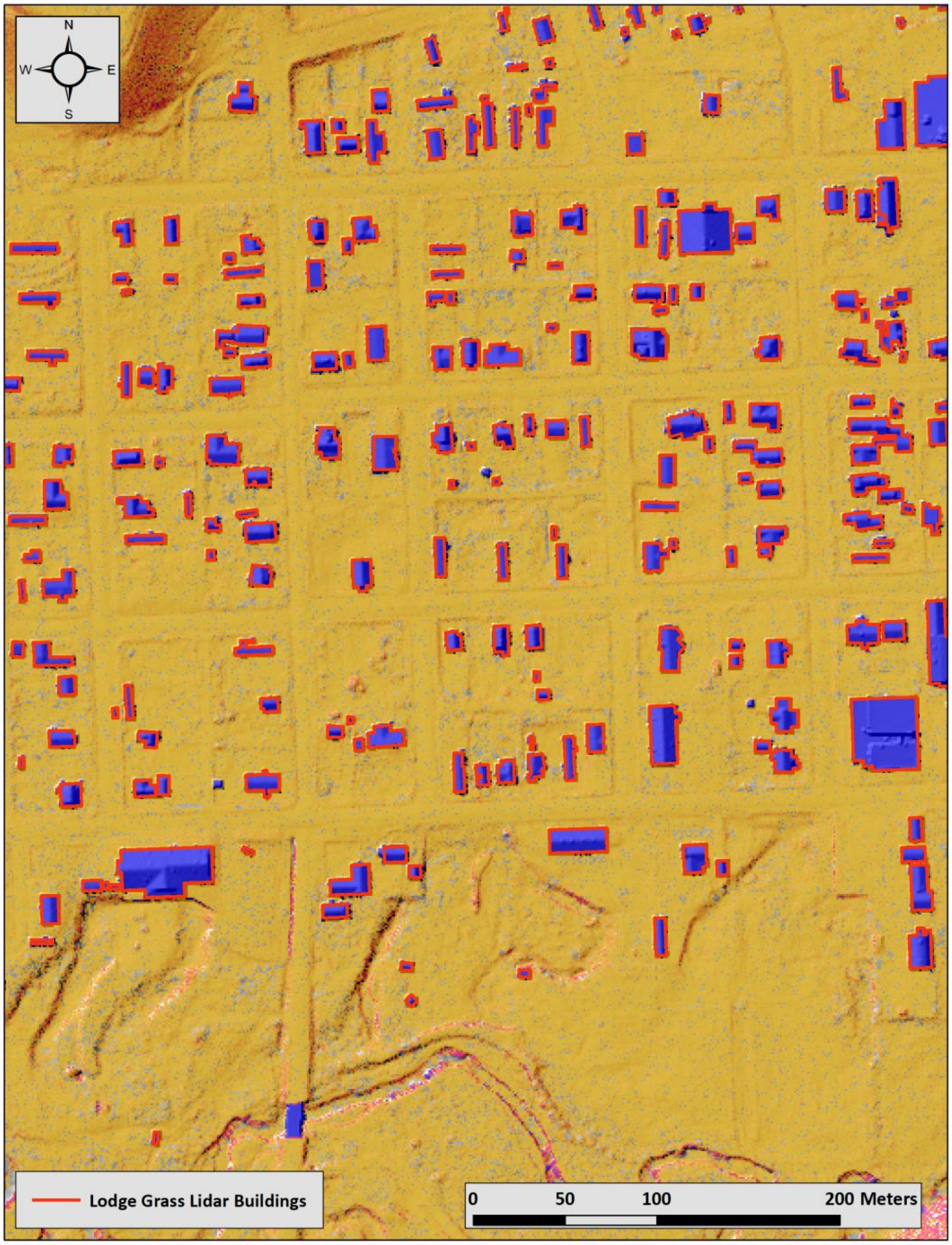
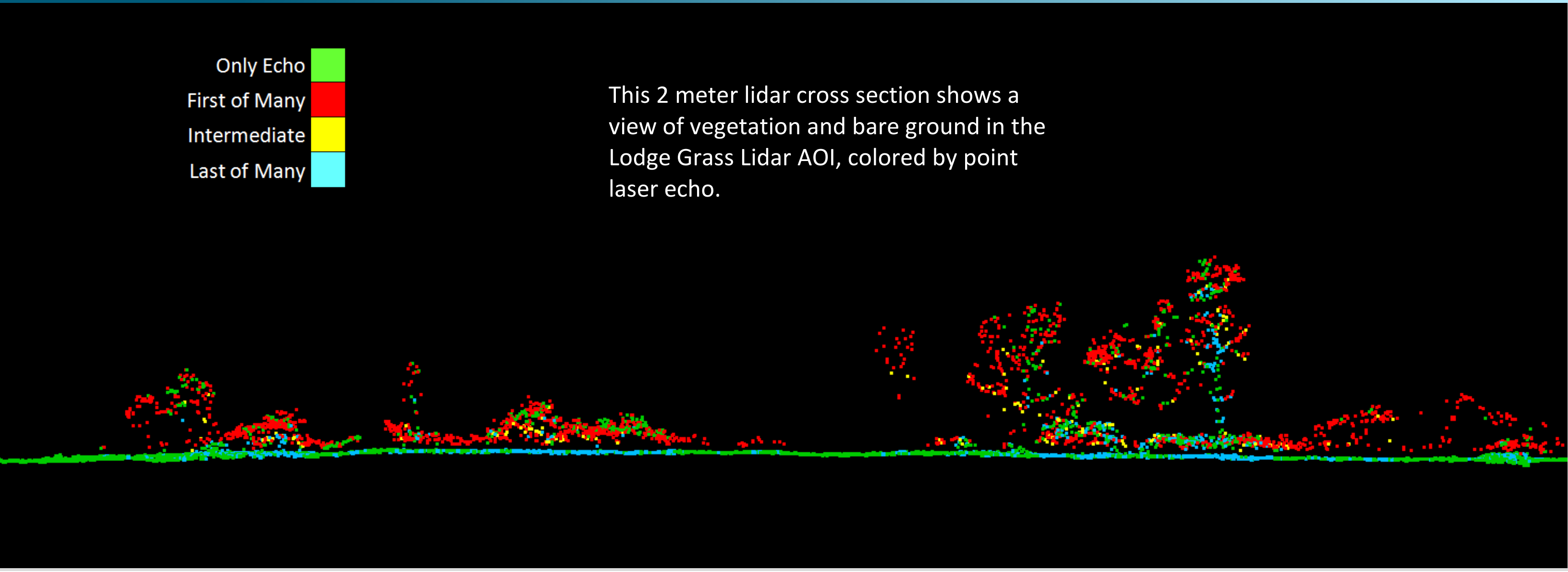


Figure 6: Sample image of building footprints in the Lodge Grass dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

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

The average first-return density of lidar data for the Lodge Grass project was 13.32 points/m^2 while the average ground classified density was 5.21 points/m^2 (Table 9). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 7 through Figure 10.

Table 9: Average lidar point densities

Classification	Point Density
First-Return	13.32 points/m^2
Ground Classified	5.21 points/m^2

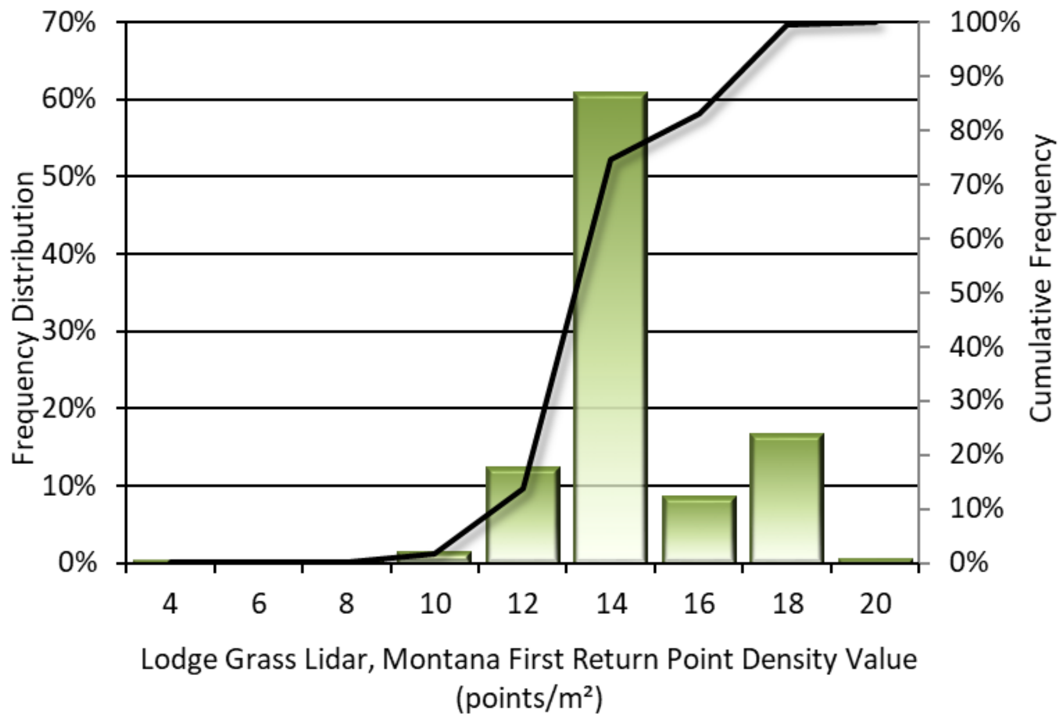


Figure 7: Frequency distribution of first return point density values per 100 x 100 m cell

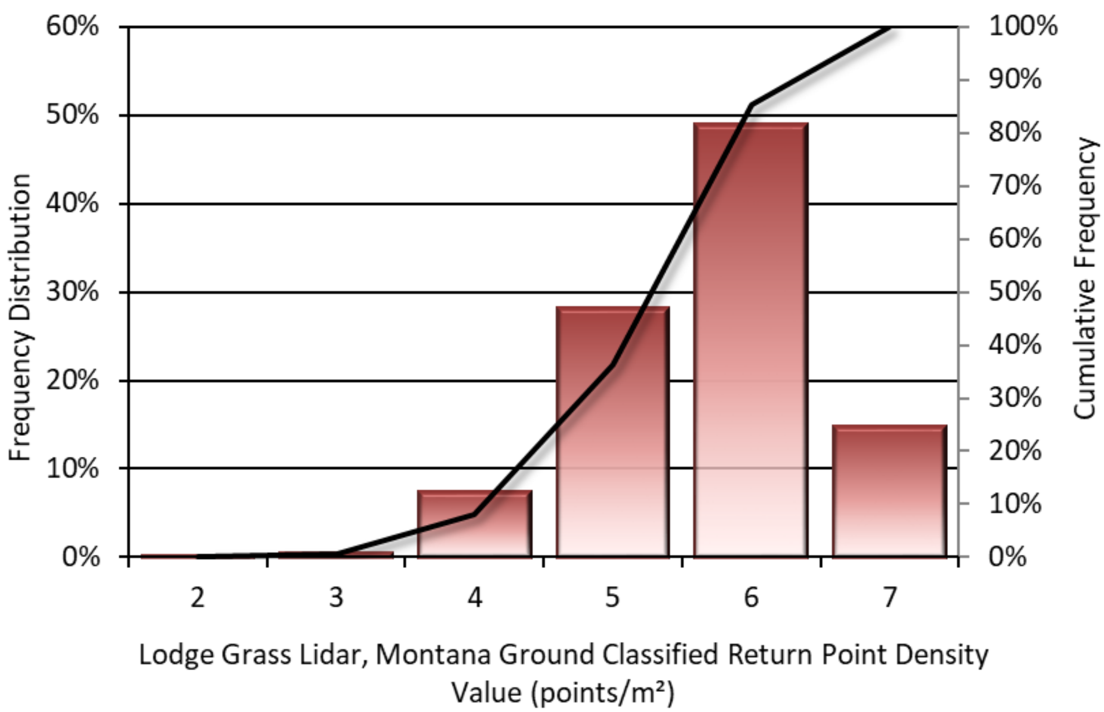


Figure 8: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

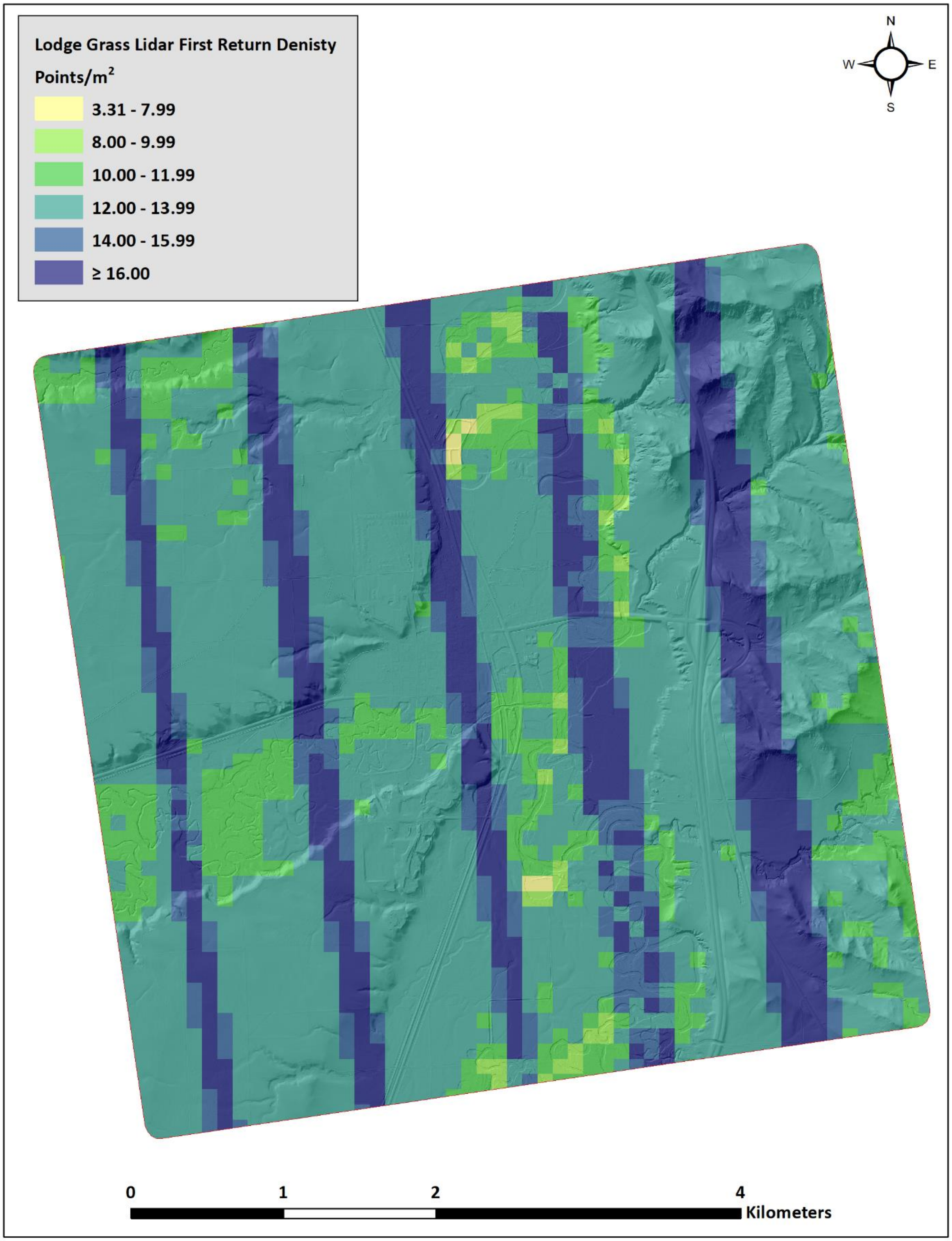


Figure 9: First return and ground-classified point density map for the Lodge Grass site (100 m x 100 m cells)

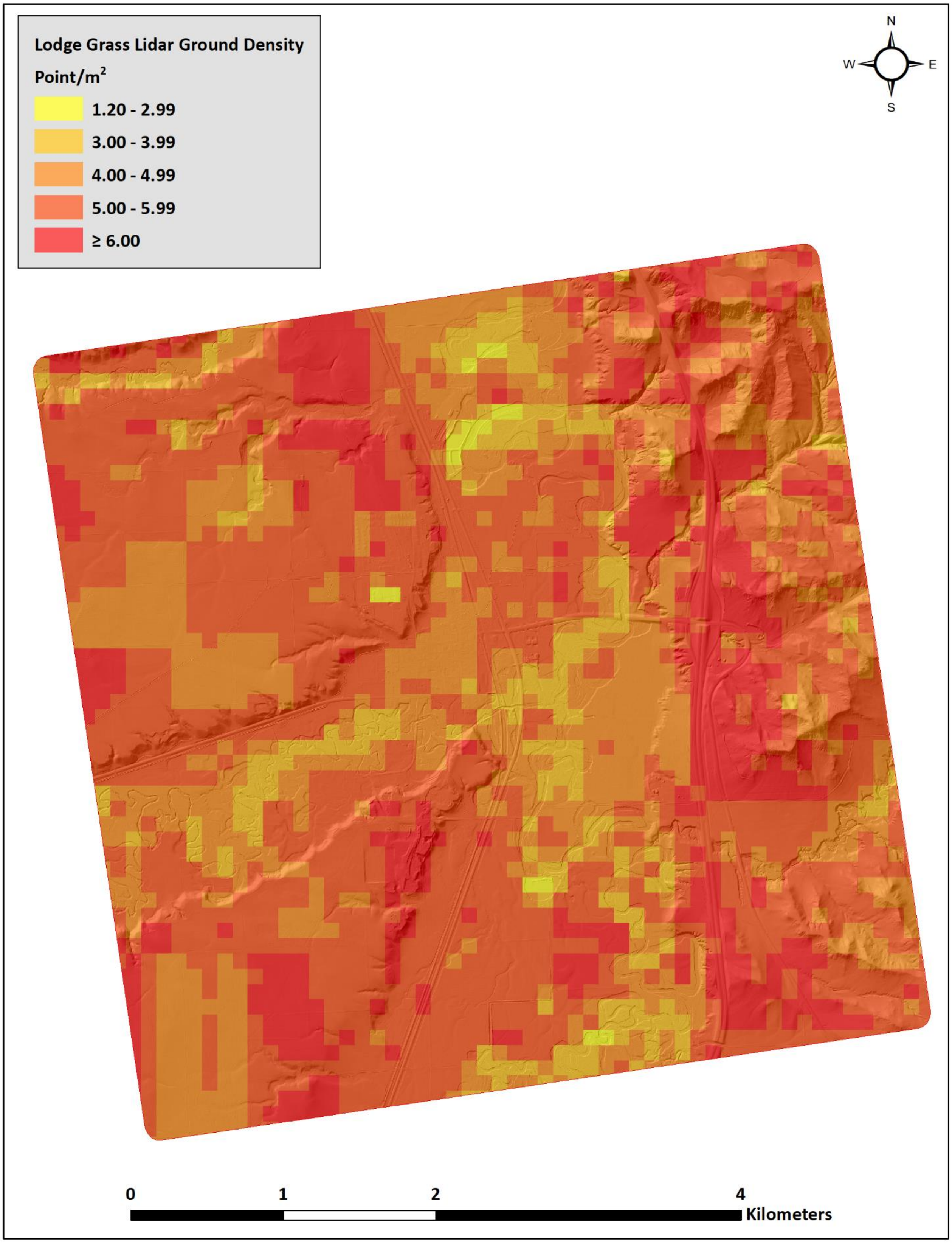


Figure 10: Ground point density map for the Lodge Grass site (100 m x 100 m cells)

Lidar Accuracy Assessments

The accuracy of the lidar data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[1]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the classified lidar point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of lidar point data in open areas where the lidar system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 10.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from quality assurance point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Lodge Grass survey, 23 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.034 meters as compared to classified LAS, and 0.038 meters as compared to the bare earth DEM, with 95% confidence (Figure 11, Figure 12, Table 10).

NV5 Geospatial also assessed absolute accuracy using 6 ground control points. Although these points were used in the calibration and post-processing of the lidar point cloud, they still provide a good indication of the overall accuracy of the lidar dataset, and therefore have been provided in Table 10 and Figure 13.

[1] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 10: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to classified LAS	**NVA, as compared to bare earth DEM**	**Ground Control Points**
Sample	23 points	23 points	6 points
95% Confidence (1.96*RMSE)	0.034 m	0.038 m	0.018 m
Average	-0.009 m	-0.011 m	-0.005 m
Median	0.008 m	-0.007 m	-0.004 m
RMSE	0.017 m	0.019 m	0.009 m
Standard Deviation (1σ)	0.015 m	0.017 m	0.009 m

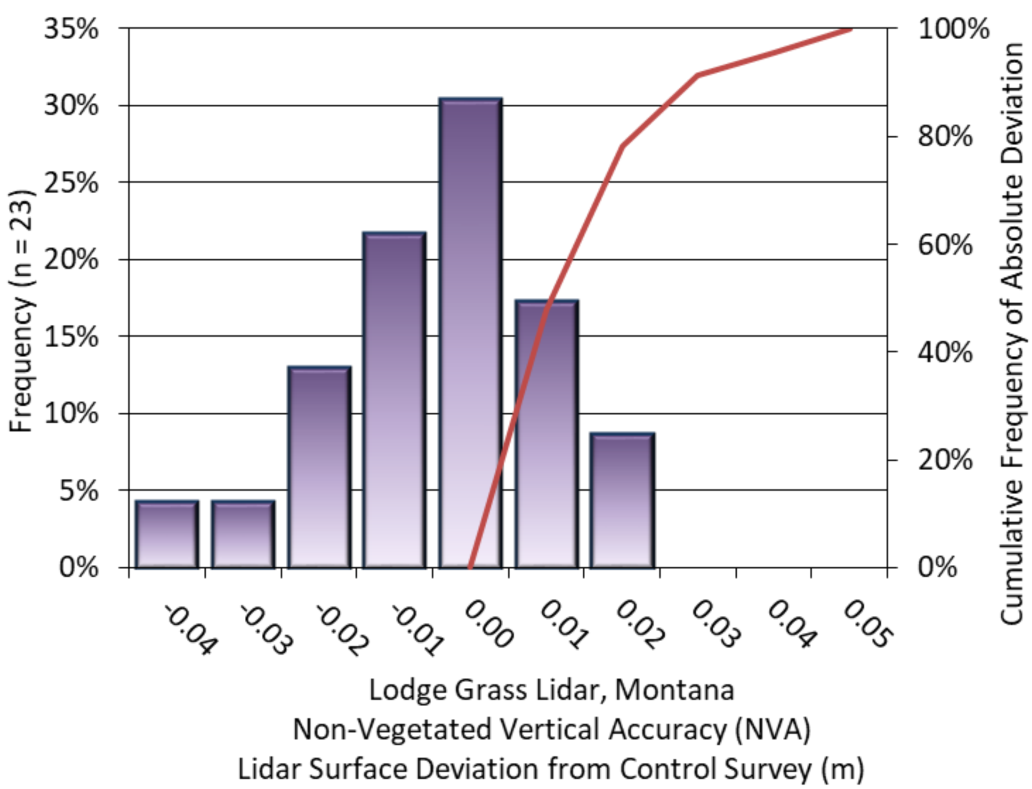


Figure 11: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA)

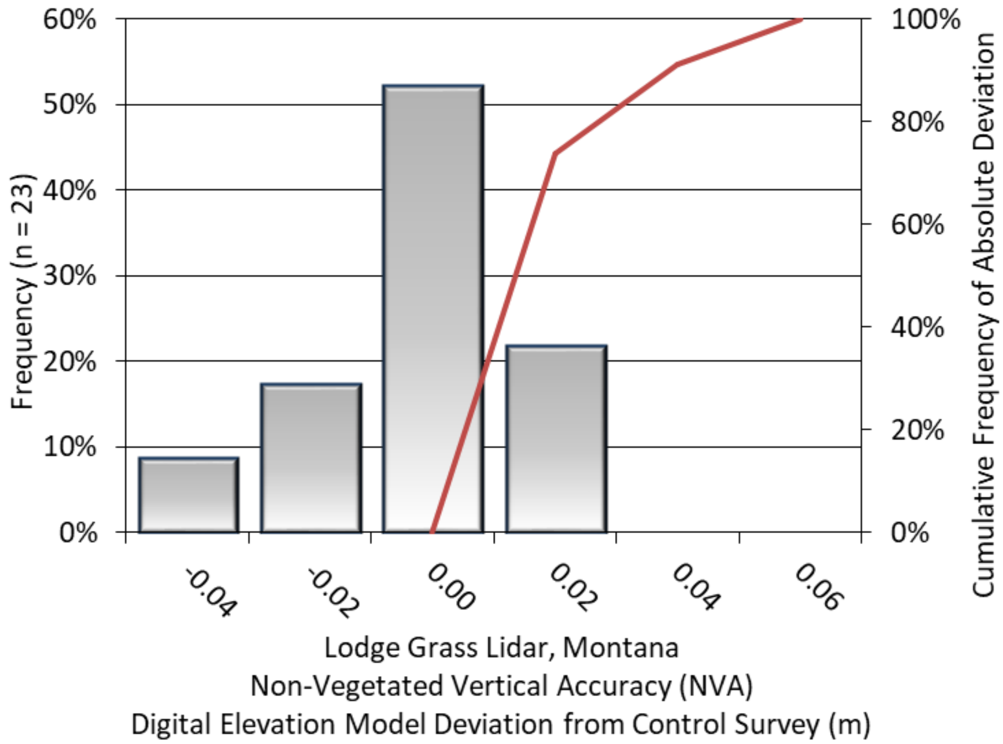


Figure 12: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA)

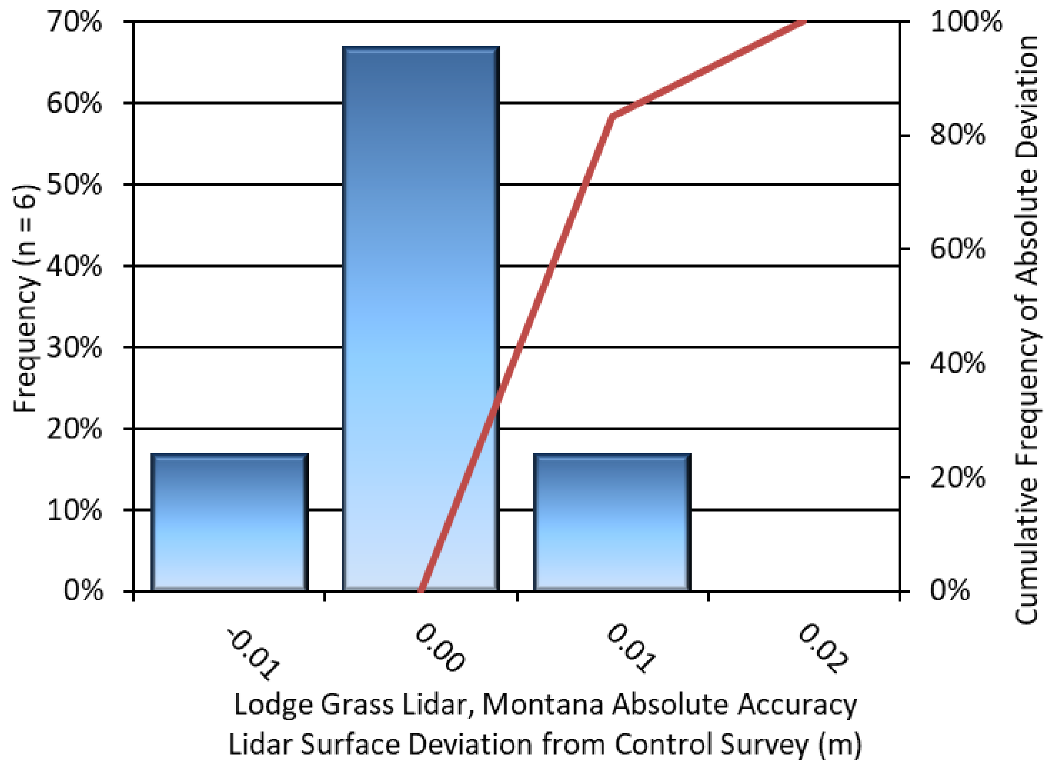


Figure 13: Frequency histogram the for lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracies

NV5 Geospatial also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified lidar points. For the Lodge Grass survey, 8 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.153 meters as compared to the classified LAS, and 0.156 meters as compared to the bare earth DEM evaluated at the 95th percentile (Table 11, Figure 14).

Table 11: Vegetated vertical accuracy results

Vegetated Vertical Accuracy		
	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
Sample	8 points	8 points
95th Percentile	0.153 m	0.156 m
Average	0.103 m	0.102 m
Median	0.099 m	0.089 m
RMSE	0.109 m	0.108 m
Standard Deviation (1σ)	0.037 m	0.038 m

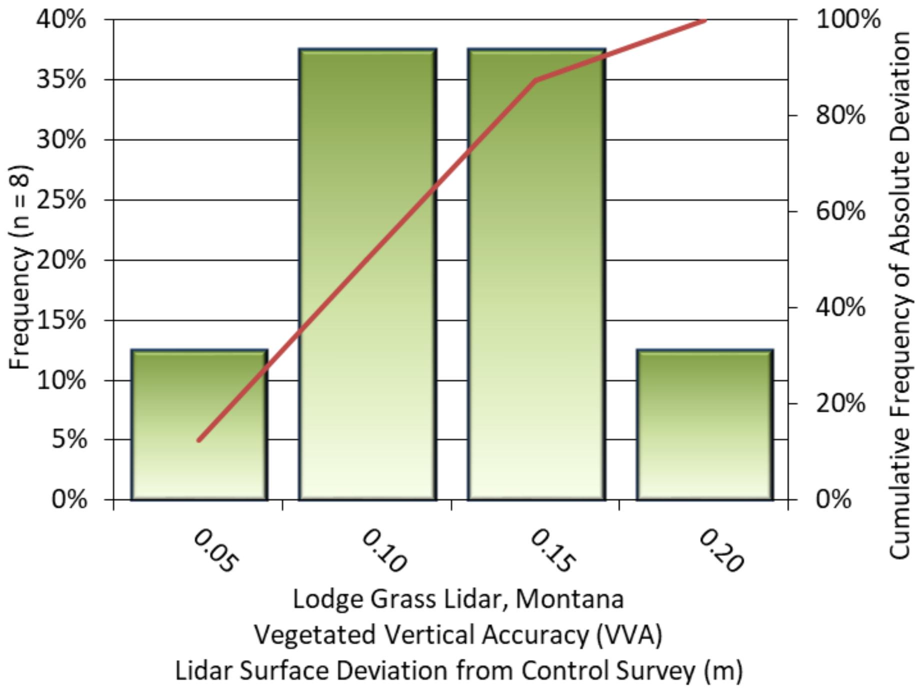


Figure 14: Frequency histogram for the lidar surface deviation from vegetated check point values (VVA)

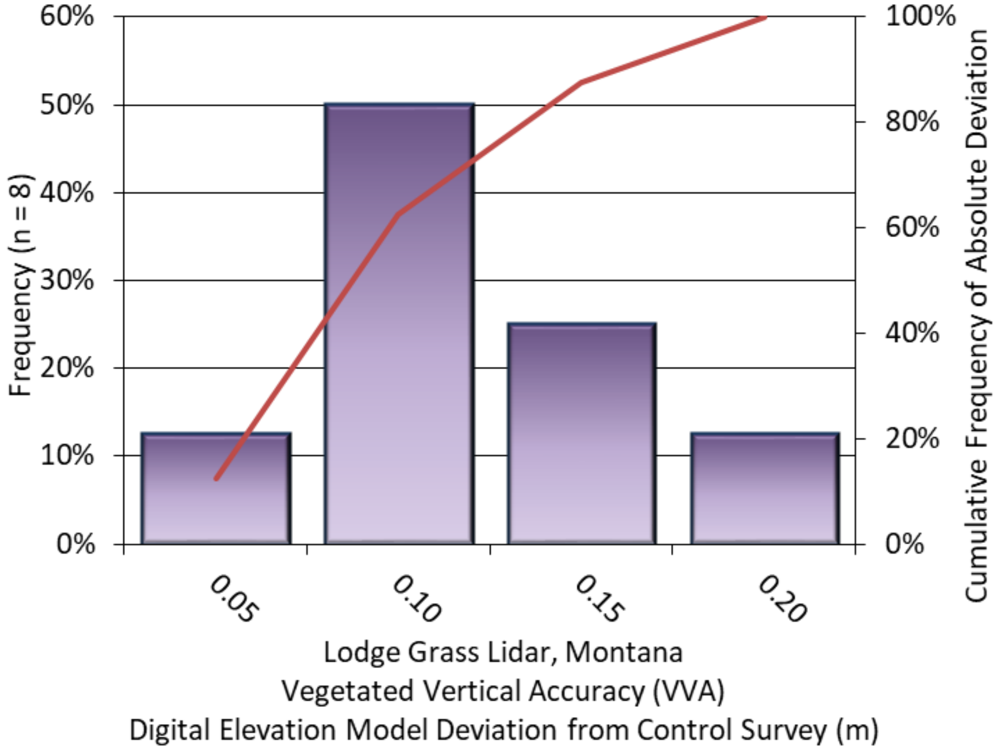


Figure 15: Frequency histogram for the lidar bare earth DEM deviation from vegetated check point values (VVA)

Lidar 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 Lodge Grass Lidar project was 0.021 meters (Table 12, Figure 16).

Table 12: Relative accuracy results

Relative Accuracy	
Sample	7 surfaces
Average	0.021 m
Median	0.021 m
RMSE	0.021 m
Standard Deviation (1σ)	0.002 m
1.96σ	0.003 m

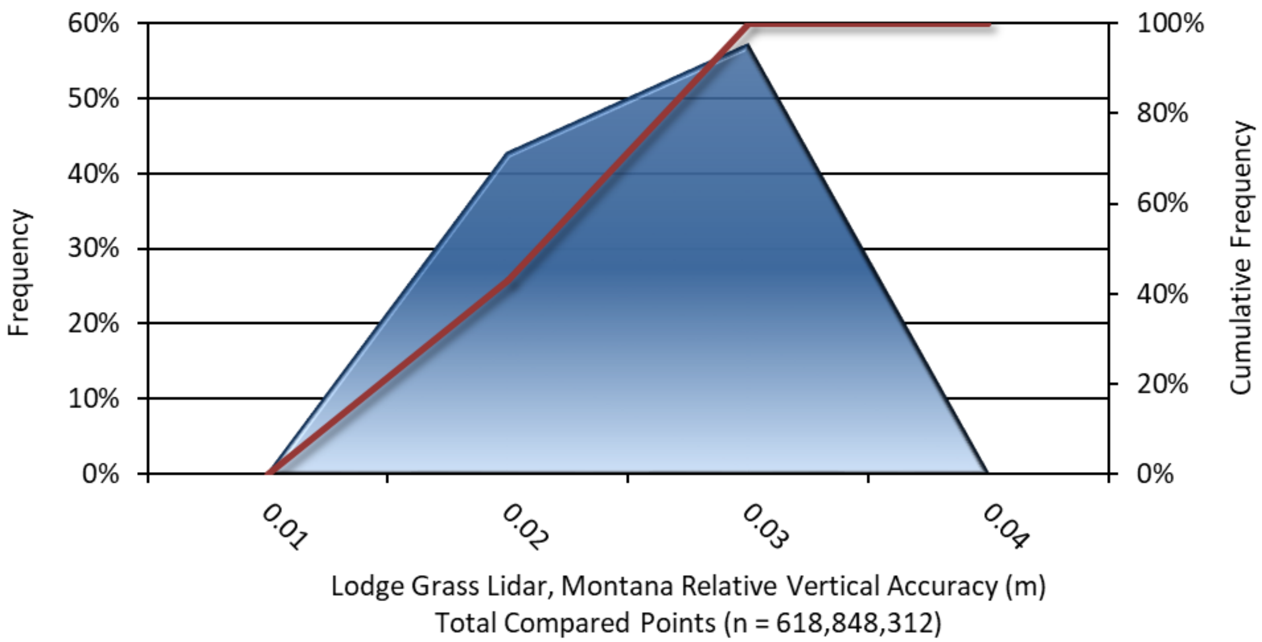


Figure 16: Frequency plot for relative vertical accuracy between flight lines

Lidar 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 percent of the time. Based on a flying altitude of 1,998 meters, an IMU error of 0.001 decimal degrees, and a GNSS positional error of 0.019 meters, this project was produced to meet 0.11 m horizontal accuracy at the 95% confidence level.

Table 13: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.06 m
ACC_r	0.11 m

Certifications

NV5 Geospatial, Inc. provided lidar services for the Lodge Grass project as described in this report.

I, Shauna Gutierrez, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Shauna Gutierrez
Shauna Gutierrez (Jul 30, 2021 13:00 PDT)

Jul 30, 2021

Shauna Gutierrez
Project Manager
NV5 Geospatial, Inc.

Figure 17: View looking east over Lodge Grass, Montana. The image was created from the lidar bare earth model overlaid with the above-ground point cloud and colored by orthoimagery.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (NVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of lidar data is described as the mean and standard deviation (sigma σ) of divergence of lidar point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the lidar system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the lidar points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of lidar resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Native Lidar Density: The number of pulses emitted by the lidar system, commonly expressed as pulses per square meter.

APPENDIX A - ACCURACY CONTROLS

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Lidar accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±29.25^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.