April 13, 2020

Powell County, Montana Lidar Technical Data Report

Prepared For:

Steve Story
Montana DNRC Water Resources Division
Helena, MT 59620
PH: 406-444-6816

Prepared By:

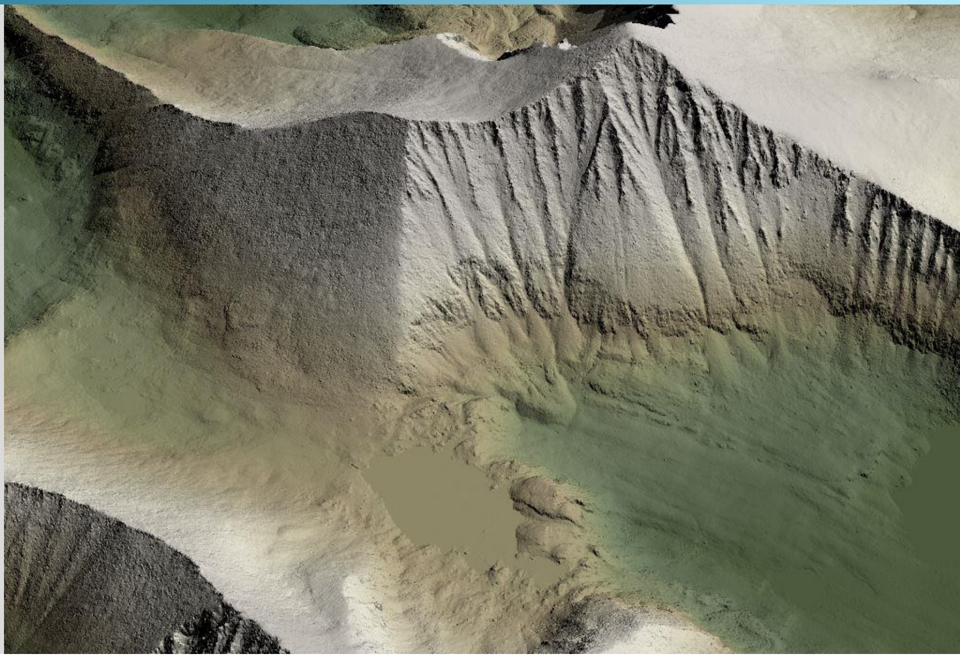
QSI Corvallis
1100 NE Circle Blvd, Ste. 126
Corvallis, OR 97330
PH: 541-752-1204

TABLE OF CONTENTS

Cover Photo: A view looking west at the Little Blackfoot River near Avon MT. The image was created from a combination of the Lidar bare earth model colored by elevation and Lidar point cloud colored by orthoimagery..

INTRODUCTION

This image depicts the bare earth model of Mount Powell in Montana.



In March 2019, Quantum Spatial (QSI) was contracted by Montana Department of Natural Resources (MTDNRC) to collect Light Detection and Ranging (Lidar) data in the summer of 2019 for Powell County in Montana. Data was collected to aid MTDNRC in assessing the topographic and geophysical properties of the study area to support MTDNRC's objective of obtaining new, high resolution Lidar-derived topographic data. This Lidar-derived data will 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 Powell County site

Project Site	Contracted Acres	Acquisition Dates	Data Type
Powell County QL1	149,690 Acres	5/11/2019 – 7/21/2019	Lidar
Powell County QL2	1,036,793 Acres	5/11/2019 – 7/21/2019	Lidar

Deliverable Products

Table 2: Products delivered to MTDNRC for the Powell County site

Powell County Lidar Products Projection: Montana State Plane FIPS 2500 Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Horizontal Units: International Feet Vertical Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns
Rasters	3-Foot GeoTiffs • Hydroflattened Bare Earth Model (DEM) • Highest Hit Digital Surface Model (DSM) ESRI Geodatabase and ASCII txt file • Digital Terrain Model (DTM) 1.5-foot GeoTiffs • Intensity Images • Density Rasters
Vectors	Shapefiles (*.shp) • Area of Interest • 3D Building Footprint Polygons • Processing Index • Aerial Acquisition Shapes (Flightlines and Total Area Flown) • Ground Survey Data • 1 ft. Contours Esri Geodatabase and ASCII txt file • Water's Edge Breaklines

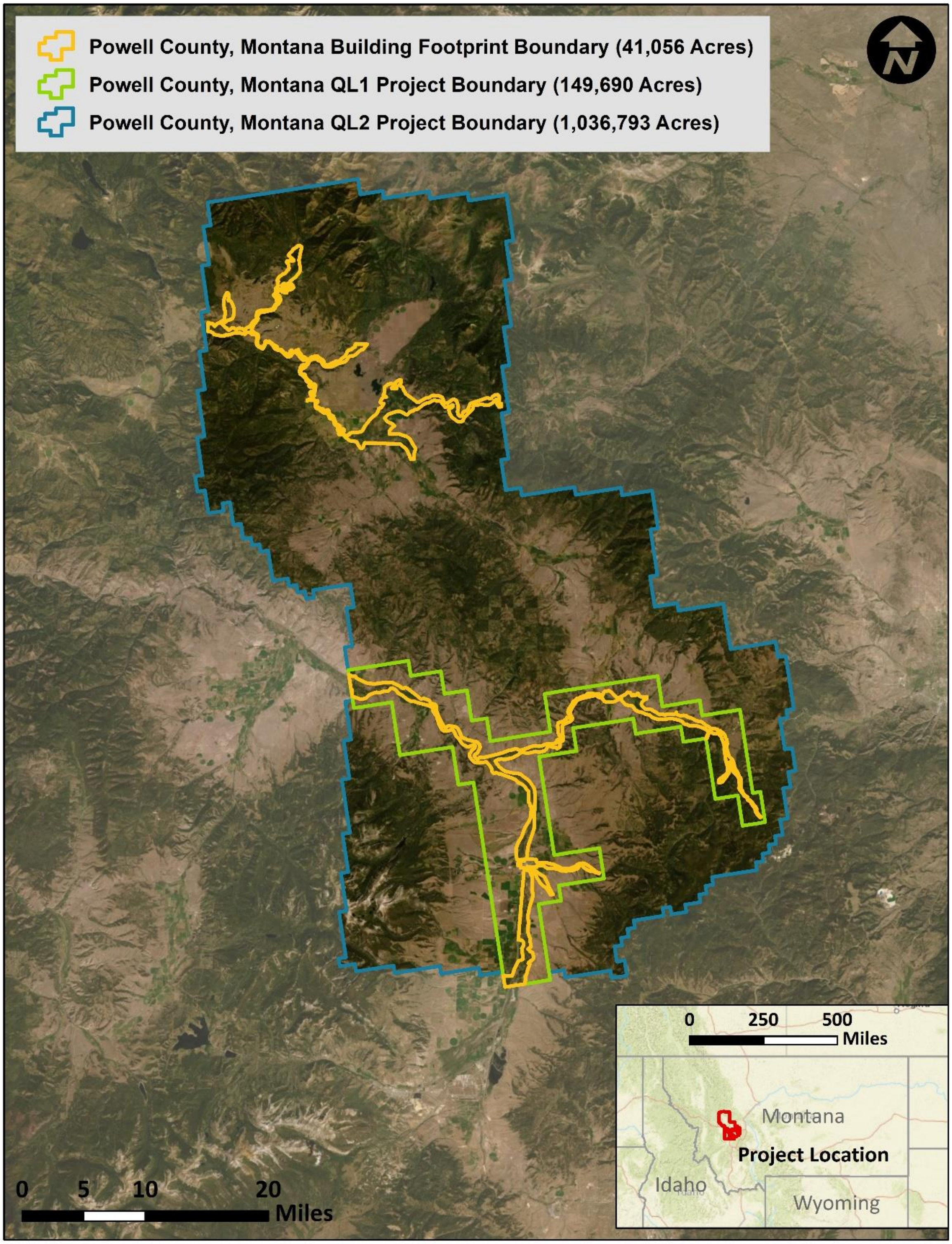


Figure 1: Location map of the Powell County site in Montana

QSI's ground acquisition equipment set up in the Powell County Lidar study area.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Powell County Lidar study area at the target point density of 8 points per square meters in the QL1 area and 2 points per square meter in the QL2 area. 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.

Airborne Lidar Survey

The Lidar survey was accomplished using a Reigl VQ-1560 laser system mounted in a Cessna Caravan to yield an average pulse density of ≥2 pulses/m^2 for the QL2 area and a Riegl LMS-Q-1560 mounted in a Piper PA-31 Navajo to yield an average pulse density of ≥8 pulses/m^2 for the QL1 area. Table 3 summarizes the settings used over the Powell County project area. The Reigl laser system can record unlimited range measurements (returns) per pulse. 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 3: Lidar specifications and survey settings

Lidar Survey Settings & Specifications		
Acquisition Dates	5/10/2019 – 7/21/2019	5/10/2019 – 7/21/2019
Aircraft Used	Cessna Caravan	Piper PA-31 Navajo
Sensor	Reigl	Riegl
Laser	VQ1560	LMS-Q1560
Maximum Returns	Unlimited	Unlimited
Resolution/Density	Average 2 pulses/m^2	Average 8 pulses/m^2
Nominal Pulse Spacing	0.71 m	0.35 m
Survey Altitude (AGL)	2300 m	1800 m
Survey speed	160 knots	160 knots
Field of View	50^o	60^o
Mirror Scan Rate	80 lines per second	60 lines per second
Target Pulse Rate	350 kHz	400 kHz
Pulse Length	2.5 ns	3.0 ns
Laser Pulse Footprint Diameter	41.4 cm	38.5 cm
Central Wavelength	1064 nm	1064 nm
Pulse Mode	Multiple-Time-Around (MTA)	Multiple-Time-Around (MTA)
Beam Divergence	0.18 mrad	0.25 mrad
Swath Width	2145 m	2078 m
Swath Overlap	50%	50%
Intensity	16-bit	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 30 cm	$RMSE_Z$ (Non-Vegetated) ≤ 30 cm
	NVA (95% Confidence Level) ≤ 29.4 cm	NVA (95% Confidence Level) ≤ 29.4 cm
	VVA (95^{th} Percentile) ≤ 45 cm	VVA (95^{th} Percentile) ≤ 45 cm

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.

Ground Survey

Ground control surveys, including monumentation, and ground survey points (GSPs) were conducted by Gaston Engineering & Surveying 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.

Base Stations

Base stations were utilized for collection of ground survey points collected by Gaston. Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized seven existing monuments provided by Gaston for the Powell County project (Table 4).

Table 4: Monument positions for the Powell County acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
CA001	46° 24’ 17.75338”	-112° 43’ 42.17678”	1370.403
CA002	46° 34’ 57.65276”	-112° 55’ 40.39189”	1263.824
CA003	46° 34’ 28.32605”	-112° 29’ 51.91441”	1485.236
CA004	46° 42’ 49.50572”	-112° 39’ 44.84364”	1499.890
CA005	46° 50’ 26.30588”	-112° 59’ 30.27329”	1334.143
CA006	46° 59’ 28.43345”	-113° 00’ 23.63638”	1267.731
CA007	47° 02’ 38.09974”	-113° 11’ 51.36369”	1212.632

Ground Survey Points (GSPs)

Ground survey points were collected by Gaston and provided to QSI to be used in LiDAR calibration and post-processing, and also for accuracy assessment. Gaston provided ground control point data for LiDAR calibration, in addition to non-vegetated (NVA) and vegetated (VVA) check point data for an independent accuracy assessment.

Land Cover Class

In addition to ground survey points, land cover class check points were collected 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 5, see Lidar Accuracy Assessments, page 19).

Table 5: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrubs	SH		Shrubland or areas dominated by other low growing woody plants	VVA
Tall Grass	TG		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FO		Areas dominated by coniferous or deciduous trees	VVA
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA

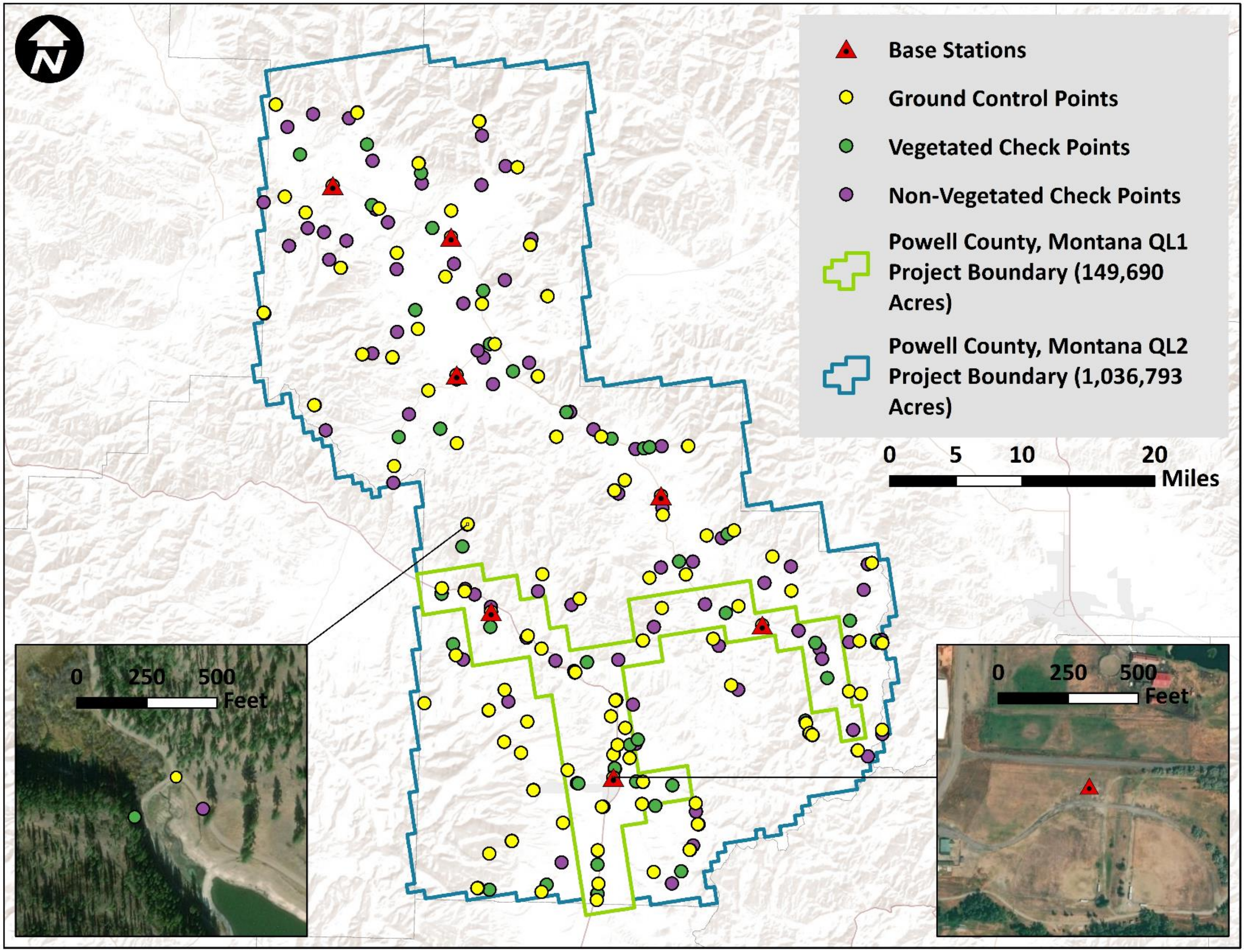
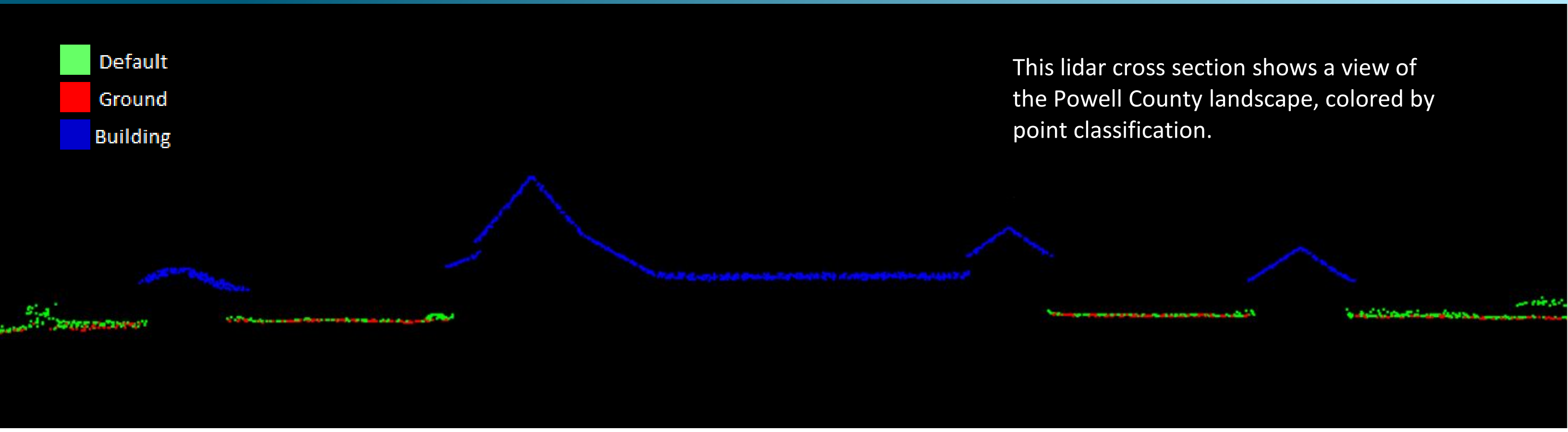


Figure 2: Ground survey location map



Lidar Data

Upon completion of data acquisition, QSI 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 6). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 7.

Table 6: ASPRS LAS classification standards applied to the Powell County dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-O	Edge Clip/Overlap	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 and Bridges	Permanent structures such as buildings and bridges
7	Noise	Laser returns that are often associated with birds, scattering from reflective surfaces, or 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
20	Ignored Ground	Ground points proximate to water’s edge breaklines; ignored for correct model creation
21	Snow	Laser returns determined to be snow

Table 7: 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.	RiProcess v.1.8.5 POSPac MMS v.8.3
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
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
Classify resulting data to ground and other client designated ASPRS classifications (Table 6). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19 TerraModeler v.19
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	LAS Product Creator 3.0 (QSI 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 GeoTiff format at a 3.0 foot pixel resolution.	LAS Product Creator 3.0 (QSI proprietary)

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Rivers and other water bodies within the 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 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 through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights Lidar-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary.

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 while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

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 3).

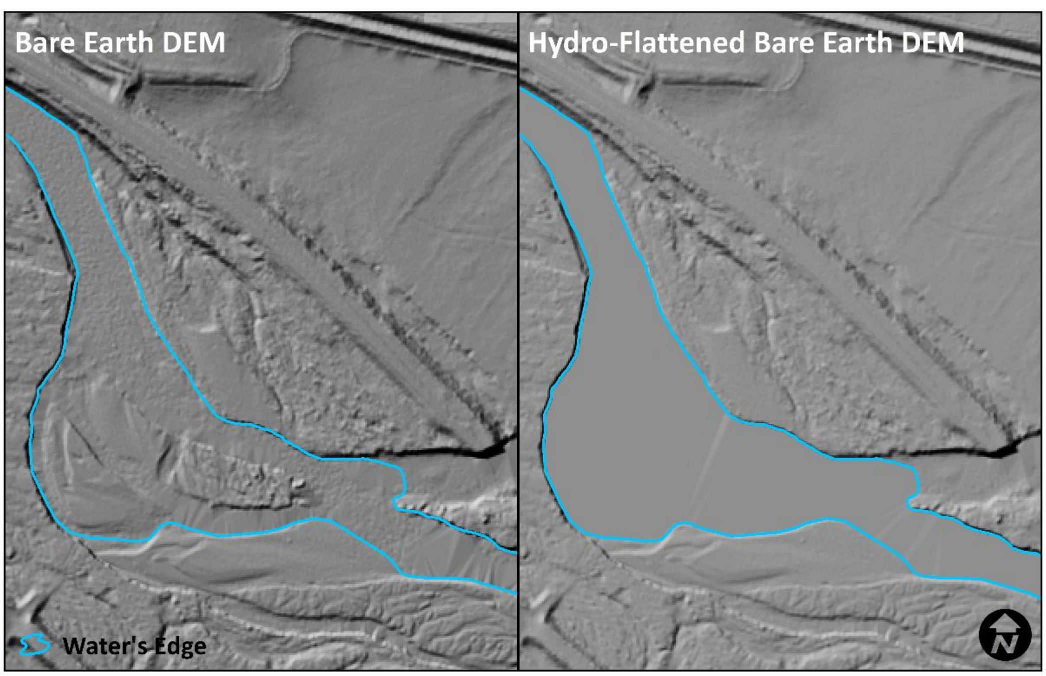


Figure 3: Example of hydroflattening in the Powell County Lidar dataset

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 foot 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.

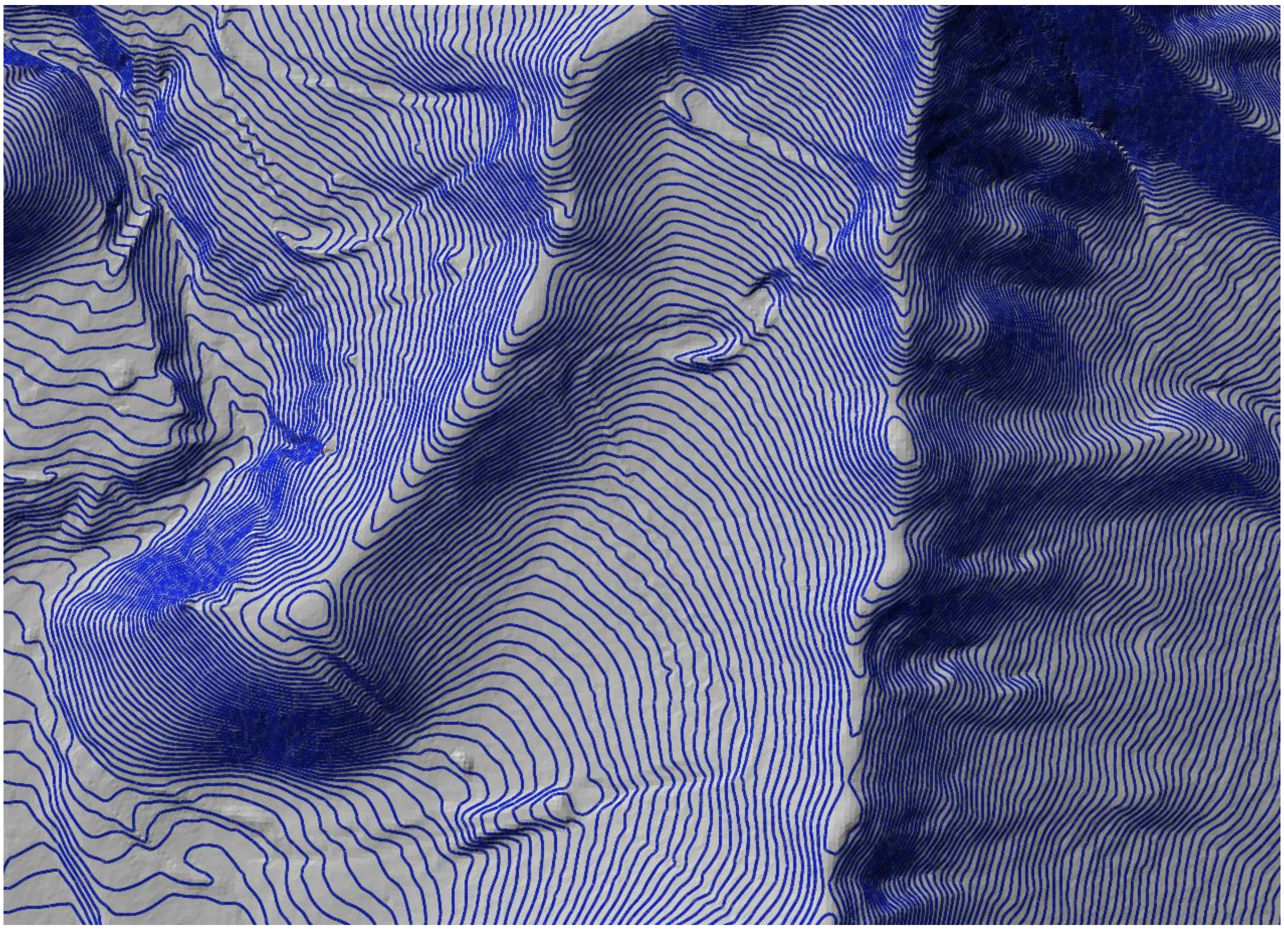


Figure 4: Contours draped over the Powell County bare earth elevation model.

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 were classified into the building category. Once classification was complete, automated routines were used generate the polygon shapefile representing building and bridge footprints. A total of 3,168 buildings were classed within the data (Figure 5).

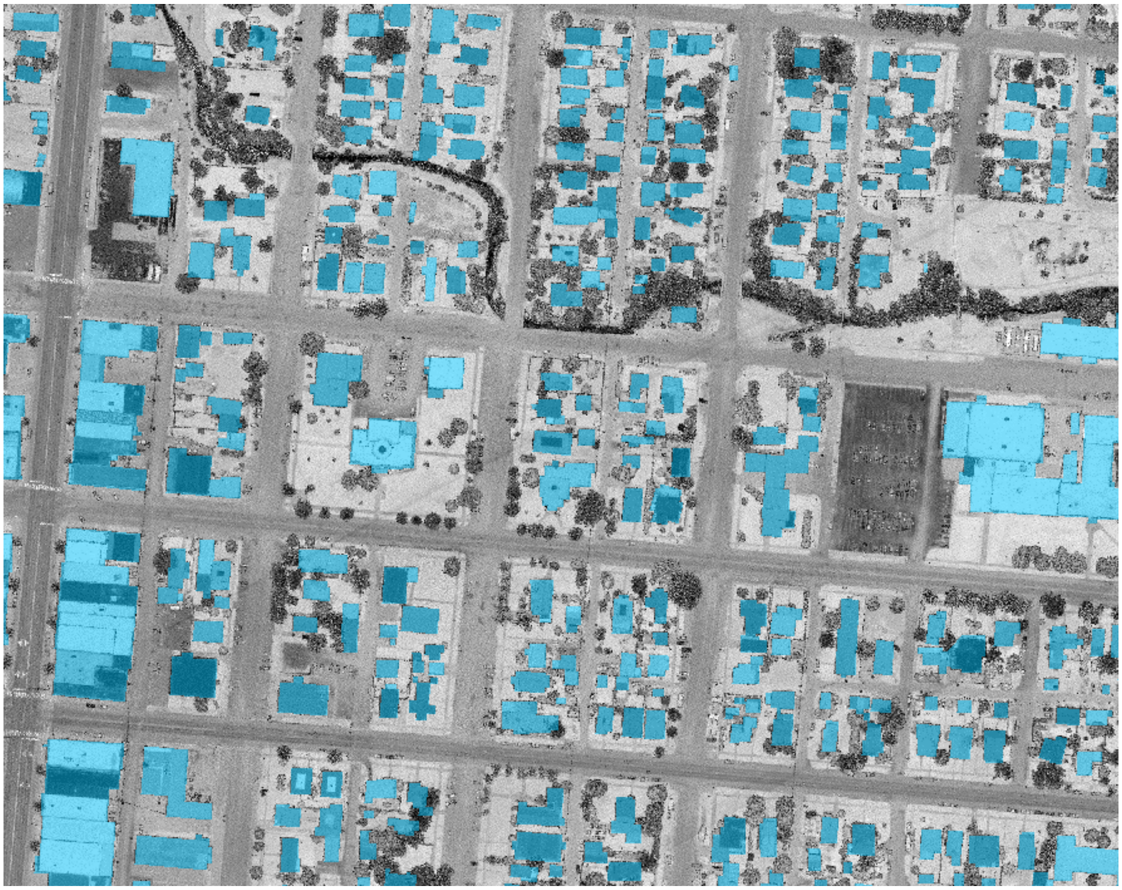
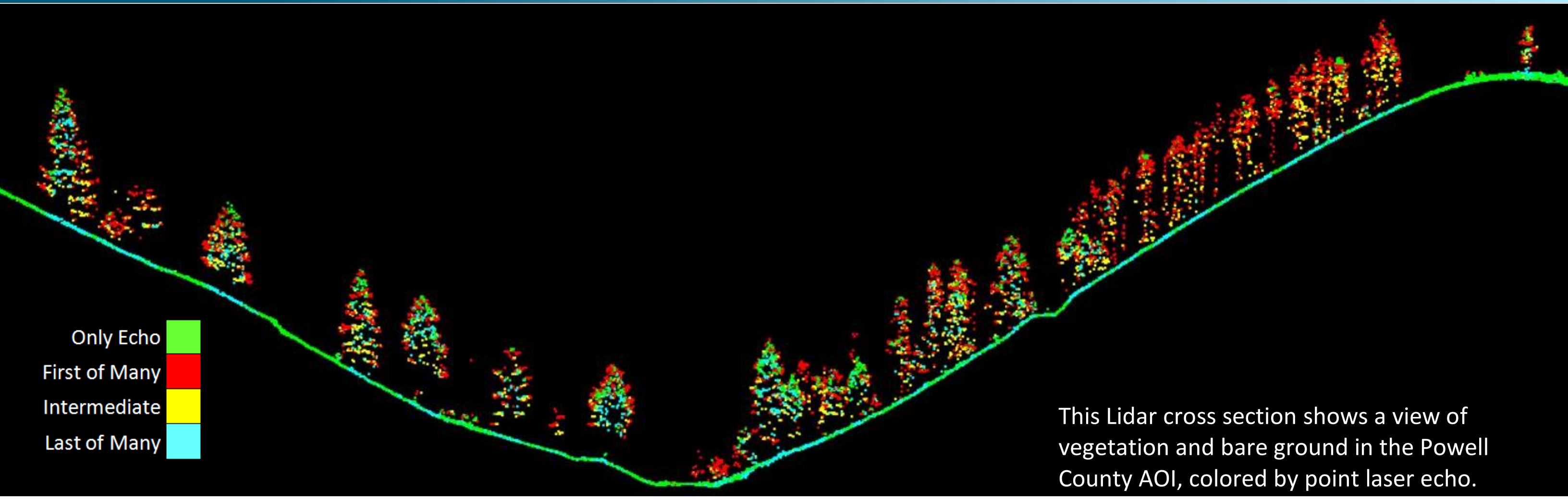


Figure 5: This aerial view of the lidar point cloud is colored by intensity and is overlaid with the 3D building footprint in the Powell County dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of ≥8.0 points/m2 for QL1 areas and ≥2.0 points/m2 for QL2 areas. 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 Powell County QL1 project area is 16.42 points/m^2 with an average ground classified density of 6.77 points/m^2. While the average first-return density for the QL2 area was 10.03 points/m^2 with an average ground density of 4.63 points/m^2 (Table 8). 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 8 through Figure 11.

Table 8: Average Lidar point densities

Project Site	Classification	Point Density
Powell County QL1	**First-Return**	16.42 points/m^2
Powell County QL1	**Ground Classified**	6.77 points/m^2
Powell County QL2	**First-Return**	10.03 points/m^2
Powell County QL2	**Ground Classified**	4.63 points/m^2

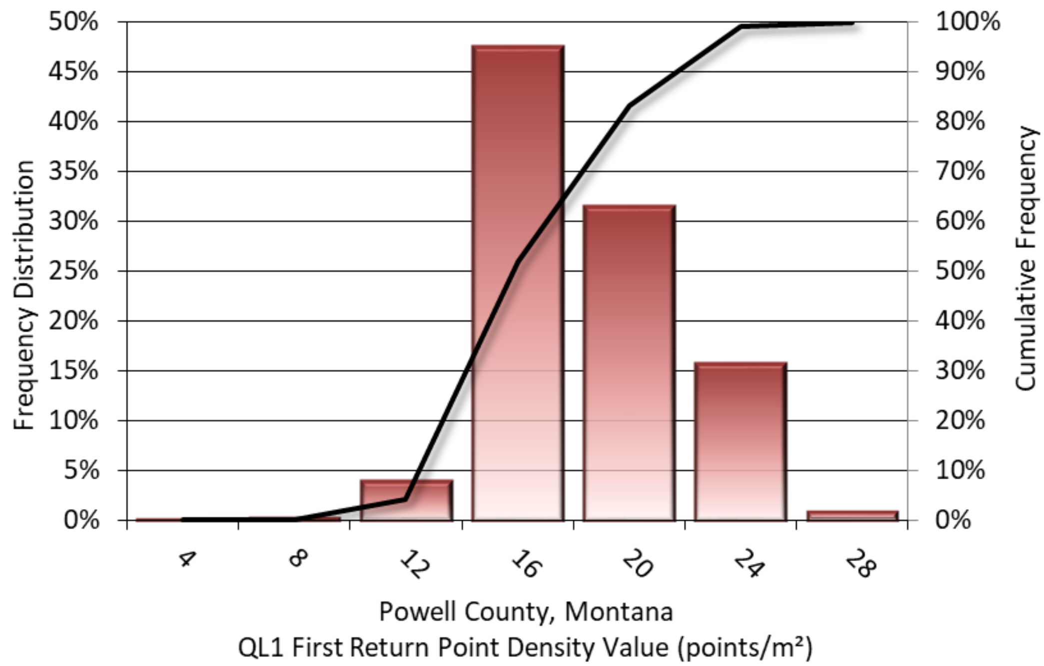


Figure 6: Frequency distribution of first return point density values in the QL1 dataset per 100 x 100 m cells

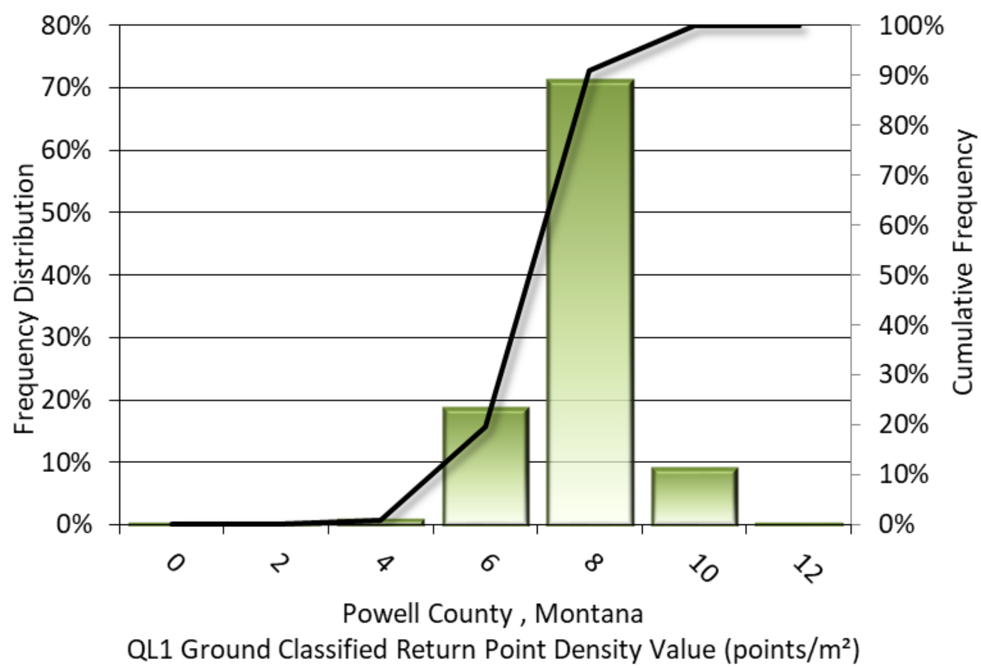


Figure 7: Frequency distribution of ground classified return density values in the QL1 dataset per 100 x 100 m cells

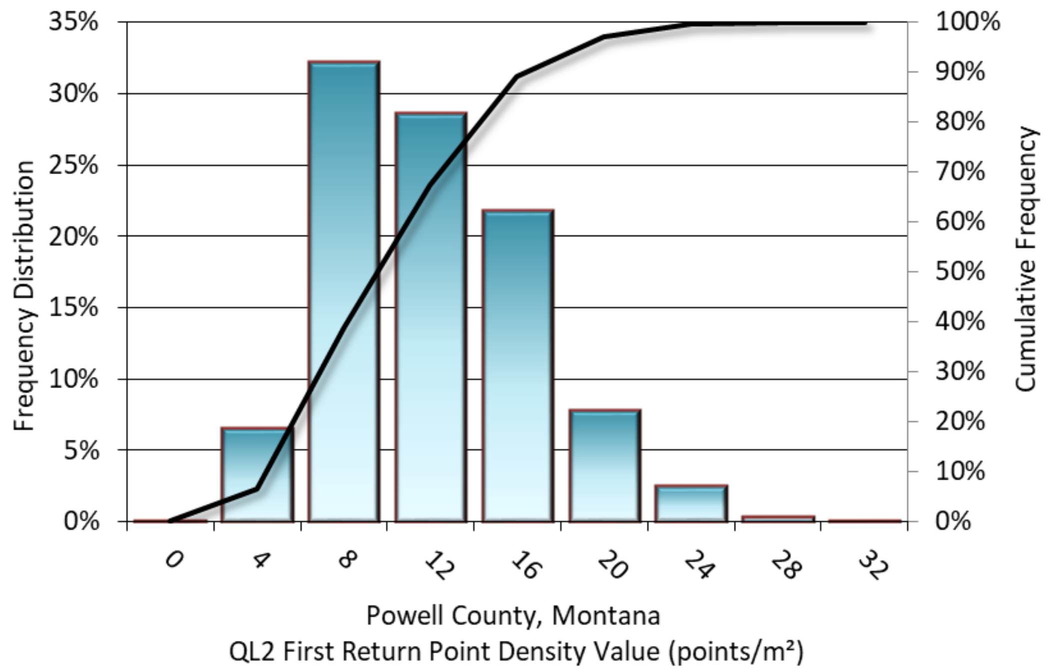


Figure 8: Frequency distribution of first return point density values in the QL2 dataset per 100 x 100 m cells

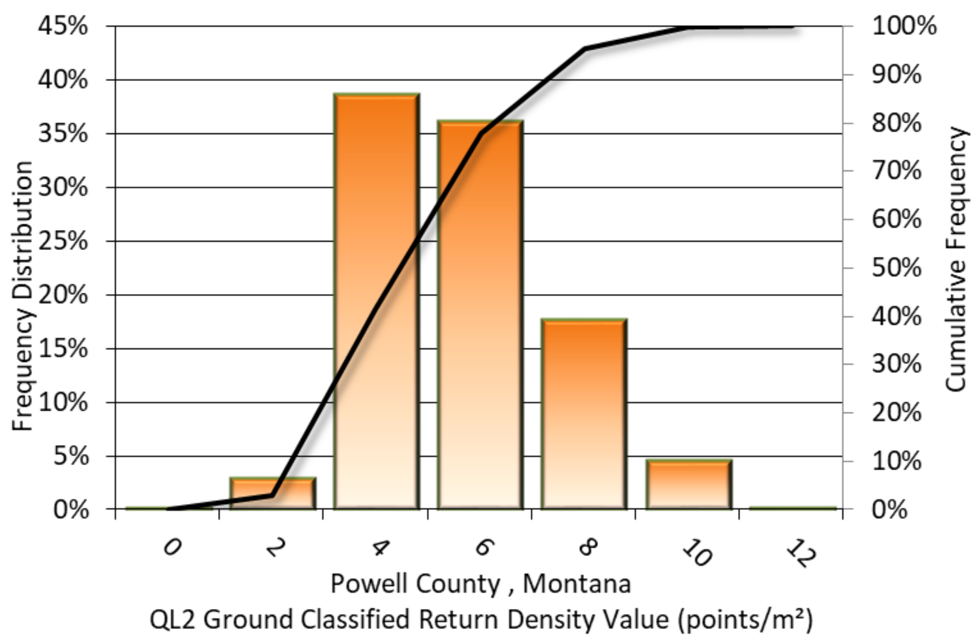


Figure 9: Frequency distribution of ground classified return density values in the QL2 dataset per 100 x 100 m cells

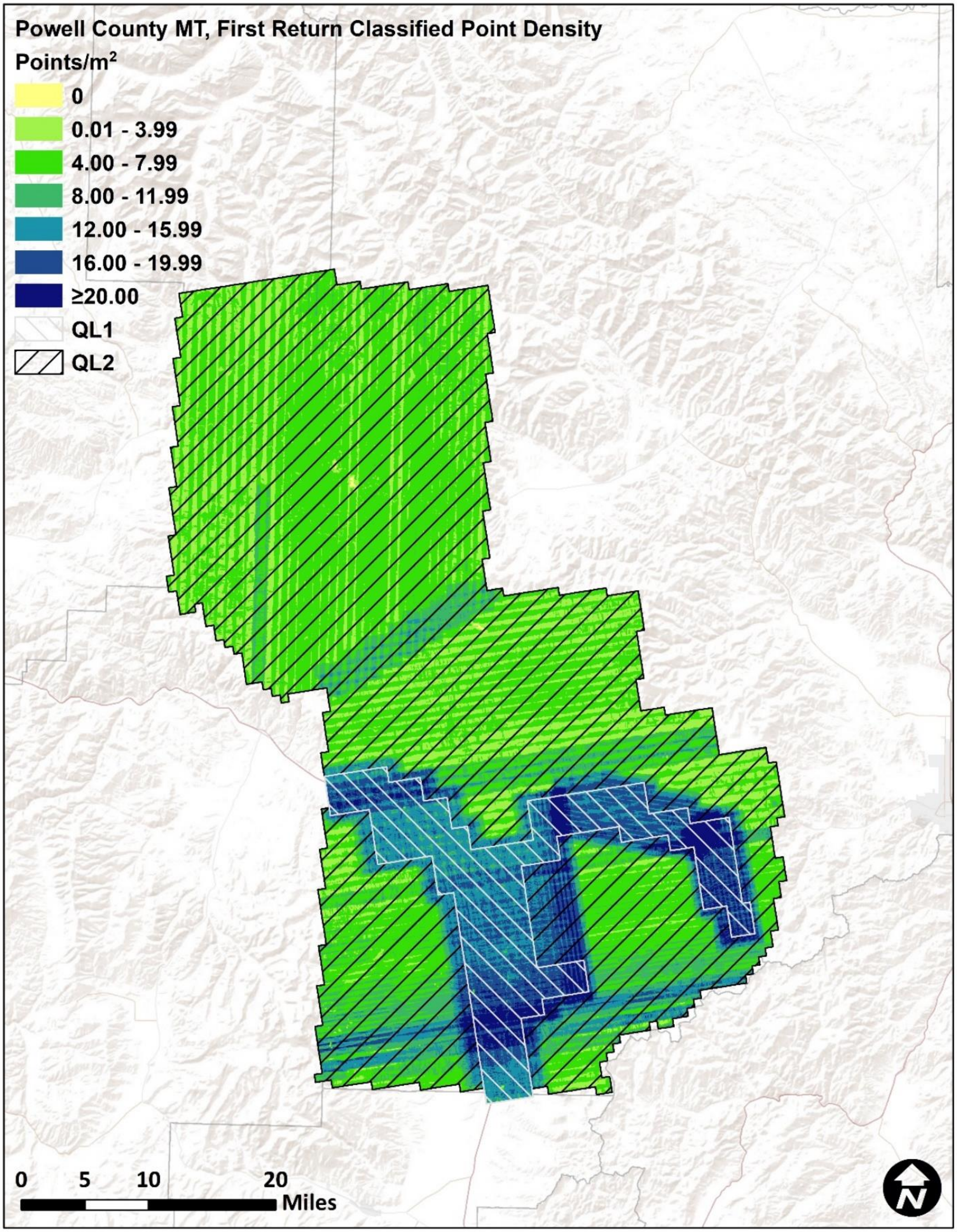


Figure 10: First return density map for the Powell County site (100 m x 100 m cells)

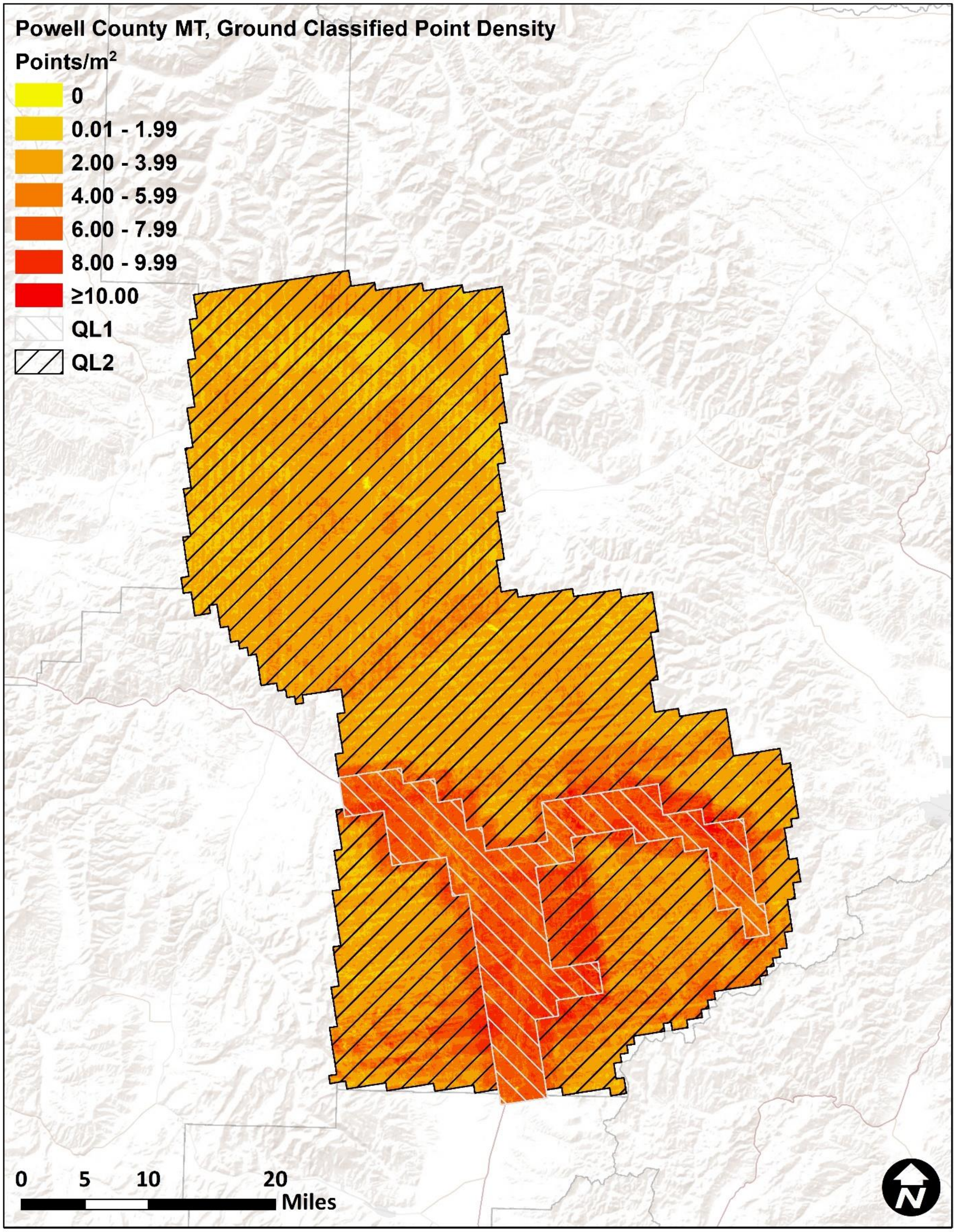


Figure 11: Ground-classified point density map for the Powell County site (100 m x 100 m cells)

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 unclassified 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 9.

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 Powell County survey, 94 ground check points were withheld from the calibration and post processing of the Lidar point cloud, with resulting non-vegetated vertical accuracy of 0.226 feet (0.069 meters) as compared to unclassified LAS, and 0.162 feet (0.049 meters) as compared to the bare earth DEM, with 95% confidence (Figure 12, Figure 13).

QSI also assessed absolute accuracy using 97 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 9 and Figure 14.

---

[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 9: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	94 points	94 points	97 points
95% Confidence (1.96*RMSE)	0.226 ft 0.069 m	0.162 ft 0.049 m	0.199 ft 0.061 m
Average	0.062 ft 0.019 m	0.025 ft 0.008 m	0.002 ft 0.001 m
Median	0.057 ft 0.018 m	0.033 ft 0.010 m	-0.010 ft -0.003 m
RMSE	0.115 ft 0.035 m	0.083 ft 0.025 m	0.101 ft 0.031 m
Standard Deviation (1σ)	0.097 ft 0.030 m	0.079 ft 0.024 m	0.102 ft 0.031 m

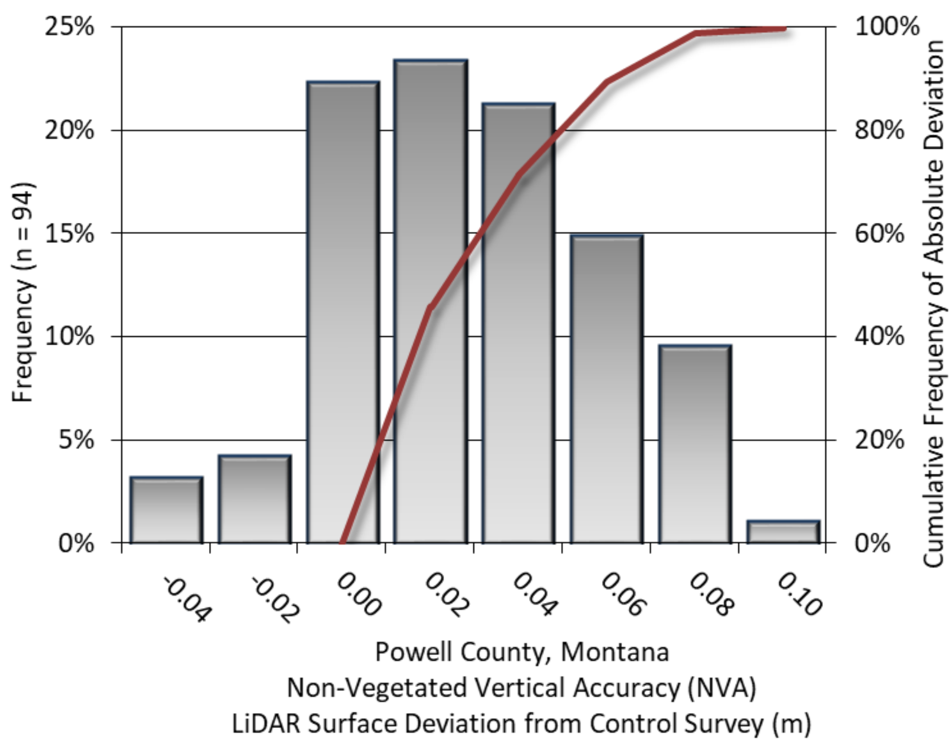


Figure 12: Frequency histogram for the Lidar unclassified LAS deviation from ground check point values (NVA)

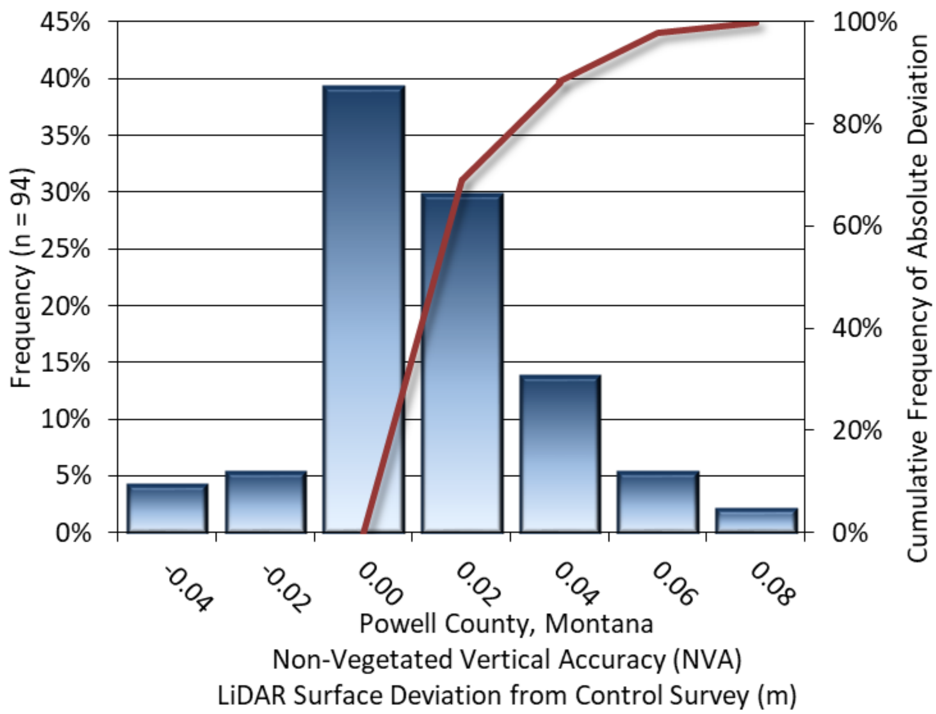


Figure 13: Frequency histogram for Lidar bare earth DEM surface deviation from ground check point values (NVA)

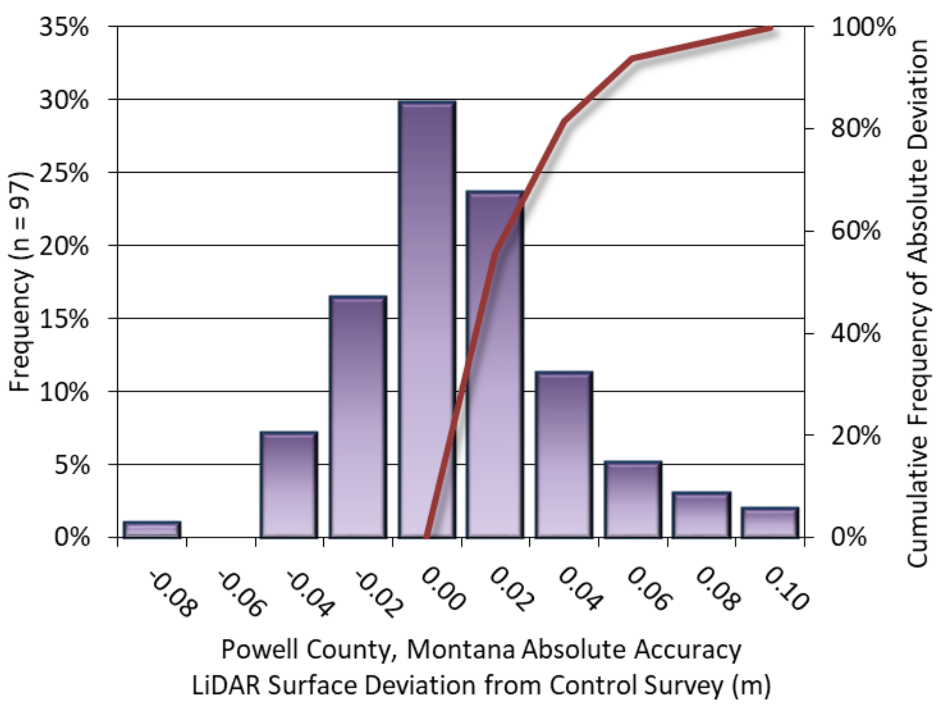


Figure 14: Frequency histogram for Lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracies

QSI 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 Powell County survey, 72 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.154 feet (0.07 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 10, Figure 15).

Table 10: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	72 points
95th Percentile	0.361 ft 0.110 m
Average	0.022 ft 0.007 m
Median	0.000 ft 0.000 m
RMSE	0.154 ft 0.047 m
Standard Deviation (1σ)	0.154 ft 0.047 m

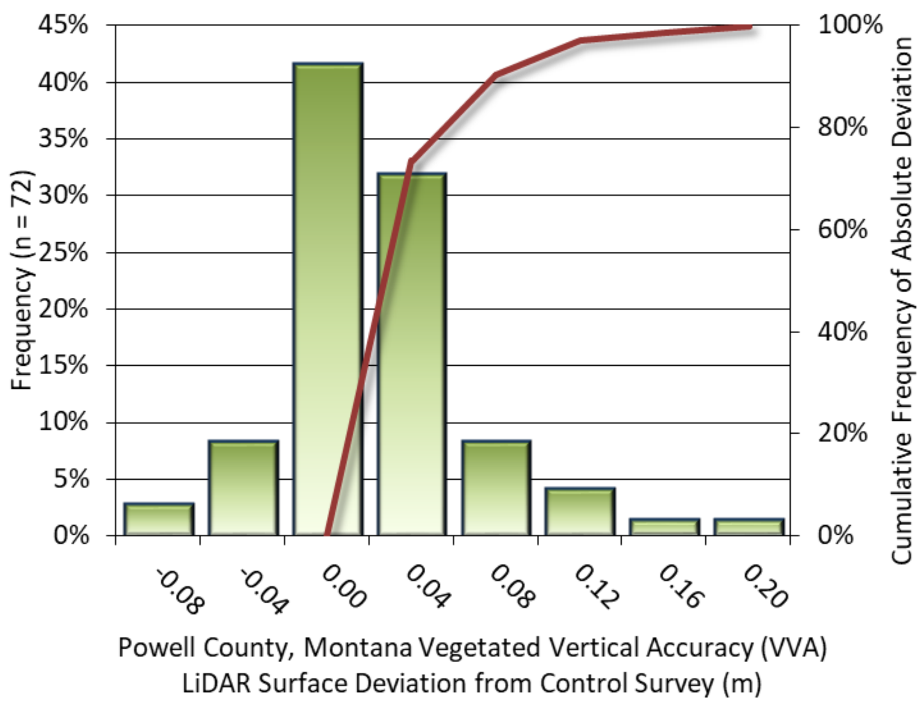


Figure 15: Frequency histogram for Lidar surface deviation from vegetated check point values (VVA)

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 Powell County Lidar project was 0.102 feet (0.031 meters) (Table 11, Figure 16).

Table 11: Relative accuracy results

Relative Accuracy	
Sample	196 surfaces
Average	0.102 ft 0.031 m
Median	0.104 ft 0.032 m
RMSE	0.106 ft 0.032 m
Standard Deviation (1σ)	0.016 ft 0.005 m
1.96σ	0.031 ft 0.009 m

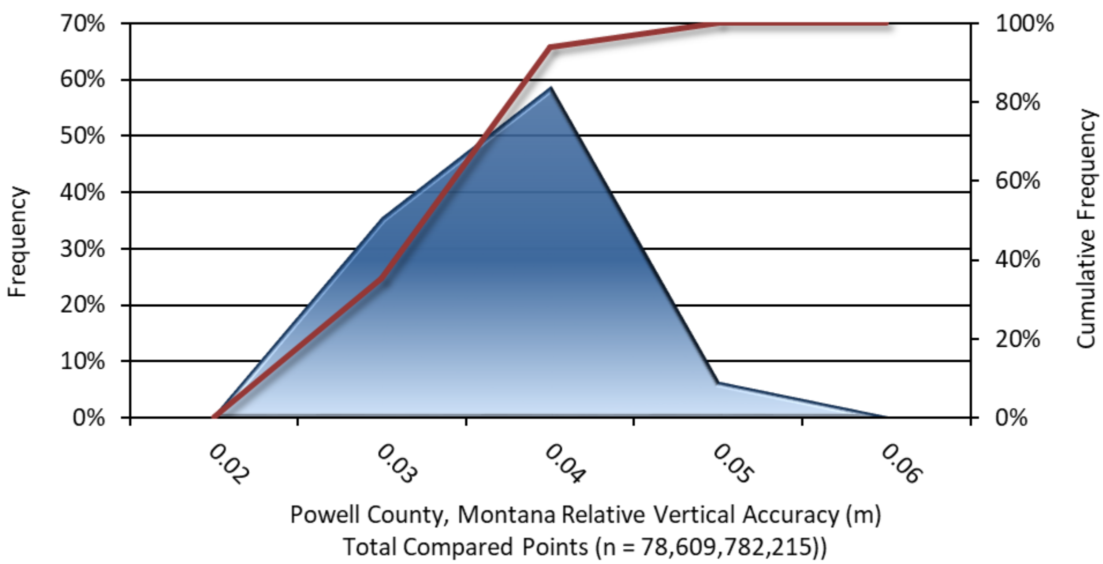


Figure 16: Frequency plot for relative vertical accuracy between flight lines

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.

Table 12: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	1.18 ft 0.36 m
ACC_r	2.04 ft 0.62 m

Figure 17: View looking east over Powell County. The image was created from the Lidar bare earth model and the above-ground point cloud overlaid with imagery.

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.

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 ±25^{o} and ±30^{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.

APPENDIX B – SURVEY REPORT

GASTON ENGINEERING & SURVEYING, P.C.

PROFESSIONAL • PROGRESSIVE • PERSONAL

August 2, 2019
W.O. #19-524

RE: **Survey Methodology Report**
Calibration & FEMA Check Point Survey
Powell County, Montana

Gaston Engineering & Surveying personnel collected ground surface information via GPS RTK surveying techniques utilizing Leica GS14 GPS equipment. Calibration and check points were collected in various ground cover categories which were bare earth, urban, forest, shrubs and tall grass/crops. RTK observations at each of the calibration and check points were occupied for 180 epochs. The x, y, z coordinates of each of the calibration and check points were tabulated in .xlsx format, and submitted to QSI for further refinement of the LiDAR dataset.

Some of the initial calibration points were derived by collection of static position and post-processed utilizing OPUS. These initial calibration points serve as the control network for the RTK collection. We occupied these points for two separate 2-hour static collections and averaged the OPUS results. All RTK surveying from these points utilized Geoid 12B, which is the most recent geoid model.

Ground survey efforts were completed in June, July & August of 2019.

MONTANA
JAMES FITZGERALD VERELLEN
No. 38363LS
LICENSED
PROFESSIONAL LAND SURVEYOR

P.O. BOX 861 • 211 HAGGERTY LN, BOZEMAN, MT 59771 • 406.586.0588 • FAX 406.586.0589
gaston@gastonengineering.com • www.gastonengineering.com

ENGINEERING/LAND SURVEYING/LAND PLANNING/MATERIALS TESTING