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Blaine County, Montana LiDAR

Technical Data Report

Prepared For:

The Montana Department of Natural Resources & Conservation

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Cover Photo: This view looks northeast over a segment of the Milk River and surrounding agricultural landscape in Blaine County. The Milk River has a high meandering course causing oxbow lakes as seen here (right center). In the bottom left hand corner, Snake Creek is seen winding into the Milk River. This image was created by layering the LiDAR point cloud on top of the LiDAR derived bare earth, and is colored by imagery.

INTRODUCTION

This photo provided by Gaston Engineering and Surveying shows survey equipment set up on site in Blaine County, Montana.

In September 2018, Quantum Spatial (QSI) was contracted by the State of Montana's Department of Natural Resources and Conservation (MTDNRC) to collect QL1 Light Detection and Ranging (LiDAR) data in the fall of 2018 for Blaine County in Montana. The Blaine County project was contracted as part of the Milk River LiDAR contract, which encompasses several counties in the state of Montana. Data were collected to aid MTDNRC in assessing the topographic and geophysical properties of the study area to support MTDNR'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 Blaine County site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Blaine County, Montana	537,833	544,707	10/19/2018 – 10/24/2018	QL1 LiDAR

Deliverable Products

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

Blaine 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 • Raw Calibrated Swaths • All Classified Returns
Rasters	Hydroflattened Bare Earth Digital Elevation Model (DEM): • 3.0 Foot Pixel Resolution • ESRI Grid Format • ESRI Grid Format in a Geodatabase (*.gdb) • Space Delimited ASCII Files (*.asc) Ground Density Raster Model: • 3.0 Foot Pixel Resolution • ESRI Grid Format
Vectors	Shapefiles (*.shp): • Contracted Site Boundary • Contracted Building Footprint Boundary • Tile Index • Ground Survey Data • Total Area Flown • 1.0 Foot Contours • 3D Building Footprints with LAG Elevations ESRI Geodatabase (*.gdb) • 1.0 Foot Contours • 3D Water's Edge Breaklines Space Delimited ASCII Text Files (*.txt): • 3D Water's Edge Breaklines

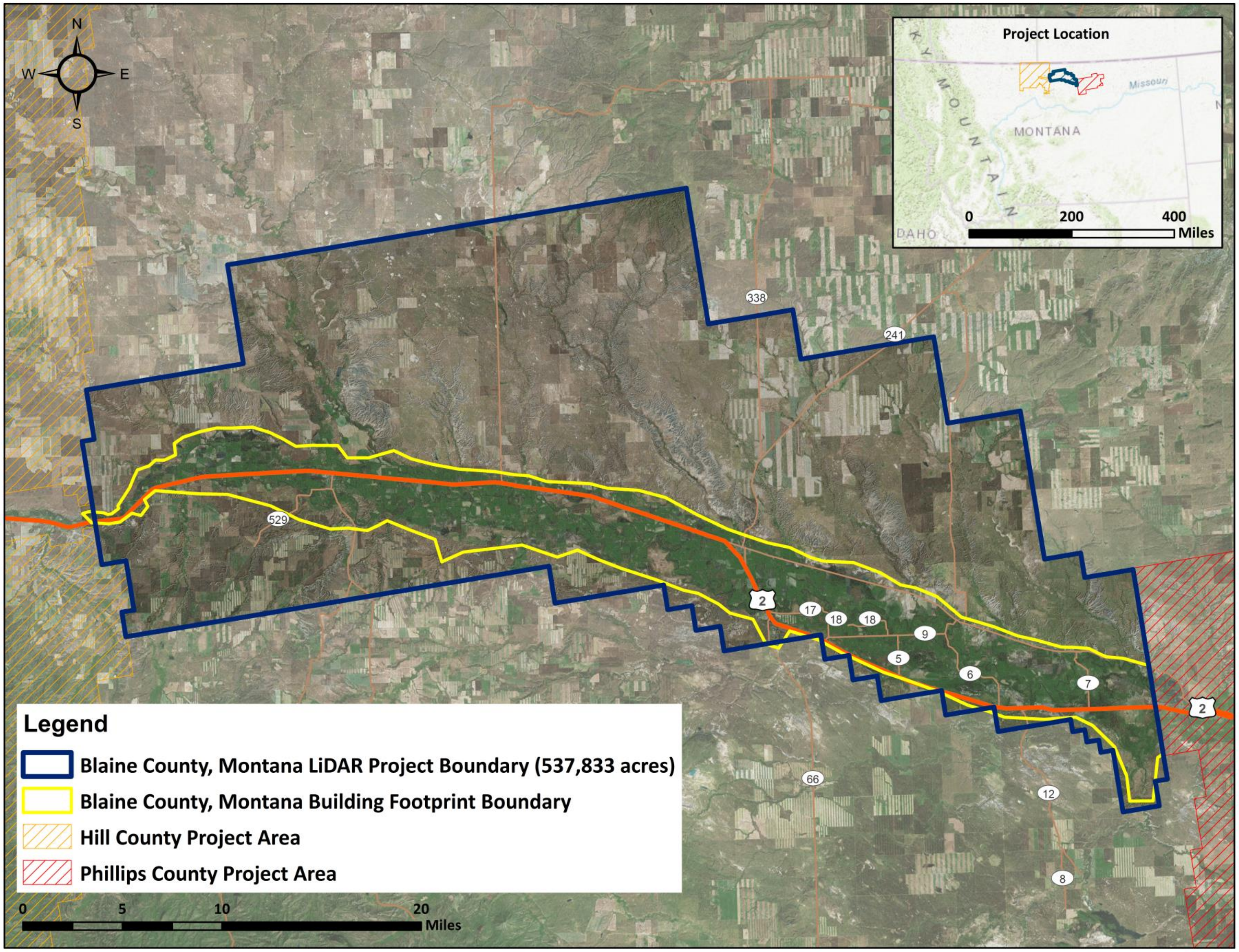


Figure 1: Location map of the Blaine County site in Montana

Acquisition

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Blaine County QL1 LiDAR study area at the target 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.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Blaine County project area. The Leica ALS80 is capable of colleting unlimited returns per pulse; however, 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	10/19/2018 – 10/24/2018
Aircraft Used	Cessna Caravan
Sensor	Leica
Laser	ALS80
Maximum Returns	Unlimited
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	1800 m
Survey speed	125 knots
Field of View	30°
Mirror Scan Rate	44 Hz
Target Pulse Rate	310 kHz
Pulse Length	2.5 ns
Laser Pulse Footprint Diameter	39.6 cm
Central Wavelength	1064 nm
Pulse Mode	Single Pulse in Air (SPiA)
Beam Divergence	0.22 mrads
Swath Width	965 m
Swath Overlap	60%
Intensity	8-bit, scaled to 16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated): ≤ 10cm

Leica ALS80 LiDAR sensor

All areas were surveyed with ≥60% overlap among swaths in order to reduce laser shadowing and minimize gaps. All overlapping flight lines were flown in opposing directions to maximize detection of swath to swath inconsistencies and used to resolve system misalignments. 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 Control

Ground control surveys, namely, monumentation and ground survey points (GSPs), were conducted to support the airborne acquisition. Gaston Engineering and Surveying (Gaston) collaborated with Quantum Spatial, Inc. in performing the ground survey work. Ground control data were used to geospatially correct the aircraft positional coordinate data, and non-vegetated and vegetated check points were collected to perform quality assurance checks on final LiDAR data (Figure 2).

Base Stations

Base stations were utilized for collection of ground survey points using real time kinematic (RTK) survey techniques. RTK positioning is a relative-positioning method that improves the accuracy of GPS signals, which enhances the precision of location data obtained from satellite-based systems; because RTK positioning allows one to obtain centimeter-level positioning in real time, it remains the procedure of choice for applications that demand high-precision mapping.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized three monuments established by Gaston, for the Blaine County LiDAR project, with each having a 60D nail with feather set as a hard ground point (Table 4).

Table 4: Monument positions for the Blaine County acquisition. Coordinates are in the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
CA001	48° 29' 45.46784"	-109° 21' 42.13120"	861.678
CA002	48° 33' 56.87924"	-108° 42' 07.80774"	778.206
CA003	48° 34' 17.53990"	-109° 22' 38.85483"	759.666

Ground Survey Points (GSPs)

In addition to ground control points, Gaston collected ground check points throughout the study area, and provided them to QSI to be used in accuracy assessment. Ground check points were collected over non-vegetated and vegetated areas, as shown in Table 5. Vertical accuracy statistics were calculated for all check points to assess confidence in the LiDAR derived ground models over non-vegetated and vegetated surfaces. Ground survey points were collected using real time kinematic (RTK) survey techniques.

GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2). Please see Appendix B for survey methods and certification provided by Gaston Engineering and Surveying.

Table 5: Types of ground check points collected for accuracy assessment

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Bare Earth	BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA
Tall Grass/Crops	TG		Herbaceous grasslands in advanced stages of growth	VVA
Shrubs	SH		Areas dominated by herbaceous shrubland	VVA
Forested	FR		Areas dominated by coniferous or deciduous trees	VVA

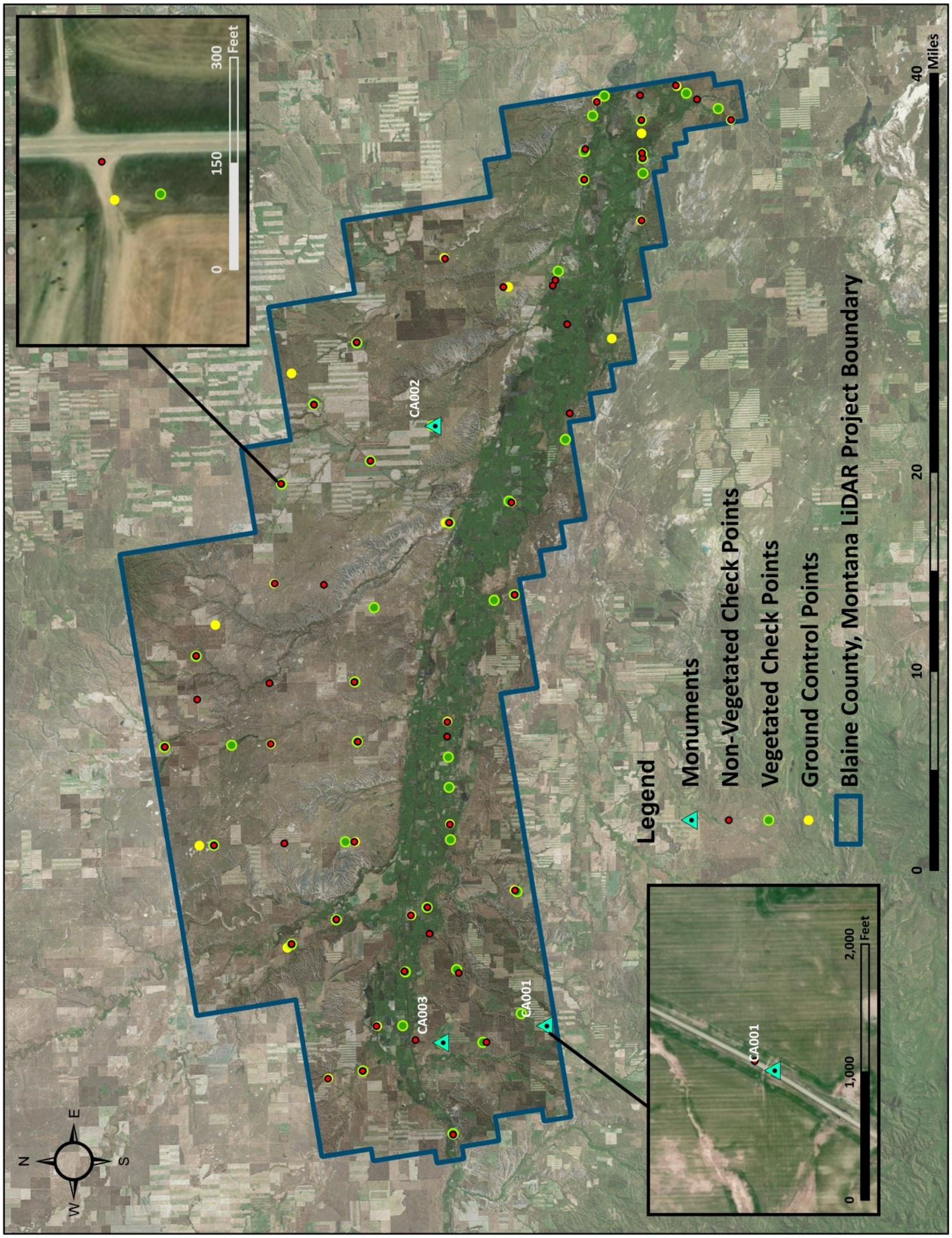
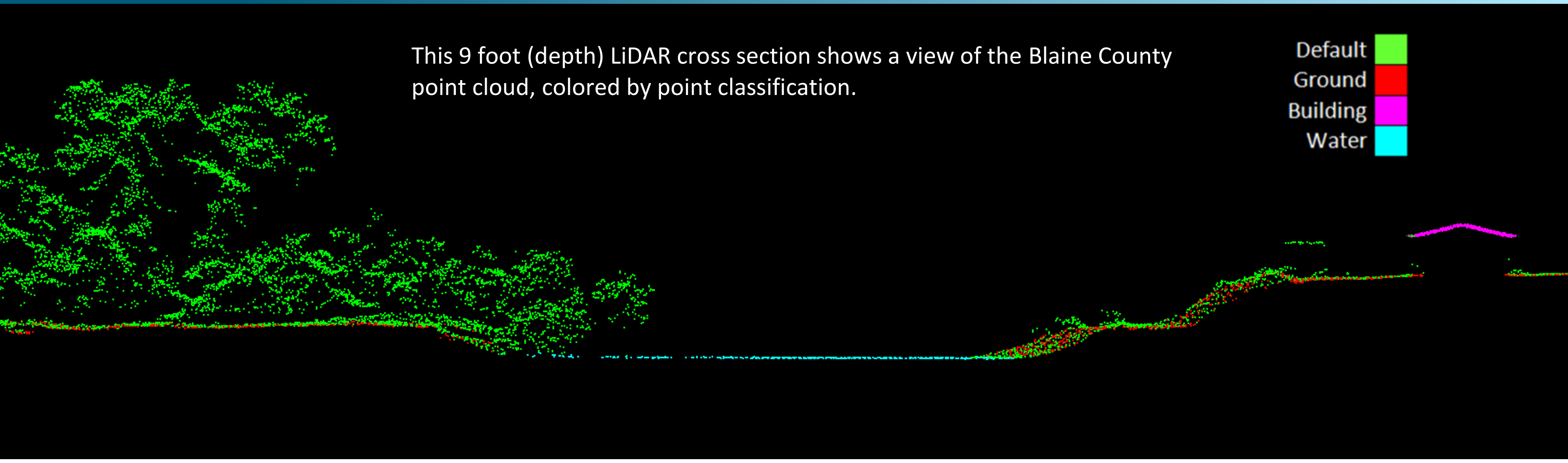


Figure 2: Ground survey location map



This 9 foot (depth) LiDAR cross section shows a view of the Blaine County point cloud, colored by point classification.

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 Blaine 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	Overlap/Edge Clip	Flightline edge clip, identified using the overlap flag
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
6	Buildings and Bridges	Permanent building structures with minimum area 100ft² or larger, classified using automated routines.
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
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation

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.	Waypoint Inertial Explorer v.8.6
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.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.4
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
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at a 3.0 foot pixel resolution.	TerraScan v.19 TerraModeler v.19 ArcMap v. 10.3.1
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

Hydroflattening was performed on the Blaine County dataset in accordance with USGS and FEMA standards for hydroflattening water bodies. 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. Bodies of water that were flattened include lakes and all other closed water bodies with a surface area greater than 2 acres, and all streams and rivers that are nominally wider than 100 feet. Due to its importance to the utility of the dataset, QSI also decided to hydroflatten the Milk River within the Blaine County area of interest, despite it being under the size threshold for required rivers. Any lakes or closed water bodies smaller than 2 acres in area were also flattened as feasible, depending on the automated results of hydroflattening and water's edge generation.

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.

Table 8: Hydroflattening Treatment

Summary of Hydroflattened Features		
Feature Type	**Required Size**	**Notable Exceptions**
Lakes & Closed Water Bodies	≥2 acres	Smaller where feasible
Rivers	≥100 feet nominal width	Milk River

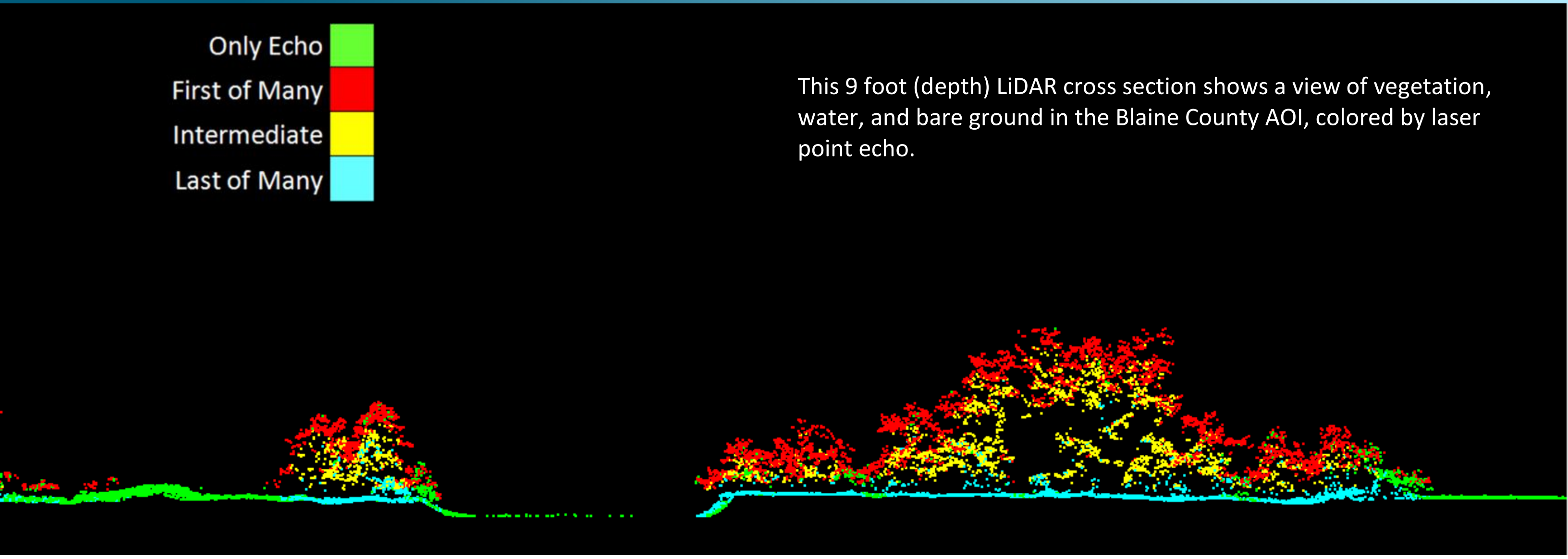
Contours

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. Contours were produced through TerraModeler by interpolating between contour key points at even elevation increments. Contours were generated at a 1 foot interval for the Blaine County dataset, with major contours labeled at 10 foot increments.

Buildings

Building classification was performed for a selected area of the Blaine County dataset, 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, with a minimum mapping size of ≥100ft², were classified into the building category. Once classification was complete, automated routines were used generate the polygon shapefile representing building footprints. A total of 5,080 buildings were classed in the data (Figure 3).

Figure 3: A highest hit digital surface model of the Blaine County LiDAR data, overlaid with the final building footprint features



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 Blaine County project was 0.95 points/ft^2 (10.27 points/m^2) while the average ground classified density was 0.43 points/ft^2 (4.60 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 4 through Figure 6.

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	0.95 points/ft^2 10.27 points/m^2
Ground Classified	0.43 points/ft^2 4.60 points/m^2

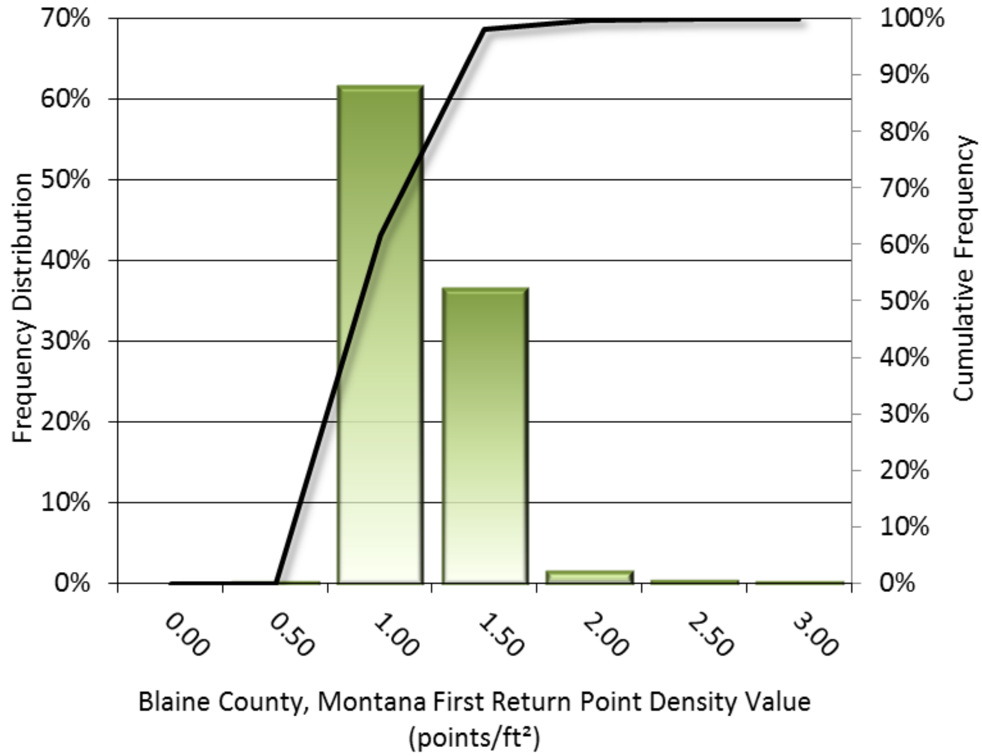


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

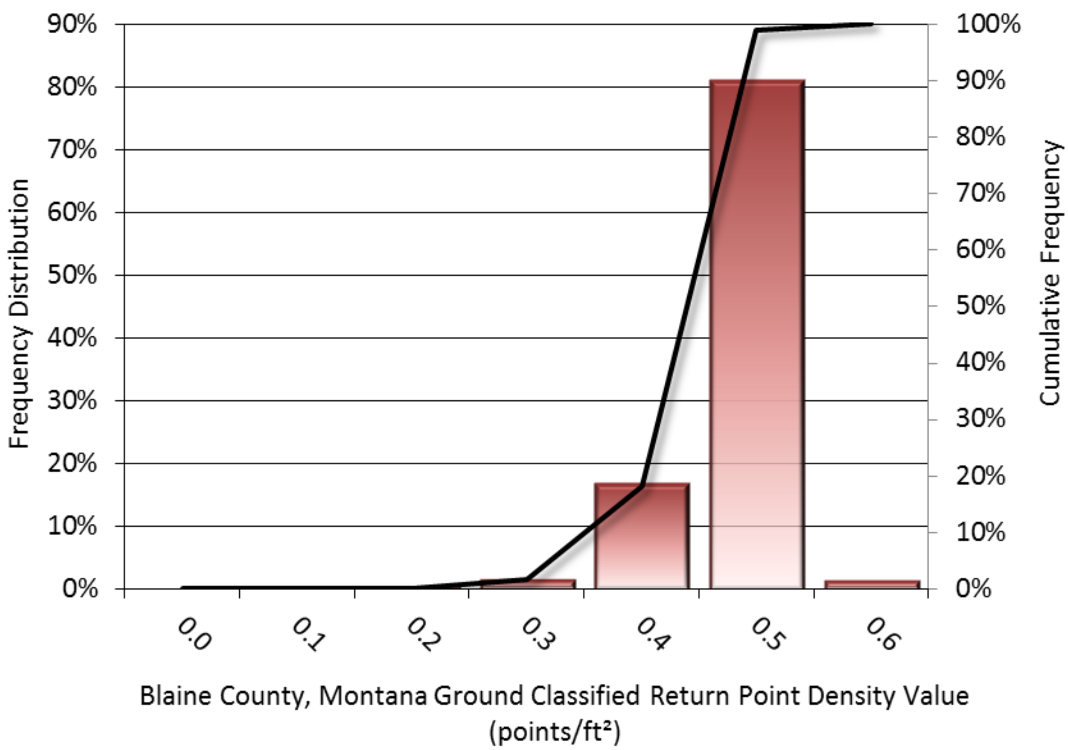


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

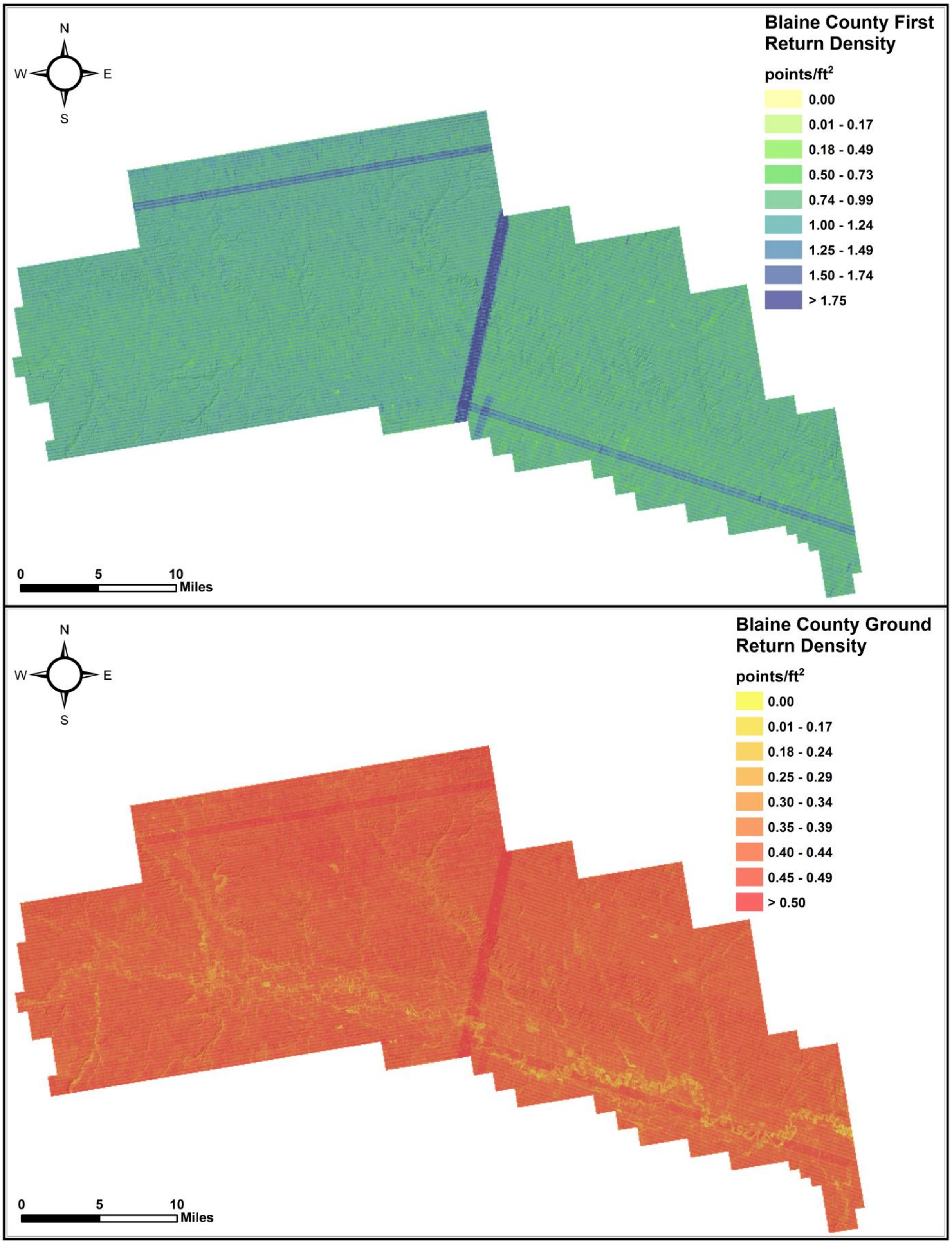


Figure 6: First return and ground-classified point density map for the Blaine County site (100 m x 100 m cells)

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 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 Blaine County survey, 56 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.196 feet (0.060 meters) as compared to unclassified LAS, and 0.173 feet (0.053 meters) as compared to the bare earth DEM, with 95% confidence (Figure 7, Figure 8).

QSI also assessed absolute accuracy using 35 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 9.

Table 10: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	56 points	56 points	35 points
95% Confidence (1.96*RMSE)	0.196 ft 0.060 m	0.173 ft 0.053 m	0.217 ft 0.066 m
Average	0.027 ft 0.008 m	-0.002 ft -0.001 m	0.007 ft 0.002 m
Median	0.013 ft 0.004 m	-0.015 ft -0.005 m	0.000 ft 0.000 m

[1] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
RMSE	0.100 ft 0.031 m	0.088 ft 0.027 m	0.111 ft 0.034 m
Standard Deviation (1σ)	0.097 ft 0.030 m	0.089 ft 0.027 m	0.112 ft 0.034 m

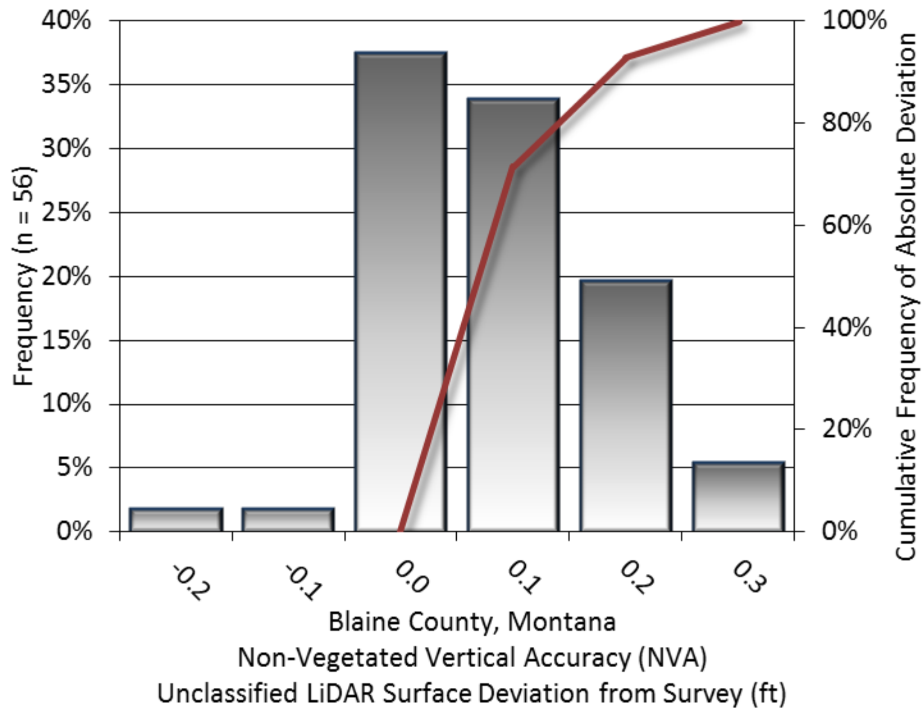


Figure 7: Frequency histogram for LiDAR unclassified LAS deviation from ground check point values (NVA)

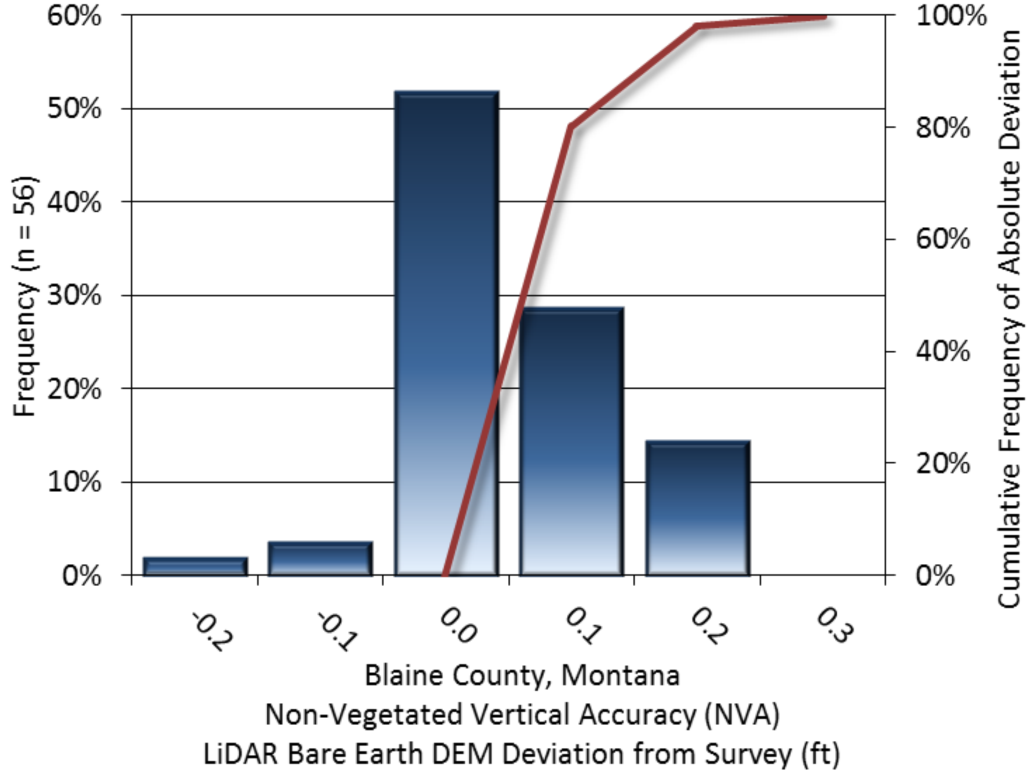


Figure 8: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)

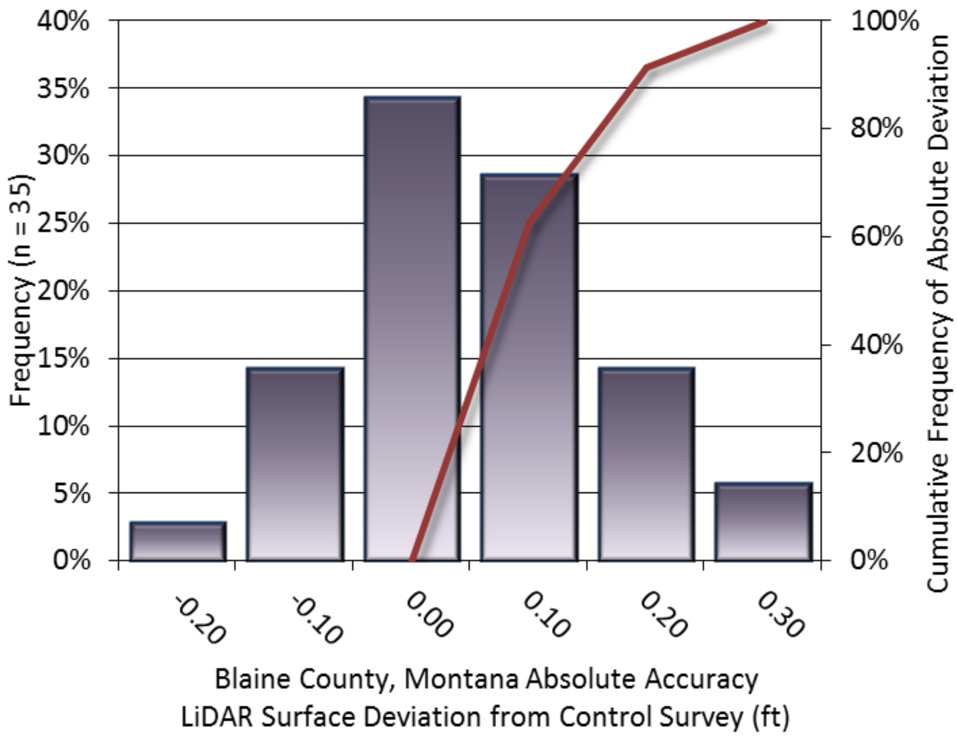


Figure 9: Frequency histogram for LiDAR surface deviation from ground control point values

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 Blaine County survey, 45 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.825 feet (0.251 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 11, Figure 10).

Table 11: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	45 points
95th Percentile	0.825 ft 0.251 m
Average	0.325 ft 0.099 m
Median	0.269 ft 0.082 m
RMSE	0.404 ft 0.123 m
Standard Deviation (1σ)	0.242 ft 0.074 m

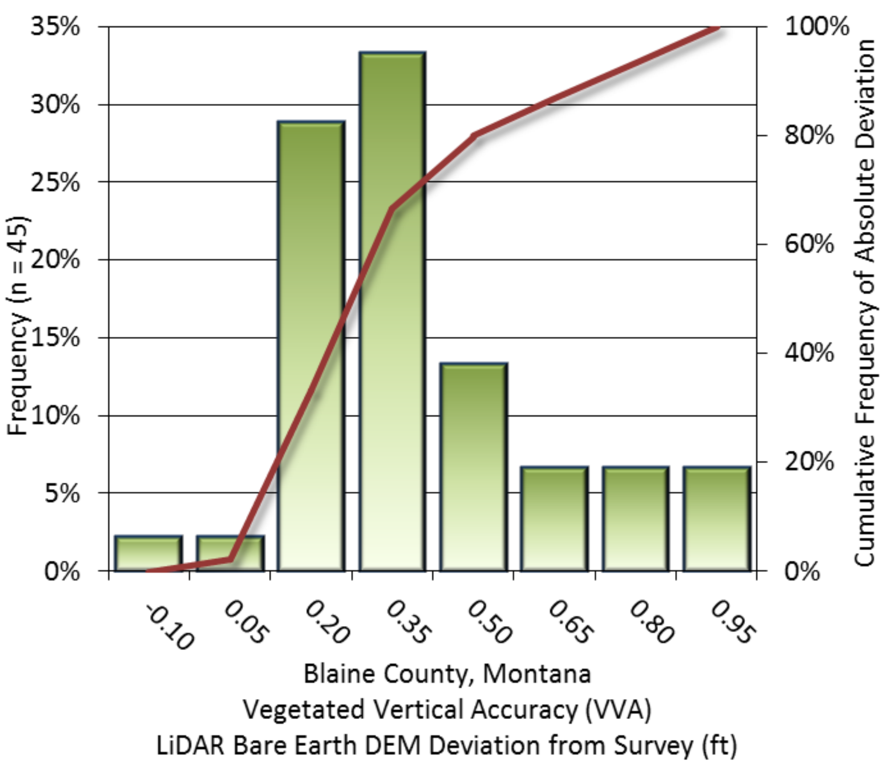


Figure 10: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)

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 Blaine County LiDAR project was 0.064 feet (0.019 meters) (Table 12, Figure 11).

Table 12: Relative accuracy results

Relative Accuracy	
Sample	189 surfaces
Average	0.064 ft 0.019 m
Median	0.063 ft 0.019 m
RMSE	0.063 ft 0.019 m
Standard Deviation (1σ)	0.004 ft 0.001 m
1.96σ	0.008 ft 0.016 m

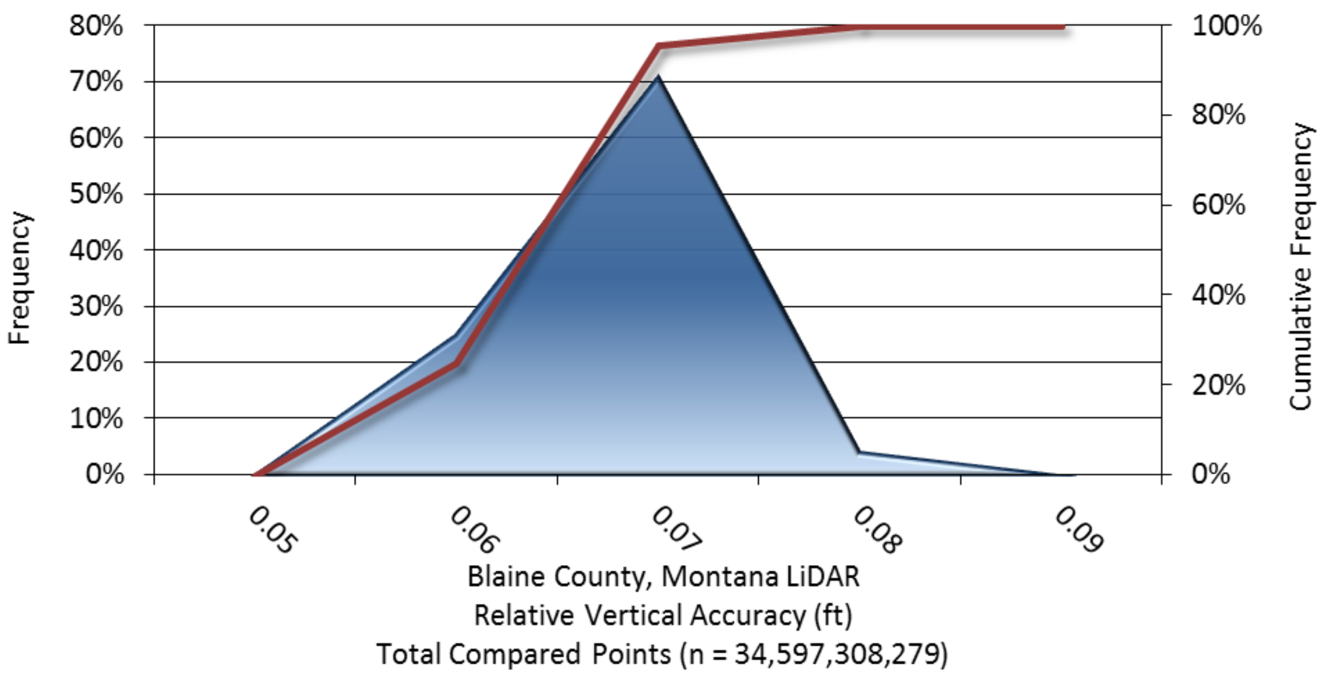


Figure 11: Frequency plot for relative vertical accuracy between flight lines

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 $\pm 15^{o}$ 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 - GASTON SURVEY

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GASTON ENGINEERING & SURVEYING, P.C.
PROFESSIONAL • PROGRESSIVE • PERSONAL

October 23, 2018
W.O. #18-573

RE: **Survey Methodology Report**
Calibration & FEMA Check Point Survey
Blaine 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, forested, shrubs and tall grass/crops. RTK observations at each of the calibration and check points were occupied for 180 epochs. Due to the limitations of GPS technology under tree canopy, the forested check points were surveyed via total station. 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.

A few 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 County-wide RTK collection. We occupied each of 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 October of 2018.

MONTANA
JAMES
FITZGERALD
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

CALIBRATION & FEMA CHECK POINTS

BLAINE COUNTY, MT

CALIBRATION POINTS

LEGEND

POINT KEY
CA = CALIBRATION POINTS
BE = BARE EARTH
UA = URBAN
TG = TALL GRASS
SH = SHRUBS
FO = FOREST

① **PLAN VIEW**
SCALE: 1" = 6 MILES

N

GASTON ENGINEERING & SURVEYING, PC
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BOZEMAN, MT 59771
(406) 586-0588

DRAWN BY: JO
CHECKED BY:
DRAWING DATE: 102318
REVISION DATE:

BLAINE COUNTY LiDAR
CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-573
BLAINE COUNTY, MT

IF THIS LINE DOES NOT MEASURE 1", THE DRAWING IS NOT SCALED CORRECTLY.

PROJECT: 18-573
DRAWING: 18-573 BASE.DWG
TAB: CALIBRATION

SHEET 1 OF 3

CALIBRATION & FEMA CHECK POINTS
BLAINE COUNTY, MT

BARE EARTH POINTS

LEGEND

POINT KEY
CA = CALIBRATION POINTS
BE = BARE EARTH
UA = URBAN
TG = TALL GRASS
SH = SHRUBS
FO = FOREST

① **PLAN VIEW**
SCALE: 1" = 6 MILES

N

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DRAWN BY: JO
CHECKED BY:
DRAWING DATE: 102318
REVISION DATE:

BLAINE COUNTY LiDAR
CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-573
BLAINE COUNTY, MT

IF THIS LINE DOES NOT MEASURE 1", THE DRAWING IS NOT SCALED CORRECTLY.

PROJECT: 18-573
DRAWING: 18-573 BASE.DWG
TAB: BARE EARTH

SHEET 2 OF 3

CALIBRATION & FEMA CHECK POINTS
BLAINE COUNTY, MT

URBAN, TALL GRASS, SHRUB & FOREST POINTS

LEGEND

POINT KEY
CA = CALIBRATION POINTS
BE = BARE EARTH
UA = URBAN
TG = TALL GRASS
SH = SHRUBS
FO = FOREST

1 PLAN VIEW
SCALE: 1" = 6 MILES

N

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DRAWN BY: JO
CHECKED BY:
DRAWING DATE: 102318
REVISION DATE:

BLAINE COUNTY LiDAR
CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-573
BLAINE COUNTY, MT

IF THIS LINE DOES NOT MEASURE 1", THE DRAWING IS NOT SCALED CORRECTLY.

PROJECT: 18-573
DRAWING: 18-573 BASE.DWG
TAB: UA, TG, SH, FO

SHEET 3 OF 3