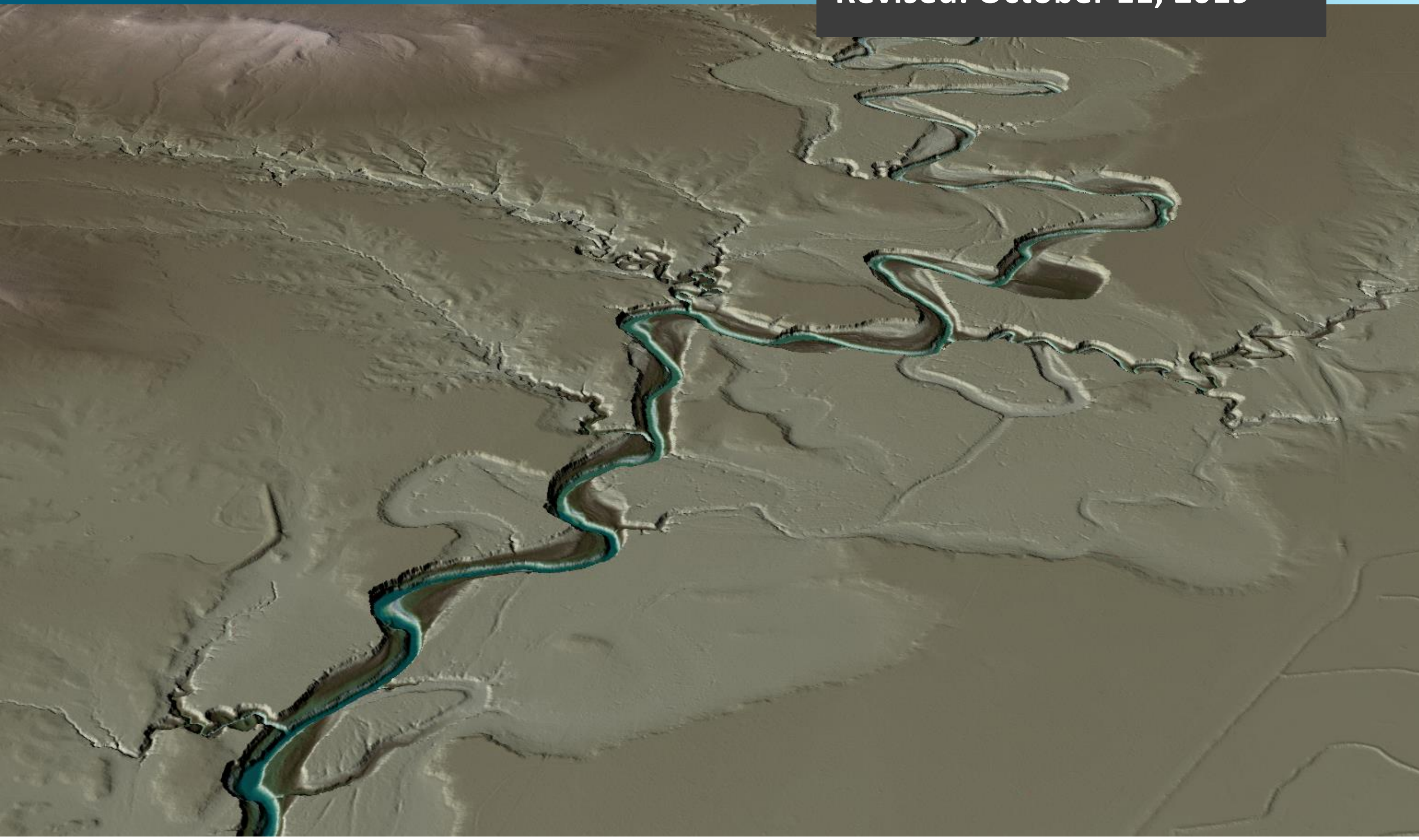

September 20, 2019
Revised: October 11, 2019

Valley County, Montana LiDAR

Technical Data Report

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Cover Photo: A view looking southwest within the Valley County Project Area. The image was created from the LiDAR bare earth model colored by elevation.

Introduction

This photo provided by Gaston Engineering and Surveying shows surveying equipment in Valley 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 QL2 Light Detection and Ranging (LiDAR) data in the fall of 2018 for the Valley County site in Montana. The Valley County project was contracted as part of the Milk River LiDAR contract, which encompasses several counties in the state of Montana. While the project area is predominately located in Valley County, Montana, a 65,874 acre addition to the initial area of interest extending into portions of Garfield and McCone counties was contracted in February of 2019. Data were 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. The 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 Valley County site

Project Site	Contracted Acres	Acquisition Dates	Data Type
Valley County	1,977,873	10/23/2018, 10/24/2018, 10/27/2018-10/31/2018, 11/14/2018, 4/13/2019 - 4/16/2019, 4/18/2019, 4/19/2019, 4/21/2019, 7/03/2019	QL2 LiDAR

Deliverable Products

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

Valley 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 • Geotiff Format • ESRI File Geodatabase Raster Dataset Format (*.gdb) • Space Delimited ASCII Files (*.asc) Ground Density Raster Model • 3.0 Foot Pixel Resolution • Geotiff Format
Vectors	Shapefiles (*.shp) • Contracted Site Boundary • Tile Index • Ground Survey Data • Total Area Flown • 1.0 Foot Contours • Low Confidence Polygon • 3D Water's Edge Breaklines • Ground Survey Data • S_Submittal ESRI Geodatabase (*.gdb) • 1.0 Foot Contours • 3D Water's Edge Breaklines • S_Elev_Inv_AR Space Delimited ASCII Files (*.txt) • 3D Water's Edge Breaklines
Table	Comma Separated Variable (CSV) • L_Source_Cit

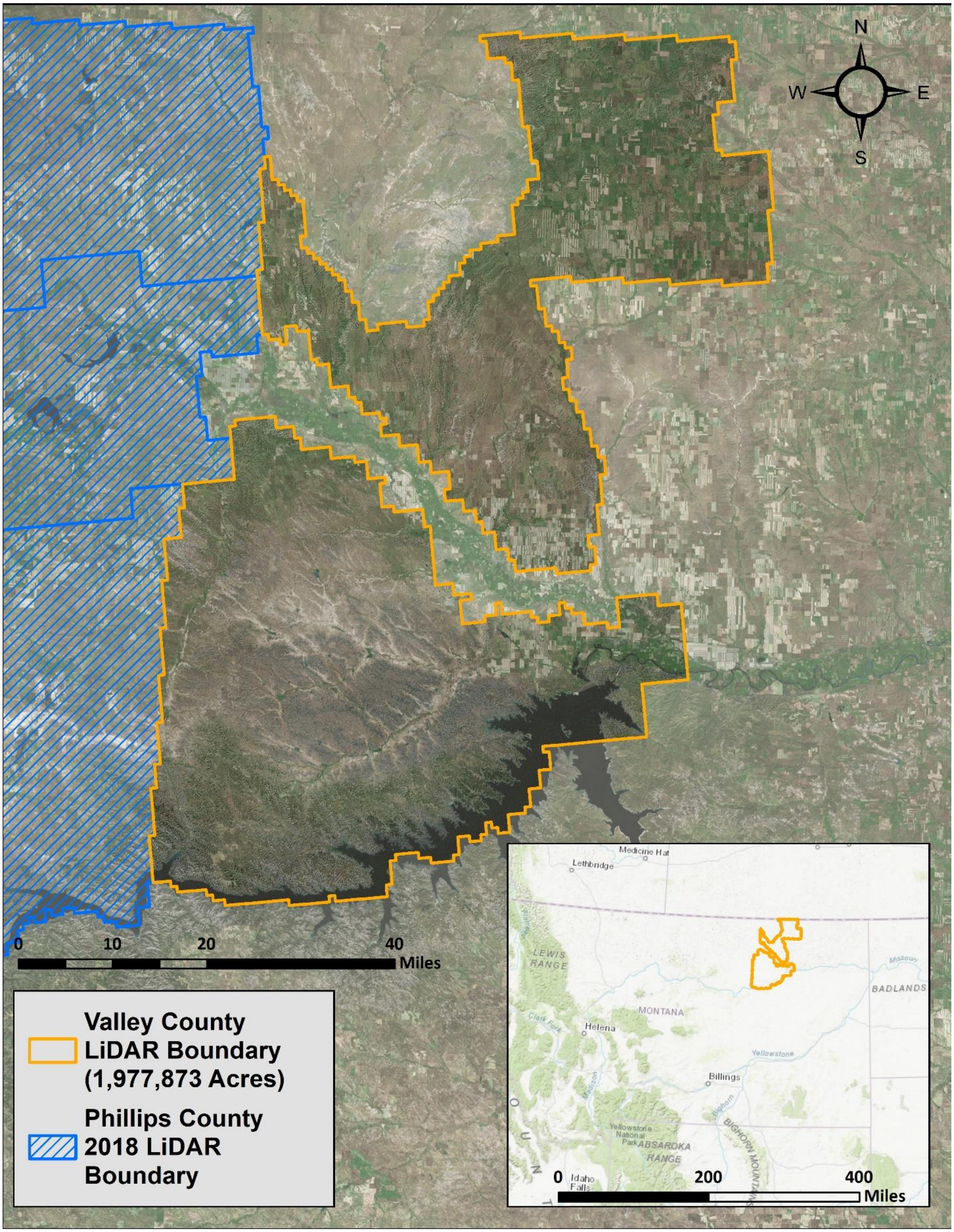


Figure 1: Location map of the Valley County site in Montana

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 Valley County LiDAR study area at the target point density of ≥2.0 points/m^2 (0.185 points/ft^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 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. Additionally, QSI requires any acquisition subcontractor aircraft to undergo a boresight calibration flight prior to data collection in order to ensure data quality. Conducted boresight calibration flights for the Valley County LiDAR data collection are detailed in Table 3 below.

Table 3: Boresight Calibration Flight Summary

LiDAR Boresight Calibration Flight Summary for Valley County, Montana Aircraft & Sensors					
Aircraft Name	Aircraft #	Sensor Name	Sensor Type	Boresight Flight Date	Boresight Flight Location
Cessna Caravan 208B	N-604MD	SN8227	Leica ALS80	06/13/2018	Provo, UT
Cessna Caravan 208B	N-208JA	SN8239	Leica ALS80	03/19/2019	Corvallis, OR

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan. Table 4 summarizes the settings used to yield an average pulse density of ≥2 pulses/m^2 over the Valley County Project Area. The Leica ALS80 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 4: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications		
Acquisition Dates	10/23/18, 10/24/18, 10/27/18, 10/28/18, 10/29/18, 10/30/18, 10/31/18, 11/14/18, 4/16/19, 4/18/19, 4/19/19, 4/21/19, 07/03/19	4/13/19, 4/14/19, 4/15/19
Aircraft Used	Cessna Caravan	Cessna Caravan
Sensor	Leica ALS80	Leica ALS80
Laser	ALS80	ALS80
Maximum Returns	Unlimited	Unlimited
Resolution/Density	Average 2 pulses/m^2	Average 2 pulses/m^2
Nominal Pulse Spacing	0.70 m	0.70 m
Survey Altitude (AGL)	1850 m	2000 m
Survey speed	145 knots	115 knots
Field of View	40°	40°
Mirror Scan Rate	48 Hz	42Hz
Target Pulse Rate	299.5 kHz	265.0 kHz
Pulse Length	2.5 ns	2.5 ns
Laser Pulse Footprint Diameter	40.7 cm	44.0 cm
Central Wavelength	1064 nm	1064 nm
Pulse Mode	Multi Pulse in Air (2PiA)	Multi Pulse in Air (2PiA)
Beam Divergence	0.22 mrad	0.22 mrad
Swath Width	1,347 m	1,456 m
Swath Overlap	29 %	20 %
Intensity	8-bit, scaled to 16-bit	8-bit, scaled to 16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated): ≤ 10cm	$RMSE_Z$ (Non-Vegetated): ≤ 10cm

All areas were surveyed with an opposing flight line side-lap of at least 20% 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 to support the airborne acquisition. Gaston Engineering and Surveying performed all ground survey work. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data (Figure 2).

Monuments

Monuments were utilized for collection of ground survey points using real time kinematic (RTK) survey techniques (Figure 2). 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 nine monuments established by Gaston for the Valley County LiDAR project, with each having a 60D nail with feather set as a hard ground point (Table 5).

Table 5: Monument positions for the Valley County acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)	Stability
CA001	48° 12' 16.70654"	-106° 34' 55.40747"	678.534	D
CA002	48° 51' 10.95440"	-106° 22' 12.12378"	967.619	D
CA003	47° 50' 37.13802"	-106° 54' 00.35045"	753.375	D
CA004	47° 47' 37.75889"	-107° 12' 16.49993"	860.316	D
CA005	48° 32' 38.49111"	-106° 50' 36.81058"	849.011	D
CA006	48° 15' 34.39167"	-107° 08' 39.41750"	750.63	D

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 6. 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 6: Land Cover Types and Descriptions

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

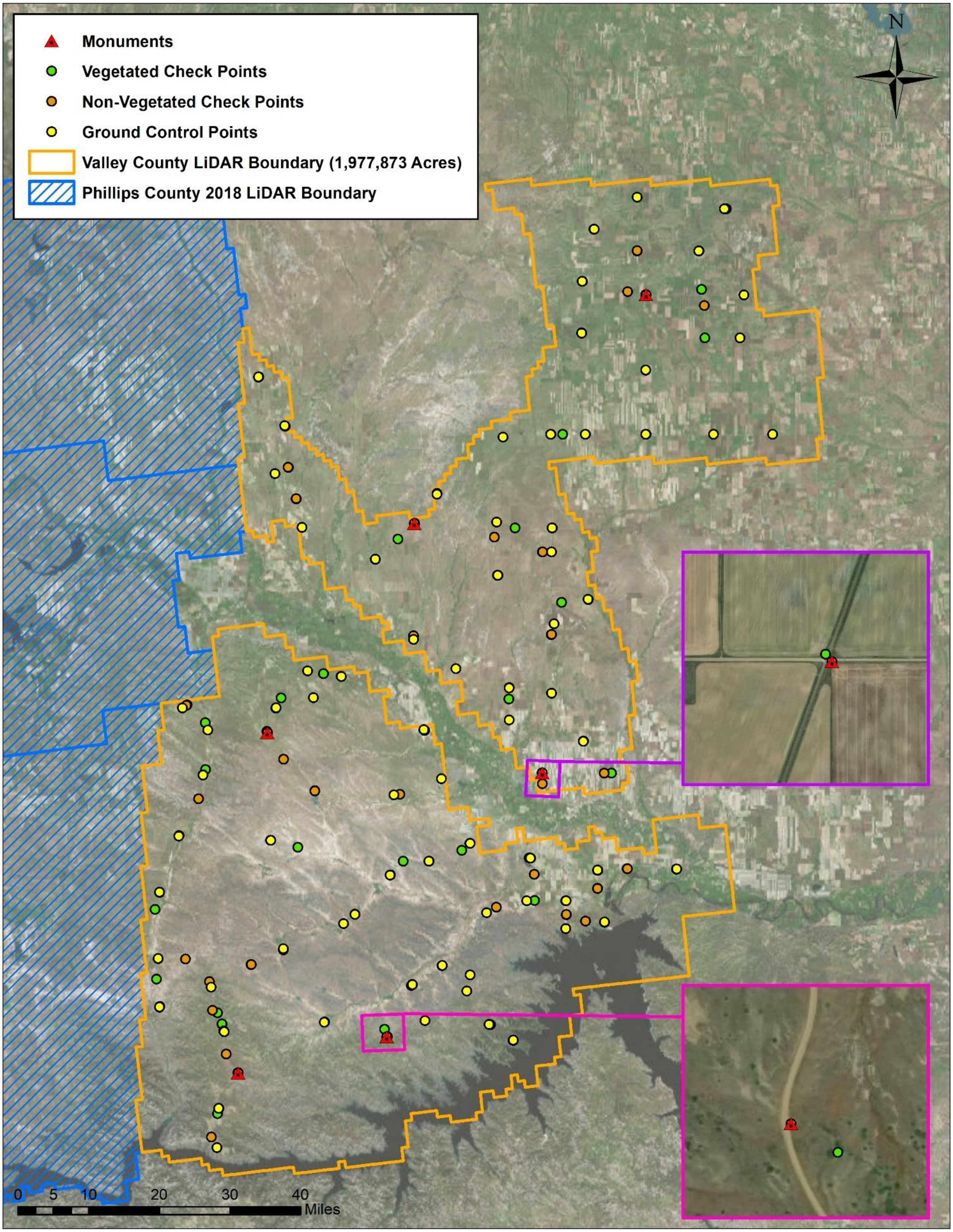
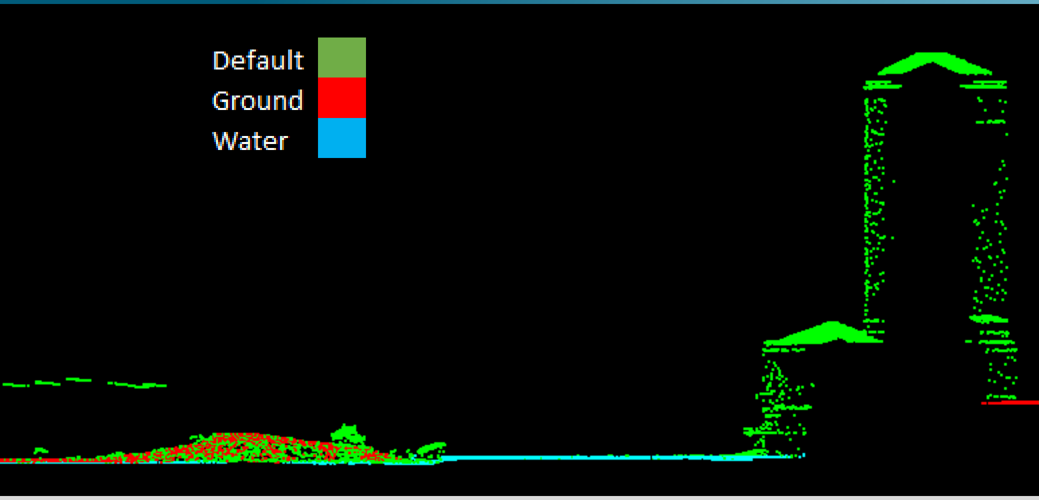


Figure 2: Ground survey location map



This 18 foot LiDAR cross section shows a view of the Fort Peck Power Plant outflow, 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 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8. Outlier points in the classified point cloud data are classified as Noise (Class 7) and make up approximately 1.29% of the delivered classified point cloud.

Table 7: ASPRS LAS classification standards applied to the Valley 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
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 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.	Waypoint Inertial Explorer v.8.6 POSPac MMS v.8.2
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 POSPac MMS v.8.2 RiProcess v1.8.5
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
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 7). 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. Export all surface models as GeoTiffs 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.	TerraScan v.19 TerraModeler v.19 ArcMap v. 10.3.1

Feature Extraction

Hydroflattening and Water's edge breaklines

Hydroflattening was performed on the Valley 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 smaller as feasible), and all streams and rivers that are nominally wider than 100 feet. Despite reaches of the Milk River being under the size requirements for hydroflattening, the entirety of the Milk River within the Valley County area of interest has been flattened in this submission due to its importance to the utility of the dataset.

Additionally, any permanent islands that exist within a water body feature that are approximately greater than 1.0 acre in size were delineated. If islands did not meet the size requirement, they were hydroflattened to maintain consistency and cartographic finishing throughout the Project Area.

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 9: 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
Islands	<1.0 acres	

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 Valley County dataset, with major contours labeled at 10 foot increments (Figure 3).

Areas averaging less than 0.05 ground-classified points per square foot were considered low confidence in the elevation data and correspond with the low confidence polygon shapefile called S_Topo_Confidence. Areas with low ground point density are commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where the LiDAR laser is unable to sufficiently penetrate to the ground surface.

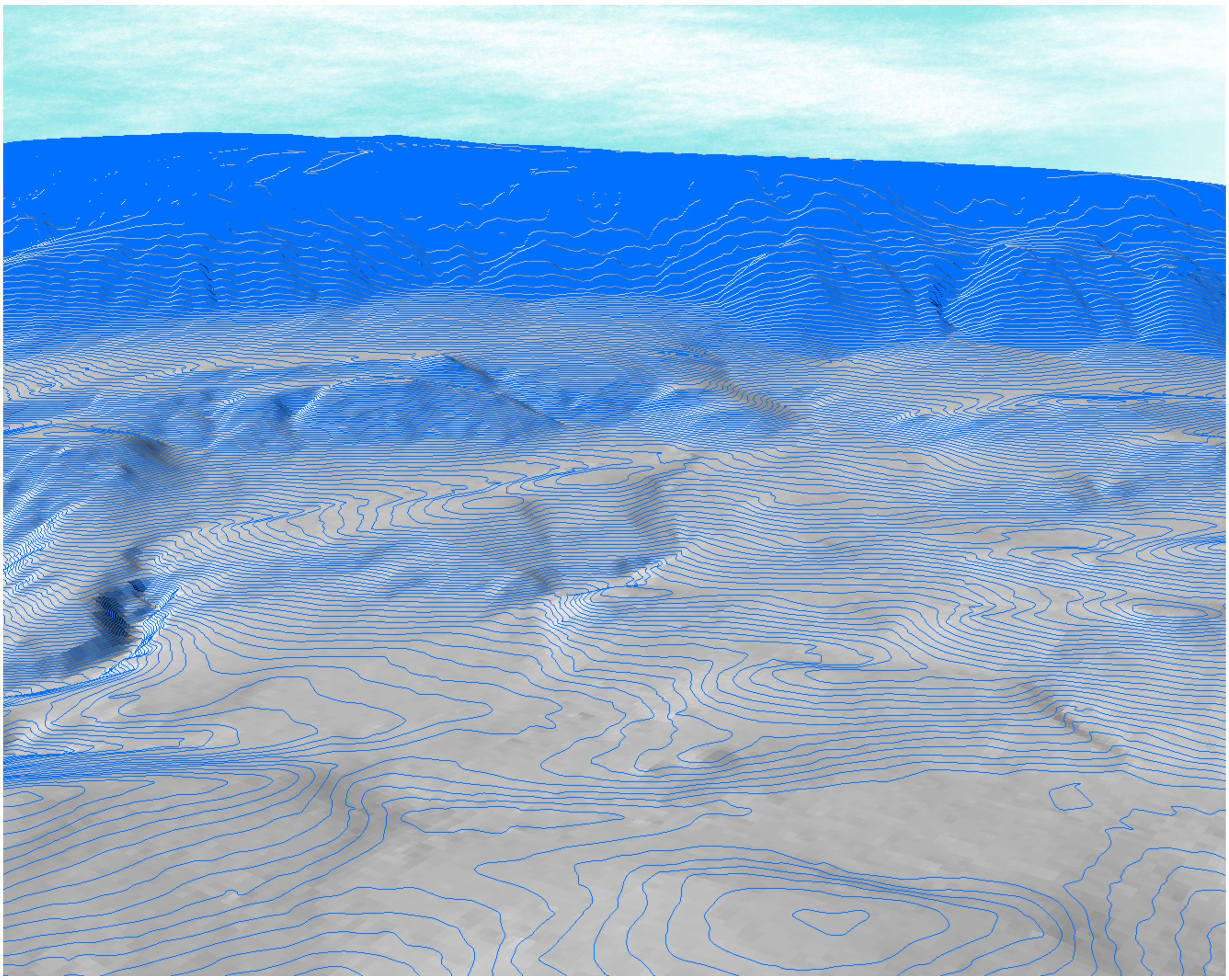
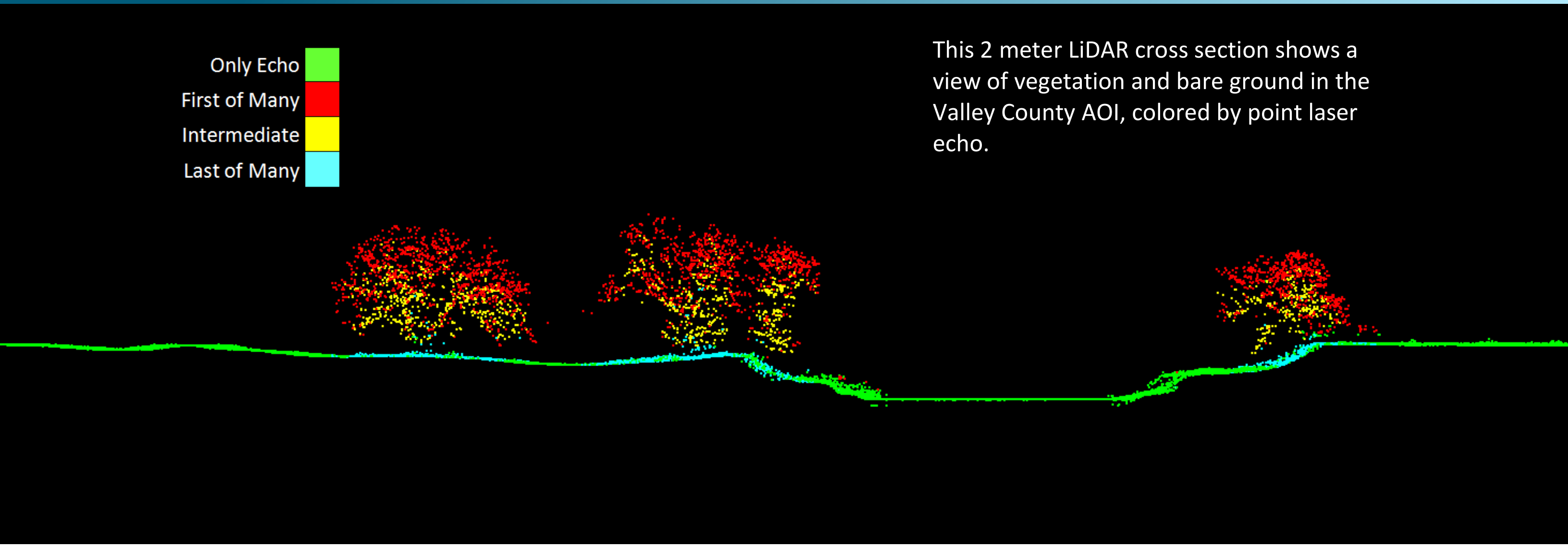


Figure 3: Contours draped over a hillshade of the Valley County, Montana bare earth digital elevation model



LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 2 points/m^2 (0.185 points/ft^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 Valley County project was 0.37 points/ft^2 (6.91 points/m^2) while the average ground classified density was 0.45 points/ft^2 (4.86 points/m^2) (Table 10). 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 7.

Table 10: Average LiDAR point densities

Classification	South Point Density
First-Return	0.37 points/ft^2 6.91 points/m^2
Ground Classified	0.45 points/ft^2 4.86 points/m^2

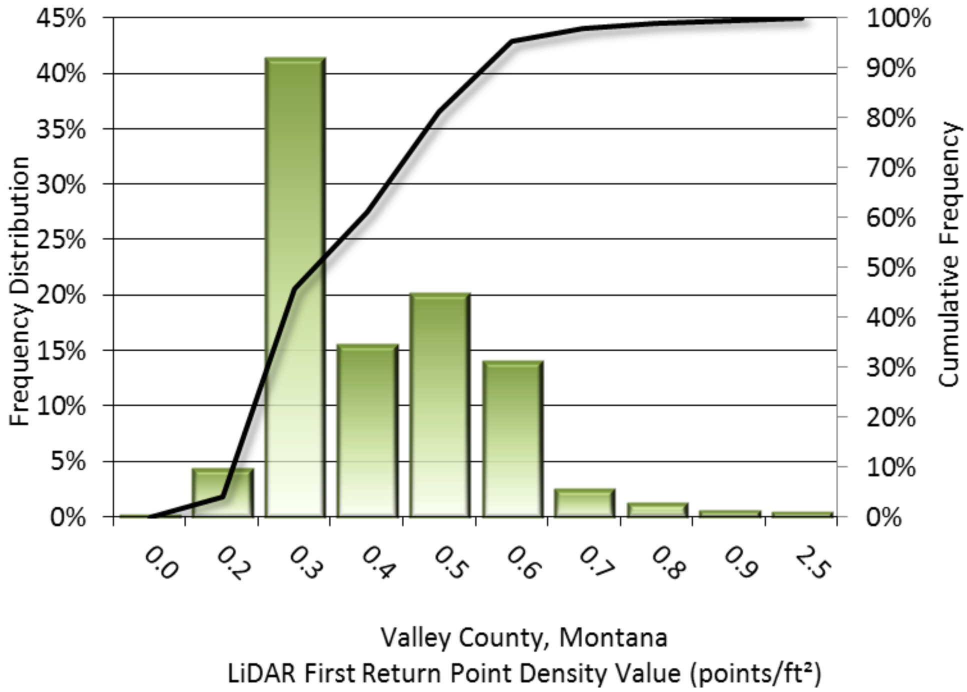


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

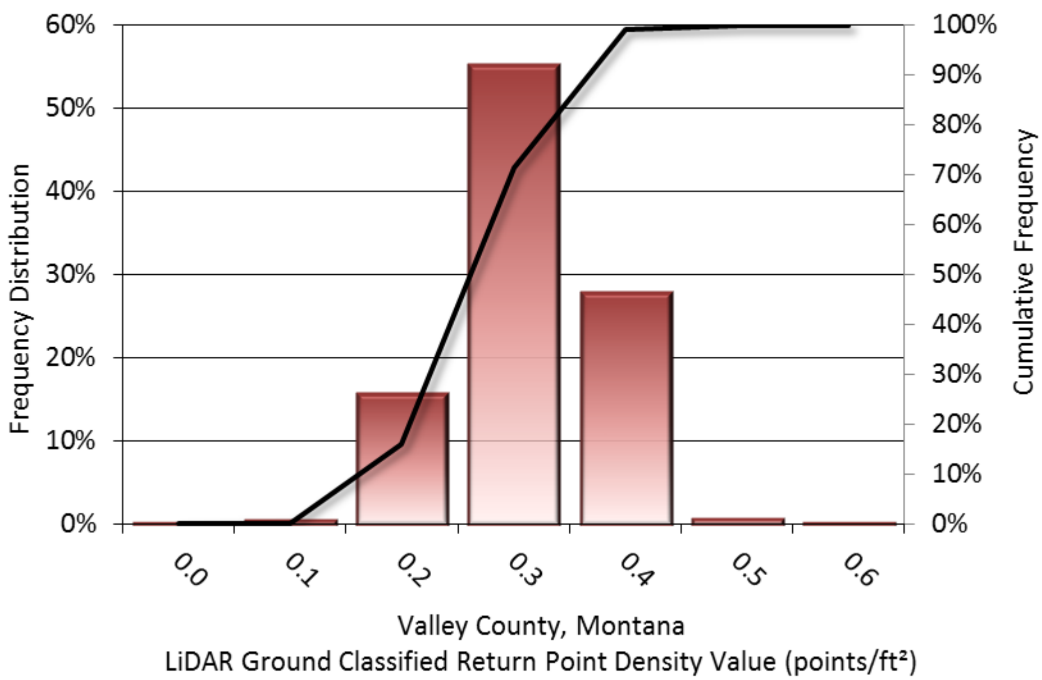


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

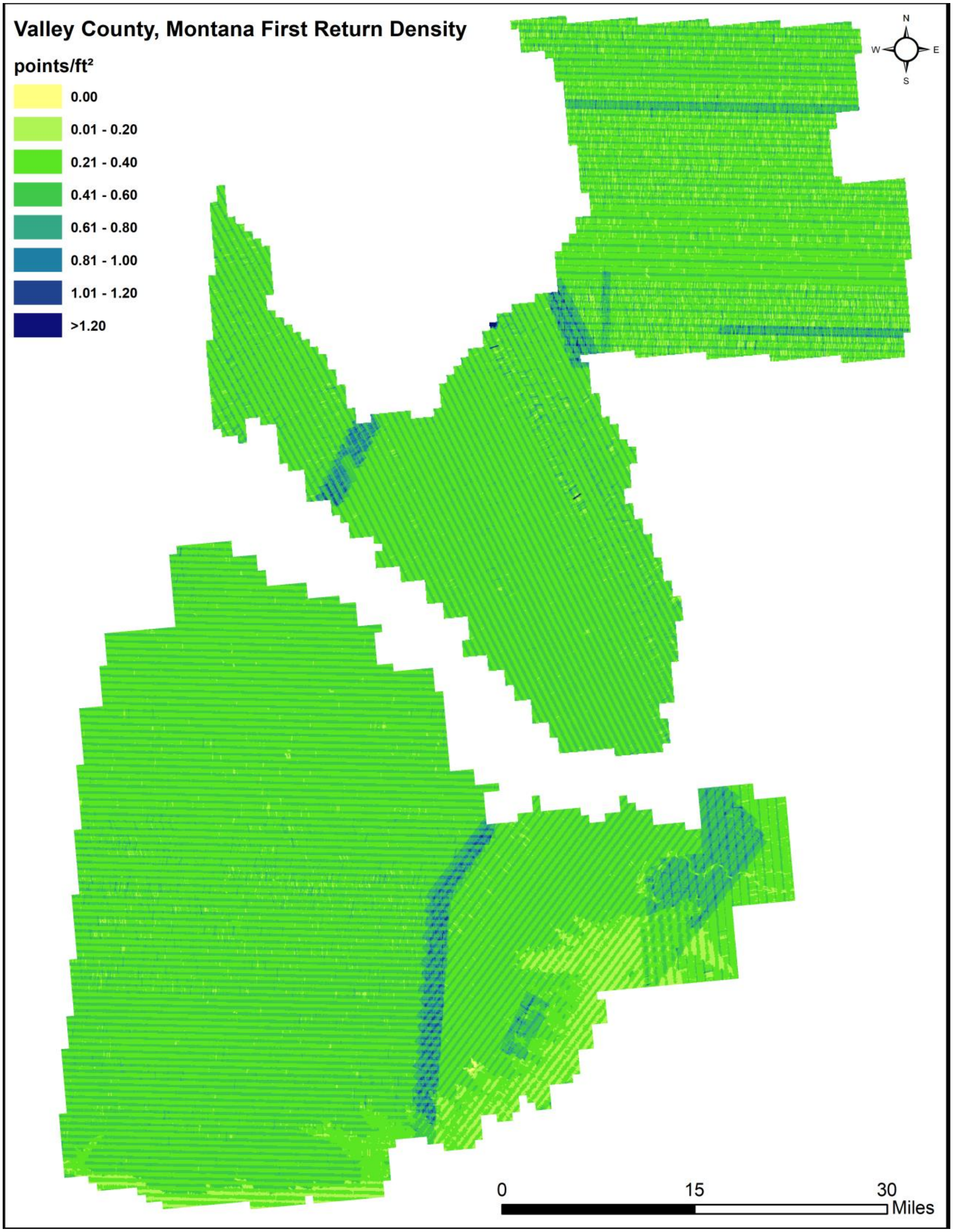


Figure 6: First return and ground-classified point density map for the Valley County site (100 m x 100 m cells)

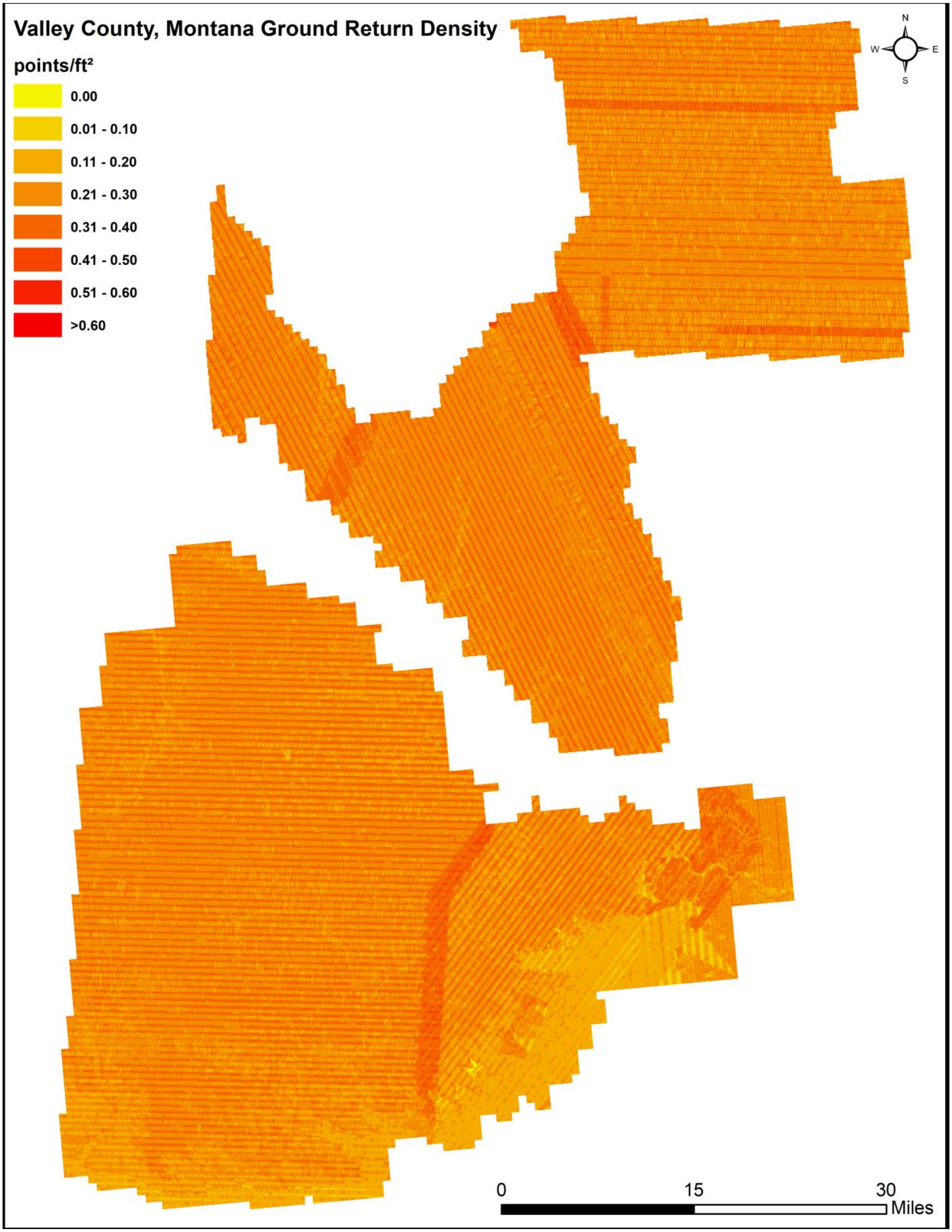


Figure 7: Ground point density map for the Valley County site (100 m x 100 m cells)

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 11.

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 Valley County survey, 91 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.239 feet (0.073 meters) as compared to unclassified LAS, and 0.239 feet (0.073 meters) as compared to the bare earth DEM, with 95% confidence (Figure 8, Figure 9).

QSI also assessed absolute accuracy using 80 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 11 and Figure 10.

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[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.

Table 11: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	91 points	91 points	80 points
95% Confidence (1.96*RMSE)	0.239 ft 0.073 m	0.239 ft 0.073 m	0.198 ft 0.060 m
Average	0.034 ft 0.010 m	-0.003 ft -0.001 m	0.007 ft 0.002 m
Median	0.023 ft 0.007 m	-0.007 ft -0.002 m	0.010 ft 0.003 m
RMSE	0.122 ft 0.037 m	0.122 ft 0.037 m	0.101 ft 0.031 m
Standard Deviation (1σ)	0.118 ft 0.036 m	0.123 ft 0.037 m	0.102 ft 0.031 m

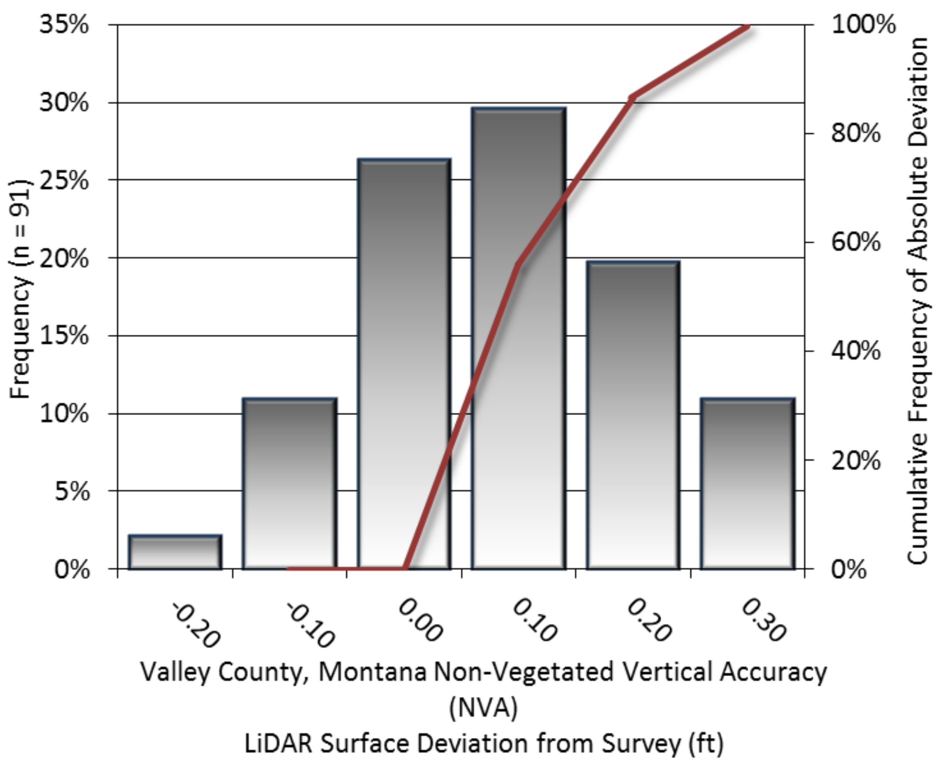

Figure 8: Frequency histogram for LiDAR unclassified LAS deviation from ground check point values (NVA)

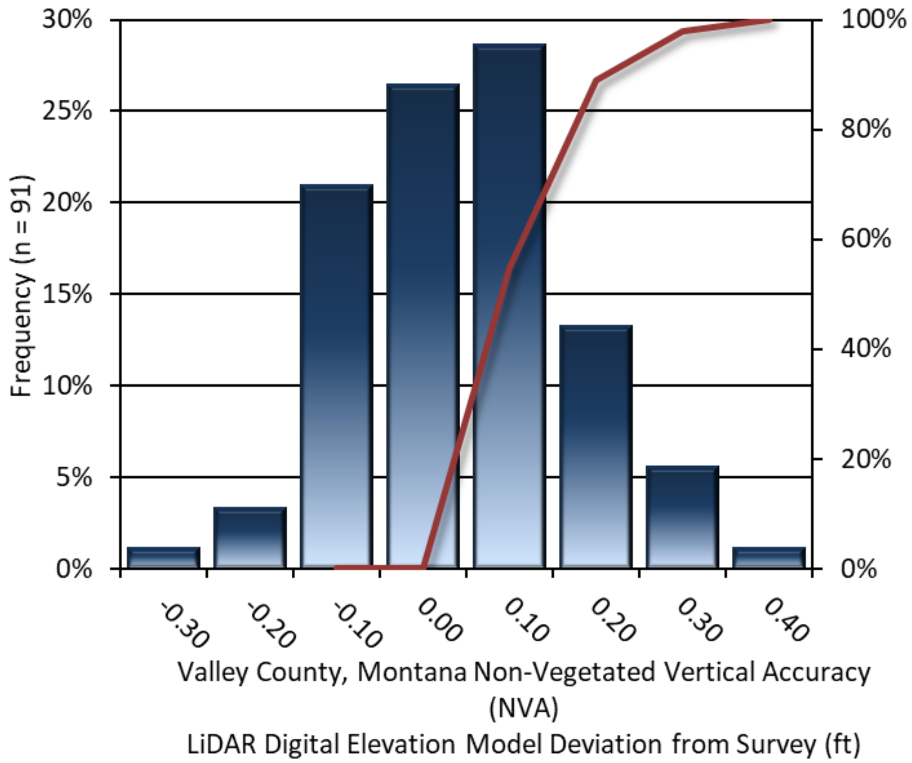

Figure 9: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)

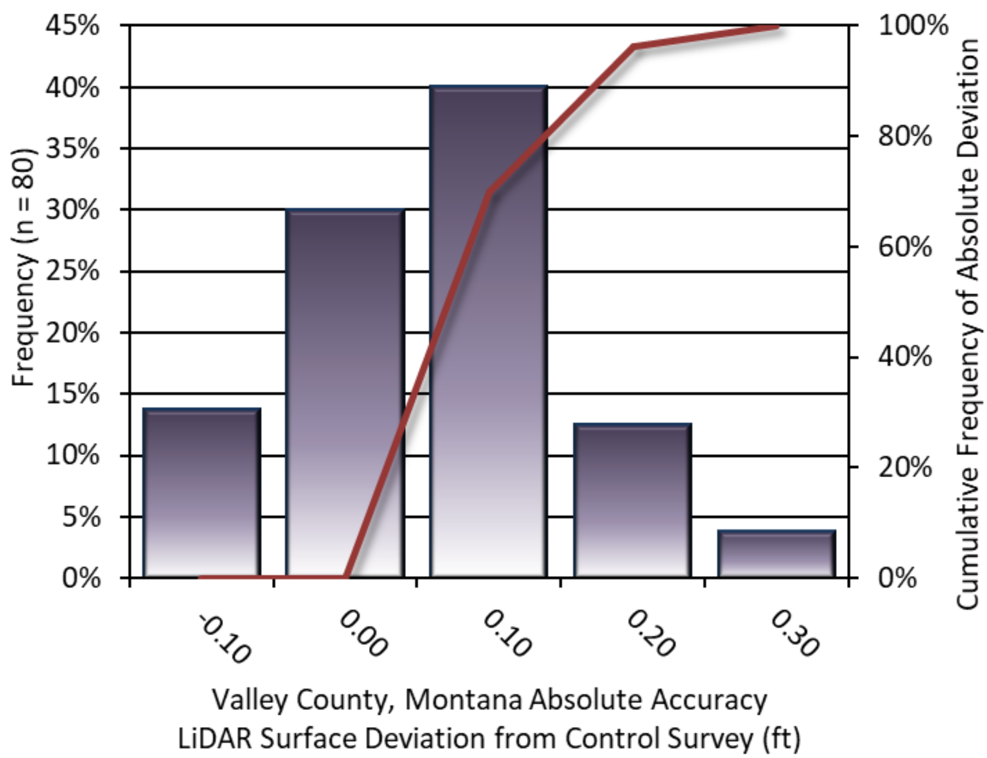

Figure 10: Frequency histogram for LiDAR surface deviation from ground control point values

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 Valley County survey, 71 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.484 feet (0.147 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 12, Figure 11).

Table 12: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	71 points
95th Percentile	0.484 ft 0.147 m
Average	-0.213 ft -0.065 m
Median	-0.197 ft -0.060 m
RMSE	0.273 ft 0.083 m
Standard Deviation (1σ)	0.171 ft 0.052 m

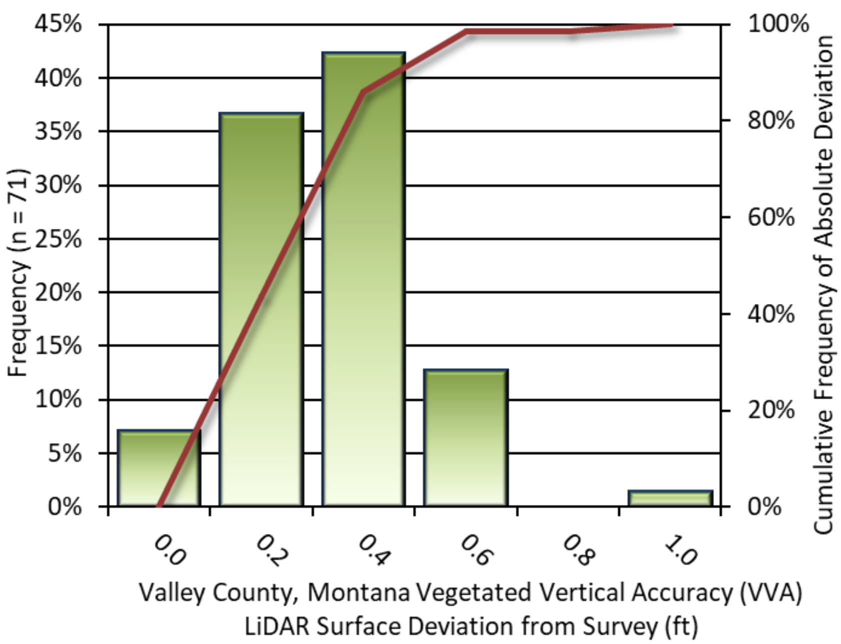

Figure 11: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)

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 Valley County LiDAR project was 0.087 feet (0.027 meters) (Table 13, Figure 12).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	283 surfaces
Average	0.087 ft 0.027 m
Median	0.078 ft 0.027 m
RMSE	0.090 ft 0.027 m
Standard Deviation (1σ)	0.028 ft 0.008 m
1.96σ	0.054 ft 0.016 m

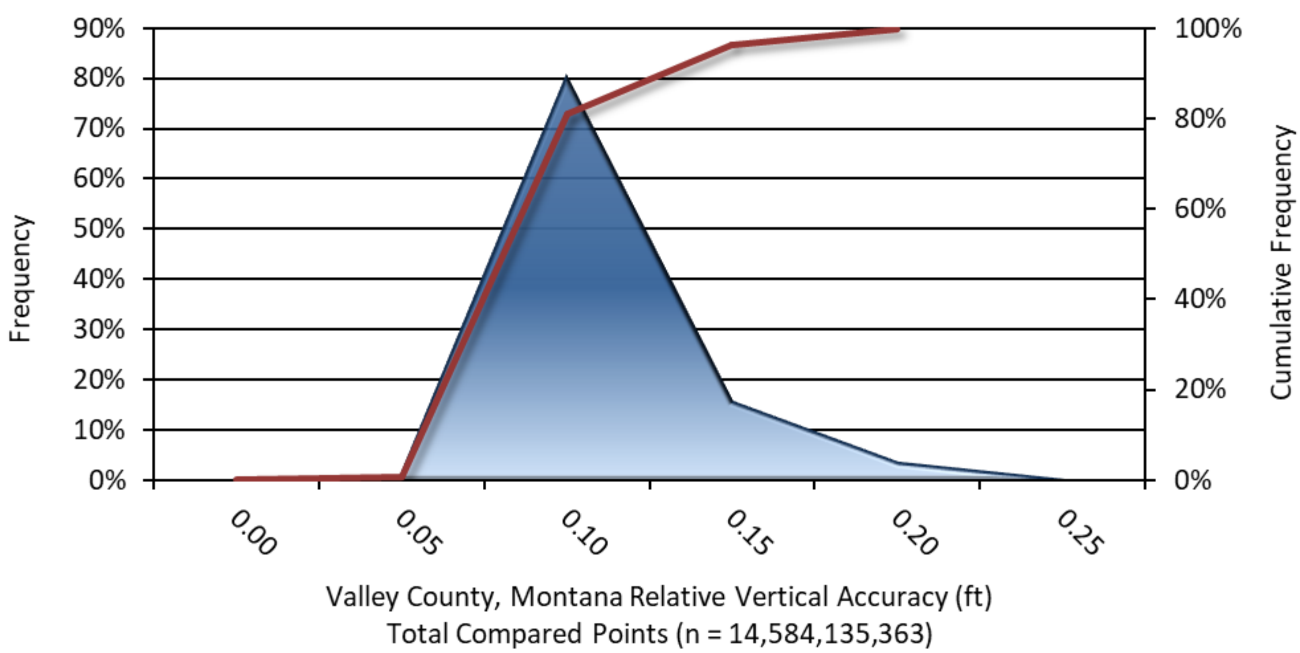

Figure 12: Frequency plot for relative vertical accuracy between flight lines

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 (ACCr) 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. Using a flying altitude of 1,850 meters, an IMU error of 0.005 decimal degrees, and a GNSS positional error of 0.032 meters, the horizontal accuracy (ACC_r) for the LiDAR collection is 1.65 feet (0.50 meters) at the 95% confidence level (Table 13). Data from the Hill County dataset have been tested to meet horizontal requirements at the 95% confidence level, using NSSDA reporting methods.

Table 14: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.95 ft 0.29 m
ACC_r	1.65 ft 0.50 m

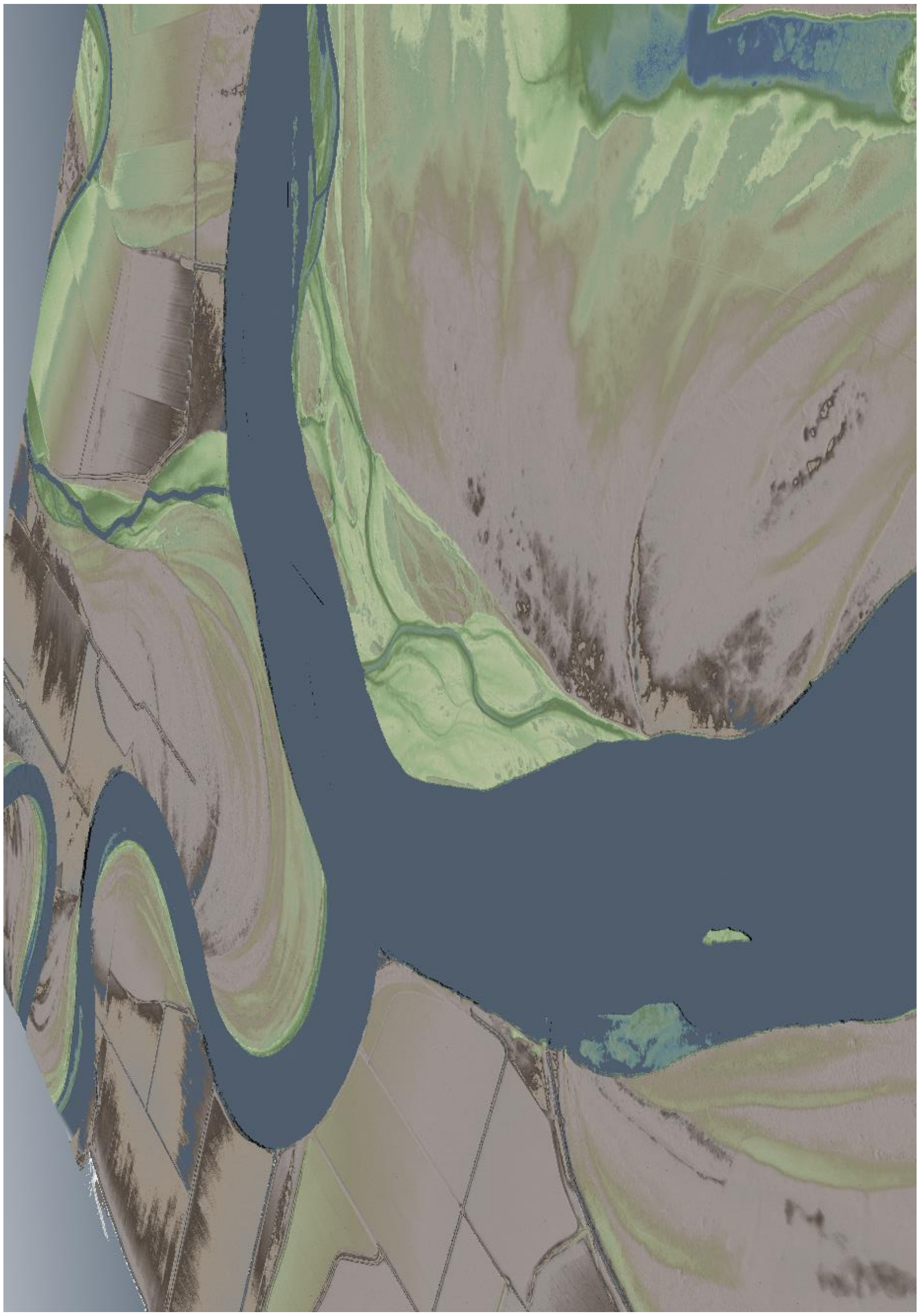

Figure 13: View looking north east over Valley County. The image was created from the LiDAR bare earth model colored by elevation.

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 ±20^{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

November 12, 2018
W.O. #18-575

RE: Survey Methodology Report
Calibration & FEMA Check Point Survey
Valley 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 and November of 2018.

MONTANA
JAMES FITZGERALD VEREELEN
LICENSED PROFESSIONAL LAND SURVEYOR

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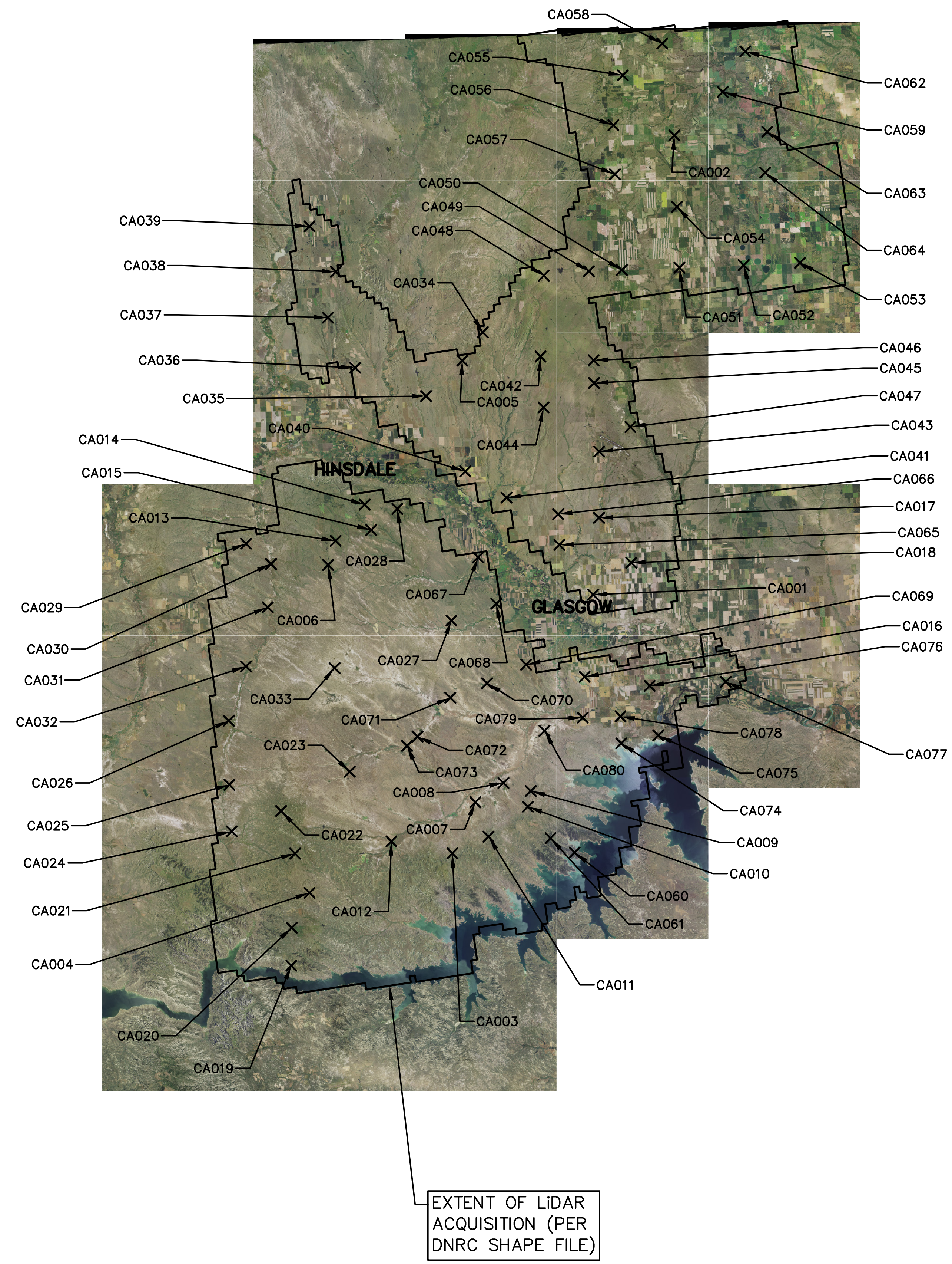
ENGINEERING/LAND SURVEYING/LAND PLANNING/MATERIALS TESTING

CALIBRATION & FEMA CHECK POINTS

VALLEY 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" = 14 MILES

N

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(406) 586-0588

DRAWN BY: JO
CHECKED BY:
DRAWING DATE: 111218
REVISION DATE:

VALLEY COUNTY LiDAR
CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-575
VALLEY COUNTY, MT

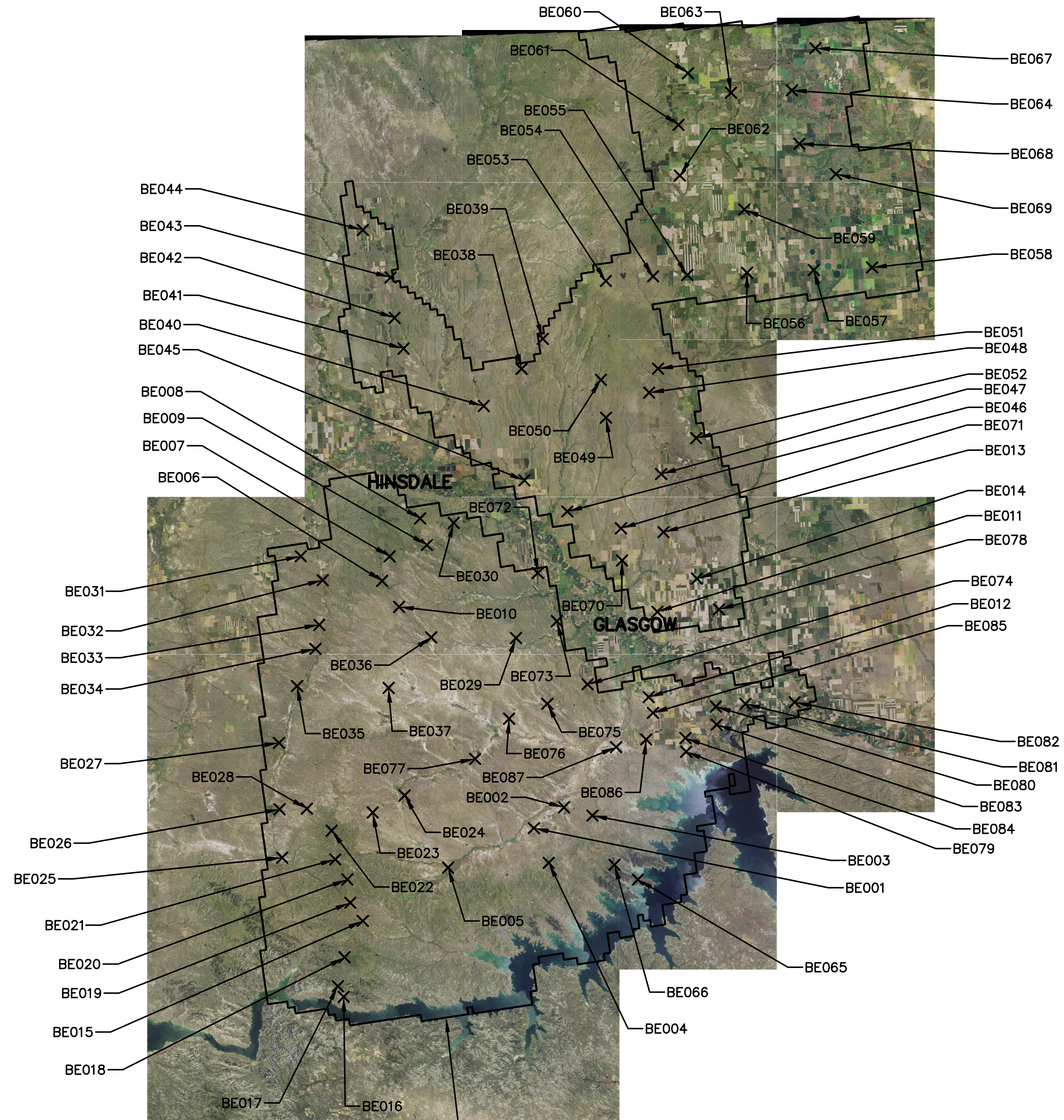
IF THIS LINE DOES NOT MEASURE 1", THE DRAWING IS NOT SCALED CORRECTLY.

PROJECT: 18-575
DRAWING: 18-575 BASE.DWG
TAB: CALIBRATION

SHEET 1 OF 3

CALIBRATION & FEMA CHECK POINTS

VALLEY COUNTY, MT



EXTENT OF LiDAR ACQUISITION (PER DNRC SHAPE FILE)

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" = 14 MILES

N

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CHECKED BY:
DRAWING DATE: 11218
REVISION DATE:

VALLEY COUNTY LiDAR
CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-575
VALLEY COUNTY, MT

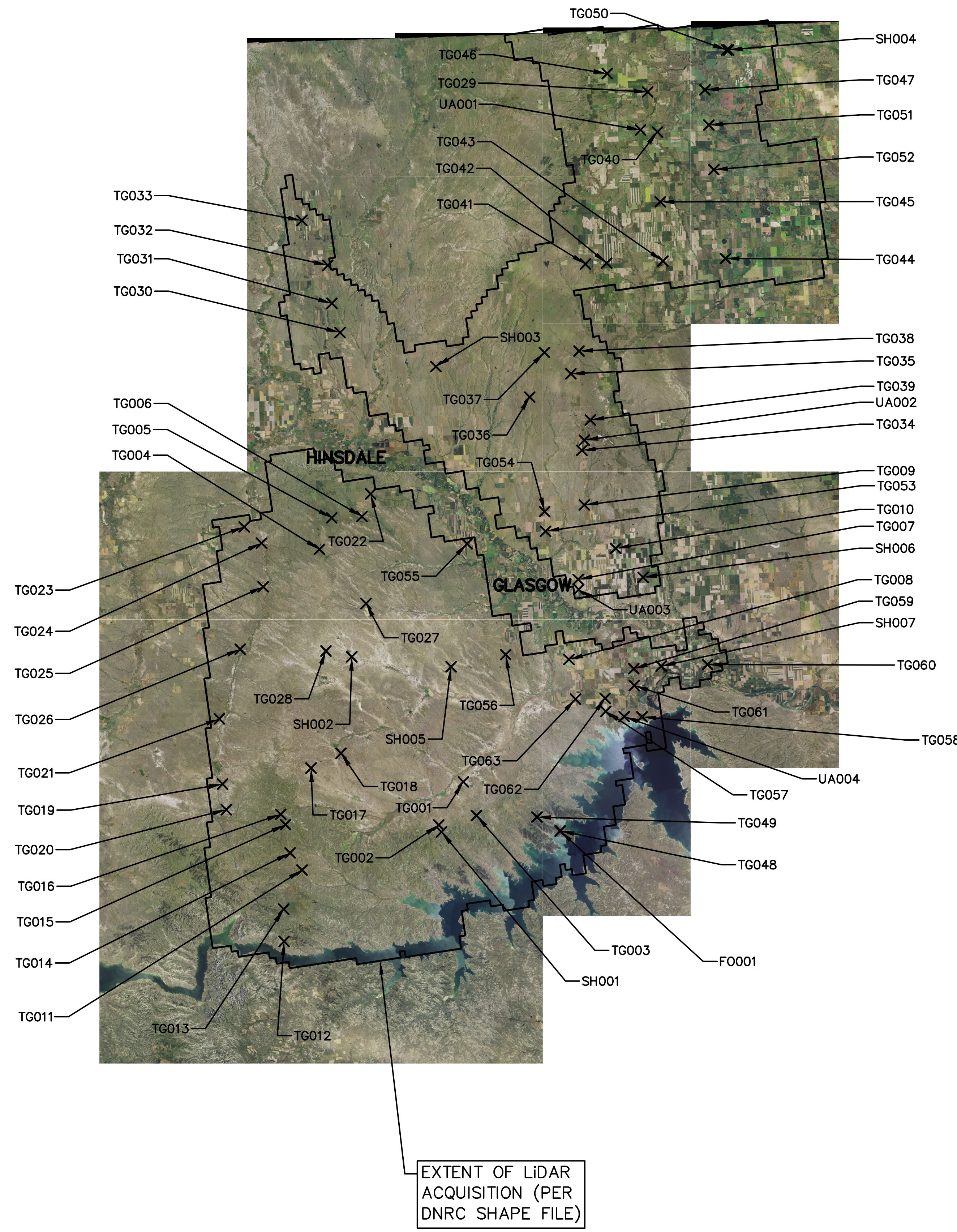
IF THIS LINE DOES NOT MEASURE 1", THE DRAWING IS NOT SCALED CORRECTLY.

PROJECT: 18-575
DRAWING: 18-575 BASE.DWG
TAB: BARE EARTH

SHEET 2 OF 3

CALIBRATION & FEMA CHECK POINTS

VALLEY 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" = 14 MILES

N

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REVISION DATE:

VALLEY COUNTY LiDAR
CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-575
VALLEY COUNTY, MT

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

PROJECT: 18-575
DRAWING: 18-575 BASE.DWG
TAB: UA, TG, SH, FO

SHEET 3 OF 3