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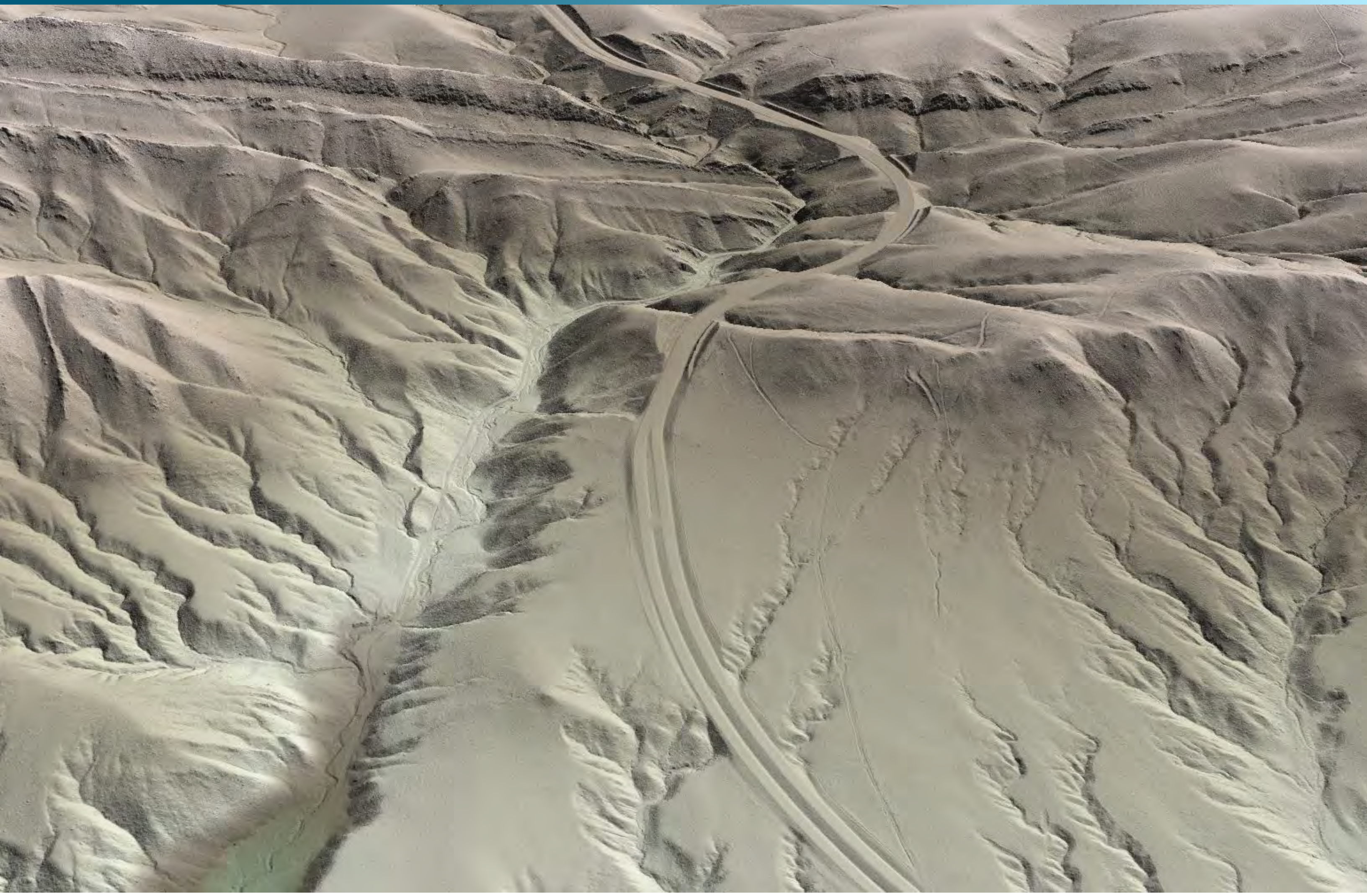

Jefferson County, Montana LiDAR

LiDAR Technical Data Report

Prepared For:

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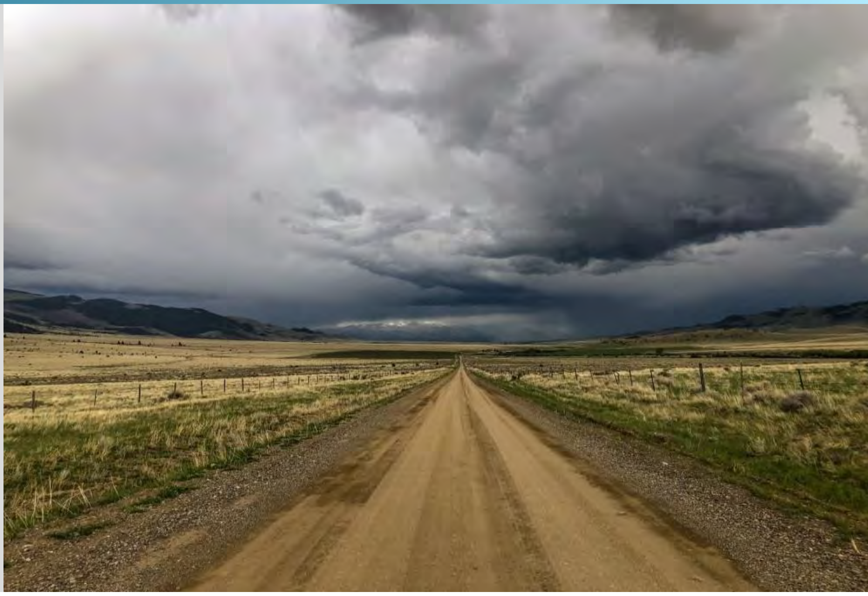
Cover Photo: A view of the Jefferson County Project Area and surrounding landscape, created from the gridded bare earth DEM colored by elevation.

INTRODUCTION

This photo provided by Gaston Engineering and Surveying shows the general landscape in Jefferson 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 and QL2 Light Detection and Ranging (LiDAR) data throughout 2018 and into 2019 for Jefferson County in Montana. 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. 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 Jefferson County site

Project Site	Acres	Acquisition Dates	Data Type
Jefferson County - QL1	9,268	09/27/2018 – 09/27/2018	QL1 LiDAR
Jefferson County – QL2	1,063,236	09/25/2019 – 07/19/2019	QL2 LiDAR
Jefferson County – Building Footprint AOI	66,375	09/27/2018 – 09/27/2018 and 09/25/2019 – 07/19/2019	QL1 & QL2 LiDAR

Deliverable Products

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

Jefferson 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): • Site Boundary • Tile Index • Ground Survey Data • Total Area Flown • 1.0 Foot Contours • 3D Building Footprints • 3D Water's Edge Breaklines ESRI Geodatabase (*.gdb) • 1.0 Foot Contours • 3D Water's Edge Breaklines Space Delimited ASCII Text Files (*.txt): • 3D Water's Edge Breaklines

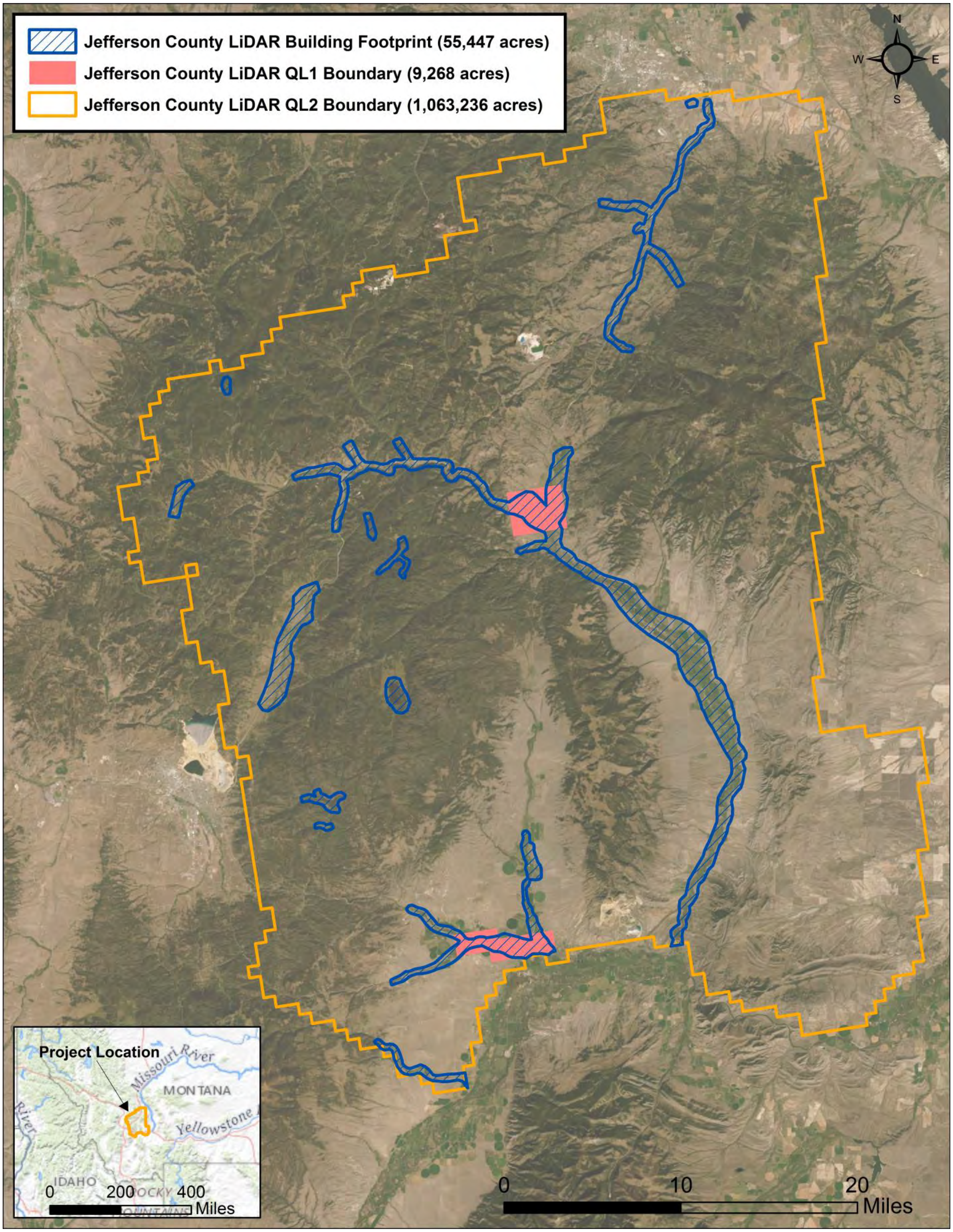


Figure 1: Location map of the Jefferson County site in Montana

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 Jefferson County LiDAR study area at the target point density of ≥8.0 points/m^2 for QL1 areas, and ≥2.0 points/m^2 for QL2 areas. 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 flights 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 Jefferson County LiDAR data collection are detailed in Table 3 below.

Table 3: Boresight Calibration Flight Summary

LiDAR Boresight Calibration Flight Summary for Jefferson County, Montana Aircraft & Sensors					
Aircraft Name	Aircraft #	Sensor Name	Sensor Type	Boresight Flight Date	Boresight Flight Location
Cessna Caravan 208B	N-208NR	SN8146	Leica ALS80	07/07/2018	Monroe, IN
Cessna Caravan 208B	N-208JA	SN8239	Leica ALS80	03/19/2019	Corvallis, OR
Cessna Caravan 208B	N-208NR	SN8227	Leica ALS80	04/22/2019	Sheboygan, WI
Cessna Caravan 208B	N-840JA	SN061	Riegl VQ-1560i	06/08/2019	Kissimmee, FL

Airborne LiDAR Survey

The QL1 and QL2 LiDAR survey was accomplished using a Leica ALS80 and a Riegl VQ-1560 sensor system mounted in a Cessna Caravan. Table 4 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Jefferson County QL1 project area, and ≥2 pulses/m^2 over the QL2 project area. Both Leica and Riegl sensors are capable of recording unlimited 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			
Quality Level	QL1	QL2	QL2
Acquisition Dates	09/27/2018 & 10/01/2019	09/25/2018 - 10/15/2018, 04/22/2019 – 07/06/2019	07/19/2019
Aircraft Used	Cessna Caravan	Cessna Caravan	Cessna Caravan
Sensor	Leica	Leica	Riegl
Laser	ALS80	ALS80	VQ1560i
Maximum Returns	Unlimited	Unlimited	Unlimited
Resolution/Density	Average 8 pulses/m^2	Average 2 pulses/m^2	Average 2 pulses/m^2
Nominal Pulse Spacing	0.35 m	0.71 m	0.71 m
Survey Altitude (AGL)	1600 m	2300 m	2300 m
Survey speed	140 knots	140 knots	140 knots
Field of View	30º	30º	58.5º
Scan Rate	46 Hz	44 Hz	Uniform Point Spacing
Target Pulse Rate	345 kHz	240 kHz	350 kHz
Pulse Length	3.0 ns	3.0 ns	2.5 ns
Laser Pulse Footprint Diameter	35.2 cm	50.6 cm	41.4 cm
Central Wavelength	1064 nm	1064 nm	1064 nm
Pulse Mode	Multi Pulse in Air (2PiA)	Multi Pulse in Air (2PiA)	Multi Times Around (MTA)
Beam Divergence	0.22 mrads	0.22 mrads	0.18 mrads
Swath Width	857 m	1,232 m	2,576 m
Swath Overlap	60%	30%	20%
Intensity	8-bit, scaled to 16-bit	8-bit, scaled to 16-bit	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated): ≤ 10cm	$RMSE_Z$ (Non-Vegetated): ≤ 10cm	$RMSE_Z$ (Non-Vegetated): ≤ 10cm

All areas were surveyed with a minimum of ≥20% 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 Survey

Ground control surveys, including monumentation and ground survey point (GSP) collection, were conducted to support the airborne acquisition. QSI in collaboration with Gaston Engineering and Surveying (Gaston) performed ground survey work for the Jefferson County LiDAR Project. 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). Please see Appendix B for survey methods and certification provided by Gaston Engineering and Surveying.

Base Stations

Base stations were utilized for collection of ground check 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. Twelve monuments in total were established for the Jefferson County LiDAR project. Six of these monuments were established by QSI and the remaining six were established by Gaston. The six monuments established by QSI were set with each having a 5/8” X 30” Rebar topped with stamped 2 ½” aluminum caps or 60D nail with feather set as a hard ground point (Table 5). QSI’s professional land surveyor Steven J. Hyde (MTPLS#60192) oversaw and certified the establishment of the monuments collected by QSI.

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

Monument ID	Latitude	Longitude	Ellipsoid (meters)	Stability Rating	Acquisition
CA001	45° 54' 58.30078"	-111° 44' 33.62404"	1393.480	D	Gaston 2018
CA002	46° 07' 23.93812"	-111° 57' 14.17957"	1402.588	D	Gaston 2018
CA003	45° 55' 30.15267"	-112° 10' 58.62142"	1481.255	D	Gaston 2018
CA004	46° 29' 51.52717"	-111° 59' 00.89759"	1390.679	D	Gaston 2018
CA005	46° 19' 07.01958"	-112° 04' 05.15152"	1767.132	D	Gaston 2018
CA006	46° 10' 01.07180"	-112° 22' 22.16366"	1895.843	D	Gaston 2018
DNRC19_RTK_01	46° 24' 27.33068"	-112° 00' 45.06770"	1345.214	D	QSI 2019
DNRC19_RTK_02	46° 04' 49.88153"	-111° 54' 32.73684"	1376.900	D	QSI 2019
DNRC19_RTK_03	45° 53' 31.41515"	-112° 10' 10.58268"	1402.128	D	QSI 2019
DNRC19_RTK_04	46° 14' 50.80694"	-112° 07' 10.54633"	1519.804	D	QSI 2019
DNRC19_RTK_05	46° 06' 10.60492"	-112° 25' 02.23458"	1907.500	D	QSI 2019

Monument ID	Latitude	Longitude	Ellipsoid (meters)	Stability Rating	Acquisition
MTHC	45° 56' 16.19773"	-112° 30' 36.10869"	1696.465	D	QSI 2019

QSI utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[2]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[3] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 6.

Table 6: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.050 m

For the Jefferson County LiDAR project, the monument coordinates contributed no more than 5.7 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

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 7. 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).

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[2] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

[3] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 7: 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

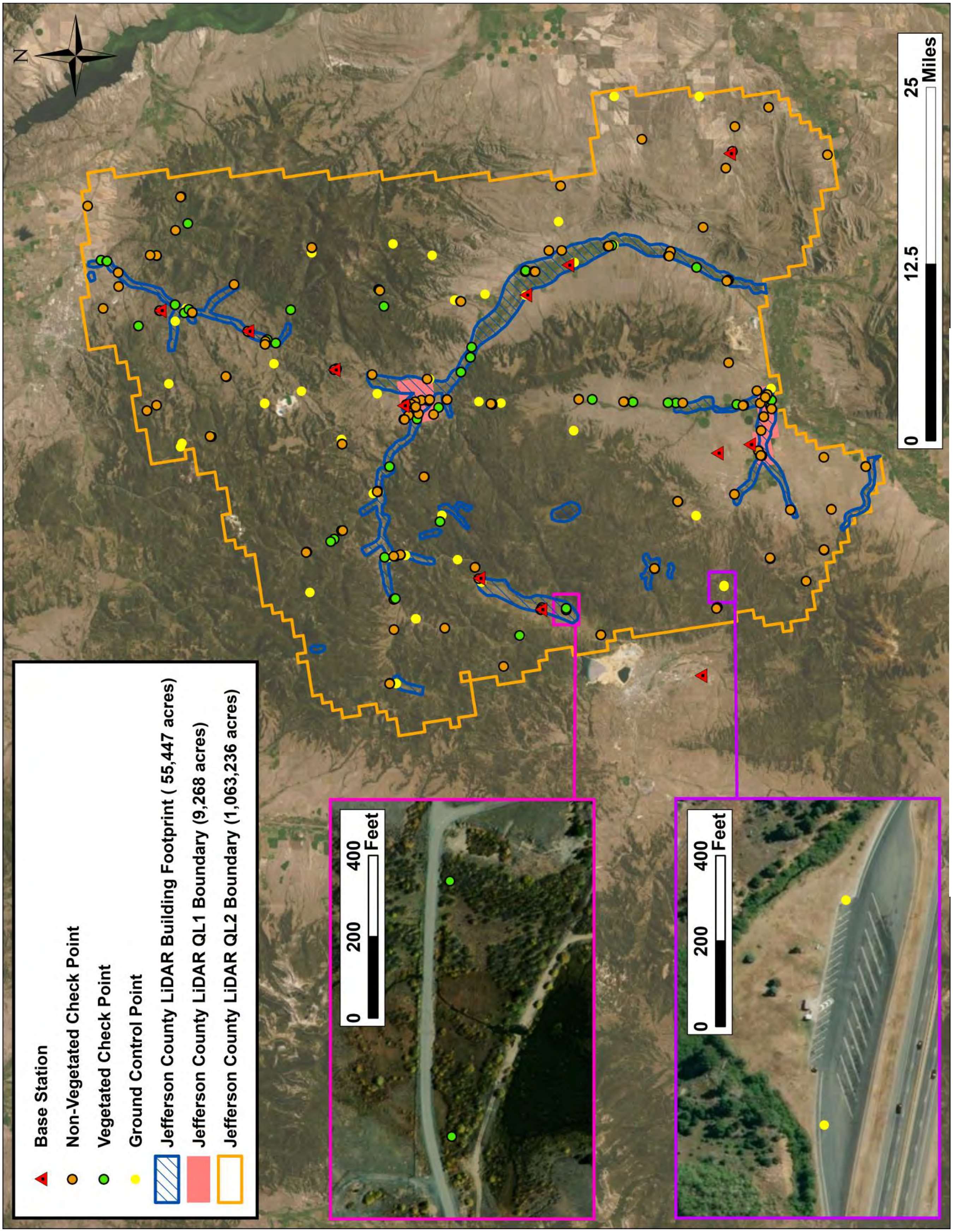
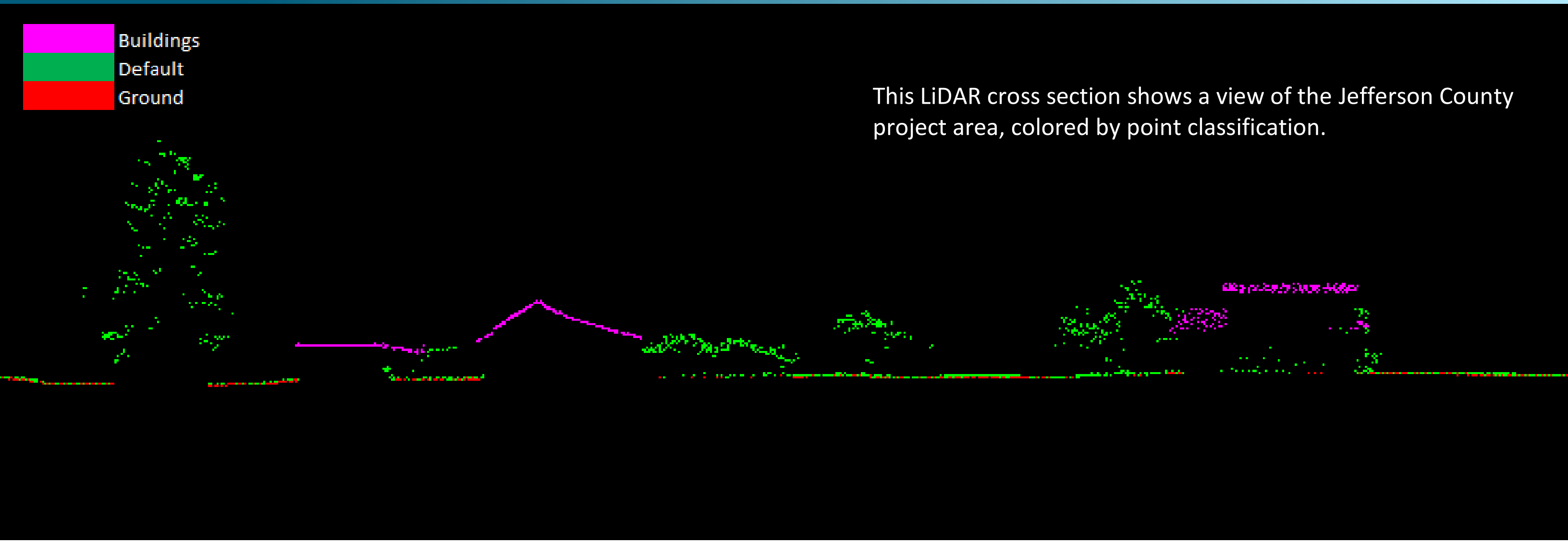


Figure 2: Ground survey location map



LiDAR Data Processing

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 8). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9. Outlier points in the classified point cloud data are classified as Noise (Class 7) and make up approximately 0.63% of the delivered classified point cloud.

Table 8: ASPRS LAS classification standards applied to the Jefferson 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	Permanent building structures with minimum area 100ft^2 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
17	Bridge	Bridge deck
20	Ignored Ground	Ground points proximate to water’s edge breaklines; ignored for correct model creation

Table 9: 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 8). 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 surface models as GeoTiffs at a 3.0 foot pixel resolution. Duplicate in .gdb and .asc format.	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

Hydroflattening and Water's Edge Breaklines

Hydroflattening was performed on the Jefferson 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. 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. Additionally, any permanent islands that exist within a water body feature 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.

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. The Jefferson County project area did not contain any rivers meeting the 100 foot nominal width specification.

Table 10: Hydroflattening Treatment

Summary of Hydroflattened Requirements	
Feature Type	**Required Size**
Lakes & Closed Water Bodies	≥2 acres
Rivers	≥100 feet nominal width
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 Jefferson County dataset, with major contours labeled at 10 foot increments.

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 is unable to sufficiently penetrate to the ground surface.

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 building 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 to generate a polygon shapefile representing building footprints. A total of 4,953 buildings were classed in the data (Figure 3).

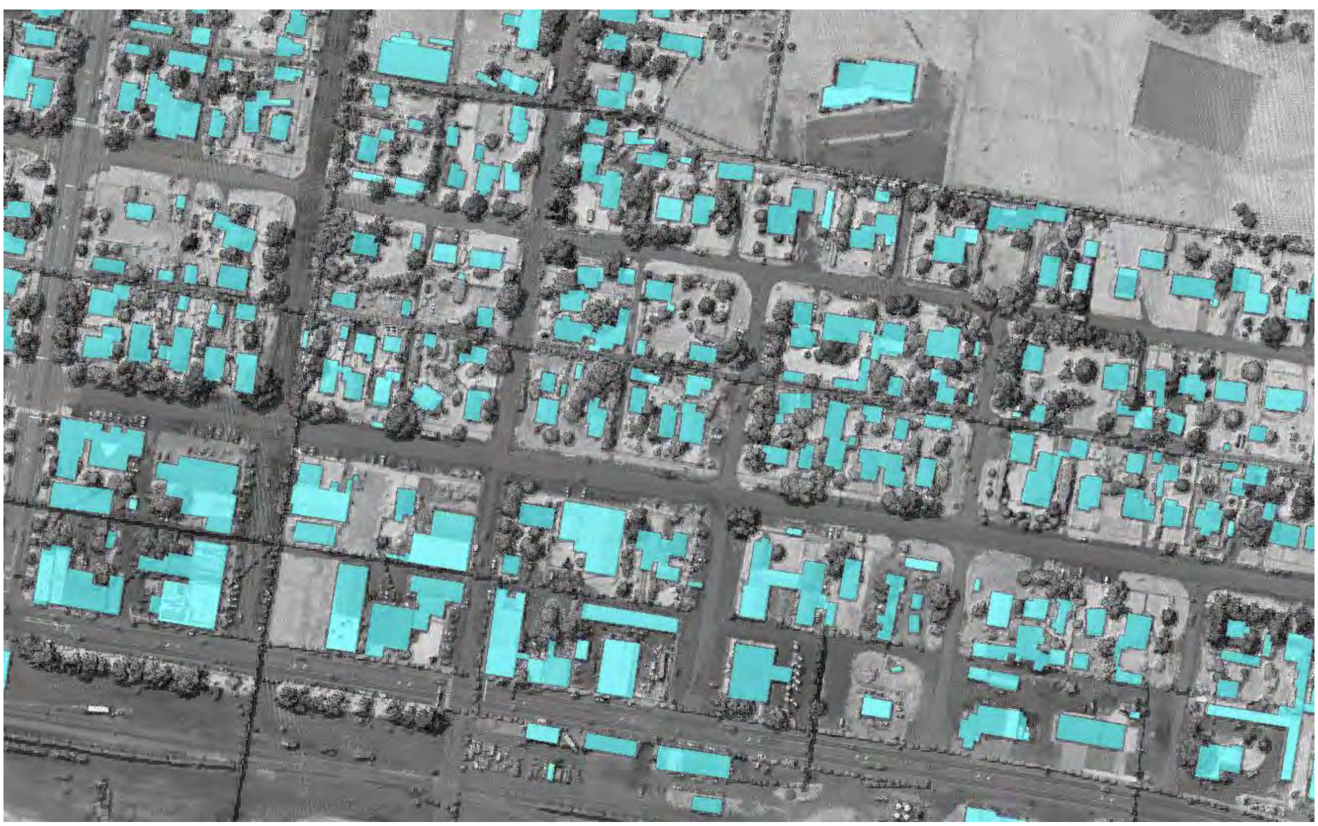
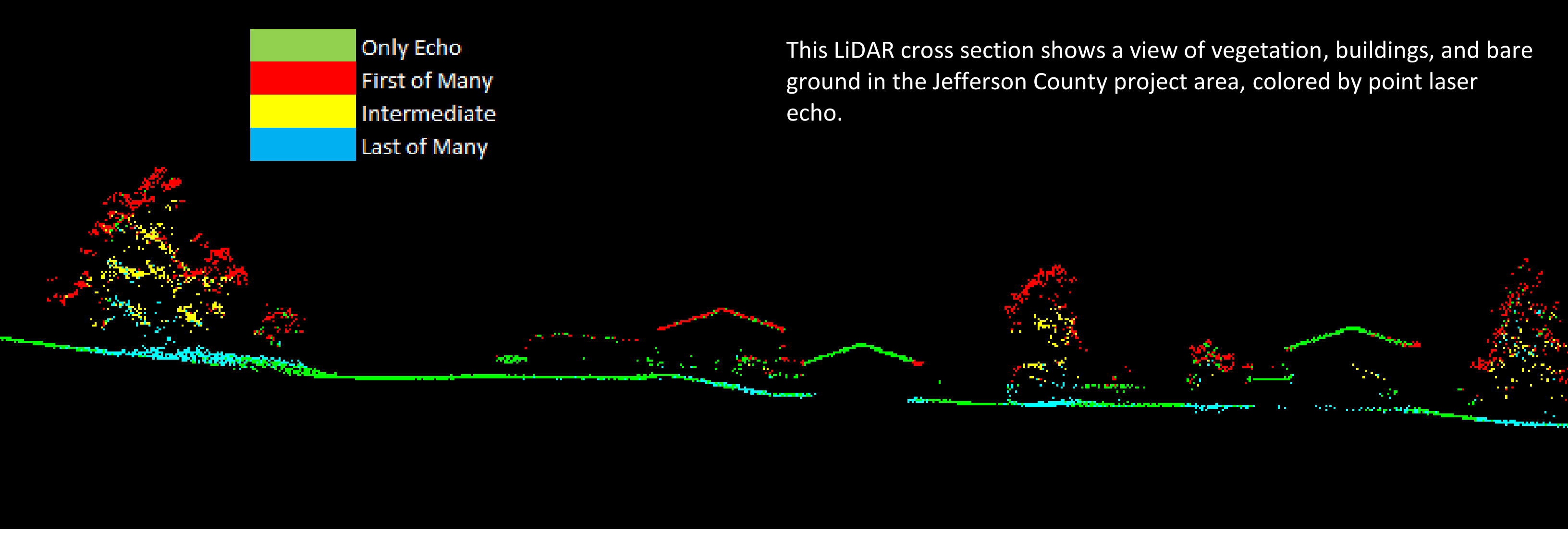


Figure 3: This aerial view of the lidar point cloud is colored by intensity, and is overlaid with the 3D building footprint in the Jefferson County project area.



This LiDAR cross section shows a view of vegetation, buildings, and bare ground in the Jefferson County project area, colored by point laser echo.

LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of ≥8.0 points/m^2 for QL1 areas and ≥2.0 points/m^2 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 Jefferson County QL1 data was 1.61 points/ft^2 (17.33 points/m^2) while the average ground classified density was 0.52 points/ft^2 (5.62 points/m^2). The average first return density for the Jefferson County QL2 data was 0.50 points/ft^2 (5.36 points/m^2), with ground classified density of 0.24 points/ft^2 (2.58 points/m^2) (Table 11). 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 8.

Table 11: Average LiDAR point densities

Classification	QL1 Point Density	QL2 Point Density
First-Return	1.61 points/ft^2 17.33 points/m^2	0.50 points/ft^2 5.36 points/m^2
Ground Classified	0.52 points/ft^2 5.62 points/m^2	0.24 points/ft^2 2.58 points/m^2

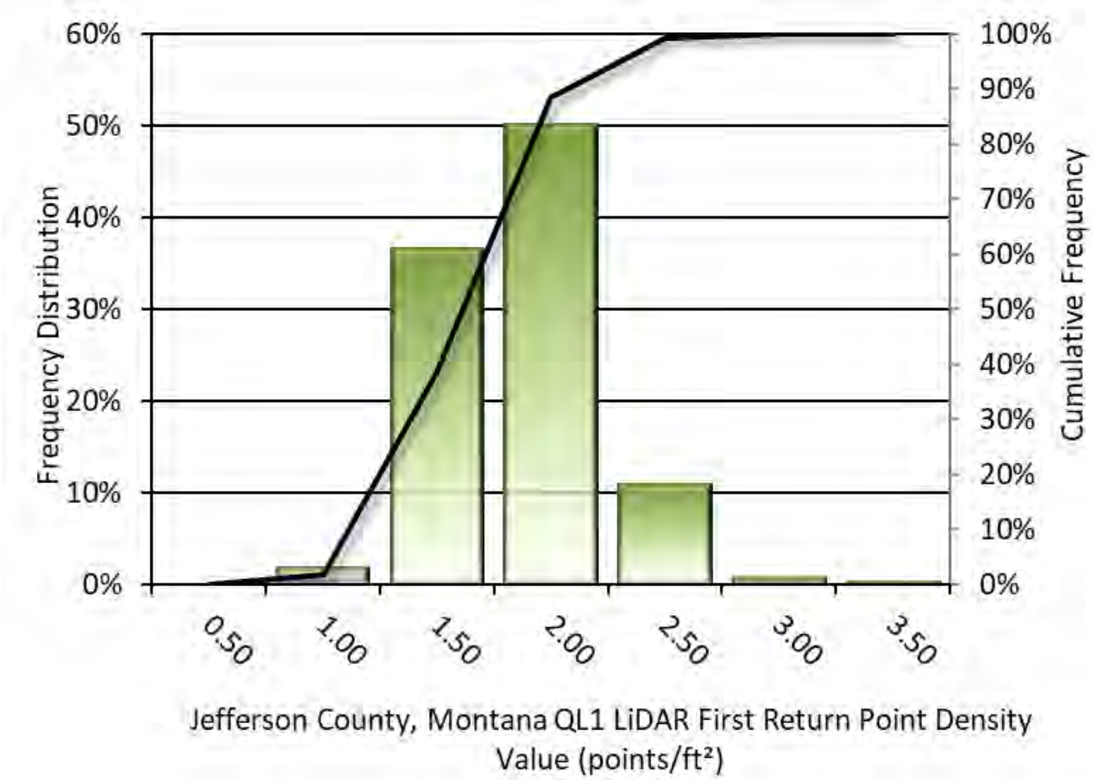


Figure 4: Frequency distribution of QL1 first return point density values per 100 x 100 m cell

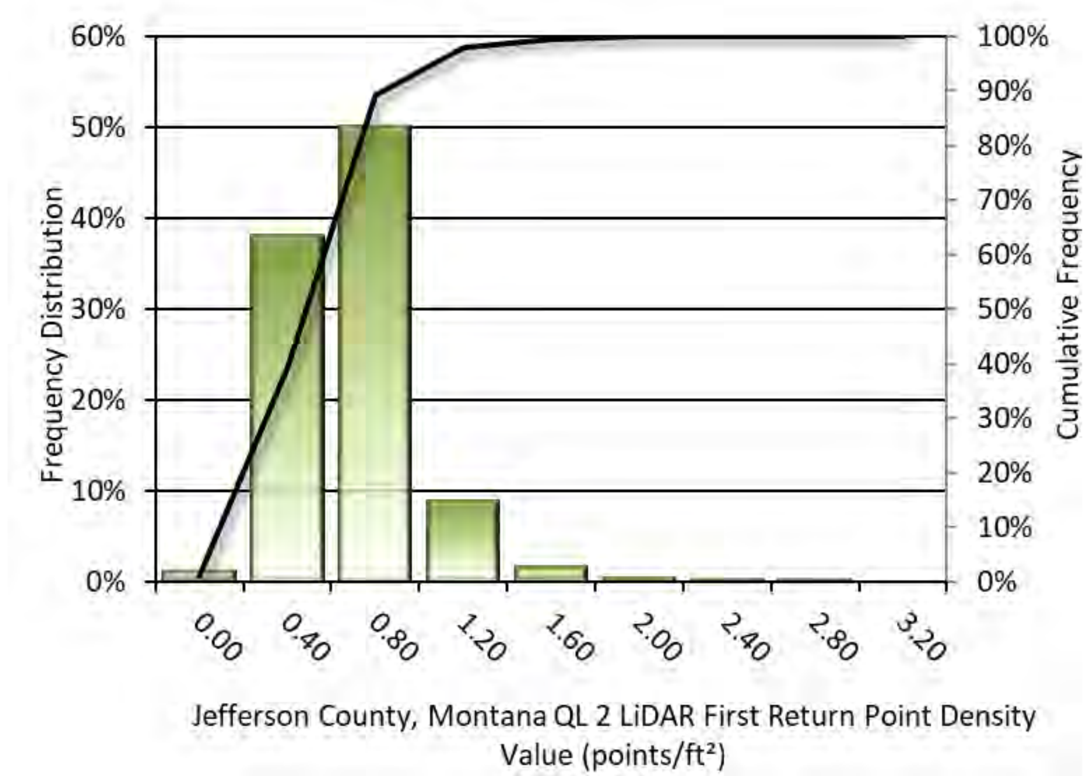


Figure 5: Frequency distribution of QL2 first return point density values per 100 x 100 m cell

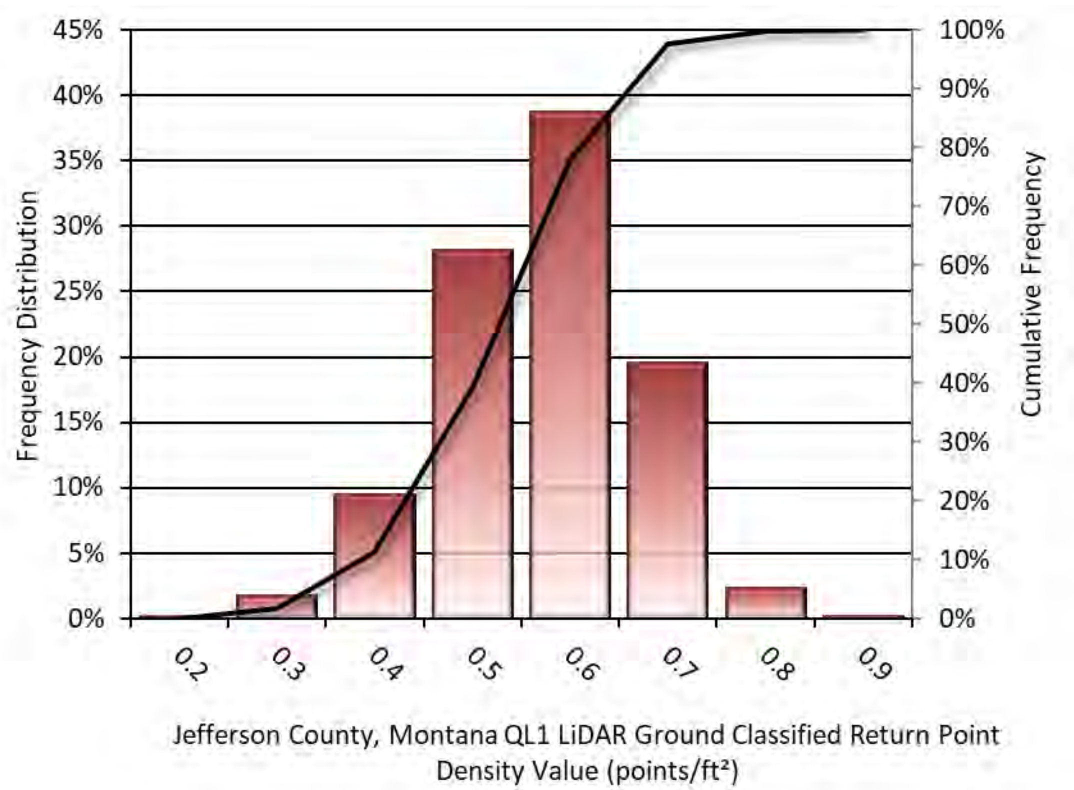


Figure 6: Frequency distribution of QL1 ground-classified return point density values per 100 x 100 m cell

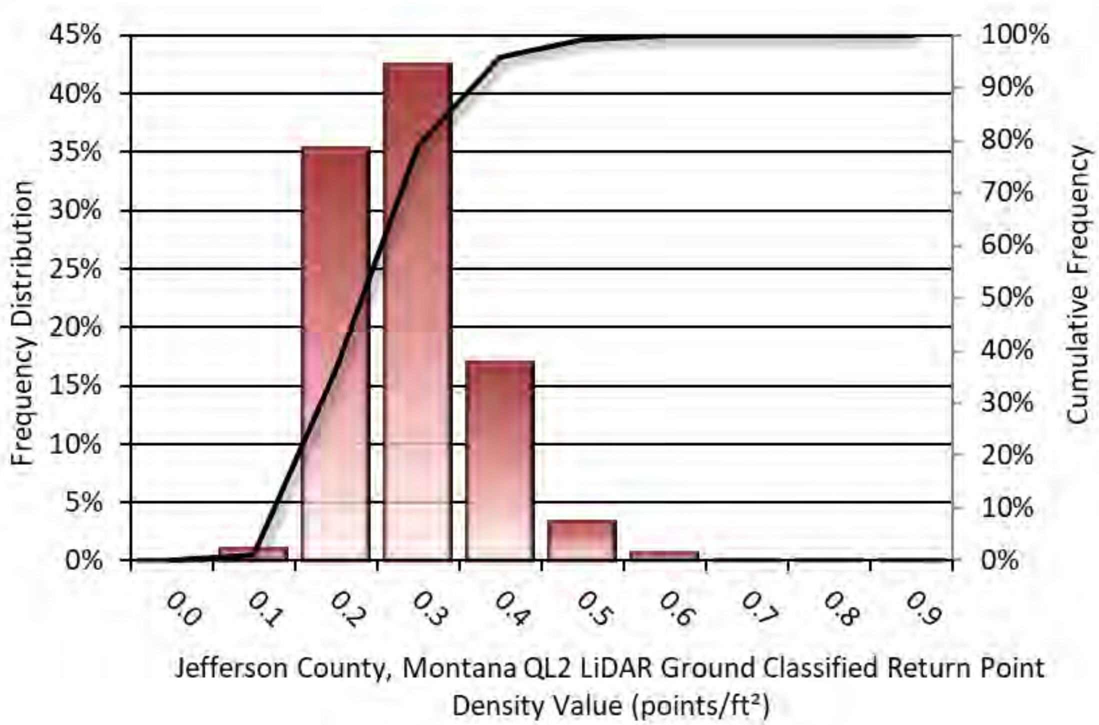


Figure 7: Frequency distribution of QL2 ground-classified return point density values per 100 x 100 m cell

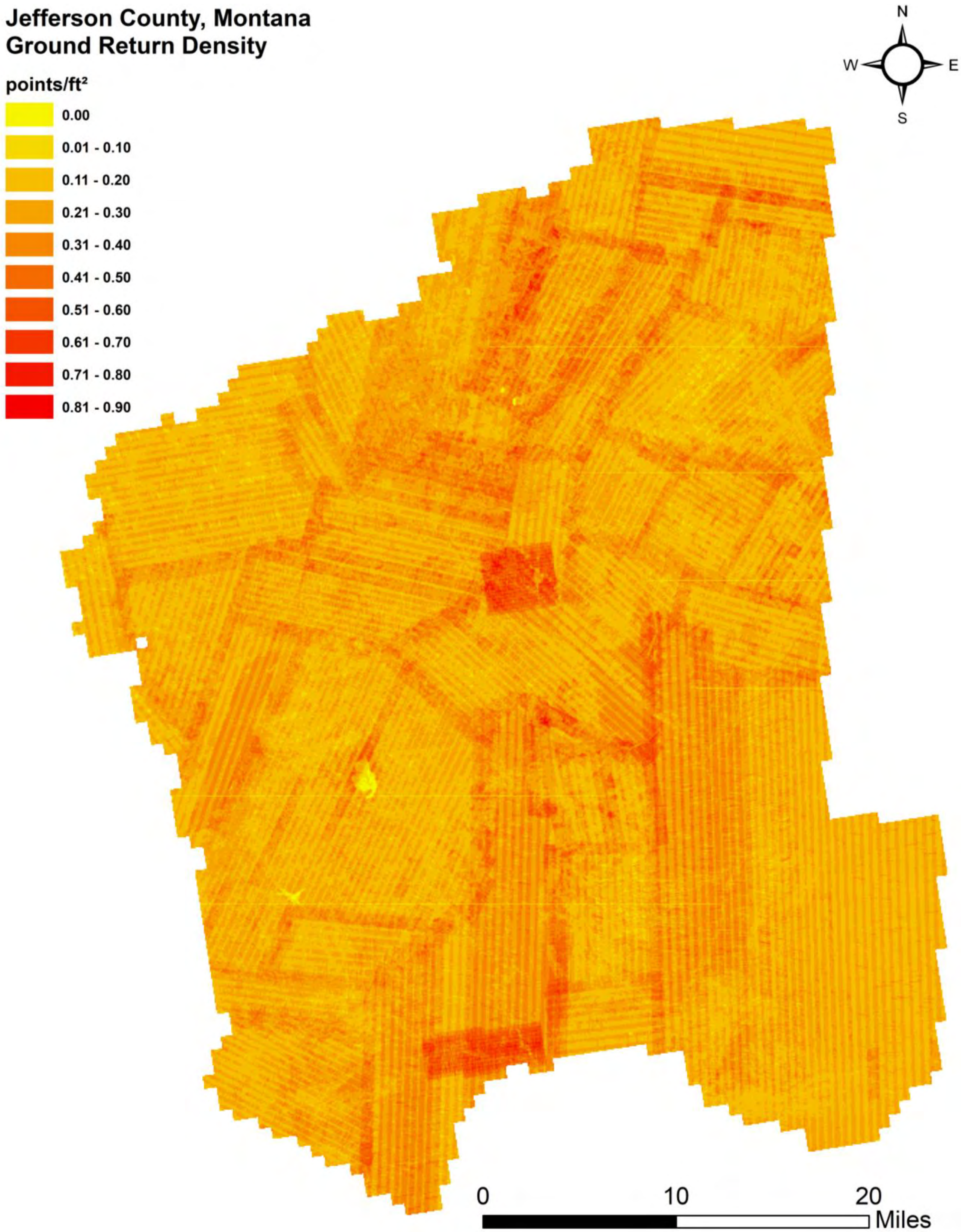


Figure 8: Ground-classified point density map for the Jefferson County site (100 m x 100 m cells)

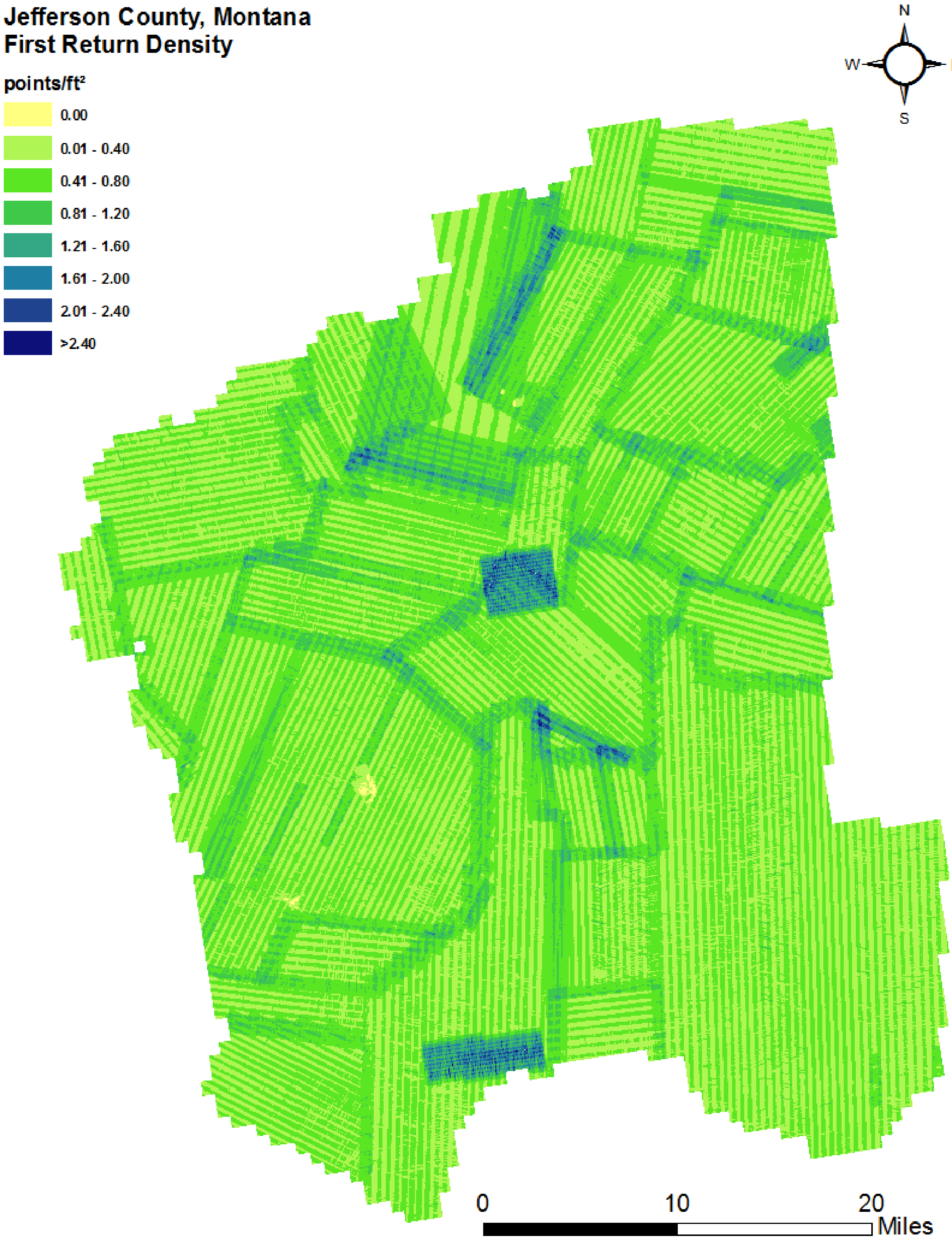


Figure 9: First return-classified point density map for the Jefferson County site (100 m x 100 m cells)

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[4]. 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 12.

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 Jefferson County survey, 136 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.261 feet (0.079 meters) as compared to unclassified LAS, and 0.250 feet (0.076 meters) as compared to the bare earth DEM, with 95% confidence (Figure 10, Figure 11).

QSI also assessed absolute accuracy using 117 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 12 and Figure 12.

Table 12: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	136 points	136 points	117 points
95% Confidence (1.96*RMSE)	0.261 ft 0.079 m	0.250 ft 0.076 m	0.251 ft 0.076 m
Average	0.040 ft 0.012 m	0.015 ft 0.005 m	-0.026 ft -0.008 m
Median	0.038 ft 0.012 m	0.007 ft 0.002 m	-0.026 ft -0.008 m

[4] 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	0.133 ft 0.041 m	0.128 ft 0.039 m	0.128 ft 0.039 m
Standard Deviation (1σ)	0.127 ft 0.039 m	0.127 ft 0.039 m	0.126 ft 0.038 m

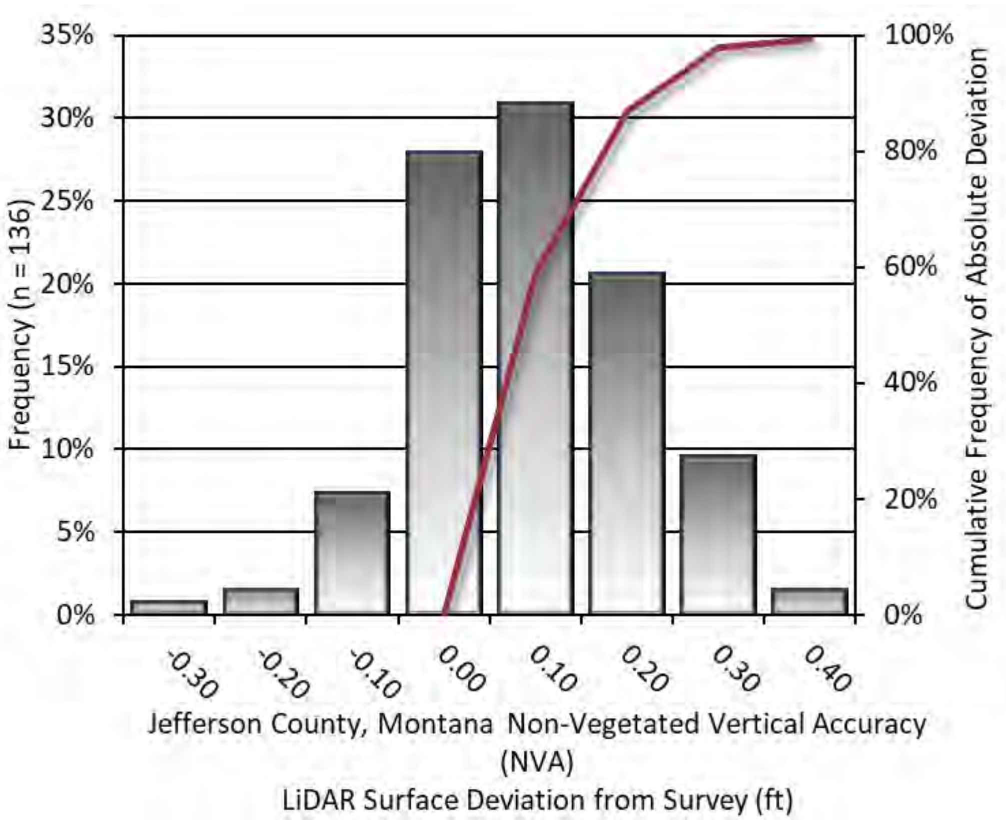


Figure 10: Frequency histogram for LiDAR unclassified LAS deviation from ground check point values (NVA)

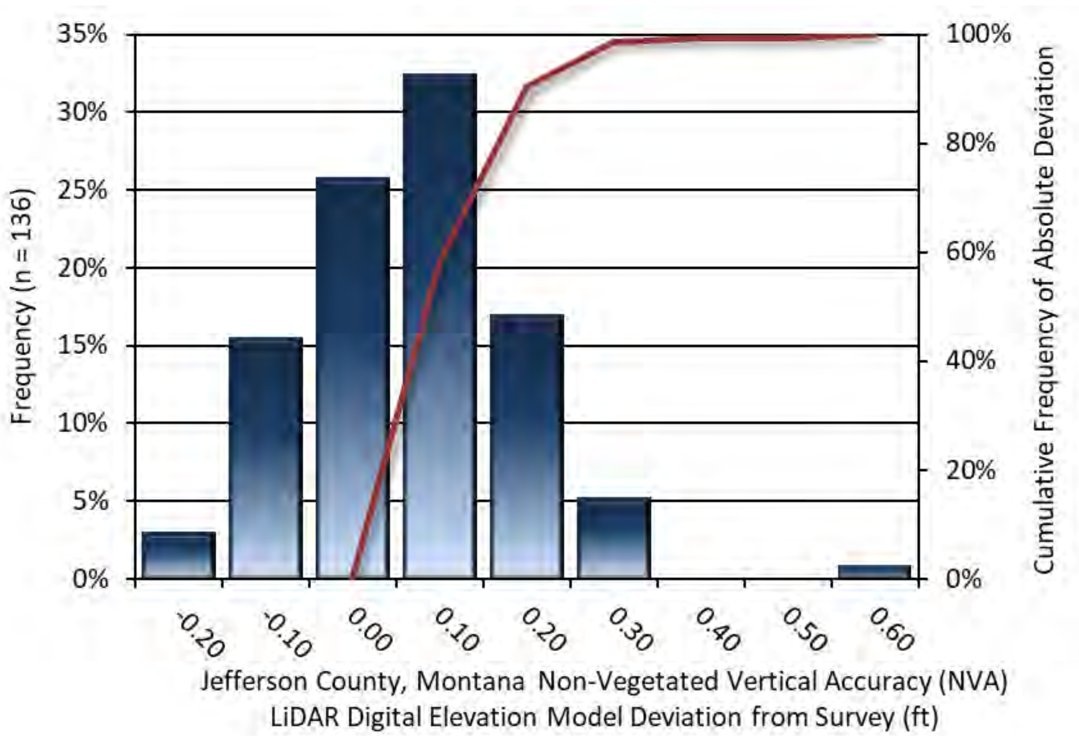


Figure 11: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)

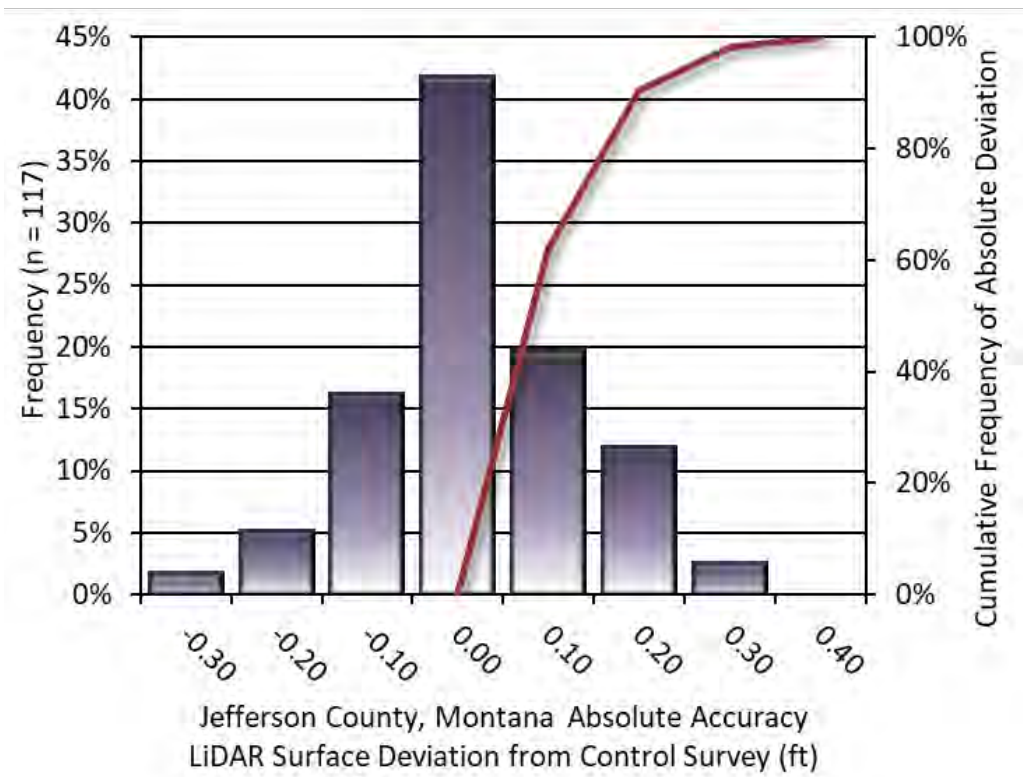


Figure 12: Frequency histogram for LiDAR surface deviation from ground control point values

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 Jefferson County survey, 84 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.902 feet (0.275 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 13, Figure 13).

Table 13: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	84 points
95th Percentile	0.902 ft 0.275 m
Average	-0.295 ft -0.090 m
Median	-0.226 ft -0.069 m
RMSE	0.509 ft 0.155 m
Standard Deviation (1σ)	0.417 ft 0.127 m

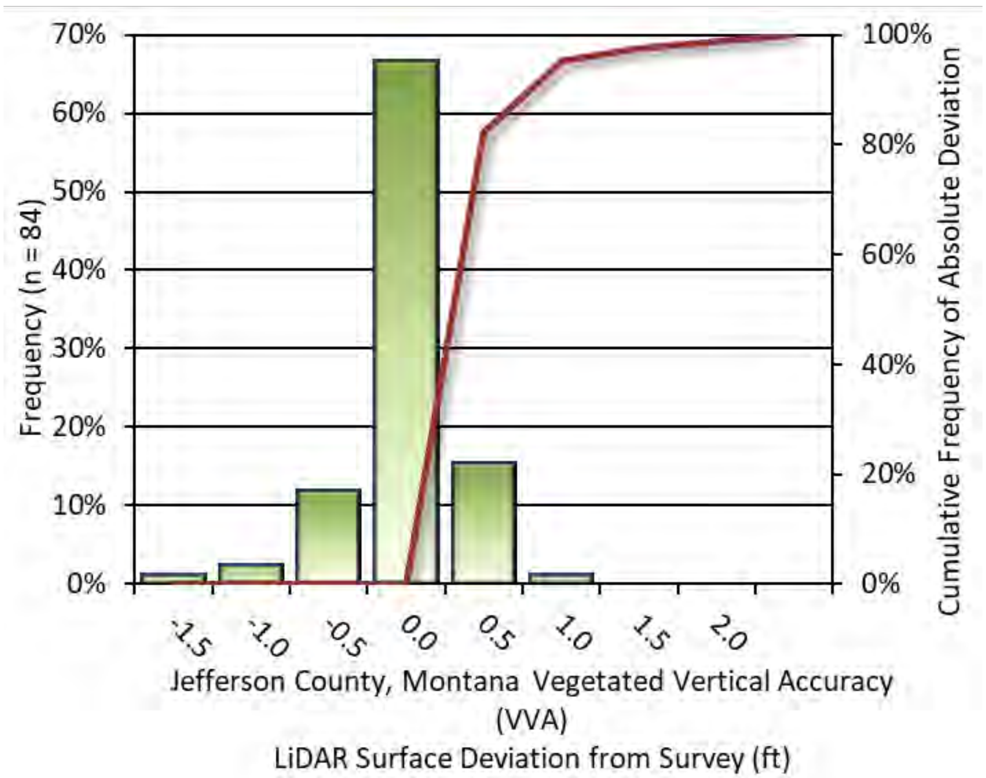


Figure 13: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)

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 Jefferson County LiDAR project was 0.139 feet (0.042 meters) (Table 14, Figure 14).

Table 14: Relative accuracy results

Relative Accuracy	
Sample	587 flight line surfaces
Average	0.139 ft 0.042 m
Median	0.139 ft 0.042 m
RMSE	0.155 ft 0.047 m
Standard Deviation (1σ)	0.045 ft 0.014 m
1.96σ	0.088 ft 0.027 m

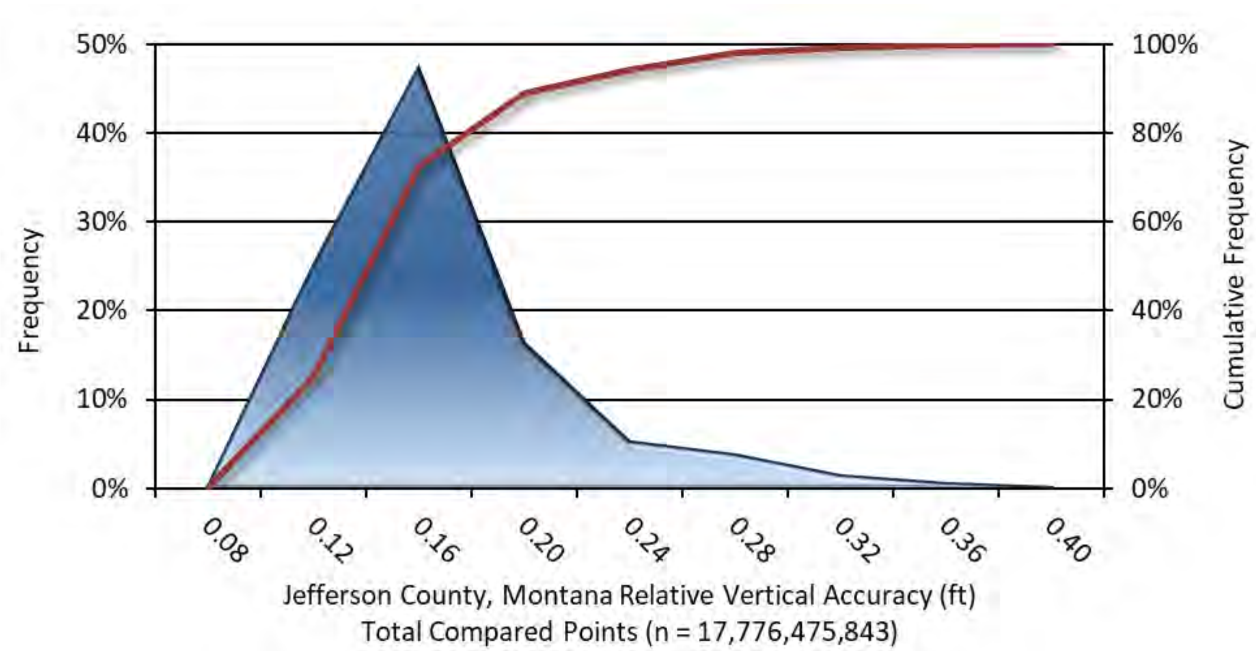


Figure 14: Frequency plot for relative vertical accuracy between flight lines

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 2,300 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 2.05 feet (0.62 meters) at the 95% confidence level (Table 13). Data from the Jefferson County dataset have been tested to meet horizontal requirements at the 95% confidence level, using NSSDA reporting methods.

Table 15: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	1.18 ft 0.36 m
ACC_r	2.05 ft 0.62 m

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the Jefferson County project as described in this report.

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

Ashley Daigle Oct 11, 2019

Ashley Daigle
Project Manager
Quantum Spatial, Inc.

I, Steven J. Hyde, PLS, being duly registered as a Professional Land Surveyor in and by the state of Montana, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between May 9 and July 7, 2019.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

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STEVEN J
HYDE
No. 60192 LS
LICENSED
PROF. LAND SURVEYOR

Steven J. Hyde, PLS
Quantum Spatial, Inc.
Corvallis, OR 97330

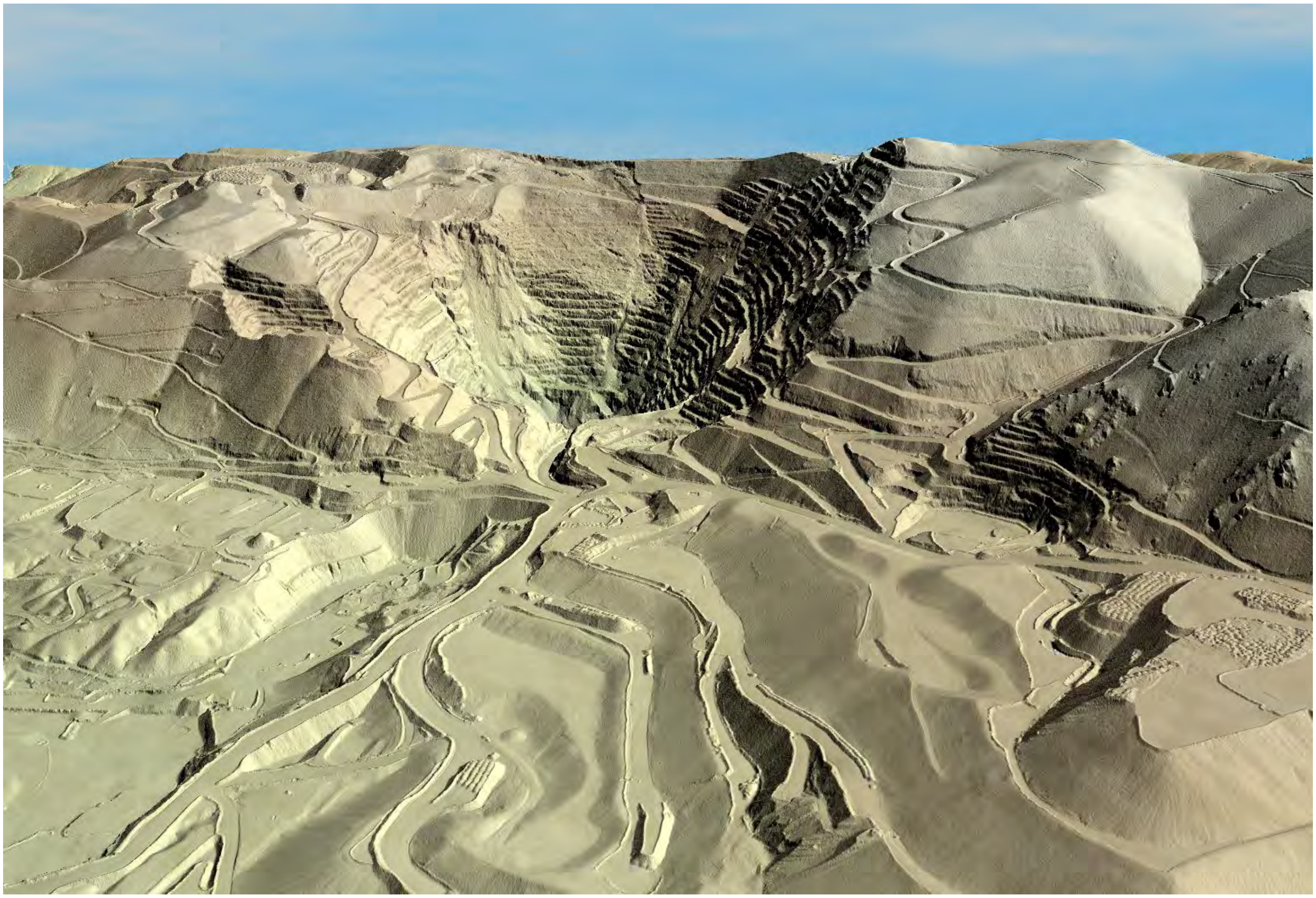

Figure 15: Southwest view of the Golden Sunlight Mine within Jefferson County. Bare earth model colored by elevation.

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 ±15-29^{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 11, 2018
W.O. #18-571

RE: Survey Methodology Report
Calibration & FEMA Check Point Survey
Jefferson 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 September and October of 2018.

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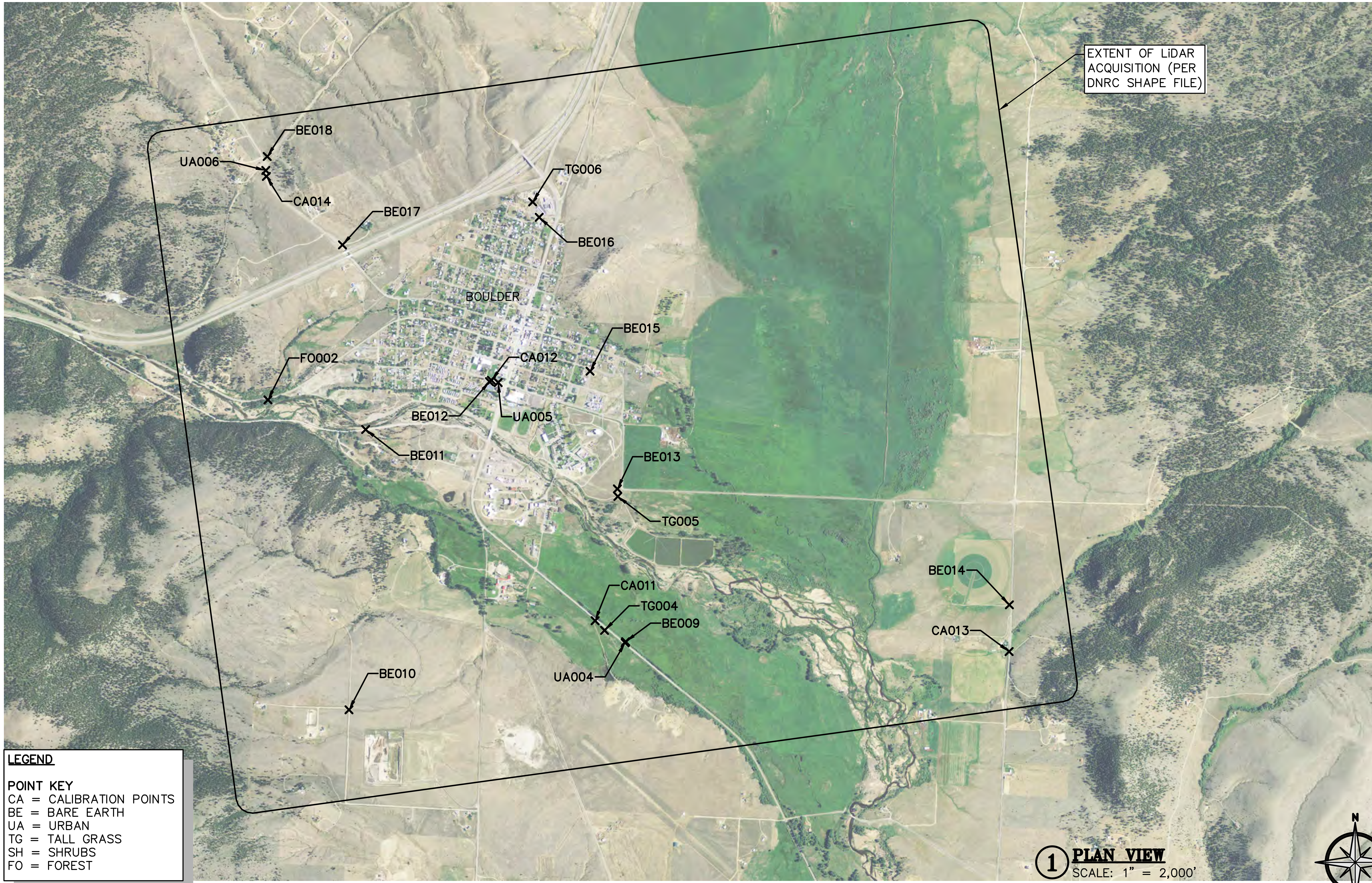
ENGINEERING/LAND SURVEYING/LAND PLANNING/MATERIALS TESTING

CALIBRATION & FEMA CHECK POINTS
JEFFERSON COUNTY, MT



1 PLAN VIEW
SCALE: 1" = 2,000'

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PROFESSIONAL PROGRESSIVE PERSONAL

P.O. BOX 861
BOZEMAN, MT 59771
(406) 586-0588

DRAWN BY: JO
CHECKED BY:
DRAWING DATE: 091418
REVISION DATE:

JEFFERSON LiDAR

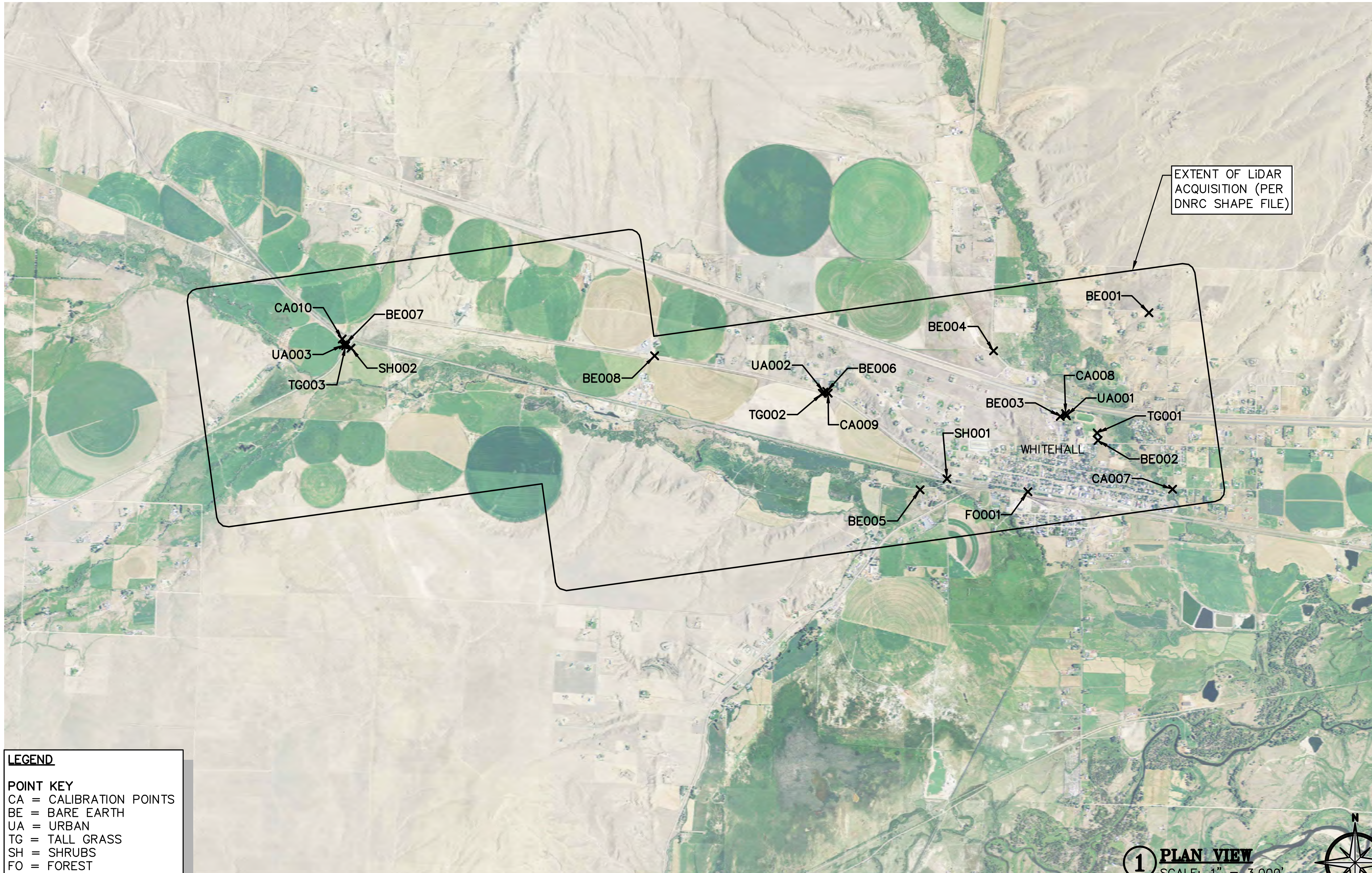
CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-571
JEFFERSON COUNTY, MT

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

PROJECT: 18-571
DRAWING: 18-571 BASE.dwg
TAB: COLLECTED POINTS QL1 BOULDER

SHEET 1 OF 2

CALIBRATION & FEMA CHECK POINTS
JEFFERSON COUNTY, MT



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PROJECT ID# 18-571
JEFFERSON COUNTY, MT

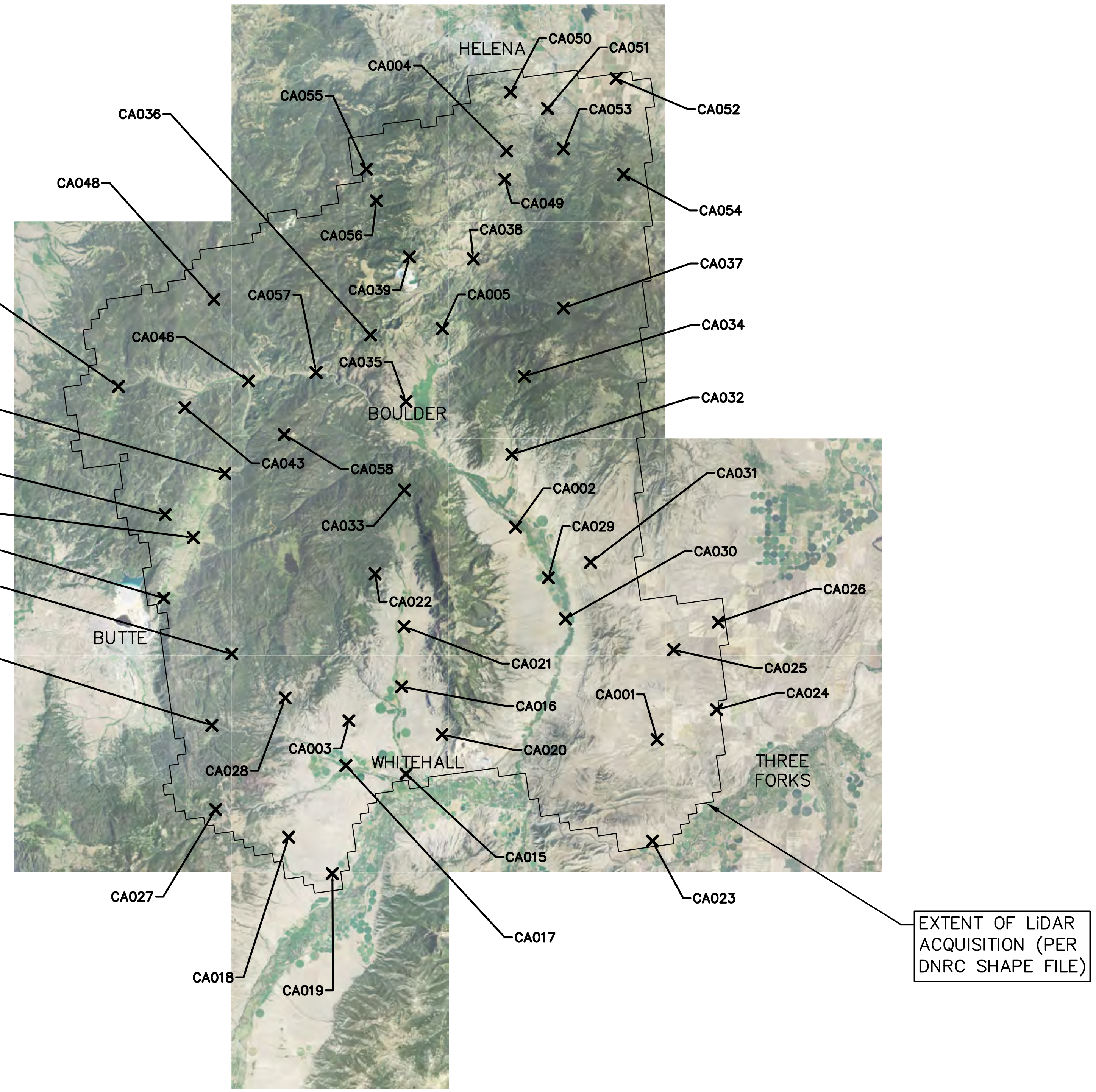
IF THIS LINE DOES NOT MEASURE 1", THE DRAWING IS NOT SCALED CORRECTLY.

PROJECT: 18-571
DRAWING: 18-571 BASE.dwg
TAB: COLLECTED POINTS QL1 WHITEHALL

SHEET 2 OF 2

CALIBRATION & FEMA CHECK POINTS

JEFFERSON 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" = 10 MILES

N

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MT DNRC
PROJECT ID# 18-571
JEFFERSON COUNTY, MT

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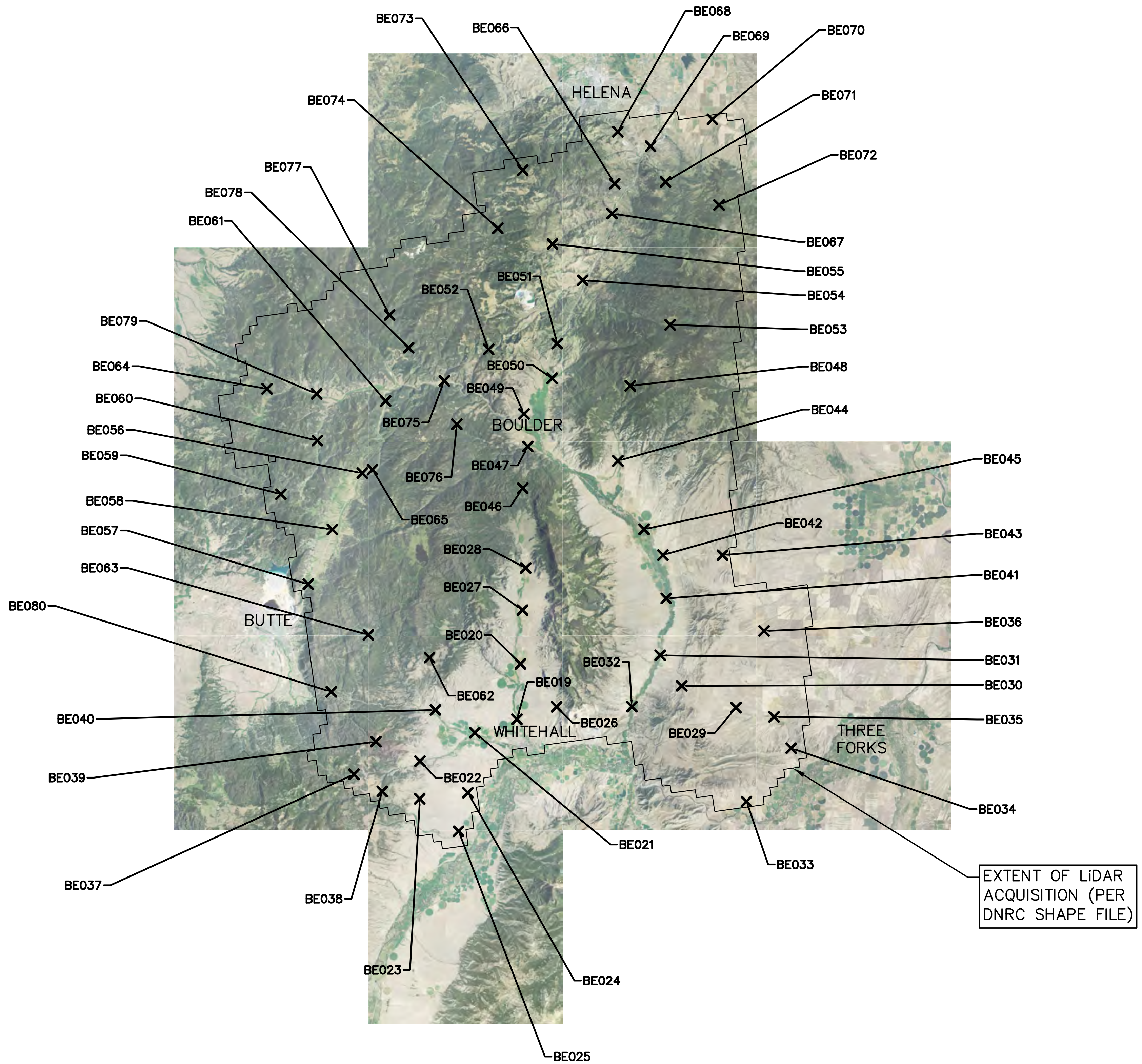
PROJECT: 18-571
DRAWING: 18-571 BASE.dwg
TAB: CALIBRATION

CALIBRATION & FEMA CHECK POINTS
JEFFERSON 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" = 10 MILES

N

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JEFFERSON COUNTY, MT

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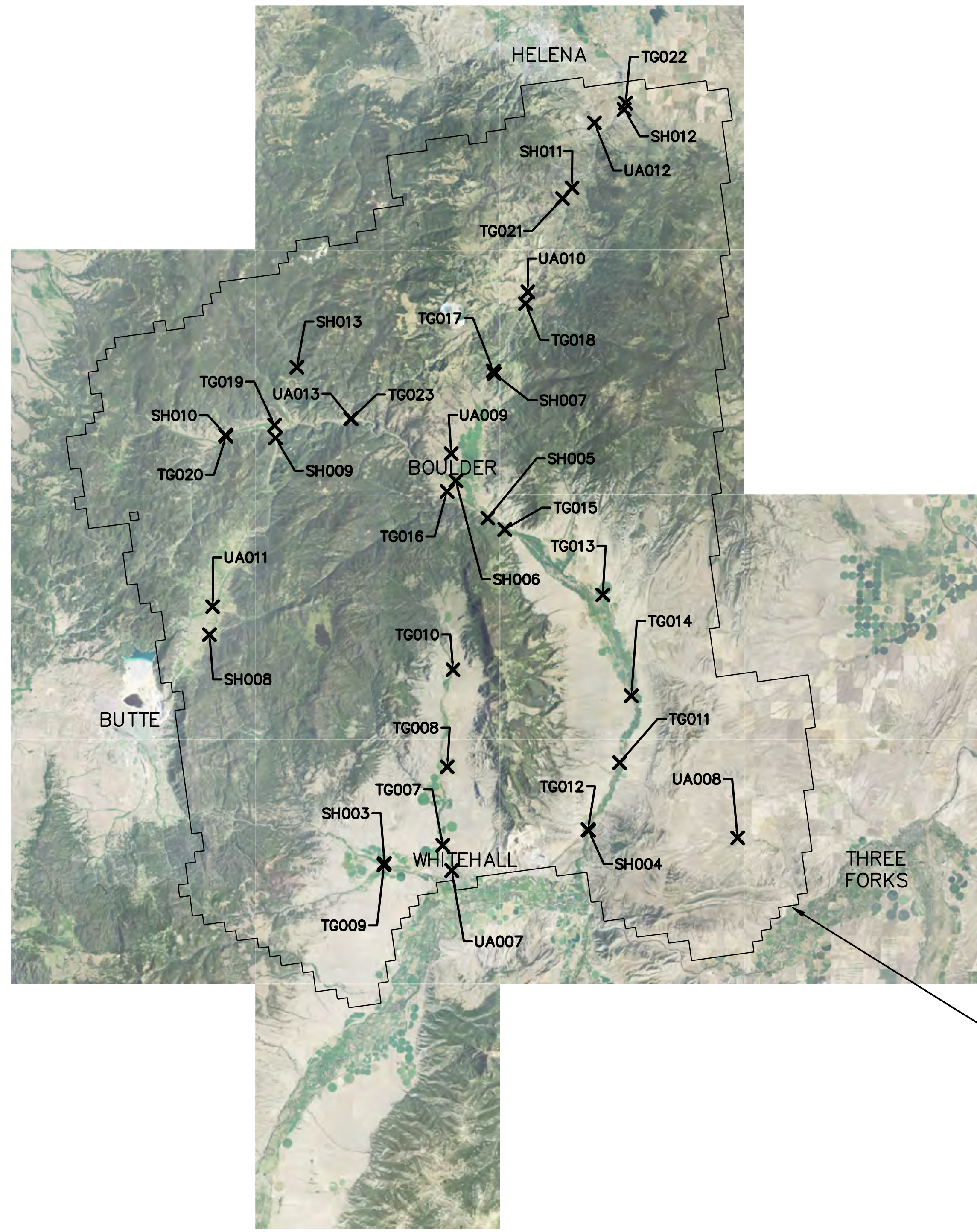
PROJECT: 18-571
DRAWING: 18-571 BASE.dwg
TAB: BARE EARTH

SHEET 2 OF 4

CALIBRATION & FEMA CHECK POINTS
JEFFERSON COUNTY, MT



EXTENT OF LiDAR ACQUISITION (PER DNRC SHAPE FILE)

URBAN, TALL GRASS, SHRUB POINTS

LEGEND

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

1 PLAN VIEW
SCALE: 1" = 10 MILES

N

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CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-571
JEFFERSON COUNTY, MT

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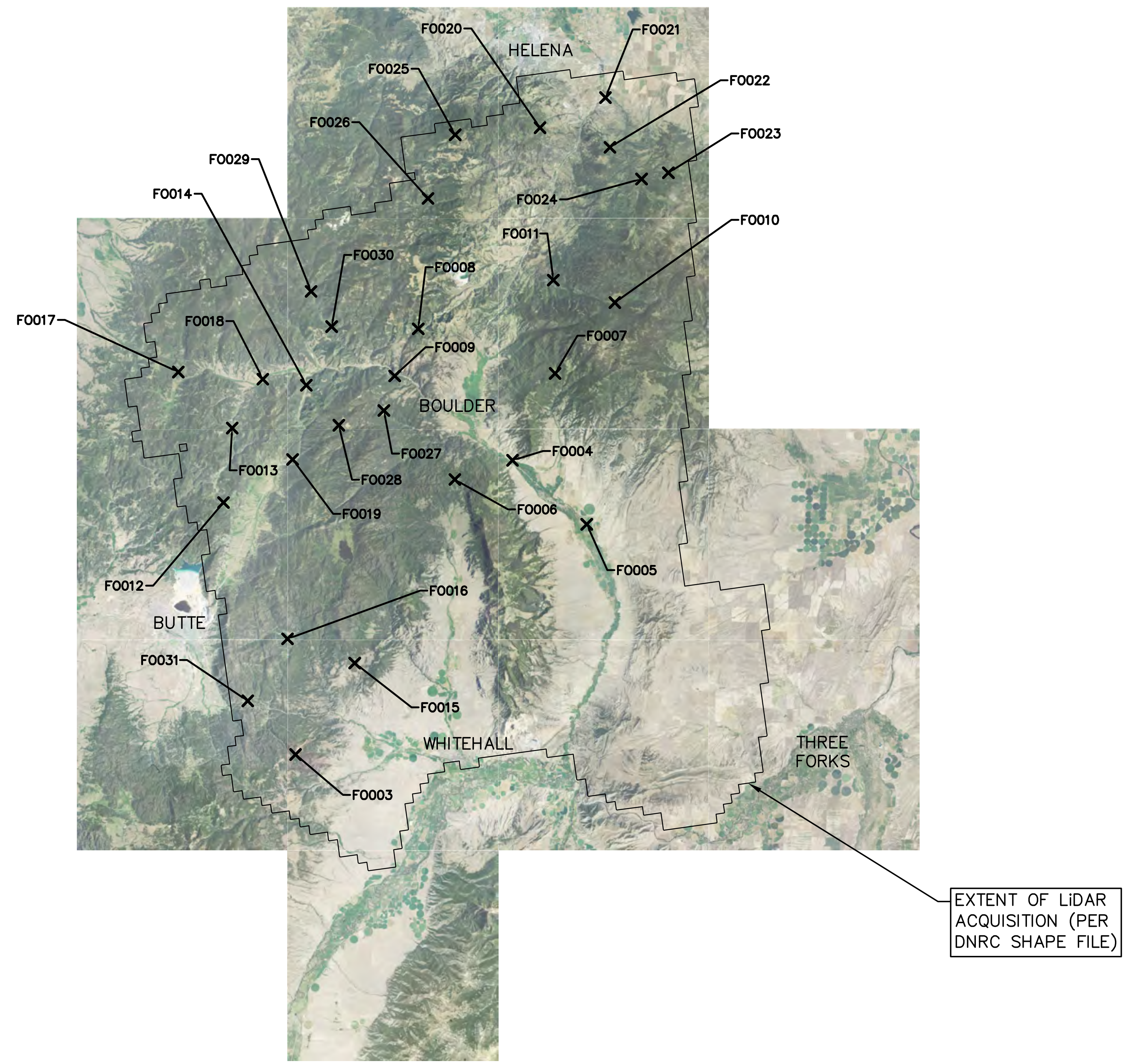
PROJECT: 18-571
DRAWING: 18-571 BASE.dwg
TAB: UA, TG, SH

SHEET 3 OF 4

CALIBRATION & FEMA CHECK POINTS

JEFFERSON COUNTY, MT



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" = 10 MILES

N

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CHECKED BY:
DRAWING DATE: 101118
REVISION DATE:

JEFFERSON LiDAR

CALIBRATION & CHECK POINTS
MT DNRC
PROJECT ID# 18-571
JEFFERSON COUNTY, MT

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

PROJECT: 18-571
DRAWING: 18-571 BASE.dwg
TAB: FOREST