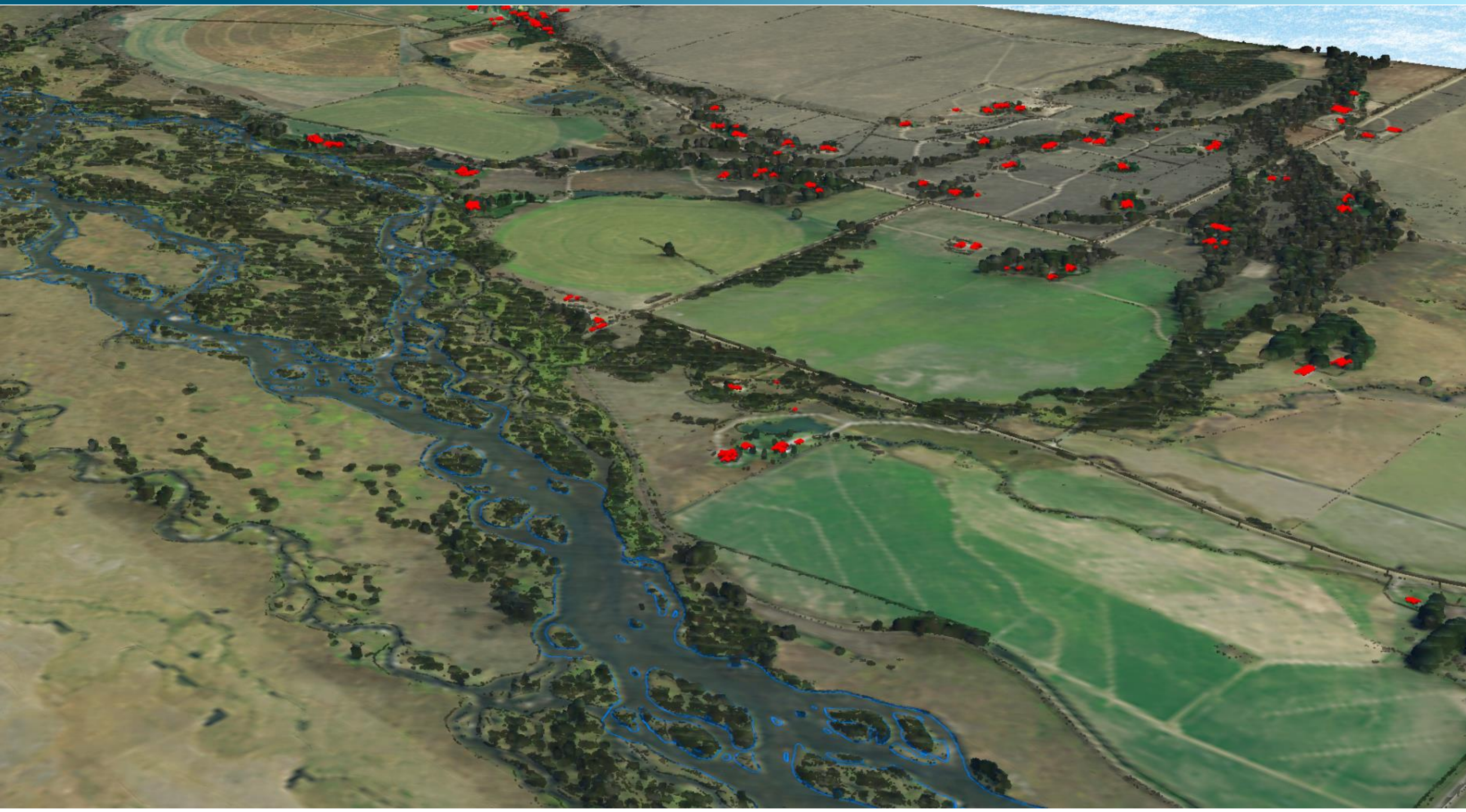
March 21, 2018



Madison River, Montana

LiDAR Technical Data Report, Revised November 2018

Steve Story
Montana Department of Natural Resources & Conservation
1424 9th Avenue
Helena, MT 59620
PH: 406-444-6816

QSI Corvallis
517 SW 2nd St., Suite 400
Corvallis, OR 97333
PH: 541-752-1204

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Cover Photo: A view looking at the Madison River within Madison County, Montana. The image was made from the bare earth model and above-ground point cloud overlaid with the water's edge breaklines. The image is colored using NAIP imagery and the buildings are colored red using the LiDAR point classification.

INTRODUCTION

This photo provided by Gaston Surveying & Engineering shows a view of the Montana landscape in the Madison River project area.

In September 2017, Quantum Spatial (QSI) was contracted by the Montana Department of Natural Resources and Conservation (MTDNRC) to collect high resolution Light Detection and Ranging (LiDAR) data in the fall of 2017 for several areas of interest in southwest Montana; the Jefferson River Watershed, Madison River, Musselshell and Wheatland Counties, and the Gallatin River & Tributaries (contract no. WO-QSI-167). This data delivery provides the Madison River LiDAR data, which falls within Madison and Gallatin Counties, Montana. Data were collected to aid MTDNRC in assessing the topographic and geophysical properties of the study area to support floodplain mapping and evaluation to meet the latest Federal Emergency Management Agency (FEMA) requirements.

This report accompanies the delivered Madison River 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 for the Madison River sites

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Madison River	89,656	96,861	10/27/17 – 10/31/17, 11/24/17, 11/28/17	LiDAR

Deliverable Products

Table 2: Products delivered to MTDNRC for the Madison River sites

<table>
<tr><th colspan="2">Madison River LiDAR Products
Projection: Montana State Plane
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12B)
Horizontal Units: International Feet
Vertical Units: US Survey Feet</th></tr>
<tr><td>Points</td><td>LAS v 1.4
All Classified Returns
Unclassified Flightline Swaths</td></tr>
<tr><td>Rasters</td><td>3.0 Foot ESRI Grids, Comma Delimited ASCII (*.asc), and ESRI Geodatabase
Hydroflattened Bare Earth Digital Elevation Model (DEM)
Ground Density (ESRI Grids)</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
Area of Interest
LiDAR Tile Index
Contours (1.0 foot)
Ground Survey Shapefiles
Total Area Flown
3D Building Footprints
ESRI Geodatabase (*.gdb)
Contours (1.0 foot)
Water’s Edge Breaklines with Z values (used in hydroflattening)</td></tr>
</table>

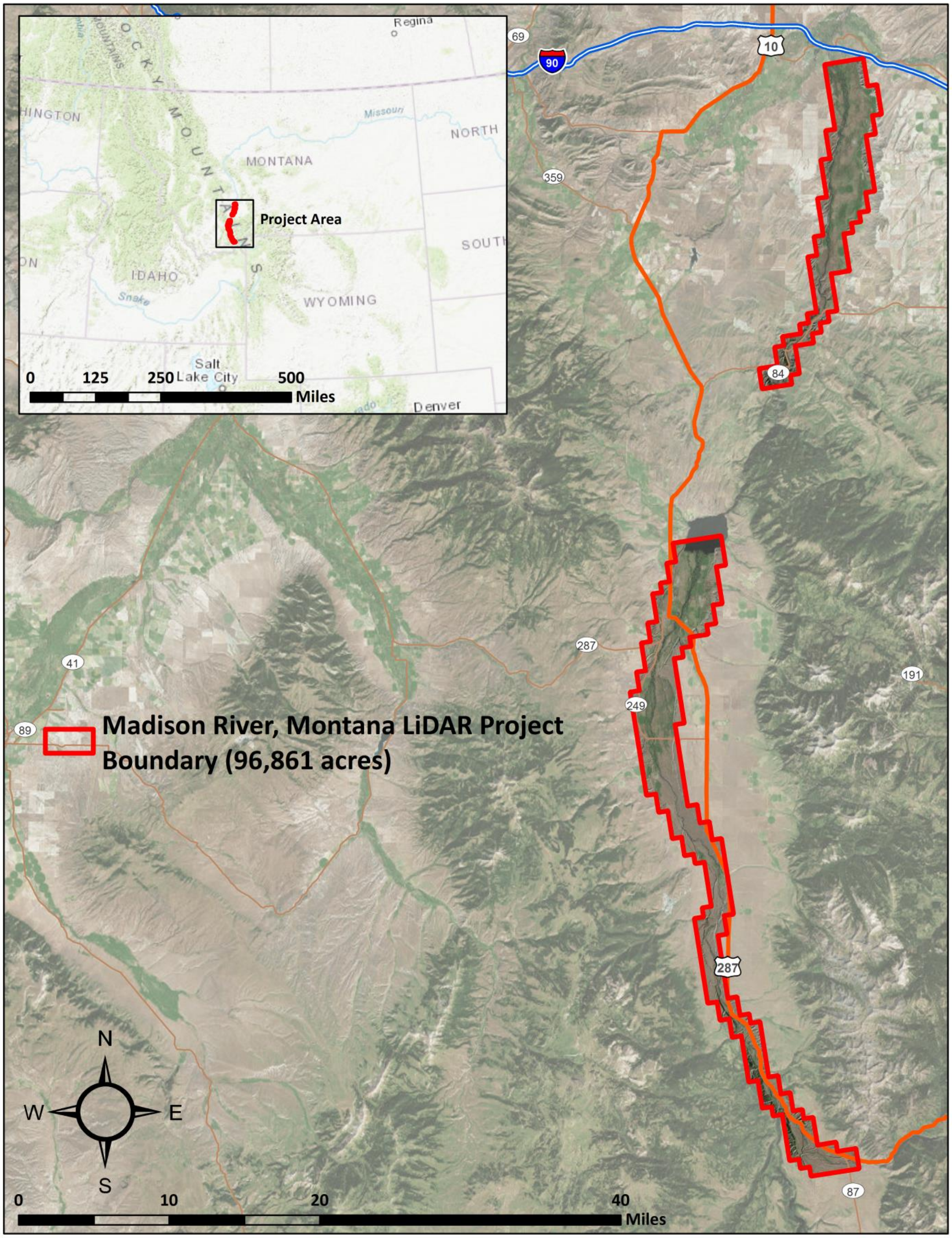


Figure 1: Location map of the Madison River sites in Montana

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 Madison River LiDAR study area at the target point density of ≥8.0 points/m^2 (0.74 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 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.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan 208B. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Madison River 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 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	10/27/17 – 10/31/17, 11/24/17, 11/28/17
Aircraft Used	Cessna Caravan 208B
Sensor	Leica
Laser	ALS80
Maximum Returns	Unlimited
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	1700 m
Survey speed	105 knots
Field of View	36º
Mirror Scan Rate	45 Hz
Target Pulse Rate	325 kHz
Pulse Length	2.5 ns
Laser Pulse Footprint Diameter	37.4 cm
Central Wavelength	1064 nm
Pulse Mode	Multi Pulse in Air (2PiA)
Beam Divergence	22 mrad
Swath Width	1,105 m
Swath Overlap	63 %
Intensity	8-bit, scaled to 16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm

Leica ALS80 LiDAR sensor

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

Ground Control

Ground control surveys, including monumentation and ground survey points (GSPs), were conducted by Gaston Engineering and Surveying (Bozeman, MT), to support the airborne acquisition. 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 surveying methods and materials provided by Gaston Engineering and Surveying.

Check Points

In addition to ground control points, Gaston Engineering and Surveying collected ground check points throughout the study area, and provided them to QSI to be used in Non-Vegetated and Vegetated Vertical Accuracy assessment. Vertical accuracy statistics were calculated for all check points to assess confidence in the LiDAR derived ground models over non-vegetated and vegetated surfaces (Table 4, see LiDAR Accuracy Assessments, page 17).

Table 4: Check Point Collection Summary

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Bare Earth	BE		Hard bare ground surfaces with level slope	NVA
Urban	U		Areas dominated by urban development, including parks	NVA

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Tall Grass/Crops	TG		Areas dominated by herbaceous grasses or crops	VVA
Shrubs	S		Areas dominated by herbaceous shrubland	VVA
Forested	F		Areas dominated by coniferous or deciduous trees	VVA

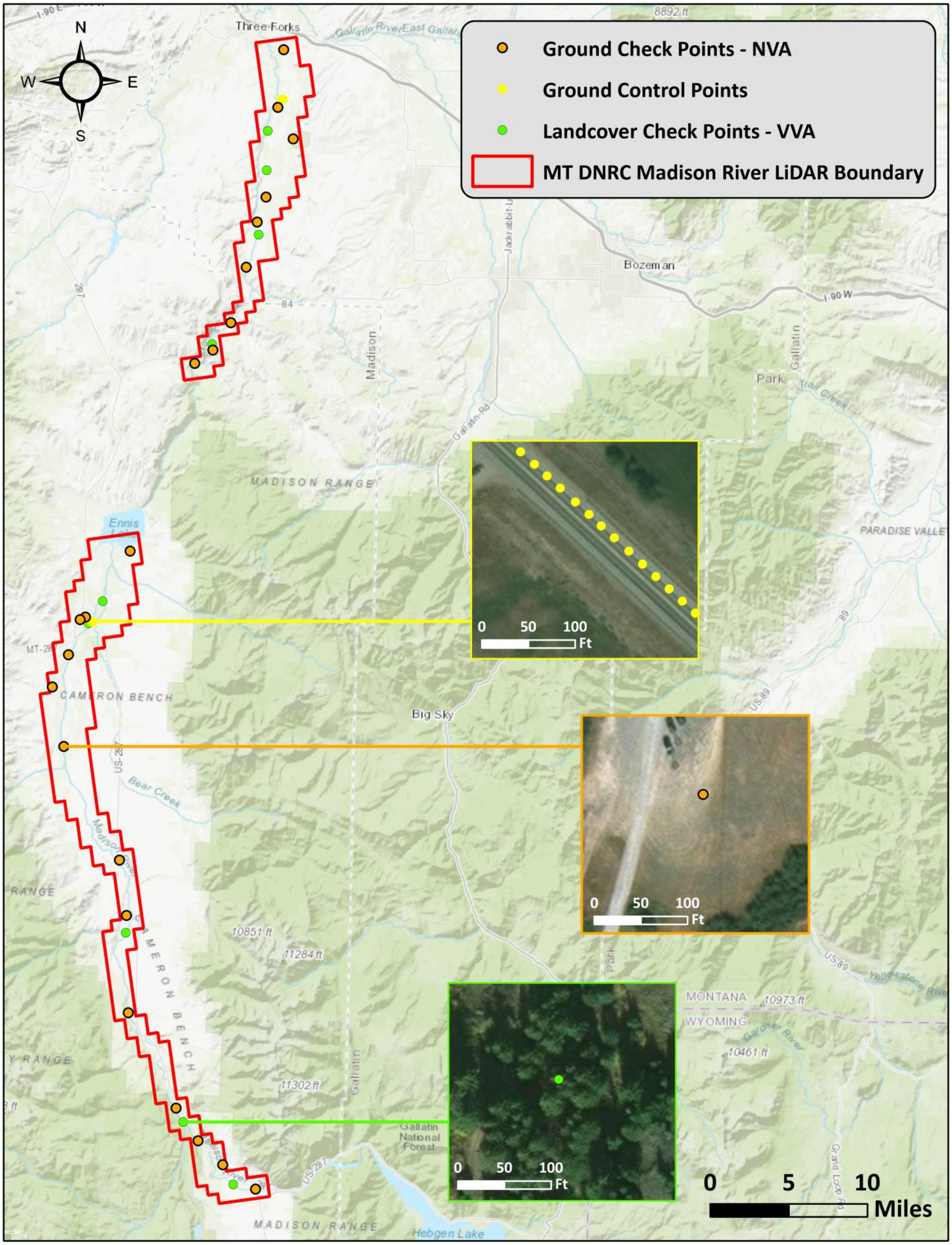
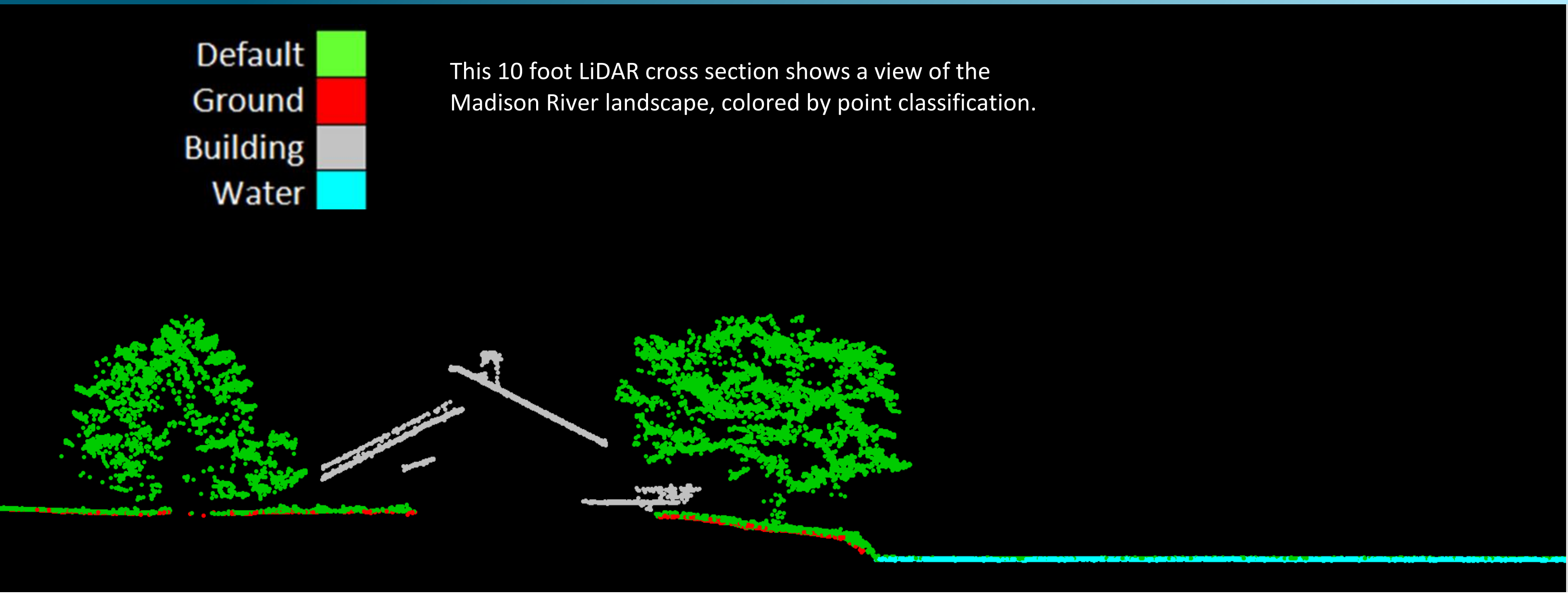


Figure 2: Ground survey location map



This 10 foot LiDAR cross section shows a view of the Madison River landscape, 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 5). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 6.

Table 5: ASPRS LAS classification standards applied to the Madison River 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
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
6	Buildings	All roofed structures with a ground floor area of 100 square feet or larger
7W	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
10	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation

Table 6: 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. 1.2) format. Convert data to orthometric elevations by applying a geoid correction.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.2
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flightlines.	TerraScan v.17
Using ground classified points per each flightline, 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 flightlines and apply results to all points in a flightline. Use every flightline for relative accuracy calibration.	TerraMatch v.17
Classify resulting data to ground and other client designated ASPRS classifications (Table 5). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.17 TerraModeler v.17
Generate bare earth models as triangulated surfaces. Export all surface models as ESRI GRIDs, Comma Delimited ASCII models, and in ESRI Geodatabase format, at a 3.0 foot pixel resolution.	TerraScan v.17 TerraModeler v.17 ArcMap v. 10.2.2
Generate building polygons from classified LiDAR returns.	TerraScan v.17 TerraModeler v.17 ArcMap v. 10.2.2 LasBoundary

Feature Extraction

Hydroflattening and Water's Edge Breaklines

The Madison River and other water bodies within the project area were flattened to a consistent water level. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 100 feet, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary. Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered LiDAR returns to create the final breaklines. Lakes were assigned a consistent elevation for an entire polygon while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

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

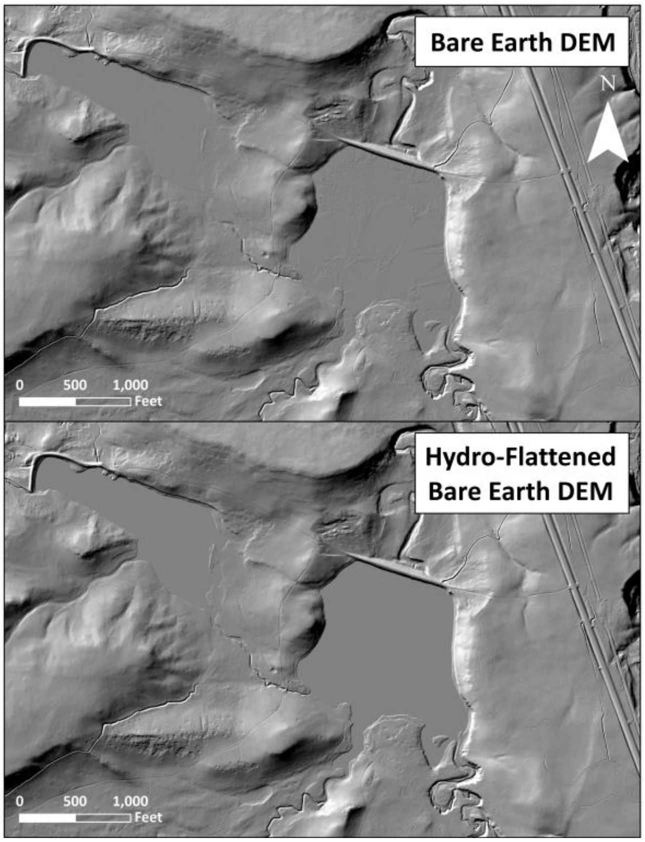


Figure 3: Example of hydroflattening in MTDNRC project sites

Contours

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

Elevation contour lines were then intersected with ground point density rasters and a confidence field was added to each contour line. Contours which crossed areas of high point density have high confidence levels, while contours which crossed areas of low point density have low confidence levels. Areas with low ground point density are commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where laser penetration to the ground surface was impeded (Figure 4).

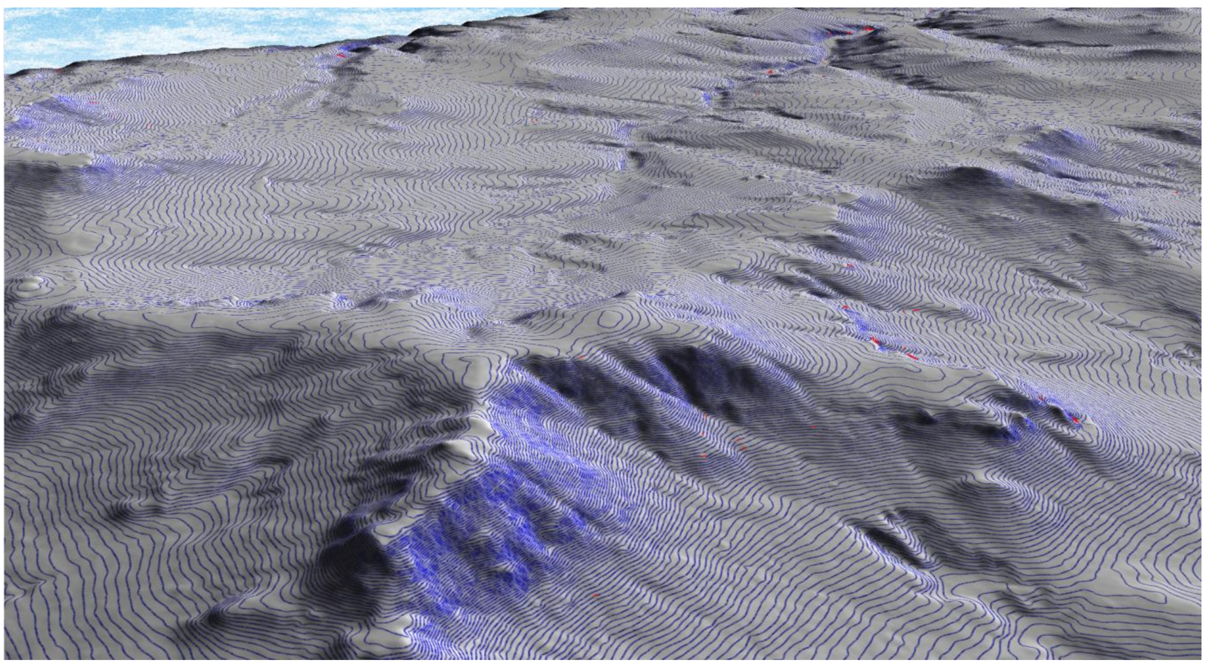


Figure 4: Contours draped over the bare earth elevation model in one of the MTDNRC project sites. Blue contours represent high confidence while the red contour segments represent low confidence.

Buildings

Building classification was performed for the Madison River project area 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 roofed structures with a ground floor area ≥ 100ft² were classified into the building category. Once classification was complete, automated routines were used generate the polygon shapefile representing building footprints. Footprints were draped over the above-ground LiDAR returns. The average height of building classified LiDAR returns was extracted and applied to the building polygons to generate a 3D building footprint for each area of interest. Additionally, the Lowest Adjacent Grade (LAG) elevation was extracted from the LiDAR-derived bare earth raster using the Zonal Statistics tool in ArcMAP v.10.3; each LAG elevation was attributed to the final building footprint polygon. In total, 3,111 polygons were mapped within the Madison River project area (Figure 5).

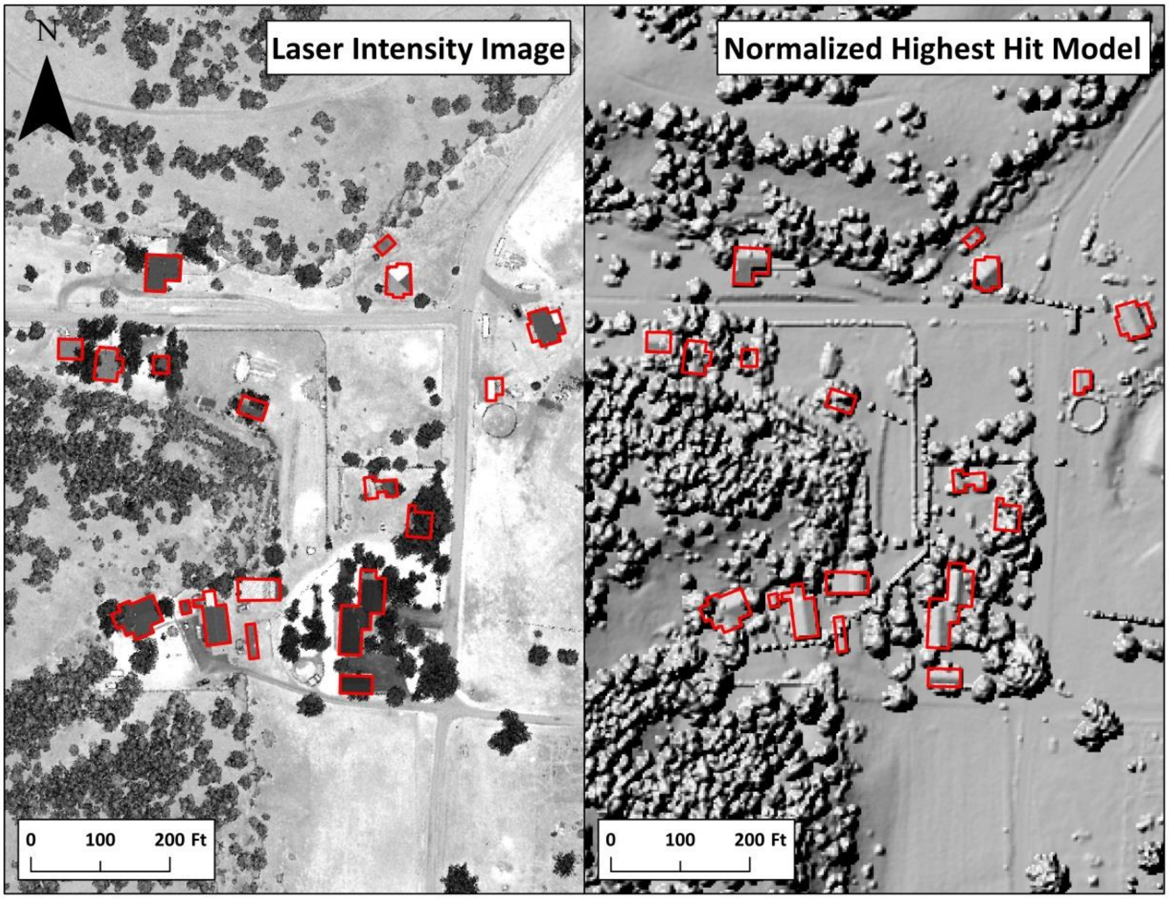
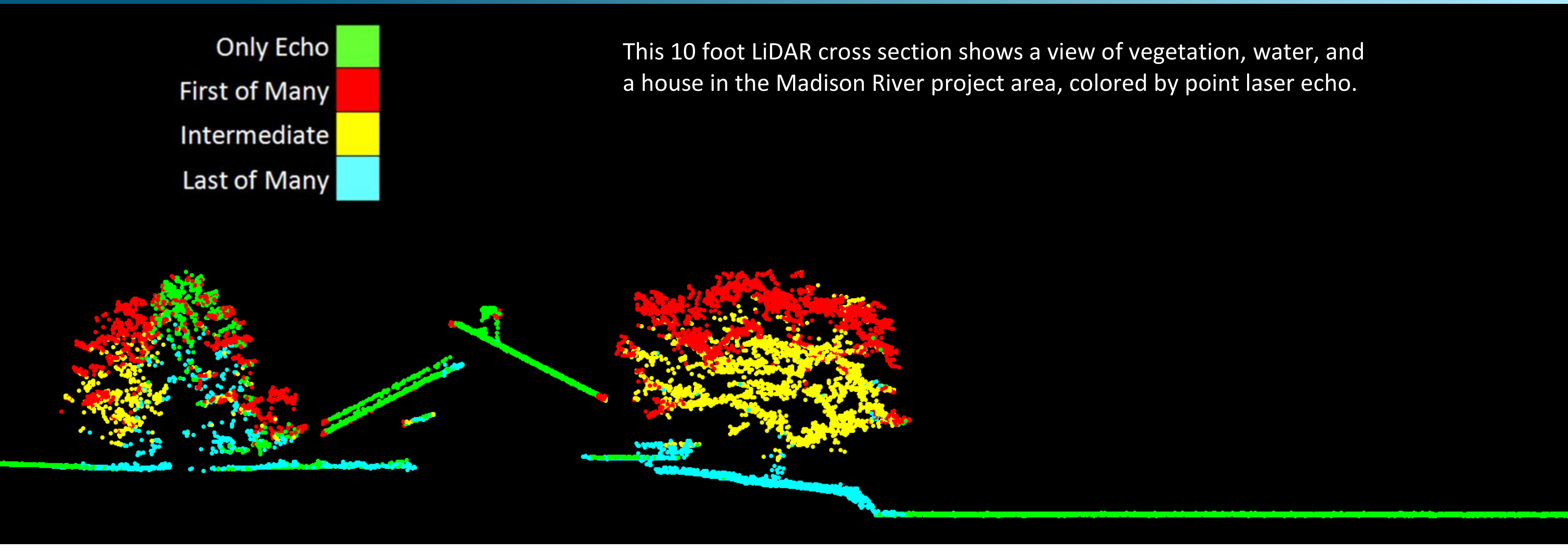


Figure 5: Sample image of building footprints in one of the MTDNRC project sites



LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 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 Madison River project was 1.23 points/ft^2 (13.26 points/m^2) while the average ground classified density was 0.44 points/ft^2 (4.78 points/m^2) (Table 7). 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 6 through Figure 8.

Table 7: Average LiDAR point densities

Classification	Point Density
First-Return	1.23 points/ft^2 13.26 points/m^2
Ground Classified	0.44 points/ft^2 4.78 points/m^2

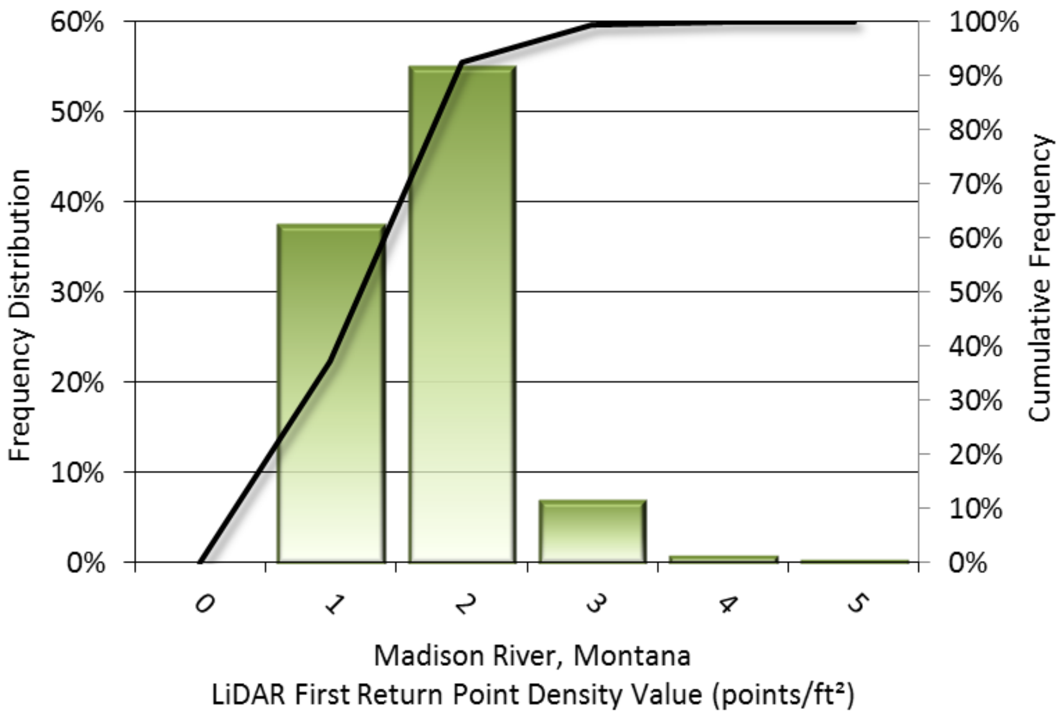


Figure 6: Frequency distribution of first return point density values per 100 x 100 m cell

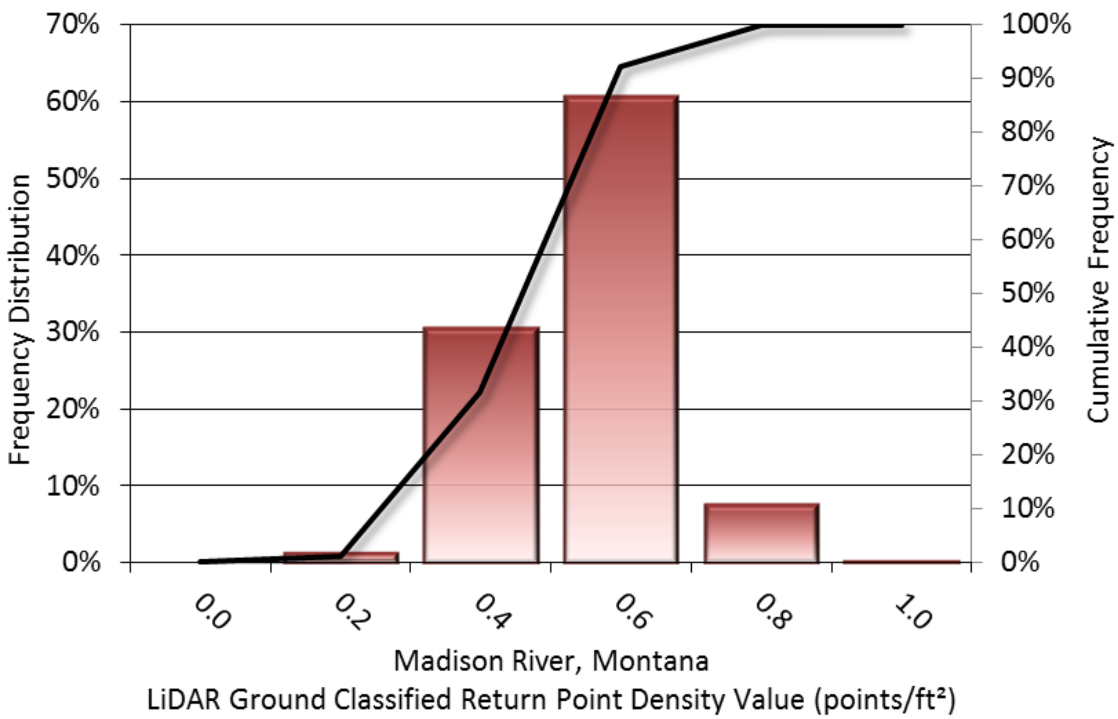


Figure 7: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

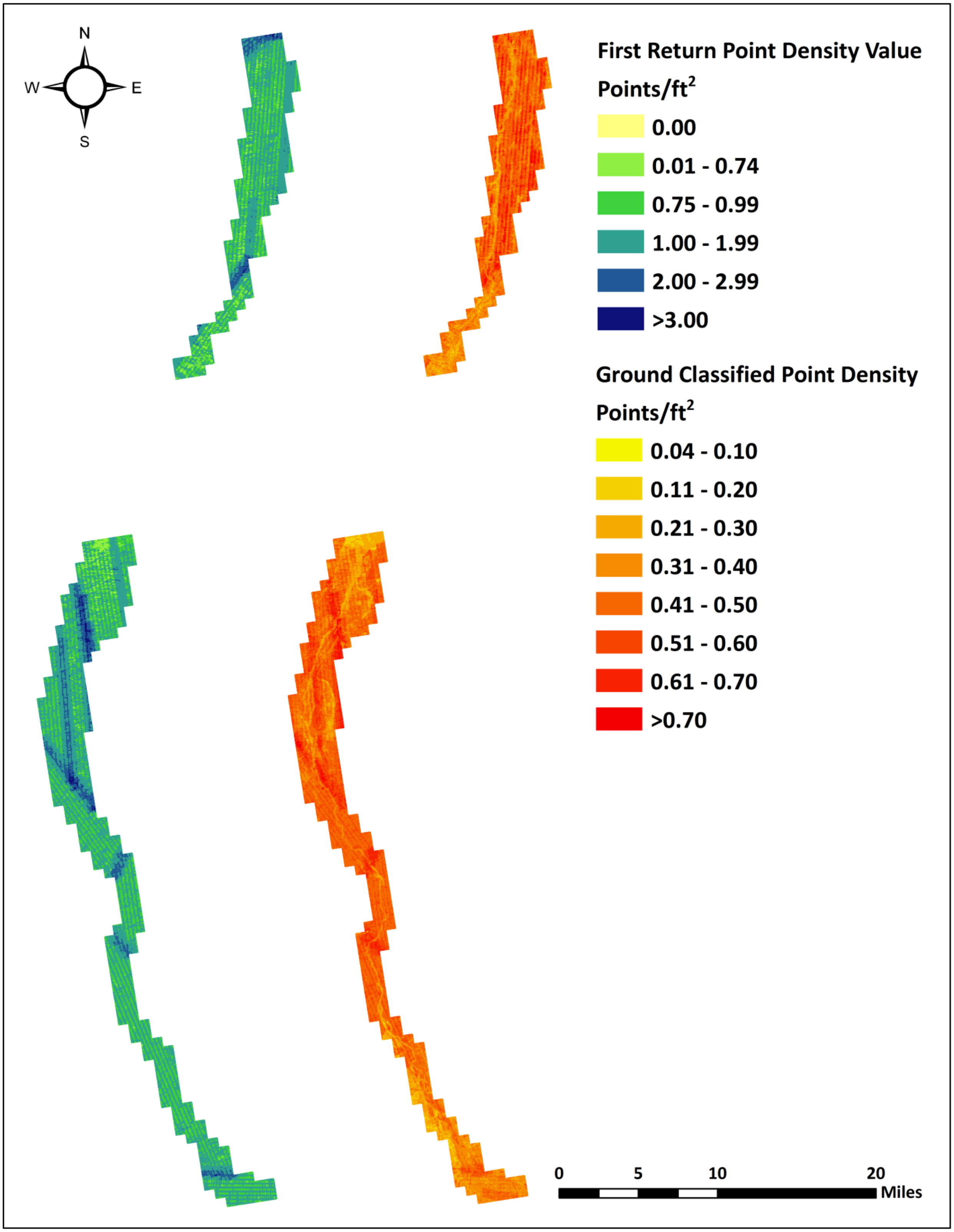


Figure 8: First return and ground-classified point density map for the Madison River site (100 m x 100 m cells)

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 quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. 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 8.

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 Madison River survey, 22 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.278 feet (0.085 meters), with 95% confidence (Figure 9).

QSI also assessed absolute accuracy using 68 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 8 and Figure 11.

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. VVA is evaluated at the 95th percentile (Table 8, 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 8: Absolute accuracy results

Absolute Vertical Accuracy			
	Non-Vegetated Vertical Accuracy (NVA)	Vegetated Vertical Accuracy (VVA)	Ground Control Points
Sample	22 points	9 points	68 points
95% Confidence (1.96*RMSE)	0.278 ft 0.085 m	N/A	0.102 ft 0.031 m
95th Percentile	N/A	0.703 ft 0.214 m	N/A
Average	-0.013 ft -0.004 m	0.230 ft 0.070 m	0.033 ft 0.010 m
Median	-0.039 ft -0.012 m	0.167 ft 0.051 m	0.034 ft 0.011 m
RMSE	0.142 ft 0.043 m	0.383 ft 0.117 m	0.052 ft 0.016 m
Standard Deviation (1σ)	0.145 ft 0.044 m	0.325 ft 0.099 m	0.040 ft 0.012 m

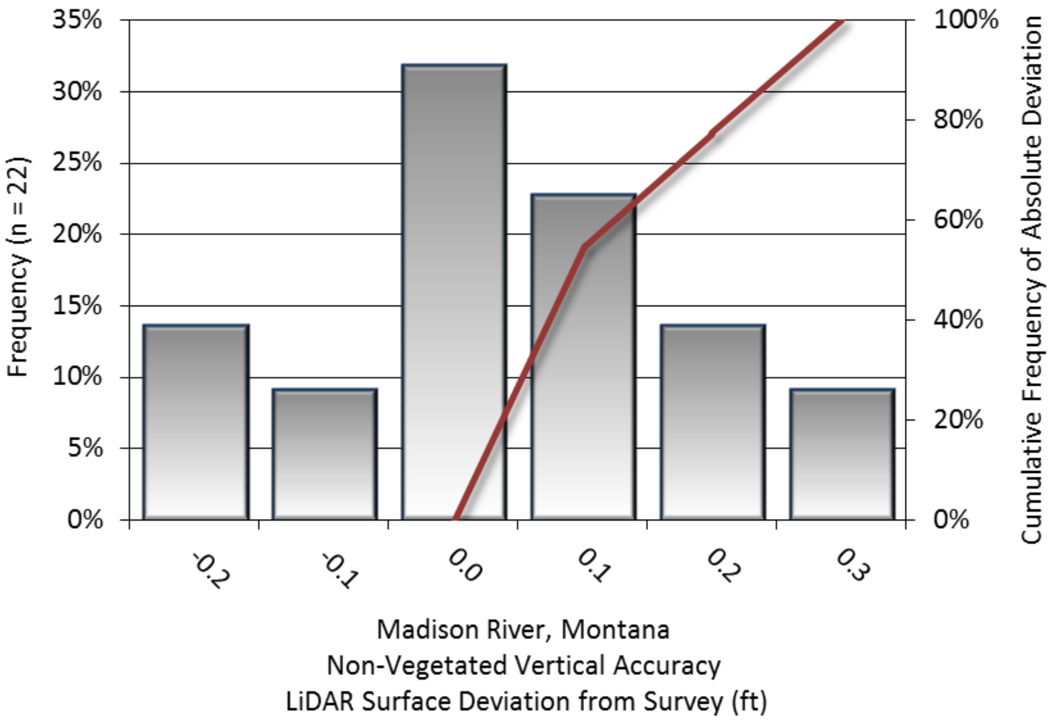

Figure 9: Frequency histogram for LiDAR surface deviation from ground check point values (NVA)

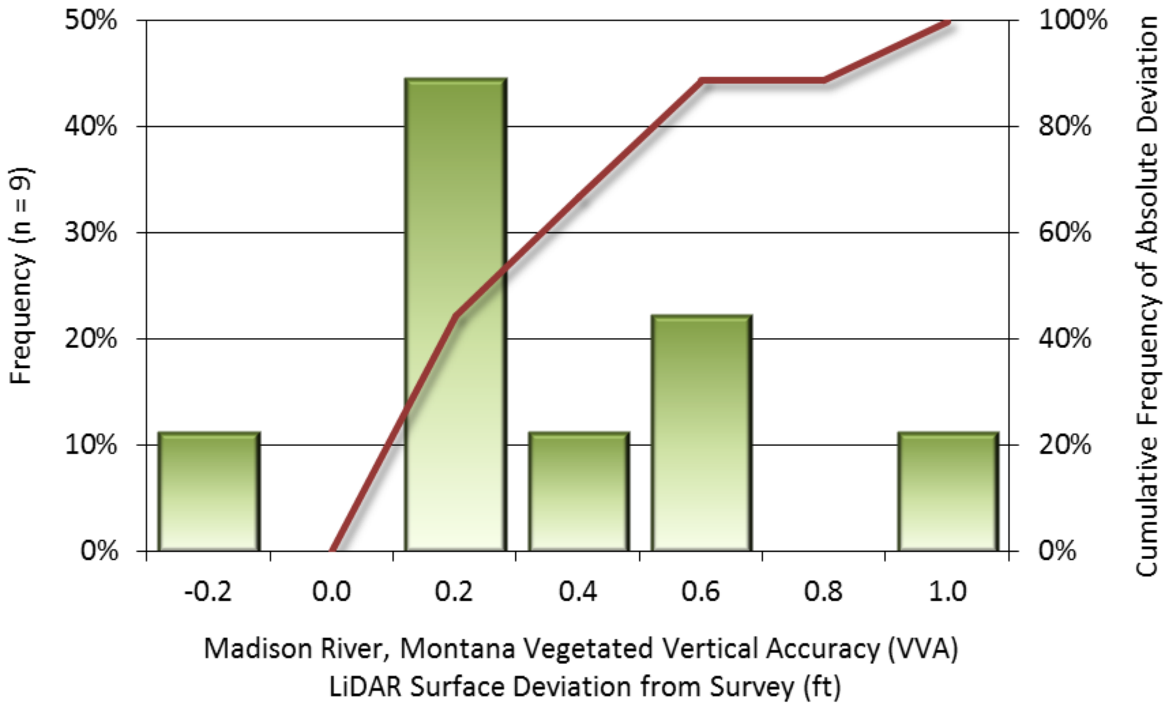

Figure 10: Frequency histogram for LiDAR surface deviation from all land cover class point values (VVA)

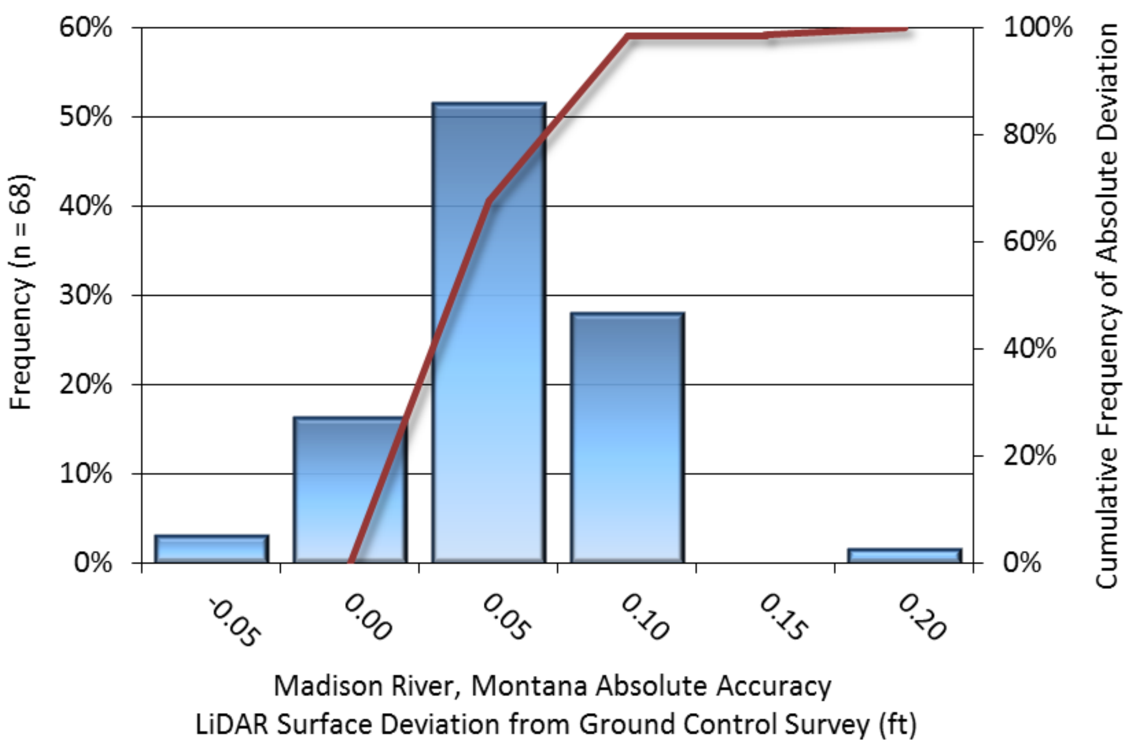

Figure 11: Frequency histogram for LiDAR surface deviation from ground control point values

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 flightlines, 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 flightline with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Madison River LiDAR project was 0.079 feet (0.024 meters) (Table 9, Figure 12).

Table 9: Relative accuracy results

Relative Accuracy	
Sample	131 surfaces
Average	0.079 ft 0.024 m
Median	0.078 ft 0.024 m
RMSE	0.082 ft 0.025 m
Standard Deviation (1σ)	0.020 ft 0.006 m
1.96σ	0.039 ft 0.012 m

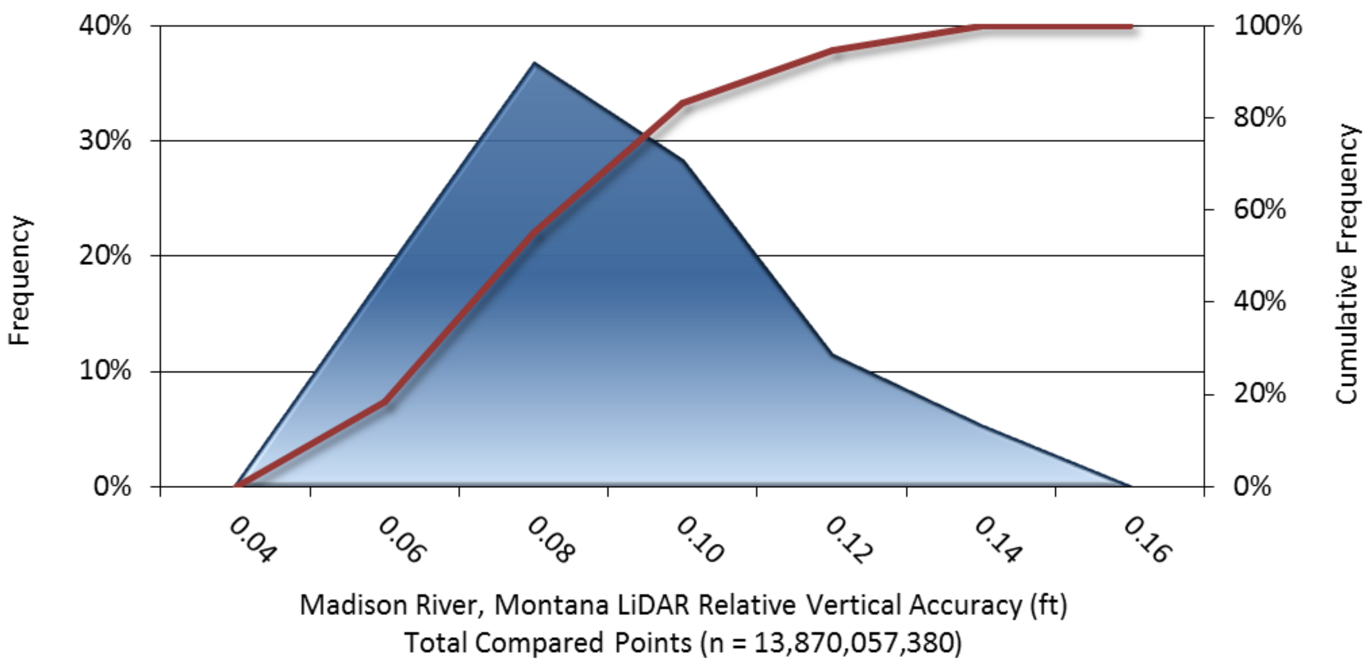

Figure 12: Frequency plot for relative vertical accuracy between flightlines

Project Manager Certification

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

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

Nov 30, 2018

Steven R. Miller
Project Manager
Quantum Spatial, Inc.

Professional Land Surveyor Certification

Project Name:	Jefferson Watershed, Madison River, Gallatin Tributaries, Musselshell-Wheatland Counties, MT
Statement of Work No.:	17-595
Interagency Agreement No.:	N/A
CTP Agreement No.:	N/A
Statement/Agreement Date:	October 31, 2017
Certification Date:	December 22, 2017

	Tasks/Activities Covered by This Certification (Check All That Apply)
☐	Base Map
☐	Topographic Data Development
☒	Survey – **Ground Control for LiDAR, Checkpoint Survey & Road Centerline RTK Collections**
☐	Hydrologic Analysis
☐	Hydraulic Analysis
☐	Alluvial Fan Analysis
☐	Coastal Analysis
☐	Floodplain Mapping
	This is to certify that the work summarized above was completed in October, November and December of 2017 in accordance with the statement/agreement cited above and all amendments thereto, together with all such modifications, either written or oral, as the Regional Project Officer and/or Assistance Officer or their representative have directed, as such modifications affect the statement/agreement, and that all such work has been accomplished in accordance with the provisions contained in *Guidelines and Specifications for Flood Hazard Mapping Partners* cited in the contract document, and in accordance with sound and accepted engineering practices within the contract provisions for respective phases of the work. This is also to certify that data files submitted for the work summarized above are complete and final. Any revisions made to the already submitted data are included in the final submittal.

Name:	Jim Verellen, PLS
Title:	Professional Land Surveyor
Firm/Agency Represented:	Gaston Engineering & Surveying, P.C.
Registration No.:	38563LS
Signature:	
	This form must be signed by a representative of the firm or agency contracted to perform the work, who must be a registered or certified professional in the area of work performed, in compliance with Federal and State regulations.

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 flightlines, 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 flightlines within an overlapping area. Divergence is most apparent when flightlines 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 flightline.

Overlap: The area shared between flightlines, 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 flightline 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 ±16^{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 flightlines 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 flightline coincides with the swath edge portion of overlapping flightlines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

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

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November 10, 2017
W.O. #17-595

RE: Survey Methodology Report
FEMA Check Point Survey
Gallatin, Jefferson, Madison & Musselshell/Wheatland Counties, Montana

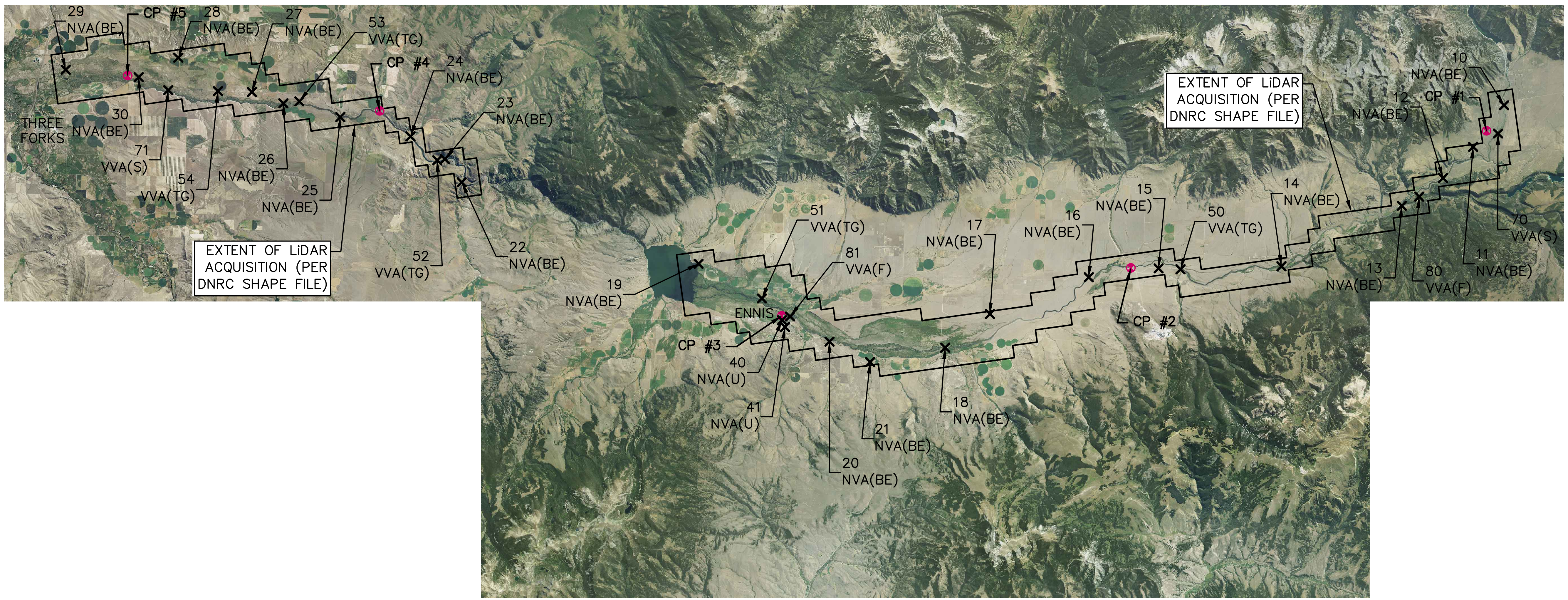
Gaston Engineering & Surveying personnel collected ground surface information via GPS RTK surveying techniques utilizing Leica GS14 GPS equipment. Check points were collected in various ground cover categories which were bare earth, urban, forested, shrubs and tall grass/crops. RTK shots at each of the check points were taken with a minimum of 2 hours' time difference to minimize error associated with poor satellite geometry.

The x, y, z coordinates of each of the check points were recorded twice (raw data), and then averaged to determine the adjusted check point data. This information was tabulated in .xlsx format, and submitted to QSI for further refinement of the LiDAR dataset.

The control point coordinates that were derived by a 4 hour static observation and 2 hour static observation averaged, served as the base control points for the RTK setup. RTK shots were surveyed utilizing Geoid 12B, which is the most recent geoid model published.

Road centerline RTK point clusters were also collected at various locations to help QSI seam the data sets together between flight lines. These RTK points were collected by averaging 5 epochs at each location, with approximately 20 feet spacing between points. Clusters of 30 points were collected throughout the area of interest(s).

FEMA CHECK POINTS & CONTROL
FLOODPLAIN STUDY, MADISON RIVER, MT



LEGEND

CHECK POINT KEY

NVA(BE) = BARE EARTH PTS # 10–30	VVA(TG) = TALL GRASS/CROPS PTS # 50–54	VVA(F) = FORESTED PTS # 80–81
NVA(U) = URBAN PTS # 40–41	VVA(S) = SHRUBS PTS # 70–71	CONTROL POINT PTS # 1–5

1 **PLAN VIEW**
SCALE: 1" = 30,000'

GASTON ENGINEERING & SURVEYING, PC
PROFESSIONAL PROGRESSIVE PERSONAL
P.O. BOX 861
BOZEMAN, MT 59771
(406) 586-0588

DRAWN BY: JO
CHECKED BY:
DRAWING DATE: 120117
REVISION DATE:

MADISON LiDAR
CONTROL & CHECK POINTS
MT DNRC
PROJECT ID# 17-595
MADISON COUNTY, MT

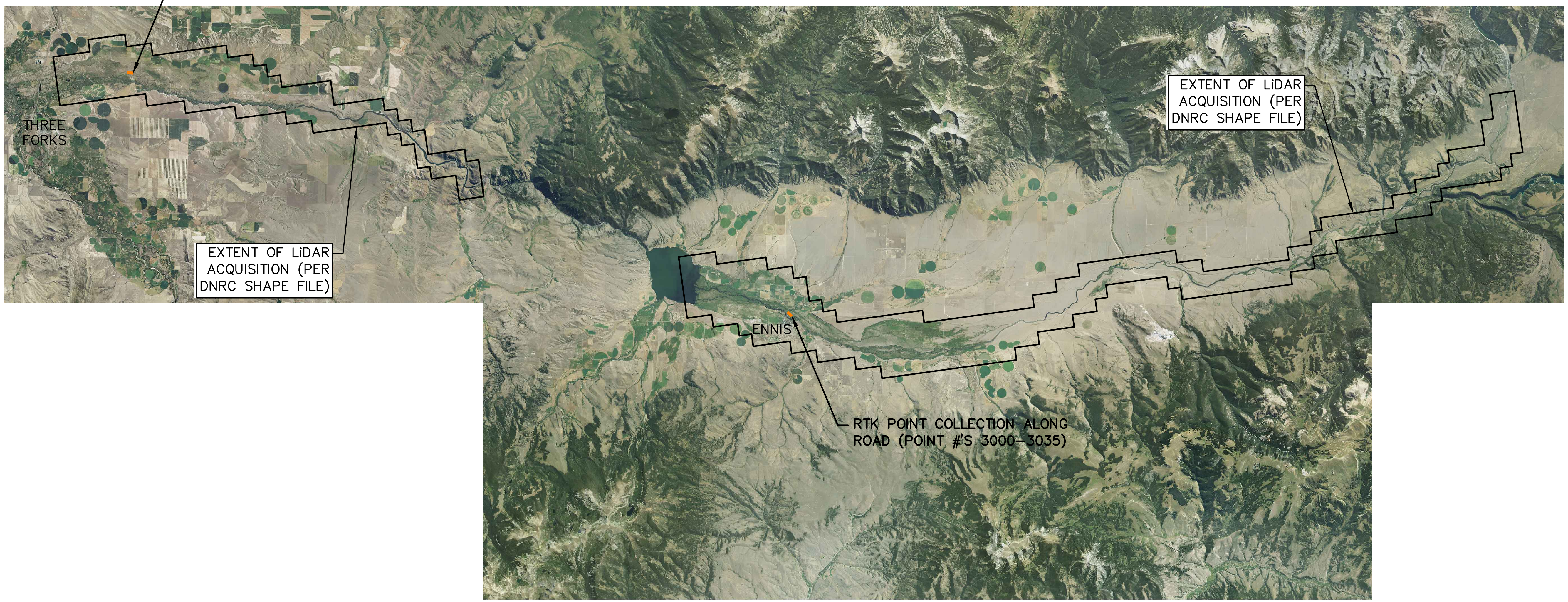
IF THIS LINE DOES NOT MEASURE 1", THE DRAWING IS NOT SCALED CORRECTLY.

PROJECT: 17-595
DRAWING: 17-595
MADISON.dwg
TAB: COLLECTED POINTS

SHEET 1 OF 1

INTERSECTING ROADS ON FLIGHT LINES

FLOODPLAIN STUDY, MADISON RIVER, MT



LEGEND

- LOCATION OF 30 RTK SHOTS (MINIMUM) ALONG ROAD PER QSI REQUEST

(1) **PLAN VIEW**
SCALE: 1" = 30,000'

N

GASTON ENGINEERING & SURVEYING, PC
PROFESSIONAL PROGRESSIVE PERSONAL
P.O. BOX 861
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MADISON LiDAR
CROSS ROAD POINTS
MT DNRC
PROJECT ID# 17-595
MADISON COUNTY, MT

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

PROJECT: 17-595
DRAWING: 17-595
MADISON.dwg
TAB: CROSS ROADS

SHEET 1 OF 1

Madison_River_LiDAR_Technical_Data_Report_Combined

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