Little Blackfoot River LiDAR

Technical Data Report

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Cover Photo: View looking East at Lois Lake. The image was created from the gridded LiDAR surface colored by elevation.

Photo of base station set up over LBR-2 in the Little Blackfoot River project area. *Photo courtesy of RDG field crew.*

In June 2015, Quantum Spatial (QSI) was contracted by River Design Group (RDG) to collect Light Detection and Ranging (LiDAR) data the summer of 2015 for the Little Blackfoot River site in Montana. Data were collected to aid RDG in assessing the topographic and geophysical properties of the study area to support river restoration activities on Little Blackfoot River and its tributaries.

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 RDG 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 Little Blackfoot River site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Little Blackfoot River	24,642	29,295	06/25/2015, 06/26/2015	LiDAR

Deliverable Products

Table 2: Products delivered to RDG for the Little Blackfoot River site

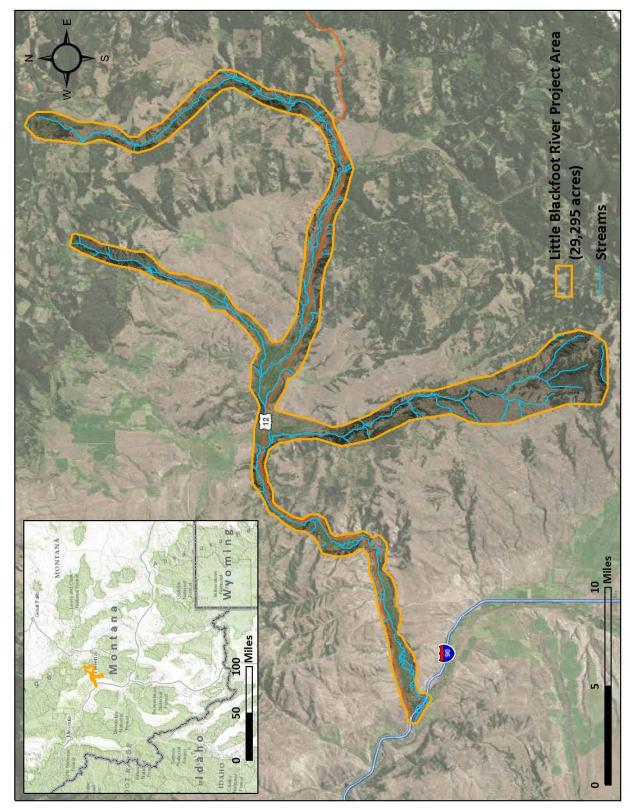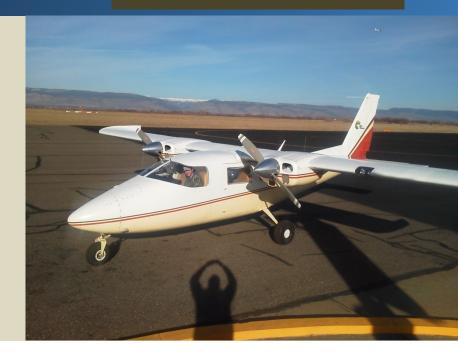| Little Blackfoot River Products Projection: Montana State Plane Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12A) Units: US Survey Feet	
Points	LAS v 1.2 - All Returns - Model Keypoints - 0.1 foot z tolerance - Model Keypoints - 0.2 foot z tolerance - Model Keypoints - 0.5 foot z tolerance - Model Keypoints - 1 foot z tolerance
Rasters	3.0 Foot ESRI Grids - Bare Earth Model - Highest Hit Model 1.5 Foot GeoTiffs - Intensity Images
Vectors	Shapefiles (*.shp) - Site Boundary - LiDAR Tile Index

Figure 1: Location map of the Little Blackfoot River site in Montana

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QSI Partenavia used in the collection
of LiDAR data.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan
to ensure complete coverage of the Little Blackfoot 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 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.

Ground Control

Ground control surveys, including monumentation and ground survey points (GSPs), were conducted by River Design Group and provided to QSI to support airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data.

Monumentation

QSI utilized two monuments provided by for the Little Blackfoot River LiDAR project (Table 3, Figure 2).

RDG-Established Monument

Table 3: Monuments established for the Little Blackfoot River acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
LBR 1	46° 35' 14.67069"	-112° 35' 13.25328"	1448.336
LBR2	46° 35' 15.76649"	-112° 35' 13.77961"	1446.268

To correct the continuously recorded onboard measurements of the aircraft position, RDG concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using Trimble Business Center for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Ground Survey Points (GSPs)

Ground survey points were collected by River Design Group and provided to QSI. GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. 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).

Land Cover Class

In addition to ground survey points, land cover class control points were collected throughout the study area. Individual accuracies were calculated for each land cover type to assess confidence in the LiDAR derived ground models across land cover classes. Land cover types and descriptions are shown in Table 4.

Table 4: Land cover descriptions of check points taken for the Little Blackfoot River site

Land cover type	Land cover code	Description
Short Grass	SHORT GRASS	Areas dominated by short grass
Tall Grass	TALL GRASS	Areas dominated by tall grass

Figure 2: Ground control location map

Airborne Survey

LiDAR

The LiDAR survey was accomplished using a Leica ALS70 system mounted in a Partenavia aircraft. Table 5 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Little Blackfoot River project area. The Leica ALS70 laser system can record unlimited range measurements (returns) per pulse, but typically does not record more than 5 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.

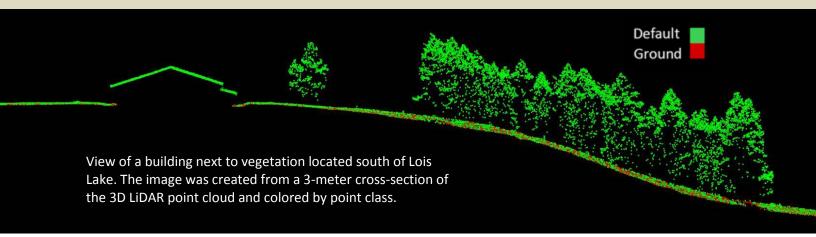**Table 5: LiDAR specifications and survey settings**

LiDAR Survey Settings & Specifications	
Acquisition Dates	June 25, 2015, June 26, 2015
Aircraft Used	Partenavia
Sensor	Leica ALS70
Survey Altitude (AGL)	1400 m
Target Pulse Rate	193 kHz
Pulse Mode	Single Pulse in Air (SPiA)
Laser Pulse Diameter	32 cm
Mirror Scan Rate	57.3 Hz
Field of View	30º
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	Unlimited, but typically not more than 5
Intensity	8-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	RMSE$_Z$ ≤ 15 cm

Leica ALS70 LiDAR sensor

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

View of a building next to vegetation located south of Lois Lake. The image was created from a 3-meter cross-section of the 3D LiDAR point cloud and colored by point class.

LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 6). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 7.
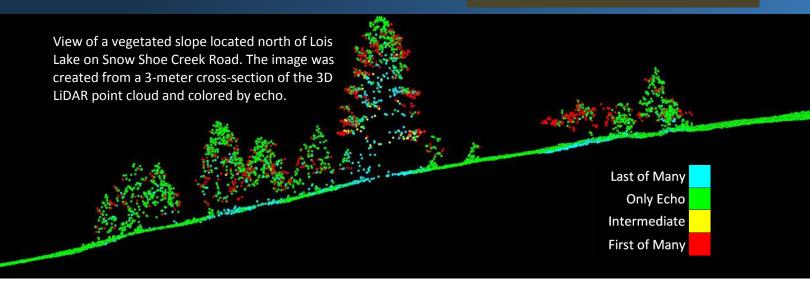
Table 6: ASPRS LAS classification standards applied to the Little Blackfoot River dataset

Classification Number	Classification Name	Classification Description
1	Default/ Unclassified	Laser returns that are not included in the ground class, composed of vegetation and man-made structures
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
8	Model Key Points	Previously classified ground points, selected with a maximum spacing of 20 feet and using z-tolerances of 0.1, 0.2, 0.5, and 1.0 feet.

Table 7: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Waypoint Inertial Explorer v.8.5
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 geoid12a correction.	Waypoint Inertial Explorer v.8.5 Leica Cloudpro v. 1.2.1
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 flight lines.	TerraScan v.15
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.15
Classify resulting data to ground and other client designated ASPRS classifications (Table 6). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.15 TerraModeler v.15
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at a 3.0 foot pixel resolution.	TerraScan v.15 TerraModeler v.15 ArcMap v. 10.1
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	TerraScan v.15 TerraModeler v.15 ArcMap v. 10.1

View of a vegetated slope located north of Lois Lake on Snow Shoe Creek Road. The image was created from a 3-meter cross-section of the 3D LiDAR point cloud and colored by echo.

Last of Many
Only Echo
Intermediate
First of Many

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 Little Blackfoot River project was 1.35 points/ft^2 (14.49 points/m^2) while the average ground classified density was 0.28 points/ft^2 (3.01 points/m^2) (

Table **8**). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 3 and Figure 4.

Table 8: Average LiDAR point densities

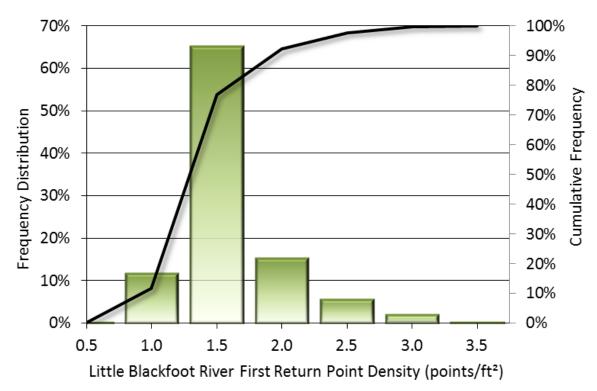| Classification	Point Density
First-Return	1.35 points/ft^2 14.49 points/m^2
Ground Classified	0.28 points/ft^2 3.01 points/m^2

Figure 3: Frequency distribution of first return densities per 100 m x 100 m cell
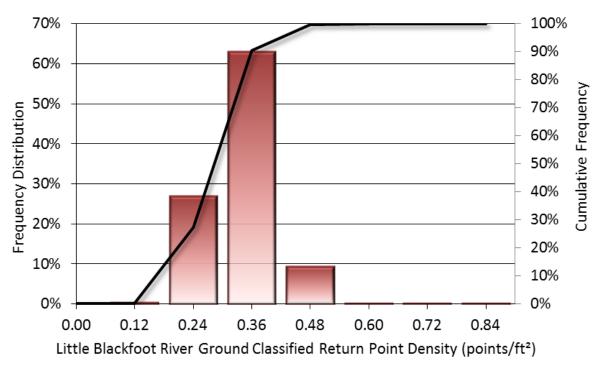

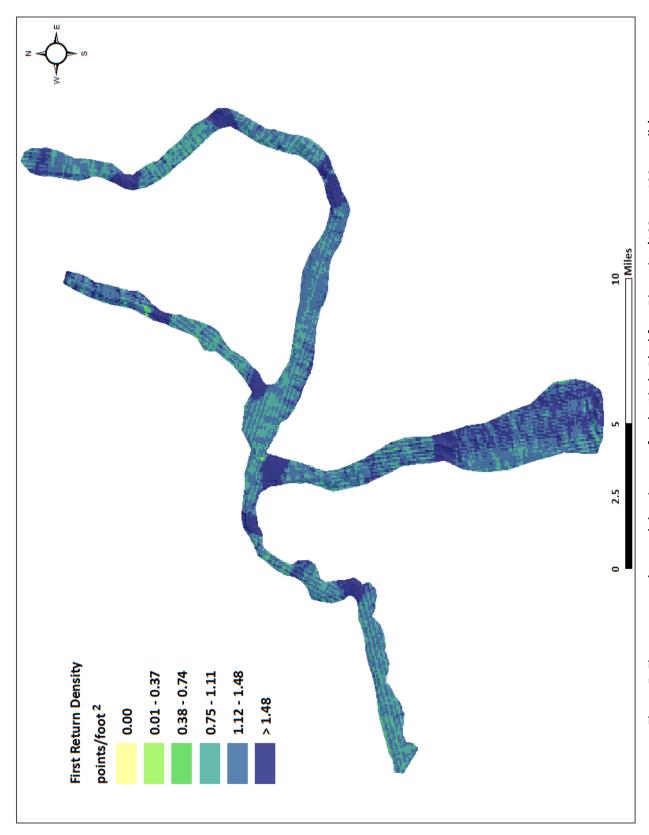**Figure 4: Frequency distribution of ground return densities per 100 m x 100 m cell**

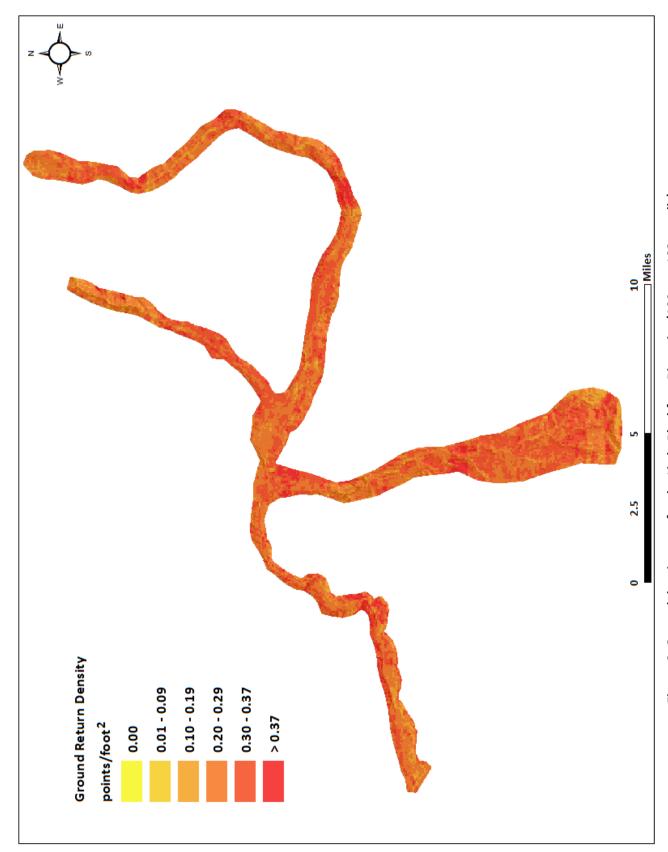**Figure 5: First return and ground density map for the Little Blackfoot River site (100 m x 100 m cells)**

First Return Density

points/foot^2

- 0.00
- 0.01 - 0.37
- 0.38 - 0.74
- 0.75 - 1.11
- 1.12 - 1.48
- > 1.48

Figure 6: Ground density map for the Little Blackfoot River site (100 m x 100 m cells)

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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 Absolute Accuracy

Absolute accuracy was assessed using Fundamental Vertical Accuracy (FVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[1]. FVA compares known RTK ground check point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. FVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 9.

QSI also assessed accuracy using ground control point data. 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 have been provided in Table 9.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey 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 Little Blackfoot River survey, 22 ground check points were collected in total resulting in an average accuracy of 0.159 feet (0.048 meters) (Figure 7).

Table 9: Fundamental Vertical Accuracy

Fundamental Vertical Accuracy		
	Ground Check Points	**Ground Control Points**
Sample	22 points	132 points
FVA (1.96*RMSE)	0.159 ft 0.049 m	0.152 ft 0.046 m
Average	0.004 ft 0.001 m	-0.002 ft -0.001 m
Median	0.016 ft 0.005 m	-0.002 ft -0.001 m
RMSE	0.081 ft 0.025 m	0.077 ft 0.024 m
Standard Deviation (1σ)	0.083 ft 0.025 m	0.078 ft 0.024 m

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[1] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.3-1998). Part 3: National Standard for Spatial Data Accuracy. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3
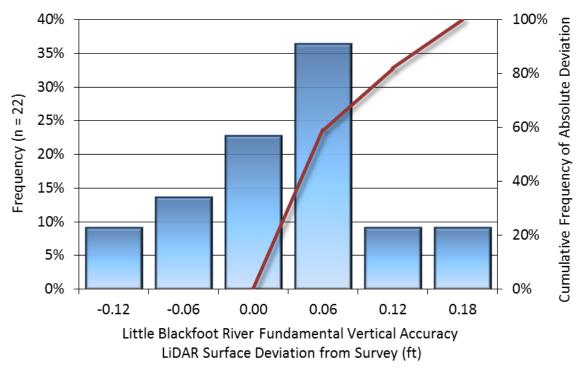
Figure 7: Frequency histogram for LiDAR surface deviation from ground check point values
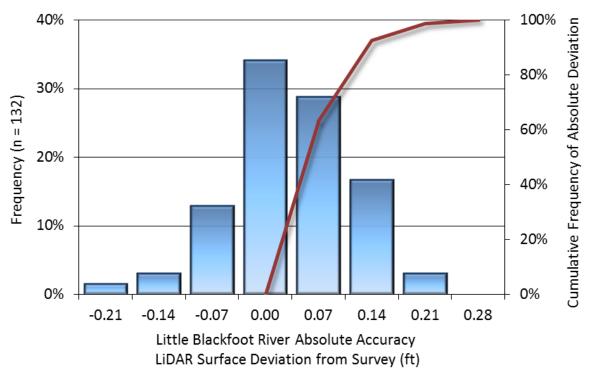

Figure 8: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Supplemental and Consolidated Vertical Accuracies

QSI also assessed absolute vertical accuracy using Supplemental Vertical Accuracy (SVA) and Consolidated Vertical Accuracy (CVA) reporting. SVA compares known ground check point data within individual land cover class categories to the triangulated ground surface generated by the LiDAR points. CVA, rather, compares known ground check points within all land cover classes to the triangulated ground surface generated by LiDAR points. SVA and CVA are measures of the accuracy of LiDAR point data in various land cover classes where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95th percentile, as shown in Table 10.

Table 10: Supplemental and Consolidated Vertical Accuracies for the Little Blackfoot River Project

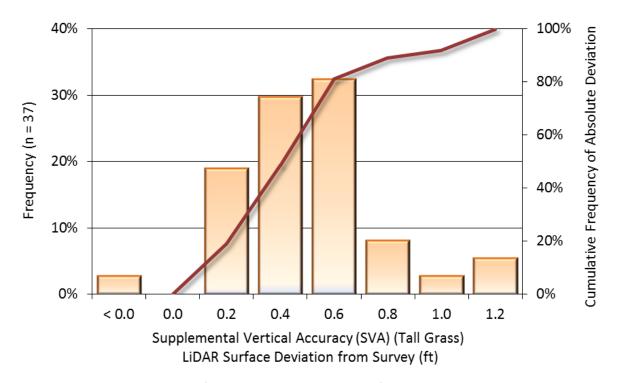| Supplemental and Consolidated Vertical Accuracies			
	SVA		CVA
Land Cover Class	Tall Grass	Short Grass	All Land Cover Classes
Sample	37 points	149 points	186 points
Average Dz	0.366 ft 0.112 m	0.126 ft 0.038 m	0.173 ft 0.053 m
Median	0.397 ft 0.121 m	0.135 ft 0.041 m	0.154 ft 0.047 m
RMSE	0.501 ft 0.153 m	0.165 ft 0.050 m	0.268 ft 0.082 m
Standard Deviation (1σ)	0.347 ft 0.106 m	0.107 ft 0.033 m	0.205 ft 0.062 m
95th Percentile	1.018 ft 0.310 m	0.284 ft 0.087 m	0.454 ft 0.139 m

Figure 9: SVA of Tall Grass in the Little Blackfoot River project area
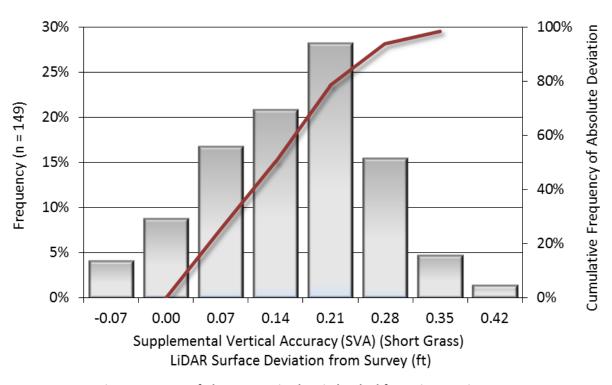

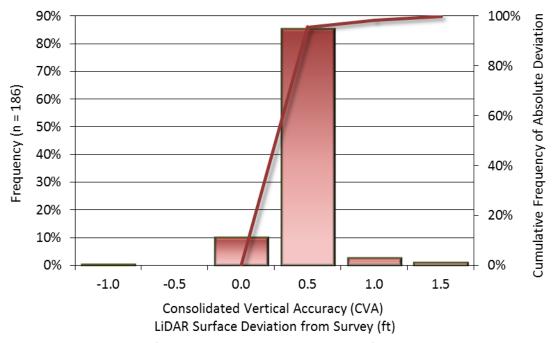**Figure 10: SVA of Short Grass in the Little Blackfoot River project area**

Figure 11: CVA of land class points in the Little Blackfoot River project area

LiDAR Vertical Relative 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 Little Blackfoot River LiDAR project was 0.124 feet (0.038 meters) (Table 11, Figure 12).

Table 11: Relative accuracy

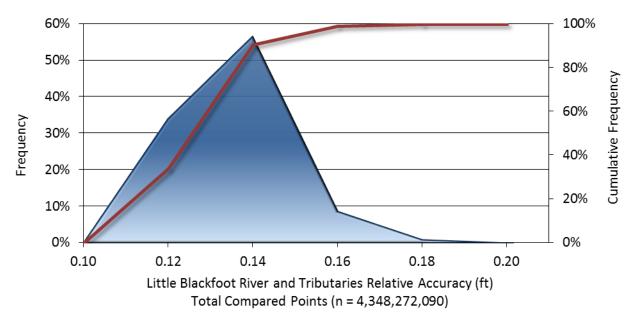| Relative Accuracy	
Sample	115 surfaces
Average	0.124 ft 0.038 m
Median	0.123 ft 0.038 m
RMSE	0.126 ft 0.038 m
Standard Deviation (1σ)	0.011 ft 0.003 m
1.96σ	0.022 ft 0.007 m

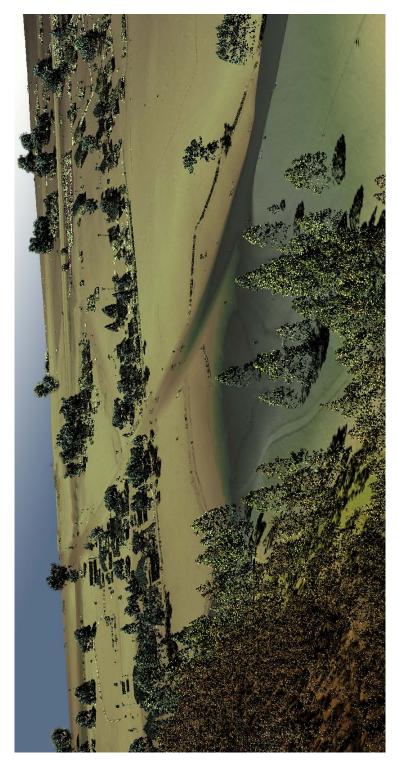**Figure 12: Frequency plot for relative vertical accuracy between flight lines**

Figure 13: View looking south over Avon, Montana. The image was created from the gridded LiDAR surface colored by elevation and overlaid with the 3-D LiDAR point cloud.

Figure 14: View looking northwest at Lois Lake. The image was created from the gridded LiDAR surface colored by elevation and overlaid with the 3D LiDAR point cloud.

Figure 15: View looking East down Hope Creek. The image was created from the gridded LiDAR surface colored by elevation.

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 Fundamental Vertical Accuracy (FVA) 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., echos) 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° 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.