Applied Remote Sensing and Analysis

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Rock Creek LiDAR

Technical Data Report

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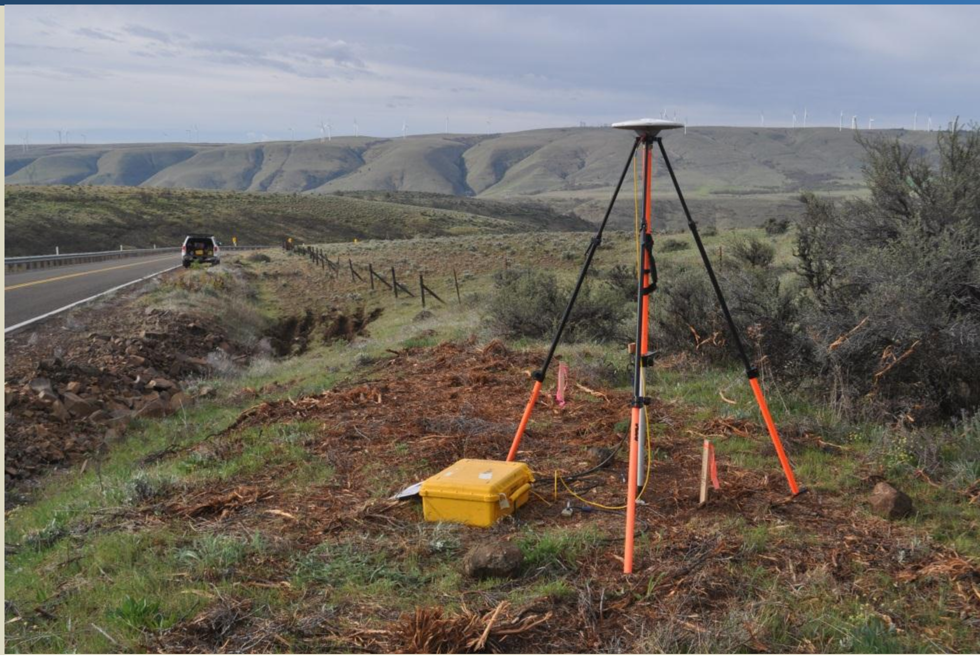
Cover Photo: 3D LiDAR point cloud of a section of Rock Creek. The LiDAR points are draped with NAIP imagery.

INTRODUCTION

View of the Rock Creek LiDAR site in Montana showing a mixed sage and grassland landscape



In July 2012, WSI (Watershed Sciences, Inc.) was contracted by Missoula County in partnership with the Big Sky Watershed Corps to collect Light Detection and Ranging (LiDAR) data in the fall of 2012 for the Rock Creek LiDAR site in Montana. Data were collected to aid in assessing river restoration and support floodplain mapping.

This report accompanies the delivered LiDAR data and documents data acquisition procedures, processing methods, and results of all accuracy assessments. Project specifics are shown in Table 1, the project extent can be seen in Figure 1, and a complete list of contracted deliverables provided to Missoula County and Big Sky Watershed Corps can be found in Table 2.

Table 1: Acquisition dates, acreages, and data types collected for the Rock Creek LiDAR site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Rock Creek	4,169	5,407	11/01/2012	LiDAR

Figure 1: Location map of the Rock Creek LiDAR site in Montana

Table 2: Products delivered for the Rock Creek LiDAR site

<table>
<tr><th colspan="2">Rock Creek LiDAR Products
Projection: Montana State Plane Zone 2500
Horizontal Datum: NAD83 (CORS96) Meters
Vertical Datum: NAVD88 (GEOID03) US Survey Feet</th></tr>
<tr><td>LAS Files</td><td>LAS v 1.2
• All Returns</td></tr>
<tr><td>Rasters</td><td>1 Meter ESRI Grids
• Bare Earth Model
0.5 Meter GeoTiffs
• Intensity Images</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Site Boundary
• LiDAR Index
• Digital Elevation Model (DEM) Index
• 2-foot Contours (X,Y,Z units in US Survey Feet)
• 2-foot Contours (X,Y units in Meters and Z units in US Survey Feet)
• RTK Checkpoints
• Landcover Checkpoints
Drawing Exchange Files (*.dwg)
• 2-foot Contours (X,Y,Z units in US Survey Feet)
• 2-foot Contours (X,Y units in Meters and Z units in US Survey Feet)</td></tr>
</table>

ALS60 LiDAR sensor installation

Planning

In preparation for data collection, WSI reviewed the project area using Google Earth, and flightlines were developed using ALTM-NAV Planner (v.3.0) software. Careful planning by acquisition staff entailed adapting the pulse rate, flight altitude, scan angle, and ground speed to ensure complete coverage of the Rock Creek LiDAR study area at the target point density of ≥6 pulses per square meter (0.74 pulses/square foot). Efforts are taken to optimize flight paths by minimizing flight times while meeting all accuracy specifications.

Factors such as satellite constellation availability and weather windows were considered. Any weather hazards and conditions affecting the flight were continuously monitored due to their impact on the daily success of airborne and ground operations. In addition, a variety of logistical considerations require review: private property access, potential air space restrictions, and availability of company resources (both staff and equipment).

Ground Survey

Ground survey data is used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data. Ground professionals set permanent survey monuments and collect real time kinematic (RTK) surveys to support the airborne LiDAR acquisition process.

Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground control points using RTK survey techniques (see **RTK** below).

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for RTK coverage. Andrew Belski, Professional Land Surveyor (MT PLS#14731) of River Design Group in Whitefish, Montana oversaw and certified the establishment of 2 monuments for the Rock Creek LiDAR project (Table 3, Figure 2). New monumentation was set using 5/8”x30” rebar topped with stamped 2" aluminum caps.

Table 3: Monuments established for the Rock Creek LiDAR acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
ROCK_CK_MT_01	46° 39’ 14.37857”	-113° 39’ 20.63581”	1,119.990
ROCK_CK_MT_02	46° 43’ 20.34583”	-113° 40’ 04.76553”	1,066.779

To correct the continuous onboard measurements of the aircraft position recorded throughout the missions, WSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. After the airborne survey, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

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

RTK Surveys

For the real time kinetic (RTK) check point data collection, a Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All RTK measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK data, the rover would record data while stationary for five seconds, then calculate the pseudorange position using at least three one-second epochs. Relative errors for the position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted.

RTK positions were collected on paved roads and other hard surface locations such as gravel or stable dirt roads that also had good satellite visibility. RTK 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. The distribution of RTK points depended on ground access constraints and may not be equitably distributed throughout the study area. See Figure 2 for the distribution of RTK in this project.

All static surveys were collected with Trimble model R7 GNSS receivers equipped with a Zephyr Geodetic Model 2 RoHS antenna. A Trimble model R8 GNSS receiver was used to collect RTK. All GNSS measurements were made with dual frequency L1-L2 receivers with carrier-phase correction. See Table 4 for Trimble unit specifications.

Table 4: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2	TRM57971.00	Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	RTK

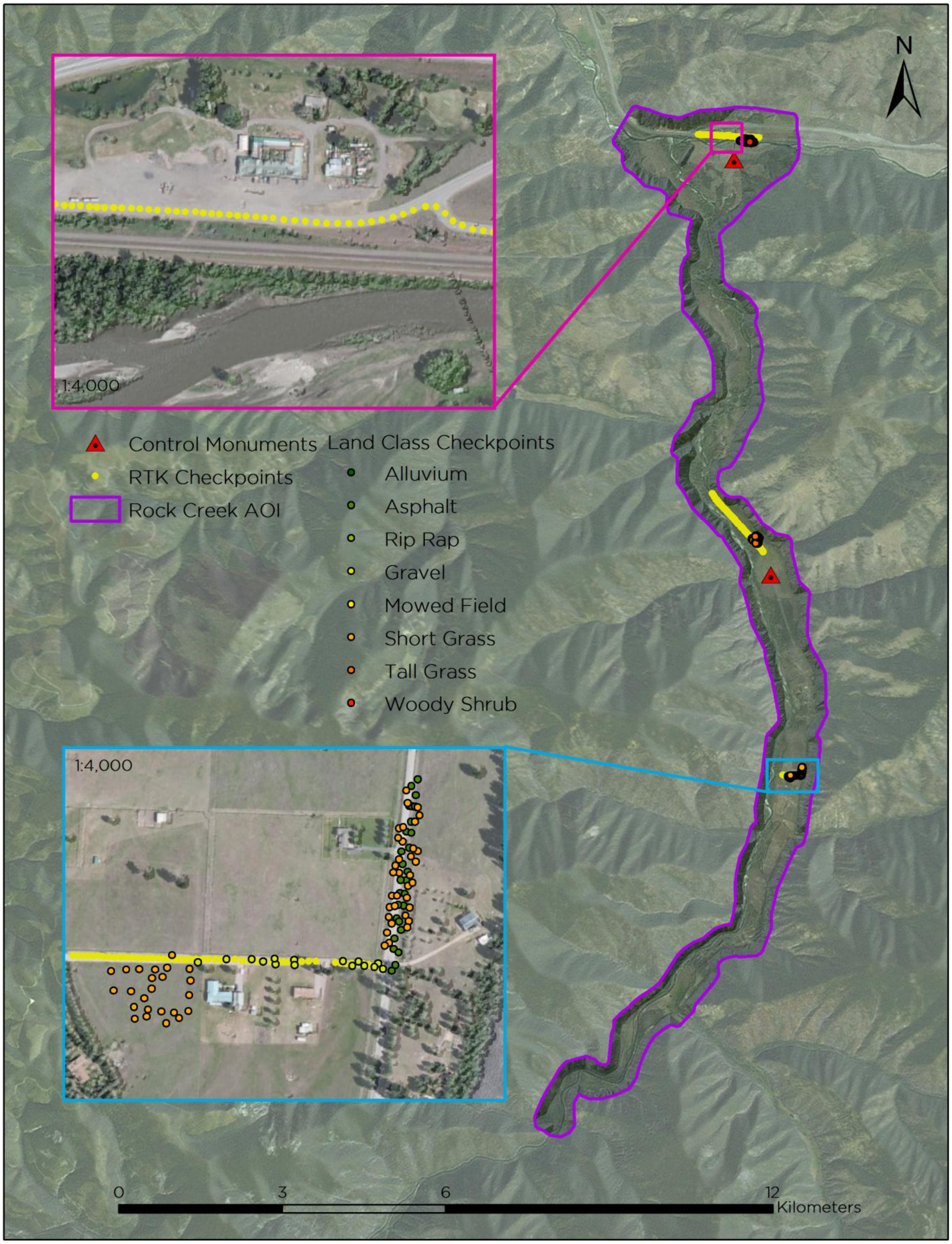


Figure 2: Basestation, land cover checkpoint, and RTK checkpoint location map

Land Cover

In addition to control point RTK, land cover check points were taken throughout the study area by River Design Group (RDG). Land cover types and descriptions can be referenced in Table 5. Individual accuracies were calculated for each land-cover type to assess confidence in the LiDAR derived ground models across land cover classes.

Table 5: Land cover descriptions of check points taken for Rock Creek by RDG

Land cover type	Description
Alluvium	6-inch alluvium
Asphalt	Paved roads, parking lots
Rip rap	Rock or other material used to armor shorelines, streambeds, bridge abutments, pilings and other shoreline structures against scour, water or ice erosion
Gravel	Gravel roads, pits
Mowed Grass	Mowed hay field
Short Grass	Grass height is below the knee (< 2 feet), points taken with RTK pole in the center of the grass patch
Tall Grass	Grass height is above the knee (> 2 feet), points taken with the RTK pole in the center of the grass patch
Woody Shrub	Areas characterized by natural or semi-natural woody vegetation with aerial stems, generally less than 6 meters tall, with individuals or clumps not touching or interlocking. Both evergreen and deciduous species of true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions are included.

Airborne Survey

LiDAR

The LiDAR survey was accomplished with a Leica ALS60 system mounted in a Cessna Caravan. Table 6 summarizes the settings used to yield an average pulse density of ≥6 pulses/m^2 over the Rock Creek LiDAR terrain. 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. These discrepancies between native and delivered density will vary depending on terrain, land cover, and the prevalence of water bodies.

Table 6: LiDAR survey settings and specifications for the Rock Creek LiDAR site

LiDAR Survey Settings & Specifications	
Sensor	Leica ALS60
Survey Altitude (AGL)	1000 m
Target Pulse Rate	99 kHz
Sensor Configuration	Single Pulse in Air (SPiA)
Laser Pulse Diameter	23 cm
Field of View	30^o
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	4
Intensity	8-bit
Resolution/Density	Average 6 pulses/m^2
Accuracy	$RMSE_Z \leq 15$ cm

To reduce laser shadowing and increase surface laser painting, all areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap). The Leica laser systems record up to four range measurements (returns) per pulse. All discernible laser returns were processed for the output dataset.

To accurately solve for laser point position (geographic coordinates x, y, 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. 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/sensor position and attitude data are indexed by GPS time.

View looking west at Rock Creek with the Clark Fork River just visible in the lower right corner. The image was created by draping the 3D LiDAR point cloud with NAIP imagery.

LiDAR Data

Upon the LiDAR data's arrival to the office, WSI processing staff initiates a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks include GPS control computations, kinematic corrections, calculation of laser point position, calibration for optimal relative and absolute accuracy, and classification of ground and non-ground points (Table 7). Processing methodologies are tailored for the landscape and intended application of the point data. A full description of these tasks can be found in Table 8.

Table 7: ASPRS LAS classification standards applied to the Rock Creek LiDAR dataset

Classification Number	Classification Name	Classification Description
1	Default/ Unclassified	Laser returns that are not included in the ground class and not dismissed as Noise or Withheld points.
2	Ground	Ground that is determined by a number of automated and manual cleaning algorithms to determine the best ground model the data can support.
7	Noise	Laser returns that are often associated with birds or artificial points below the ground surface "pits".
11	Withheld	Laser returns that have intensity values of 0 or 255.

Table 8: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.	Waypoint GPS v.8.3 Trimble Business Center v.2.80 Blue Marble Desktop v.2.5
Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor head position and attitude are calculated throughout the survey. The SBET data are used extensively for laser point processing.	IPAS TC v.3.1
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. Data are converted to orthometric elevations (NAVD88) by applying a Geoid12 correction.	ALS Post Processing Software v.2.74
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).	TerraScan v.12.004
Using ground classified points per each flight line, the relative accuracy is tested. Automated line-to-line calibrations are then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations are calculated on ground classified points from paired flight lines and results are applied to all points in a flight line. Every flight line is used for relative accuracy calibration.	TerraMatch v.12.001
Classify resulting data to ground and other client designated ASPRS classifications (Table 7). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground RTK survey data.	TerraScan v.12.004 TerraModeler v.12.002
Generate bare earth models as triangulated surfaces. All surface models were exported as ESRI Grids at a 1 meter pixel resolution.	TerraScan v.12.004 ArcMap v. 10.1 TerraModeler v.12.002

Feature Extraction

Contours

Contour generation from LiDAR point data requires a thinning operation in order to reduce contour sinuosity. The thinning operation reduces point density where topographic change is minimal (flat surfaces) while preserving resolution where topographic change is present. These model key points are selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature (Z tolerance of 0.25 feet). Generation of model key points eliminates redundant detail in terrain representation, particularly in areas of low relief, and provides for a more manageable dataset. Contours are produced through TerraModeler by interpolating between the model key points at even elevation increments.

Elevation contour lines are then intersected with ground point density rasters and a confidence field is added to each contour line. Contours crossing areas of high point density have high confidence levels. Contours crossing areas with low ground point densities preclude the generation of contours at the specified interval resulting in contours being classified as 'low' confidence. These 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 is impeded (Figure 3).

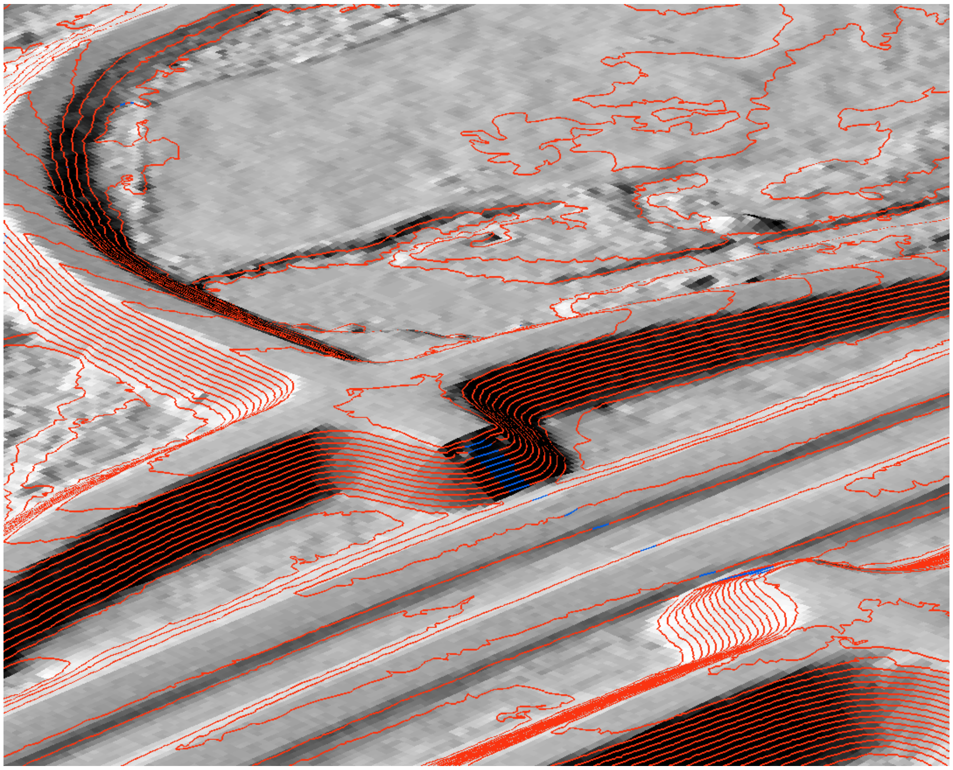
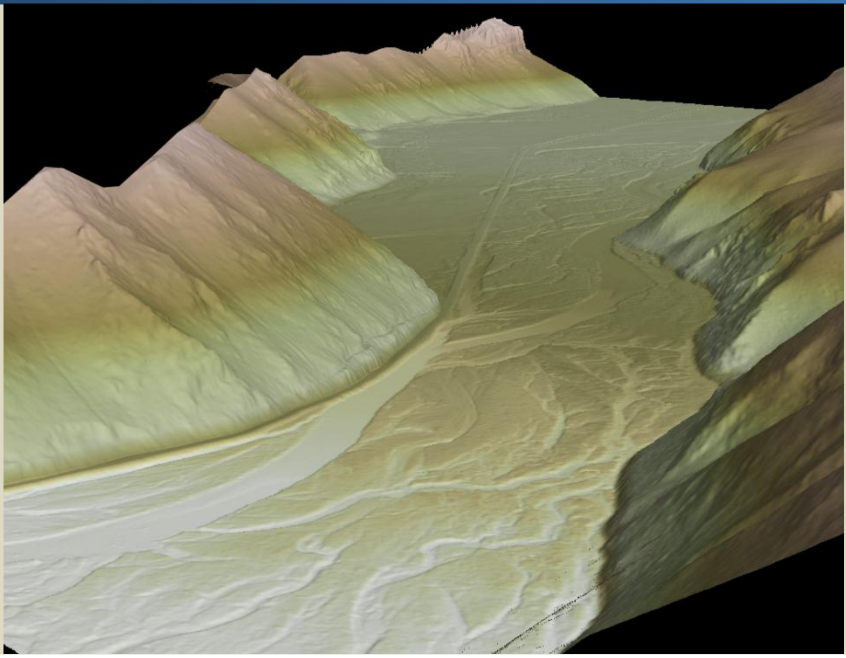


Figure 3: Contours draped over the Rock Creek LiDAR bare earth elevation model. Red contours represent high confidence while the blue contours represent lower confidence.

Bare earth image colored by elevation, looking over the Rock Creek drainage



LiDAR Density

The average first-return density for the Rock Creek LiDAR was 7.01 points/m^2 (Table 9). The pulse density distribution will vary within the study area due to laser scan pattern and flight conditions. Additionally, some types of surfaces (i.e. breaks in terrain, water, steep slopes) may return fewer pulses to the sensor (delivered density) than originally emitted by the laser (native density).

The statistical distribution of first returns (Figure 4) and classified ground points (Figure 5) are portrayed below. Also presented are the spatial distribution of average first return densities (Figure 6) and ground point densities (Figure 7) for each 100 m^2 cell.

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	7.01 points/m^2
Ground Classified	3.56 points/m^2

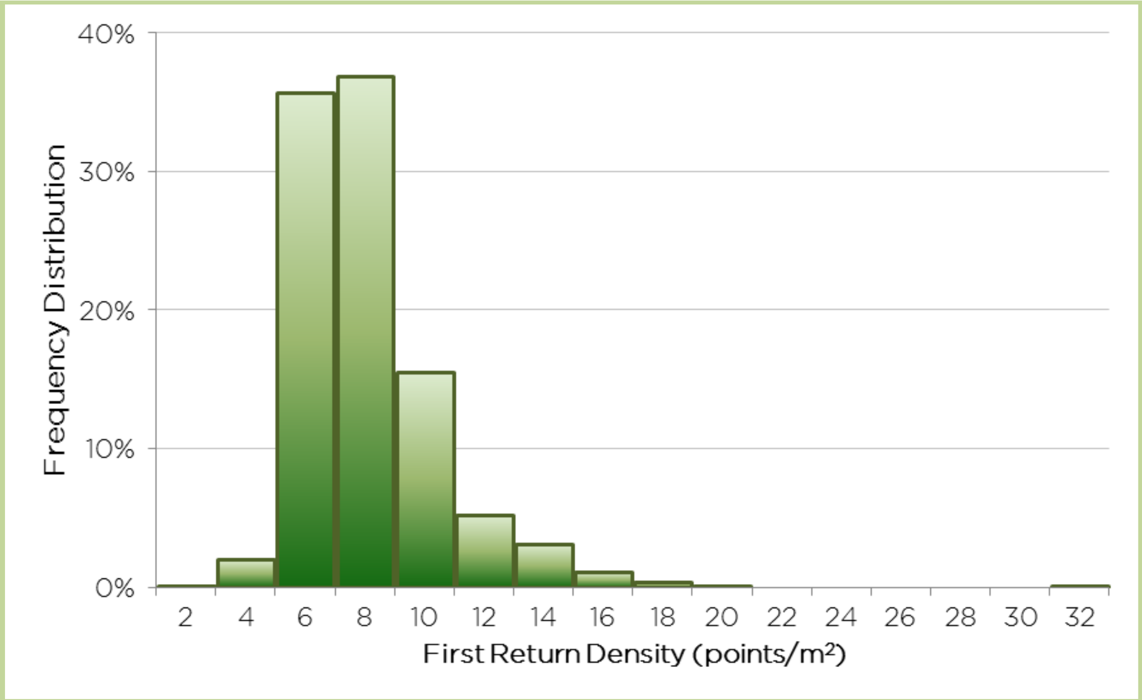


Figure 4: Frequency distribution of first return densities (native densities) of the 1m gridded study area

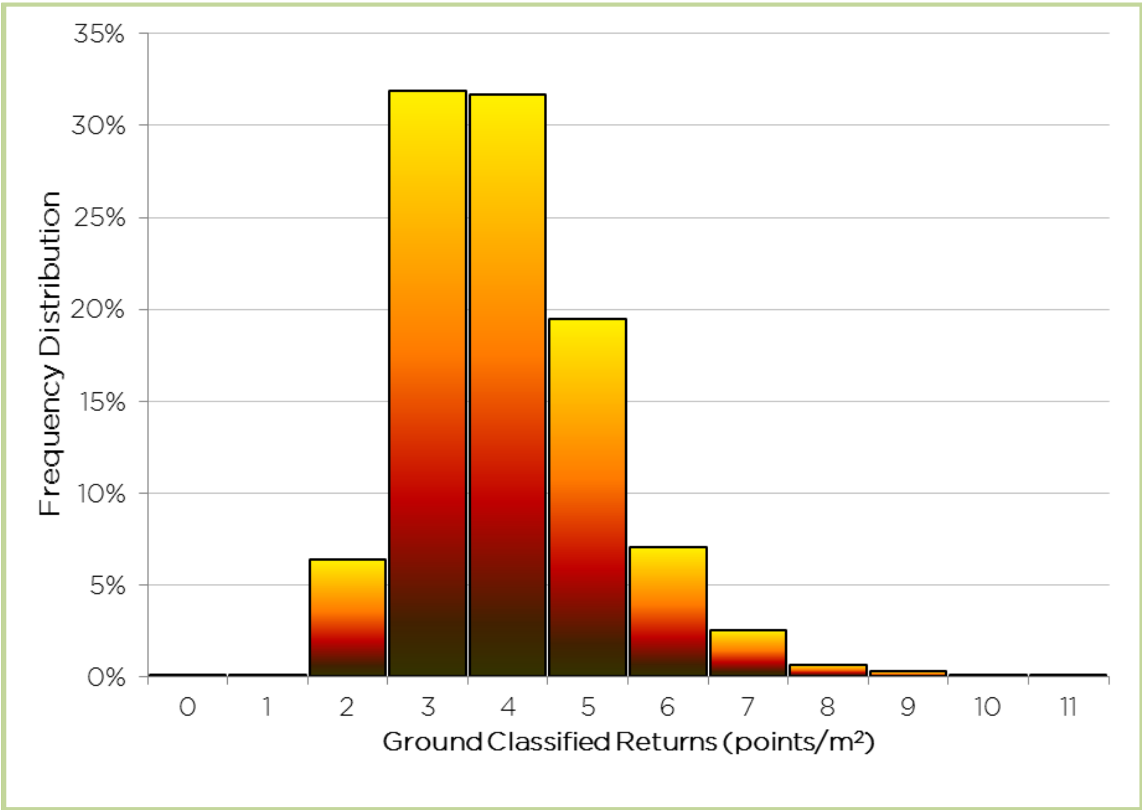


Figure 5: Frequency distribution of ground return densities of the 1m gridded study area

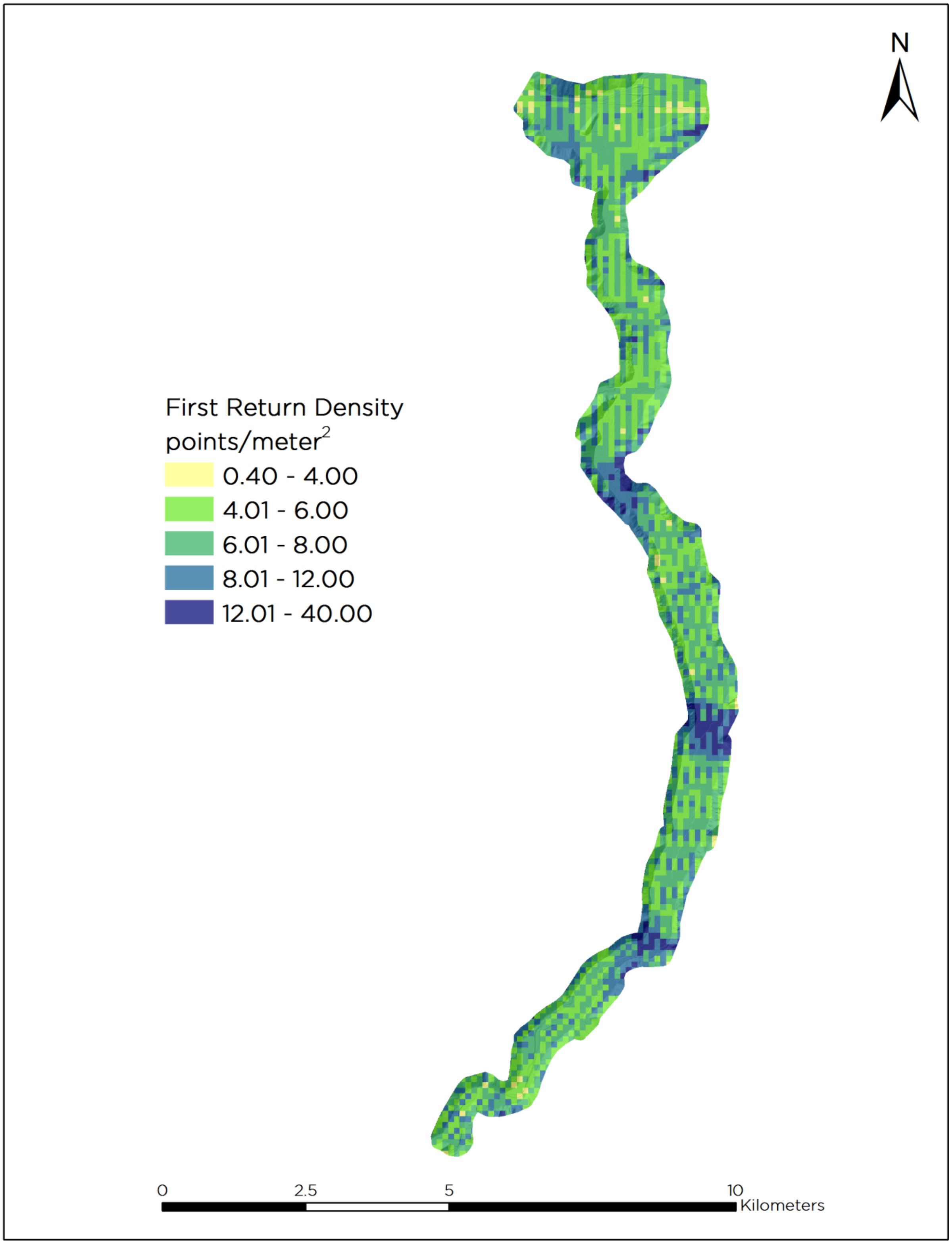


Figure 6: Native density map for the Rock Creek LiDAR site

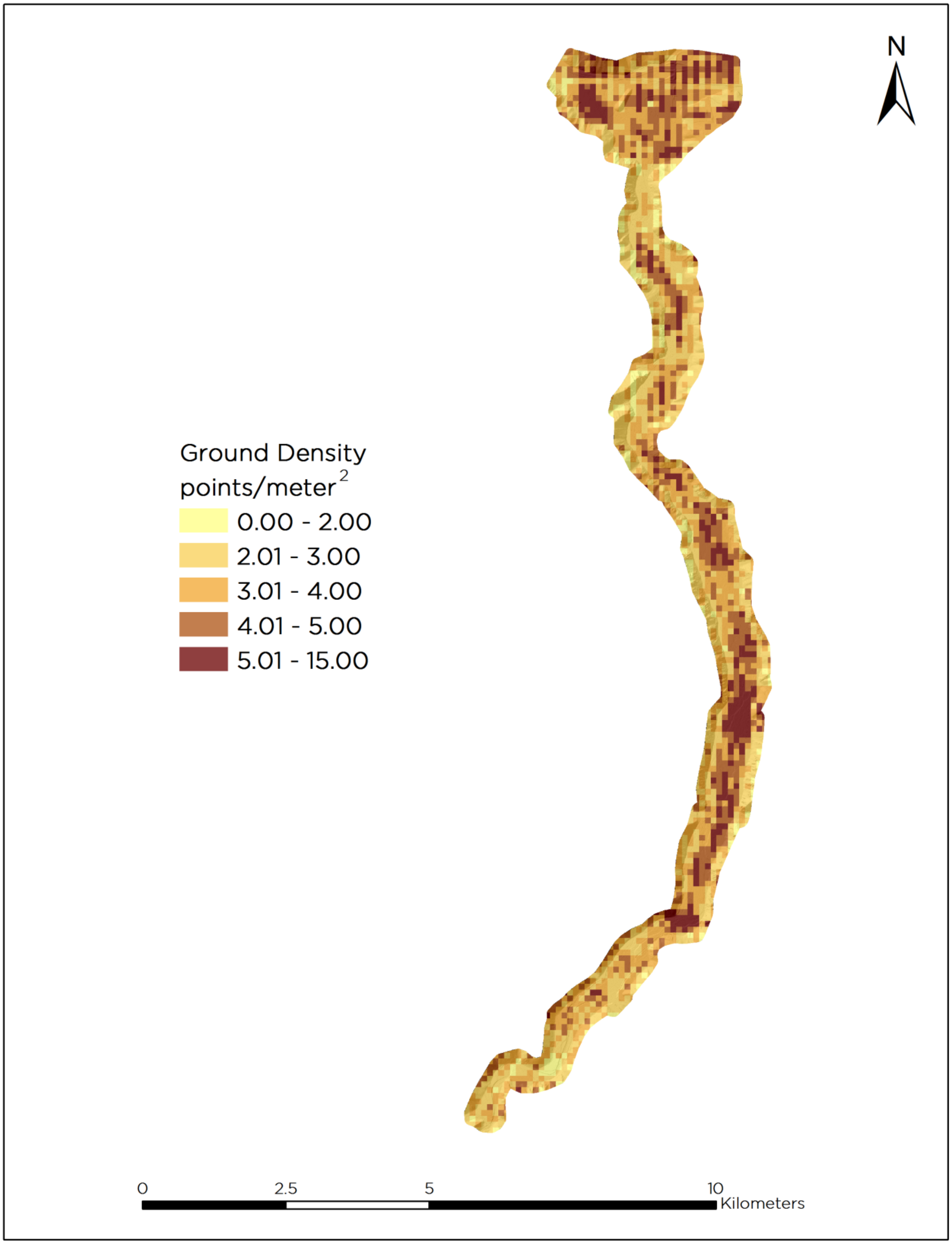


Figure 7: Ground density map for the Rock Creek LiDAR site

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 and B for further information on sources of error and operational measures used to improve accuracy.

LiDAR Absolute Accuracy

Vertical absolute accuracy was primarily assessed from RTK ground check point (GCP) data collected on open, bare earth surfaces with level slope (<20°). Fundamental Vertical Accuracy (FVA) reporting is designed to meet guidelines presented in the National Standard for Spatial Data Accuracy (FGDC, 1998). FVA compares known RTK ground survey check points to the triangulated ground 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 "very high probability" of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 σ).

Absolute accuracy is described as the mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey point coordinates. 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 Rock Creek LiDAR survey, 360 RTK points were collected in total resulting in an average accuracy of -0.015 feet (Table 10, Figure 8).

Table 10: Absolute and relative accuracies.

	Absolute Accuracy	Relative Accuracy
Sample	360 points	46 surfaces
Average	-0.015 ft -0.005 m	0.152 ft 0.046 m
Median	-0.013 ft -0.004 m	0.160 ft 0.049 m
RMSE	0.064 ft 0.020 m	0.167 ft 0.051 m
1σ	0.063 ft 0.019 m	0.043 ft 0.013 m
2σ	0.123 ft 0.037 m	0.084 ft 0.026 m

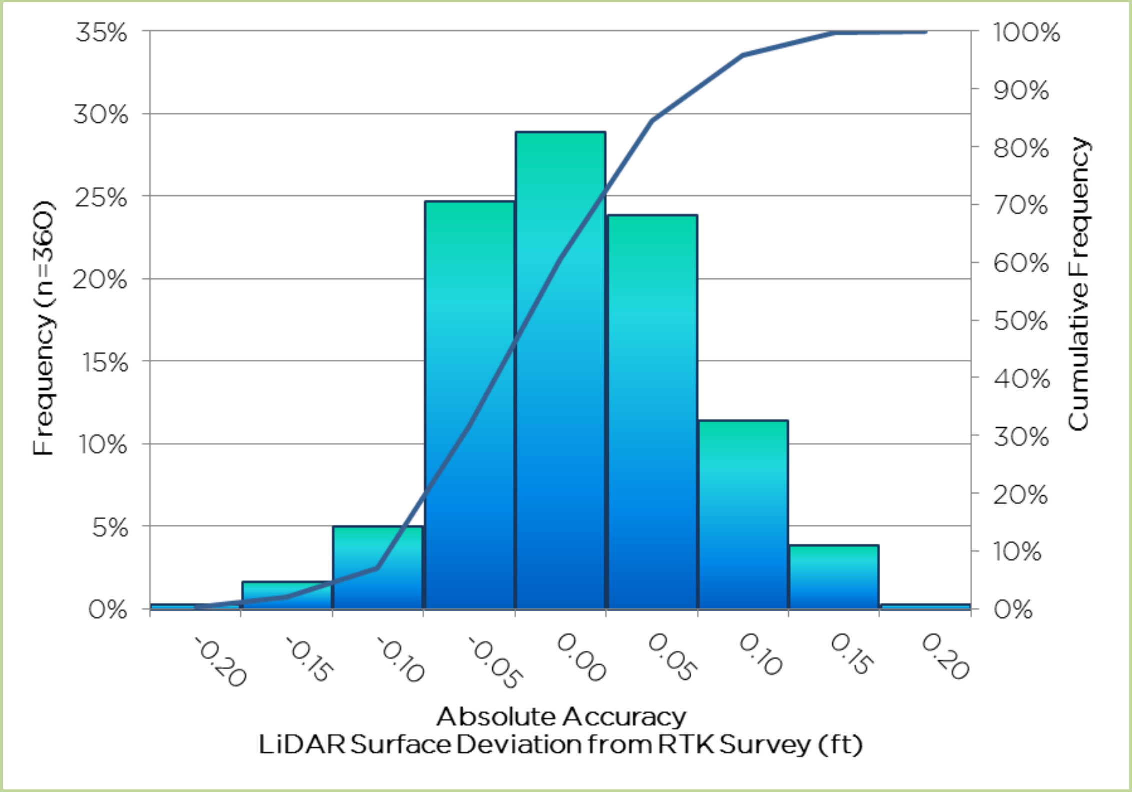


Figure 8: Frequency histogram for LiDAR surface deviation from RTK values

In addition to hard surface RTK, 148 land cover check points were taken throughout the entire study area. Land cover types and descriptions can be referenced in Table 5. Individual accuracies were calculated for each land-cover type to assess confidence in the LiDAR derived ground models across land-cover classes (Table 11).

Table 11: Land cover statistics (in feet) for the Rock Creek LiDAR area

Land Cover	Sample Size (n)	Mean Dz (feet)	Std. Dev.	1.96 sigma (σ)	RMSE
Alluvium	34	0.076	0.072	0.141	0.104
Asphalt	42	0.108	0.086	0.170	0.138
Rip rap	31	0.061	0.130	0.255	0.142
Gravel	15	0.082	0.084	0.165	0.116
Mowed Grass	25	0.139	0.080	0.157	0.159
Short Grass	66	0.199	0.119	0.234	0.232
Tall Grass	52	0.820	0.572	1.120	0.997
Woody Shrubs	35	0.220	0.267	0.524	0.344

LiDAR Relative Accuracy

Relative 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 divergence is low (<0.10 meters). The relative accuracy is computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average relative accuracy for the Rock Creek LiDAR was 0.152 feet (Table 10, Figure 9).

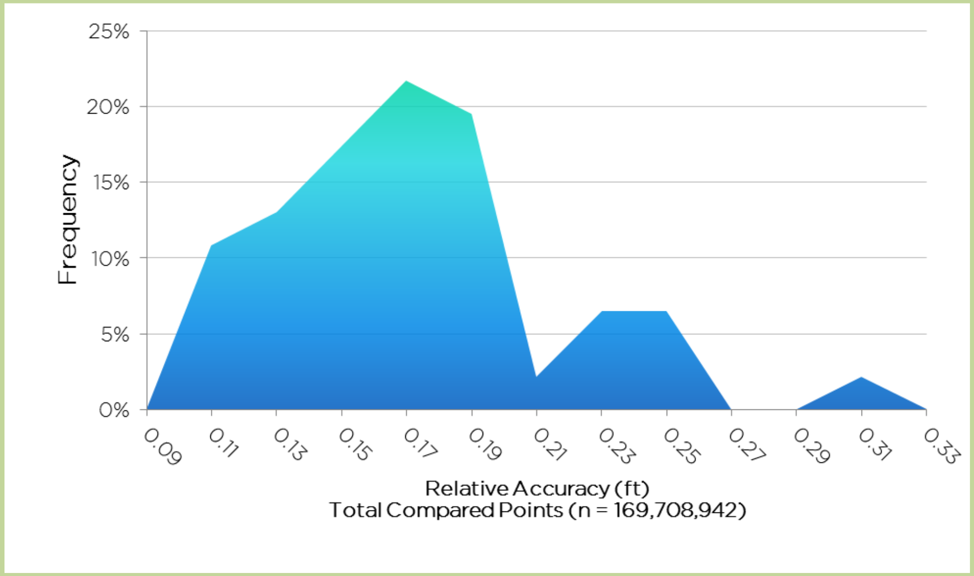


Figure 9: Frequency plot for relative accuracy between flight lines

RIVER DESIGN GROUP, INC.

Watershed Sciences, Inc. – Rock Creek
November 29, 2012

River Design Group, Inc. has completed the required control survey processing to establish horizontal and vertical coordinates and FEMA sample points for the Rock Creek, Montana LiDAR Acquisition.

The following established positions were utilized in this survey.

NGS CORS (continuously operating reference stations)

1. **MSOL** - located in Missoula, MT
2. **MTUM** - Located in Missoula, MT
3. **LOLO** - Located in Lolo, Montana

Newly established Control Monuments

1. **ROCK_CK-01** 5/8" X 30" rebar with a 2" Aluminum Cap stamped "Watershed Sciences, Inc."
2. **ROCK_CK-01** 5/8" X 30" rebar with a 2" Aluminum Cap stamped "Watershed Sciences, Inc."

DATA COLLECTION METHODOLOGY

Utilizing Trimble survey grade GPS receivers, multiple redundant long *(> 4 hour)* GPS static observations were measured on each primary control point during the LiDAR flight.

STATIC OBSERVATION PROCESSING METHODOLOGY

The static occupations discussed above were processed and adjusted against the three NGS CORS positions utilizing Trimble Business Center Software Version 2.81. These solutions were used to provide survey grade horizontal solutions and geoid03 vertical solutions.

FINAL GEODETIC COORDINATES

Horizontal Datum: North American Datum of 1983 (CORS 2011)
Horizontal Projection: Montana State Plane
Horizontal Units: Meters
Vertical Datum: NAVD88 North American Vertical Datum of 1988 – Geoid03
Vertical Units: US Survey Feet

POINT	NORTH (M)	EAST (M)	ELEV (ussft)	LATITUDE	LONGITUDE	HEIGHT (ussft)
ROCK_CK_01	275567.756	282233.178	3720.315	46d39'14.37892"	-113d39'20.63459"	3674.408
ROCK_CK_02	283197.572	281700.477	3546.206	46d43'20.34619"	-113d40'04.76430"	3499.804

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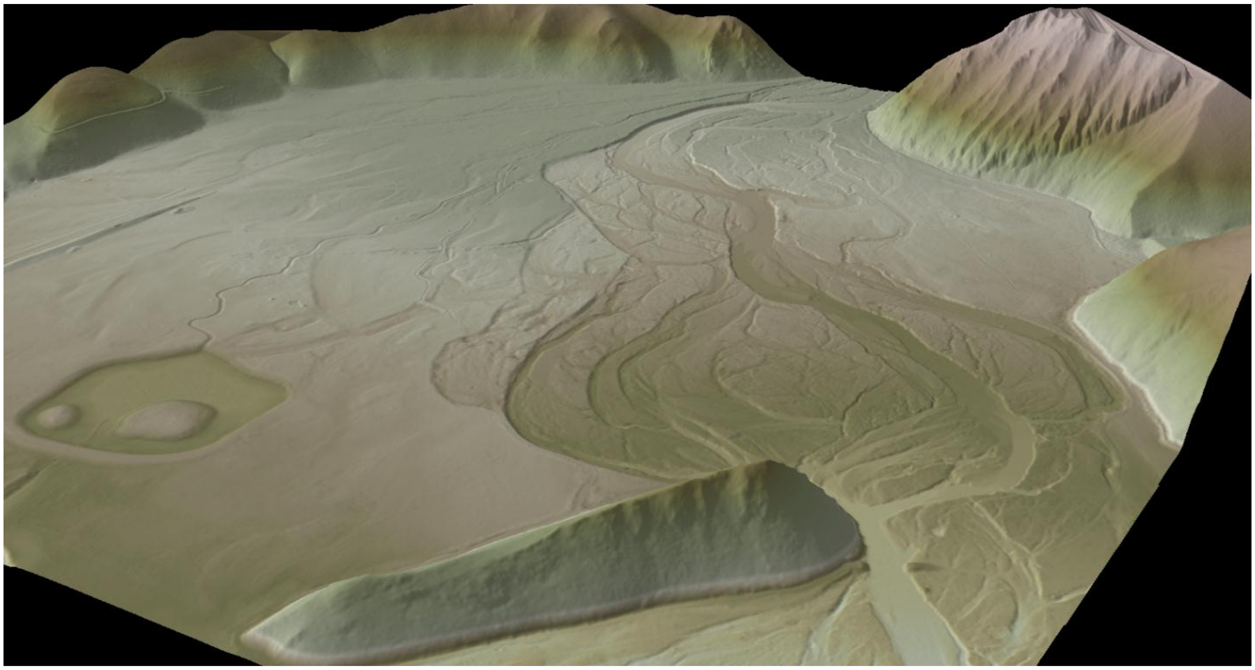

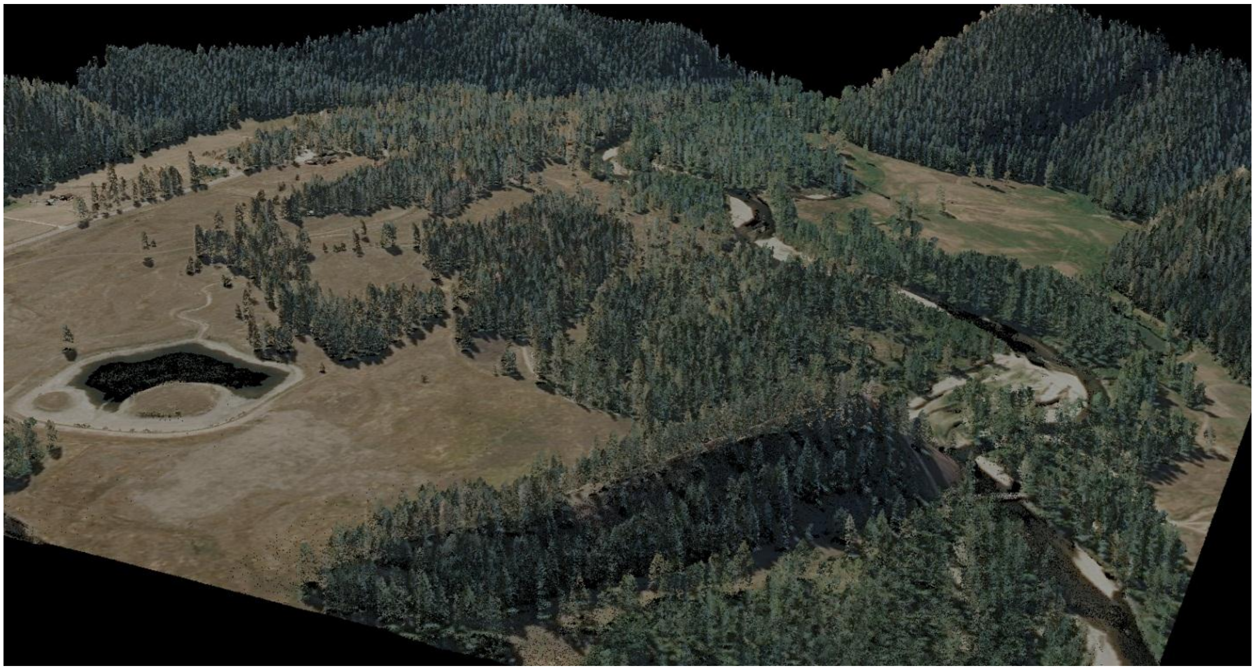

Figure 10: The top image is the LiDAR bare earth model colored by elevation looking south up Rock Creek. The bottom image is the 3D LiDAR point cloud colored with NAIP imagery.

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-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set.

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.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured as thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the Leica ALS 60 system can record *up to four* wave forms reflected back to the sensor. Portions of the wave form that return earliest 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.

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).

Intensity Values: The peak power ratio of the laser return to the emitted laser. It is a function of surface reflectivity.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Spot Spacing: Also a measure of LiDAR resolution, measured as the average distance between laser points.

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.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Overlap: The area shared between flight lines, typically measured in percent; 100% overlap is essential to ensure complete coverage and reduce laser shadows.

DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

Real-Time Kinematic (RTK) Survey: GPS surveying is 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.

Laser Noise

For any given target, laser noise is the breadth of the data cloud per laser return (i.e., last, first, etc.). Lower intensity surfaces (roads, rooftops, still/calm water) experience higher laser noise. The laser noise range for this survey was approximately 0.02 meters.

Relative Accuracy

Relative accuracy refers to the internal consistency of the data set - 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).

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.

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 RTK 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, thus we also consider the skew and kurtosis of distributions when evaluating error statistics.

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 is employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 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 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^{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 19 km (11.5 miles) at all times.

Ground Survey: Ground survey point accuracy (i.e. <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 RTK 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 most nadir portion of one flight line coincides with the edge (least nadir) 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 are opposing. 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.