Applied
Remote Sensing
and Analysis

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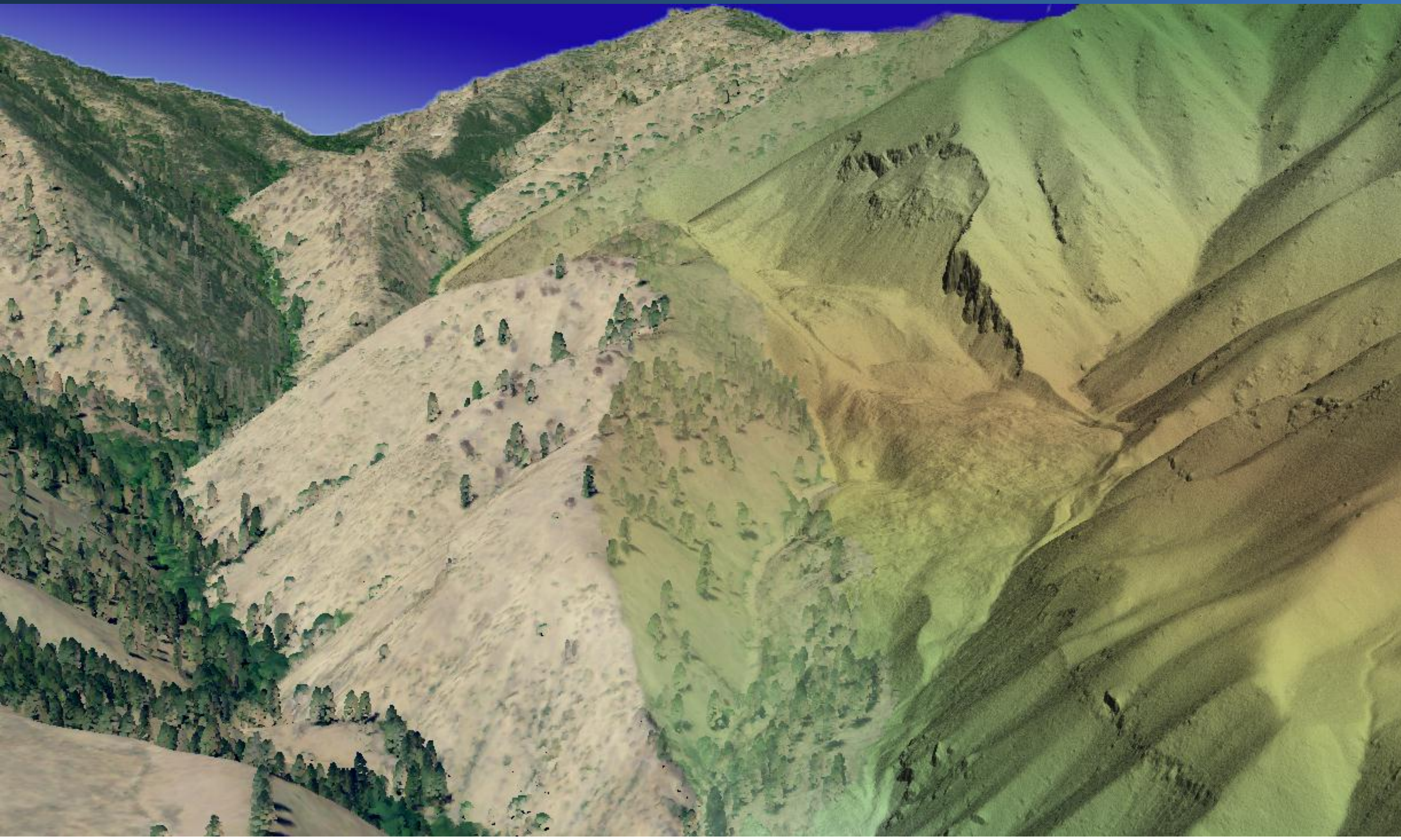

Entiat River LiDAR

Technical Data Report

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Cover Photo: View looking towards Keystone Point from Spencer Canyon in the Entiat Mountains at a fault scarp and landside. Image created from a composite of a gridded ground-classified LiDAR points colored by elevation and the LiDAR Point cloud with RGB values assigned by 2011 NAIP imagery.

INTRODUCTION

View of the Entiat River survey area in Washington.

In October 2012, WSI (Watershed Sciences, Inc.) was contracted by the Puget Sound LiDAR Consortium (PSLC) to collect Light Detection and Ranging (LiDAR) data for the Entiat River site in central Washington. The area is adjacent to several other LiDAR projects collected in the greater Wenatchee area since 2008. Data were collected to aid in assessing the topographic and geophysical properties of the study area to support fault line and geologic instability within the area.

This data delivery and report describes the 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 PSLC can be found in Table 2.

Table 1: Acquisition dates, acreages, and data types collected on the Entiat River site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type	Delivery Date
Entiat Site	65,345	67,067	06/23/2013 06/26/2013 06/28-30/2013	LiDAR	08/23/2013

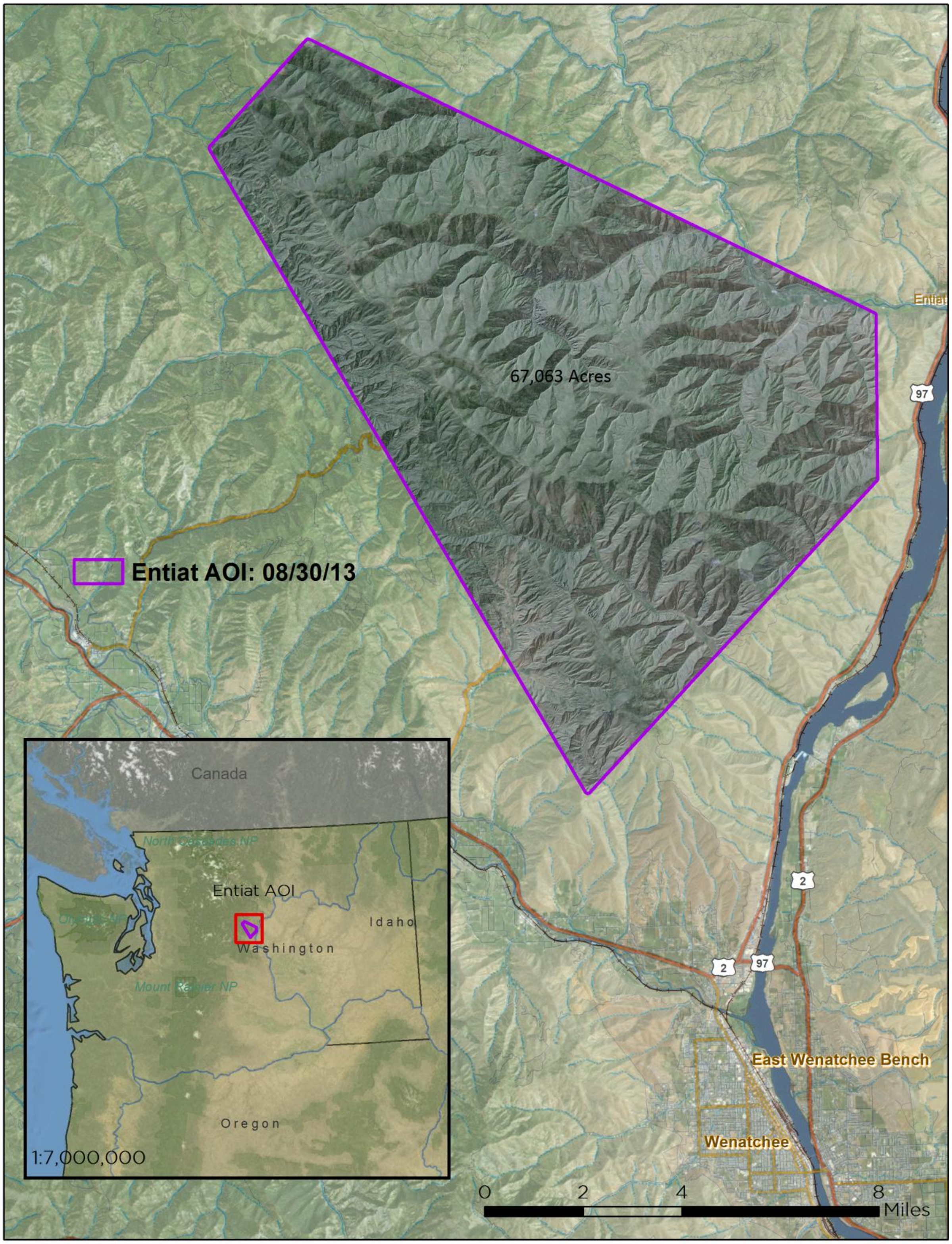


Figure 1: Location map of the Entiat River site in central Washington

Table 2: Products delivered to PSLC

Entiat River Products Projection: Washington State Plane North FIPS 4601 Horizontal Datum: NAD83 (CORS96)** Vertical Datum: NAVD88 (GEOID03) Units: U.S. Survey Feet	
LAS Files	LAS v 1.2 • All Returns Text Files (*.txt) • All Returns • Ground Returns
Rasters	3-foot ESRI Grids • Bare Earth Model • Highest Hit Model 1.5-foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Index • DEM/DSM Index • Smooth Best Estimate Trajectory (SBETs) • Ground Control Points Text Files (*.txt) • Smooth Best Estimate Trajectory (SBETs)

defined as NAD83 (HARN) for GIS purposes

WSI Cessna Caravan

Planning

In preparation for data collection, WSI reviewed the project area using Google Earth, and flightlines were developed using a combination of specialized software. Careful planning by acquisition staff entailed adapting the pulse rate, flight altitude, scan angle, and ground speed to ensure complete coverage of the study area at the target point density of ≥8 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 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, a variety of logistical considerations required review including private property access, potential air space restrictions, and availability of company resources (both staff and equipment).

Ground Survey

Ground survey data are used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data. Ground surveys, including monumentation and ground check points, are conducted to support the airborne 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. WSI established four new monuments for the Entiat River project (Table 3, Figure 2). New monumentation was set using 5/8”x30” rebar topped with stamped 2" aluminum caps. WSI’s professional land surveyor, Chris Yotter-Brown (WAPLS#46328 LS) oversaw and certified the establishment of all monuments.

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

Monument ID	Latitude	Longitude	Ellipsoid (meters)
ENTIAT_01	47° 35' 27.38683"	-120° 25' 11.19776"	836.584
ENTIAT_02	47° 39' 56.83905"	-120° 17' 17.87122"	259.675
ENTIAT_03	47° 43' 03.44464"	-120° 26' 27.74566"	880.617
ENTIAT_04	47° 41' 58.62685"	-120° 29' 59.78099"	1464.282

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.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project can be seen in Table 4.

Table 4: Federal Geographic Data Committee monument rating

Direction	Rating
St Dev $_{NE}$:	0.001 m
St Dev $_{z}$:	0.050 m

For the Entiat project, the monument positions contributed no more than 5 cm of vertical error to the final RTK and LiDAR positions, with 95% confidence.

RTK Surveys

For the real time kinematic (RTK) check point data collection, Trimble R7 base units were 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. See Table 5 for Trimble unit specifications.

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.

Table 5: Trimble equipment identification

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

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

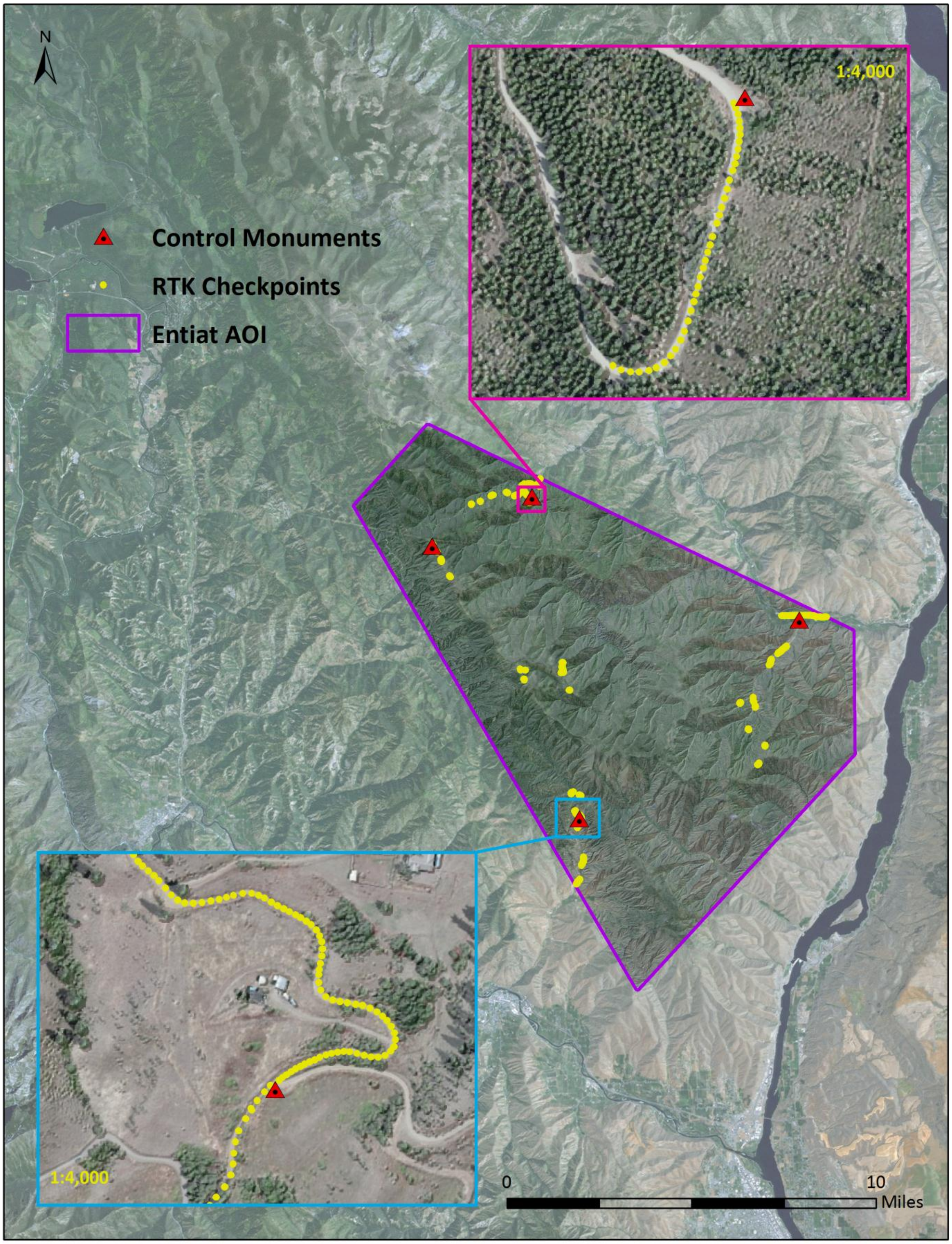


Figure 2: Basestation and RTK checkpoint location map

Airborne LiDAR Survey

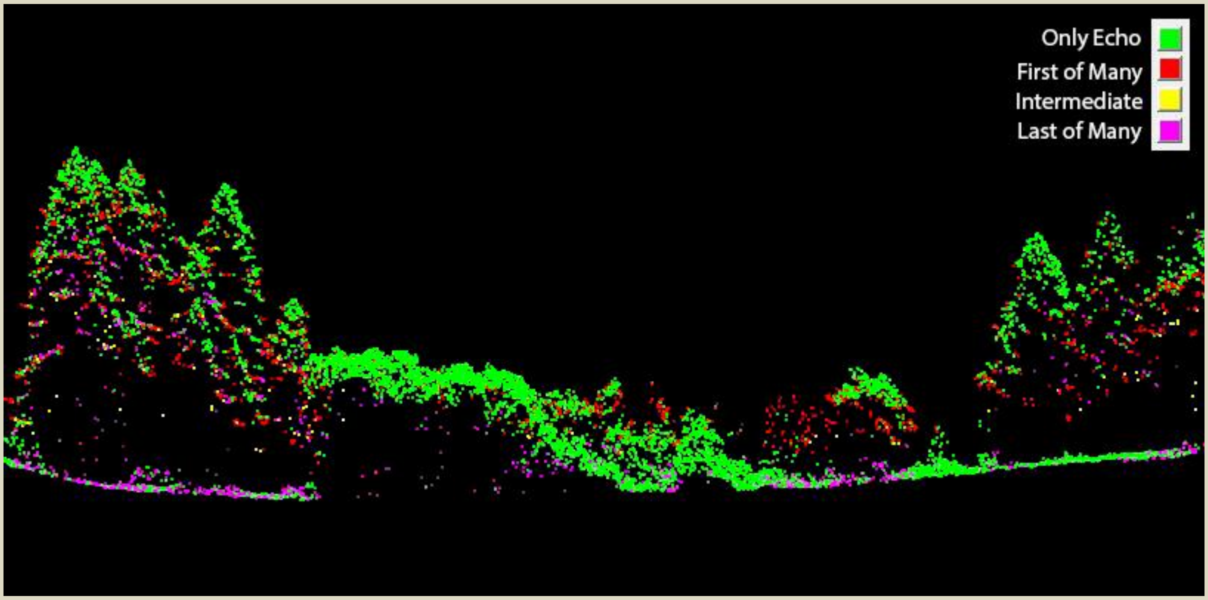
The LiDAR survey was accomplished with a Leica ALS60 system mounted in a Cessna Caravan. Table 6 summarizes the settings used to yield an average pulse density of ≥ 8 pulses/m^2 over the Entiat River survey site. It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return 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 specifications and survey settings

LiDAR Survey Settings & Specifications	
Survey Dates	06/23/2013 06/26/2013 06/28-30/2013
Sensor	Leica ALS60
Survey Altitude (AGL)	900 m
Target Pulse Rate	95-106 kHz
Sensor Configuration	Single Pulse in Air (SPiA)
Laser Pulse Diameter	21 cm
Mirror Scan Rate	64 Hz
Field of View	28°
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	4
Intensity	8-bit
Resolution/Density	Average 8 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.



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, smoothed best estimate trajectory (SBET) calculations, 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 Entiat River 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

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.3.00 Geographic Calculator 2013
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.13.008
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.13.002
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.13.008 TerraModeler v.13.002
Generate bare earth models as triangulated surfaces. Highest hit models were created as a surface expression of all classified points (excluding the noise and withheld classes). All surface models were exported as ESRI grids at a 3-foot pixel resolution.	TerraScan v.13.008 ArcMap v. 10.1 TerraModeler v.13.002

Image created from LiDAR point cloud with RGB values assigned by 2011 NAIP imagery. View looking at an historic landslide above Spencer Lake in the Entiat Mountains.

LiDAR Density

The sensor is set to acquire a native density of 8 points/m^2 (0.74 points/ft^2). Depending on the nature of the terrain, the first returned echo will be the highest hit surface. In vegetated areas, the first return surface will represent the top of the canopy, while in clearings or on paved roads, the first return surface will represent the ground. The ground density differs from the first return density due to the fact that in vegetated areas, fewer returns may penetrate the canopy. The ground classification is generally determined by first echo returns in non-vegetated areas combined with last echo returns in vegetated areas. 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 than originally emitted by the laser.

The average first-return density for the LiDAR data for the Entiat River was 1.25 points/ft^2 (13.43 points/m^2), while the average ground classified density was 0.38 points/ft^2 (4.12 points/m^2) (Table 9). The statistical distribution of first returns (Figure 3) and classified ground points (Figure 4) are portrayed below. Also presented are the spatial distribution of average first return densities (Figure 5) and ground point densities (Figure 6) for each 100mx100m cell.

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	1.25 points/ft^2 13.43 points/m^2
Ground Classified	0.38 points/ft^2 4.12 points/m^2

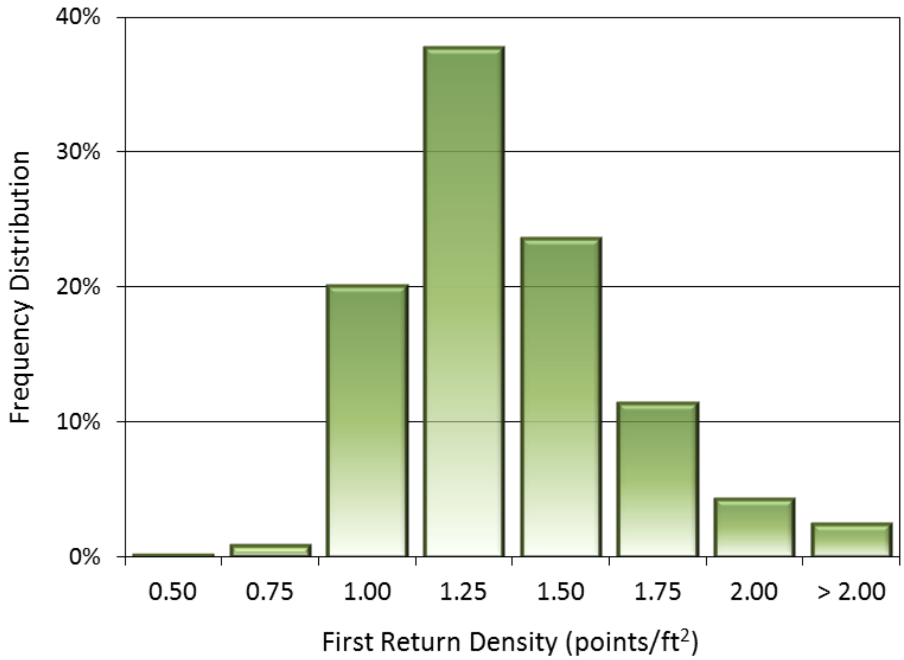


Figure 3: Frequency distribution of first return densities (native densities) of the gridded study area

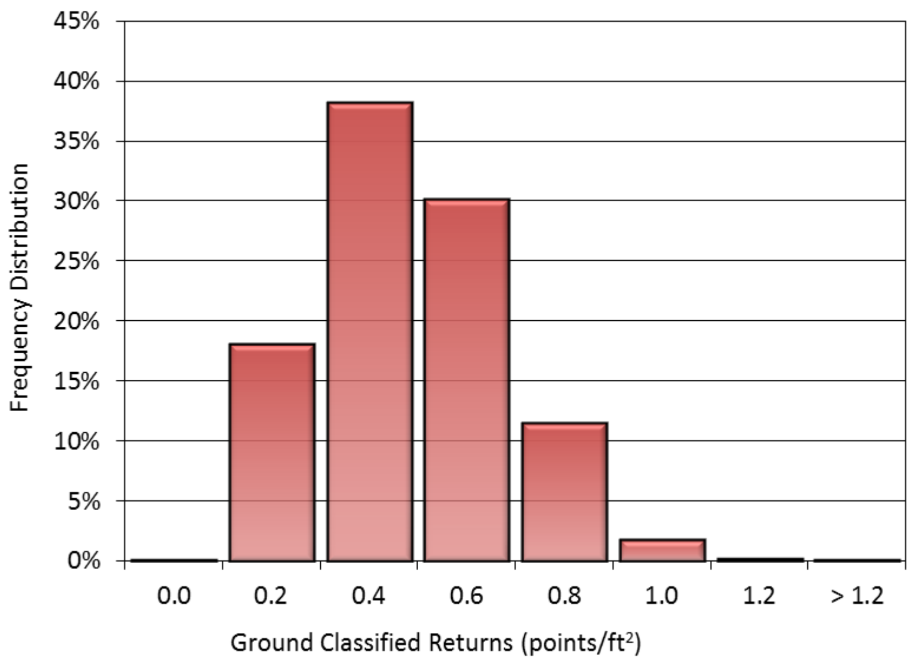


Figure 4: Frequency distribution of ground return densities of the gridded study area

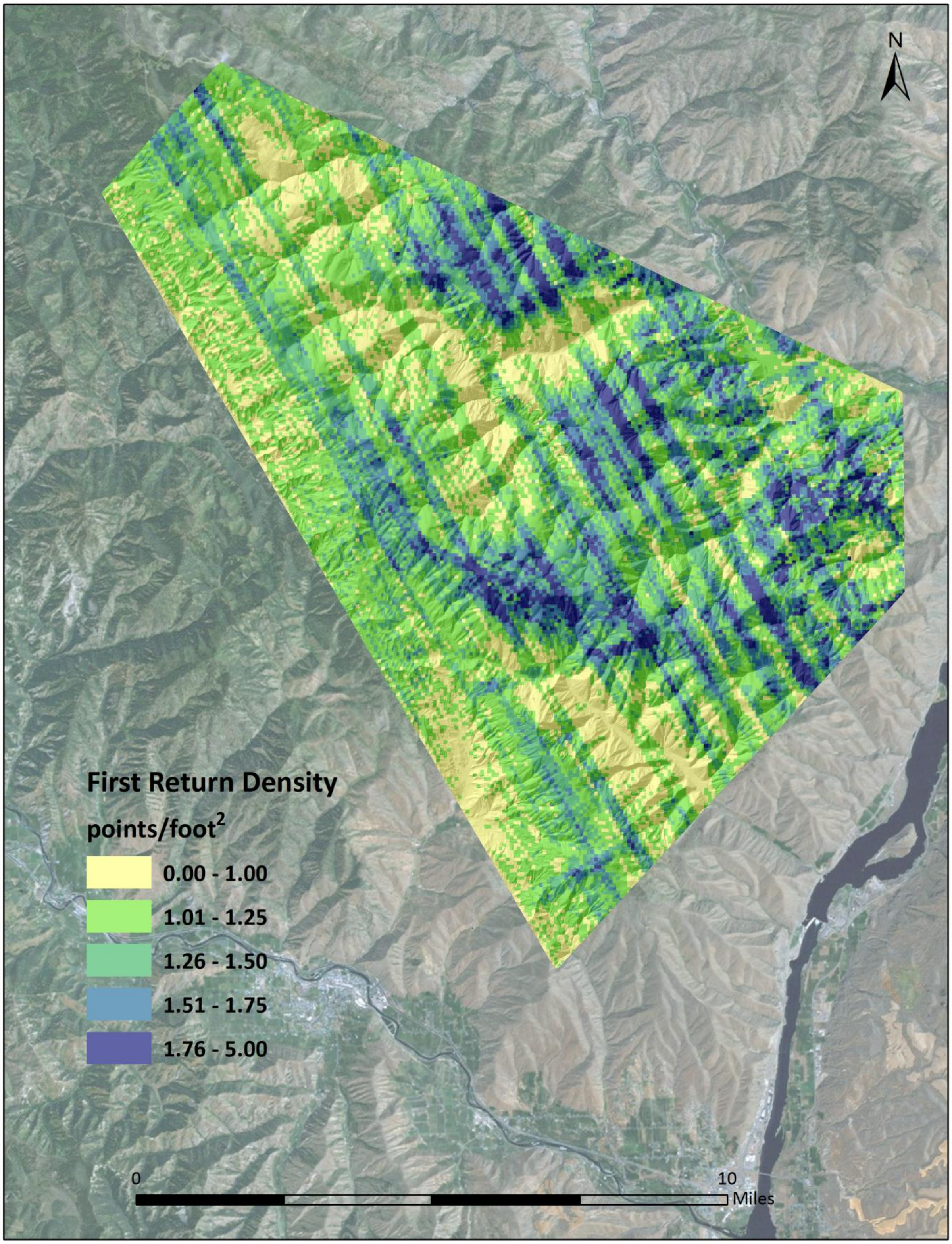


Figure 5: Native density map for the Entiat LiDAR site (100mx100m cells)

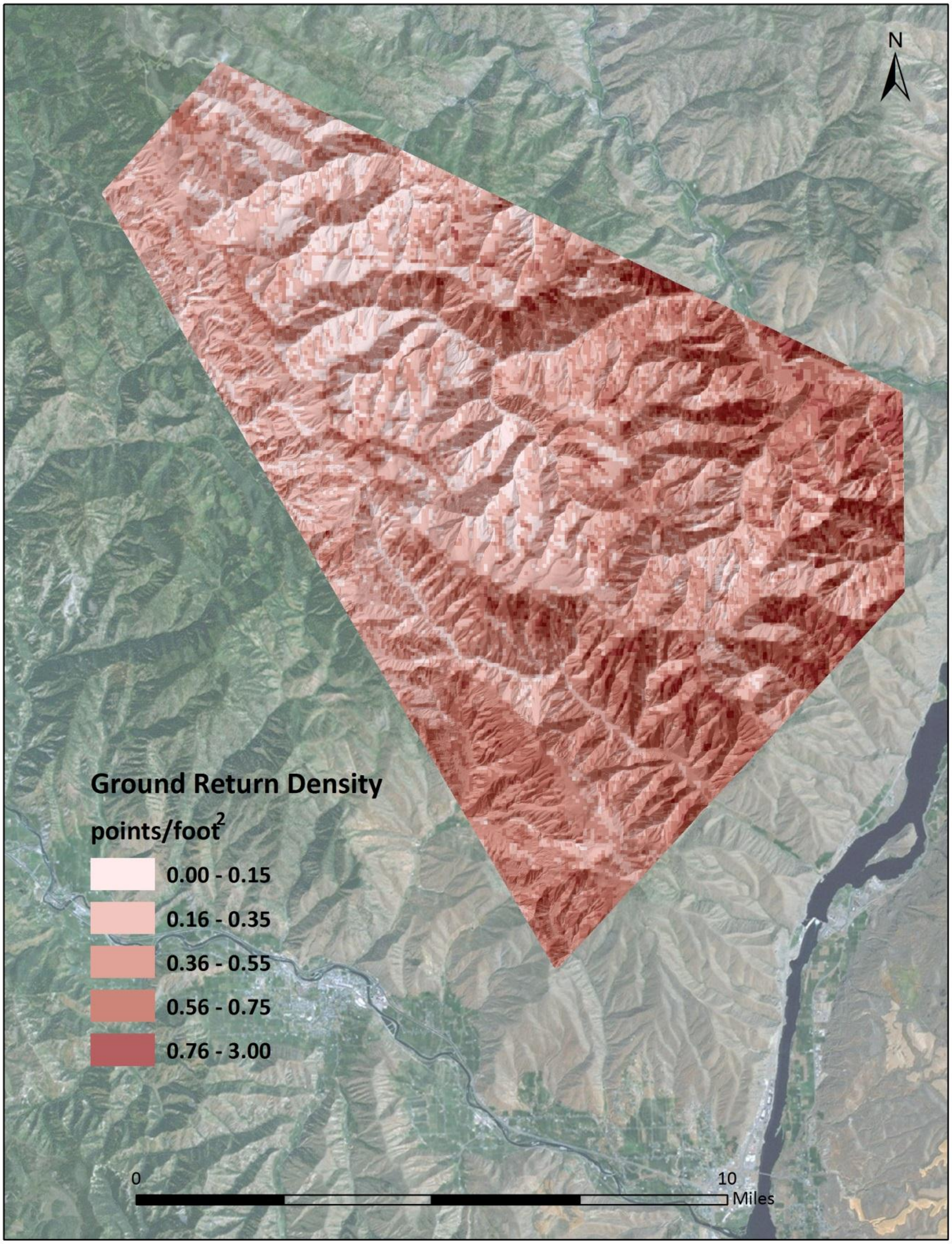


Figure 6: Ground density map for the Entiat LiDAR site (100mx100m cells)

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 Absolute Vertical 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 FGDC National Standard for Spatial Data Accuracy[3]. 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 Entiat River survey, 1,265RTK points were collected in total resulting in an average accuracy of 0.001 feet (0.000 meters) (Table 10, Figure 7).

Table 10: Absolute and relative vertical accuracies

	Absolute Accuracy	Relative Accuracy
Sample	1,265 points	184 surfaces
Average	0.001 ft 0.000 m	0.172 ft 0.052 m
Median	-0.003 ft -0.001 m	0.169 ft 0.052 m
RMSE	0.078 ft 0.024 m	0.172 ft 0.053 m
1σ	0.078 ft 0.024 m	0.025 ft 0.008 m
1.96σ	0.152 ft 0.046 m	0.048 ft 0.015 m

[3] 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

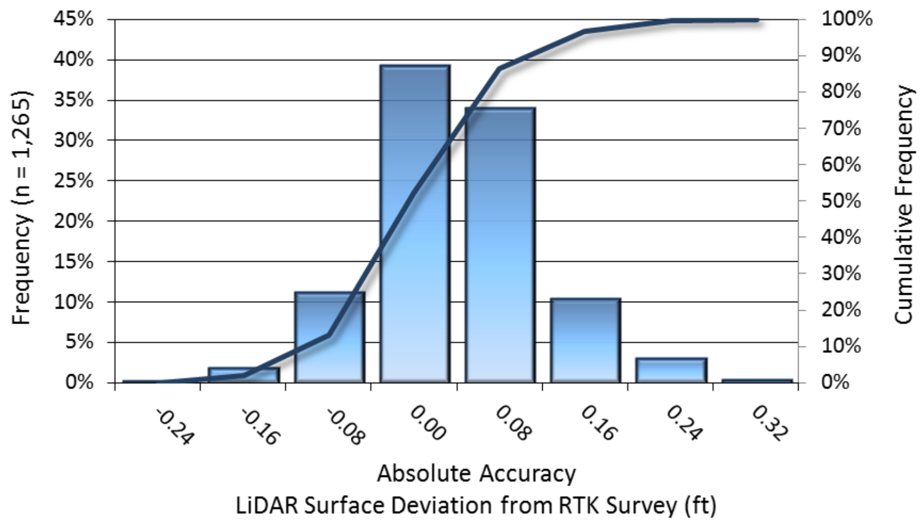


Figure 7: Frequency histogram for LiDAR surface deviation from RTK values

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 elevation 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 is 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 Entiat River area was 0.172 feet (0.052 meters) (Table 10, Figure 8).

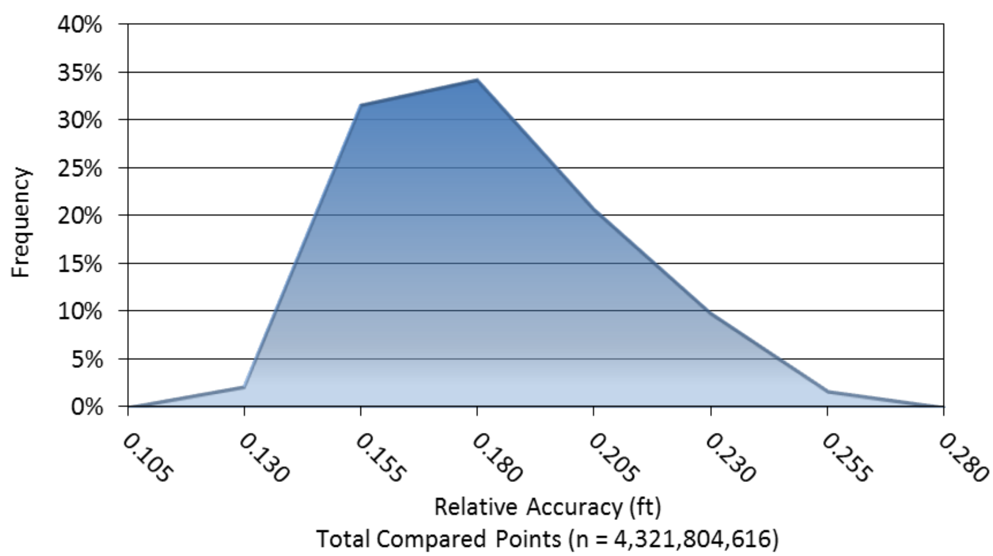


Figure 8: Frequency plot for relative accuracy between flight lines

CERTIFICATIONS

Watershed Sciences provided LiDAR services for the Entiant River project as described in this report.

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

Russ Faux
Principal
WSI

I, Christopher W. Yotter-Brown, being first duly sworn, say that as described in the Ground Survey subsection of the Acquisition section of this report was completed by me or under my direct supervision and was completed using commonly accepted standard practices. Accuracy statistics shown in the Accuracy Section have been reviewed by me to meet National Standard for Spatial Data Accuracy.

8/22/2013
Christopher W. Yotter-Brown, PLS Oregon & Washington
WSI
Portland, OR 97204

Renews: 12/21/2014

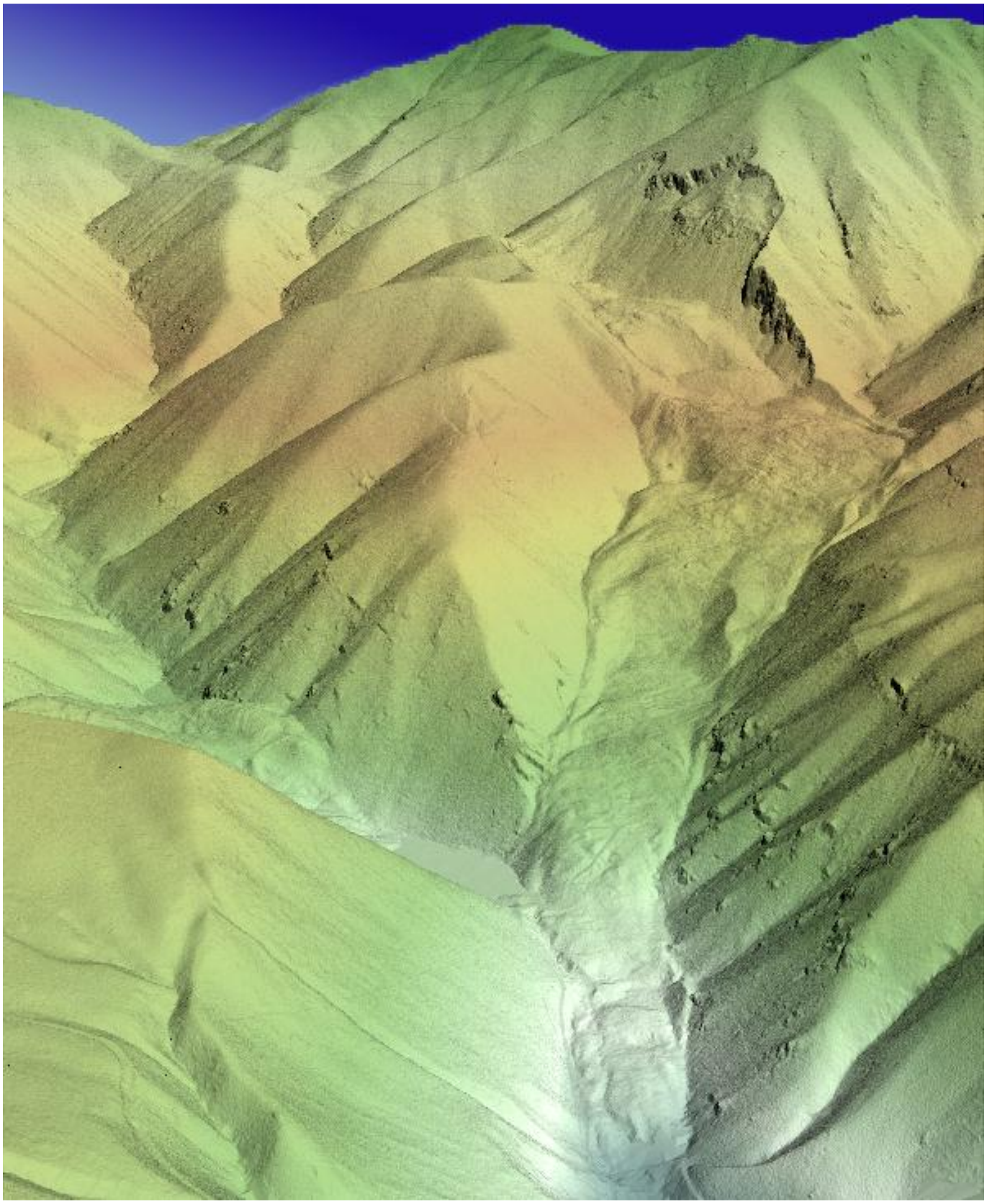


Figure 9: View looking towards Keystone Point from Spencer Canyon in the Entiat Mountains at a fault scarp and landside. Image created from gridded ground-classified LiDAR points colored by elevation.

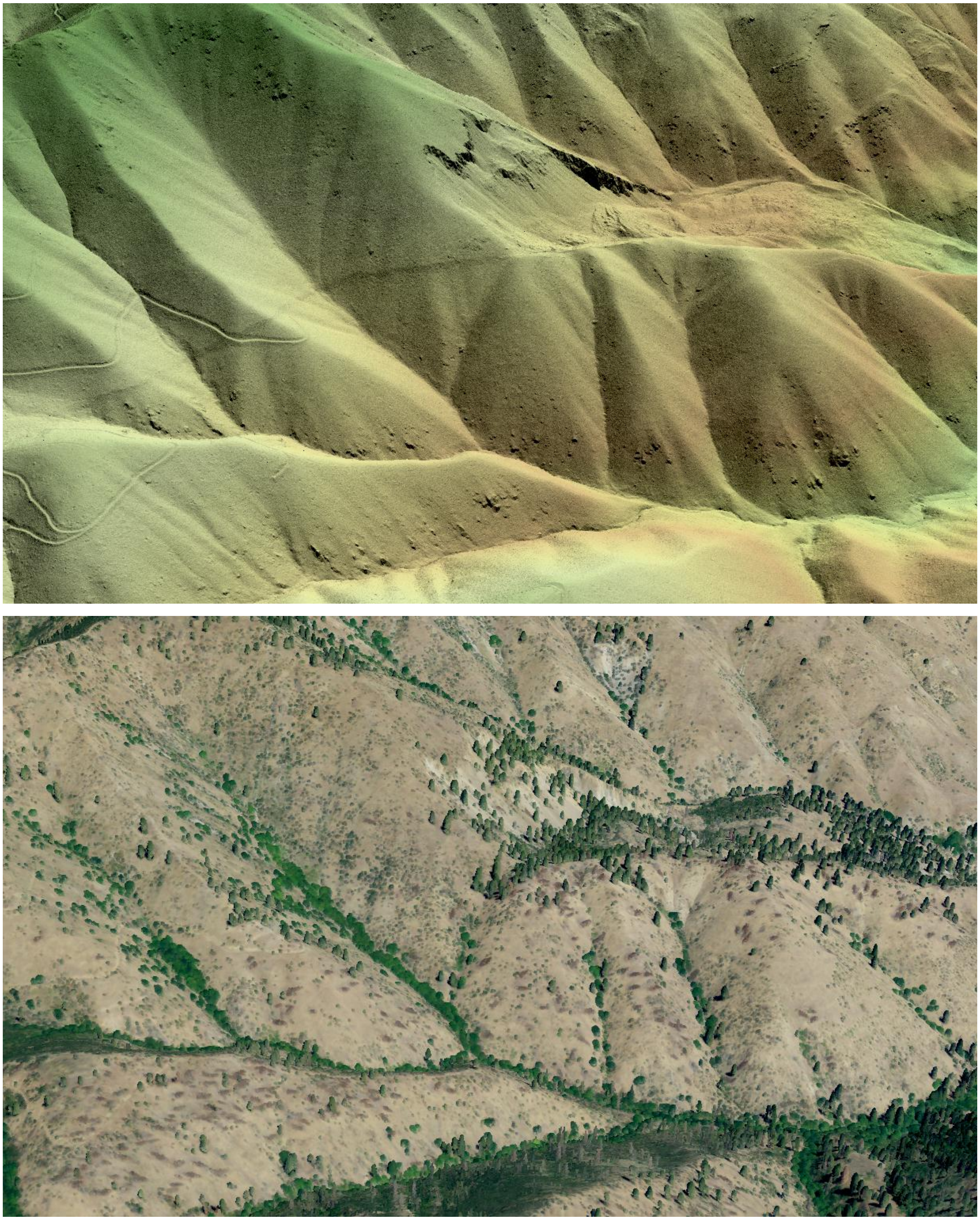


Figure 10: Down canyon view of fault scarp and landside in Spencer Canyon. Top image created from gridded ground-classified LiDAR points colored by elevation. Lower image created from highest hit LiDAR point cloud with RGB values assigned by 2011 NAIP imagery.

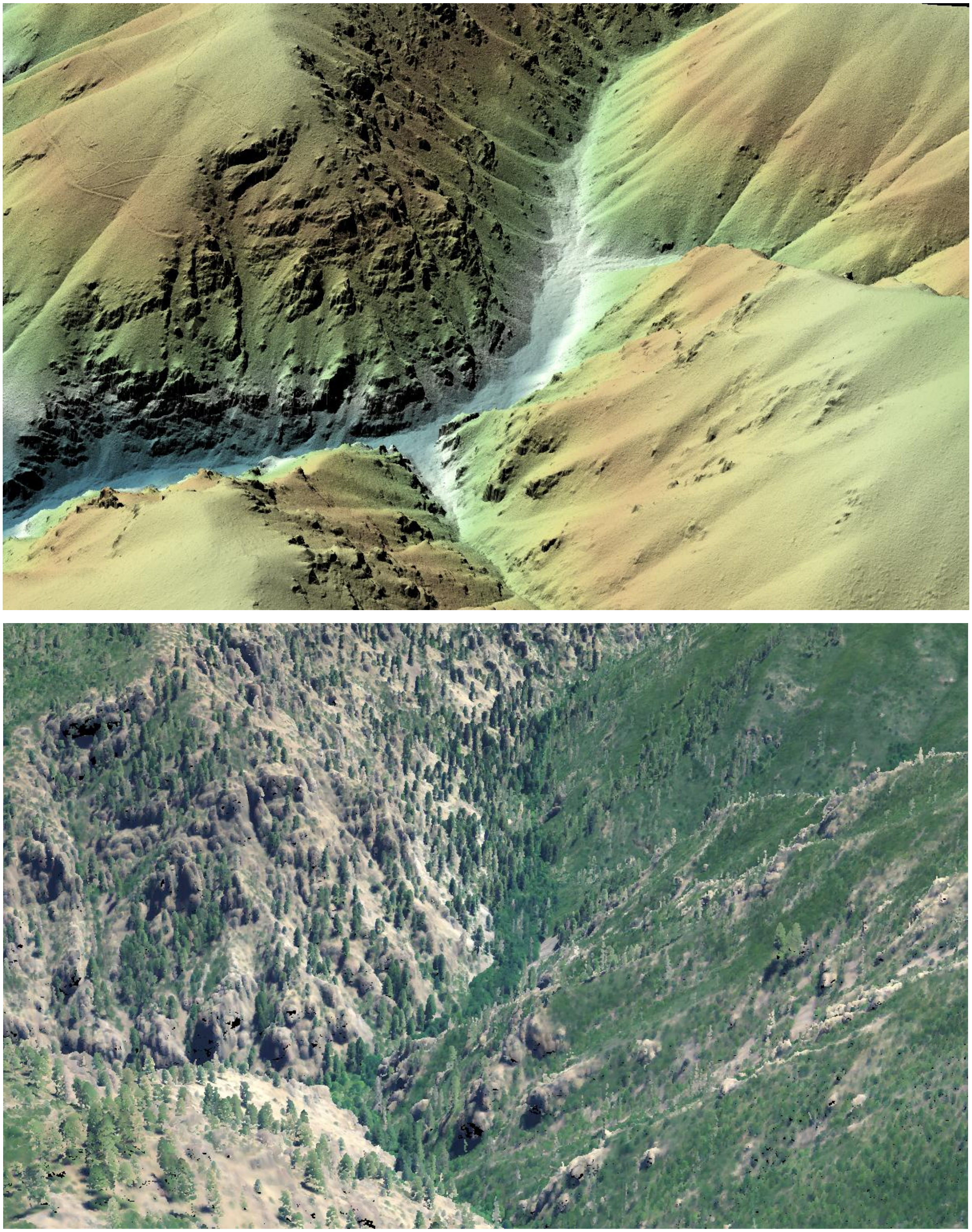


Figure 11: View looking south at a rocky canyon along Tamarack Creek in the Entiat Mountains. Top image created from gridded ground-classified LiDAR points colored by elevation. Bottom image created from highest hit LiDAR point cloud with RGB values assigned by 2011 NAIP imagery.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68^{th} percentile) of a normally distributed data set.

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

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 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.
>
> **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).
>
> **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.

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.

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

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.

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 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.

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.

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

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

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 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.