LiDAR REMOTE SENSING

CLE ELUM RIVER & GOLD CREEK • WASHINGTON

(DELIVERY 2 – 8/17/2012)

CARDNO ENTRIX

GEORGE FOWLER - 200 First Avenue West, Suite 500 - Seattle, WA 98119

WSI • 517 SW 2nd Street, Suite 400 - Corvallis, OR 97333

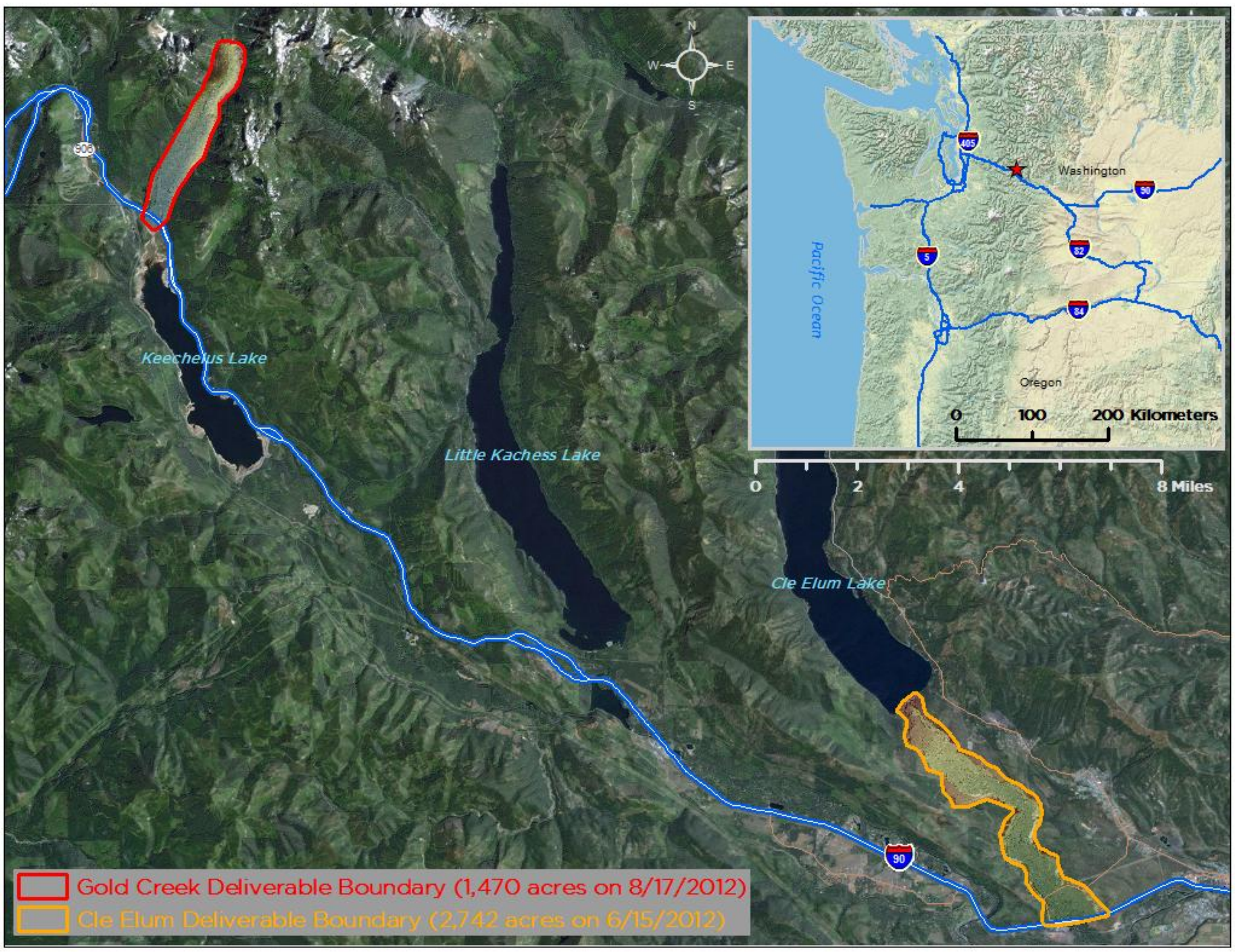
LiDAR Remote Sensing Data Collection: Cle Elum River and Gold Creek, Washington

Table of Contents

1. Overview

Watershed Sciences, Inc. (WSI) collected Light Detection and Ranging (LiDAR) data of the Cle Elum River and Gold Creek areas of interest (AOIs) in Kittitas County, WA for Cardno ENTRIX. Cle Elum LiDAR data was acquired on April 26th and 27th. Due to snow levels the Gold Creek LiDAR acquisition was postponed to July 25th, 2012. Acquisition of the Cle Elum River was specifically timed to meet Cardno ENTRIX's flow level requirements of less than 2400 cubic feet per second. Gauge measurements during the time of acquisition over the active river channel can be found in Table 1. The Cle Elum River and Gold Creek survey boundaries were buffered by 100 meters to ensure complete coverage and adequate point densities around the survey area boundaries. This results in a total of 2,742 acres of delivered LiDAR data for the Cle Elum River site and 1,470 acres of delivered LiDAR data for the Gold Creek site (Figure 1). This report documents the data acquisition, processing methods, and accuracy assessment of the Cle Elum River and Gold Creek LiDAR datasets.

Figure 1. Cle Elum and Gold Creek LiDAR survey sites



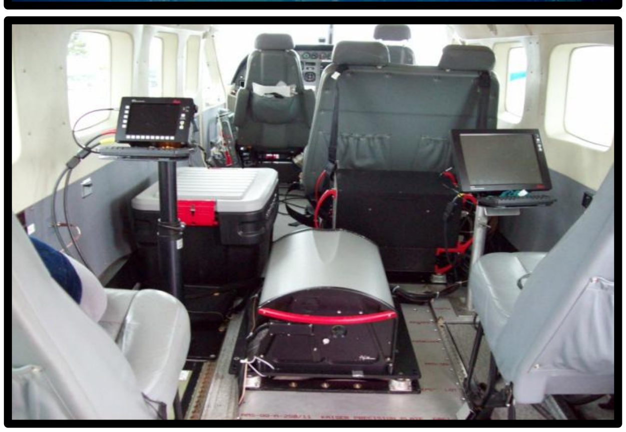
2. Acquisition

Table 1. Flight dates and times for LiDAR acquisition with Cle Elum Lake Reservoir Discharges and Gauge Heights

AOI	LiDAR Flight Date	Gauge ID	Time of Reading	Gauge Ht	Discharge (CFS)
Cle Elum	04/26/12	CLE	17:00	8.05	2228
Cle Elum	04/26/12	CLE	17:15	8.05	2228
Cle Elum	04/26/12	CLE	17:30	8.05	2228
Cle Elum	04/26/12	CLE	17:45	8.06	2237
Cle Elum	04/26/12	CLE	18:00	8.06	2237
Cle Elum	04/26/12	CLE	18:15	8.06	2237
Cle Elum	04/26/12	CLE	18:30	8.06	2237
Cle Elum	04/26/12	CLE	18:45	8.06	2237
Cle Elum*	04/27/12	CLE	9:15	8.48	2640
Cle Elum*	04/27/12	CLE	9:30	8.48	2640
Cle Elum*	04/27/12	CLE	9:45	8.59	2750
Cle Elum*	04/27/12	CLE	10:00	8.6	2760
Cle Elum*	04/27/12	CLE	10:15	8.6	2760
Cle Elum*	04/27/12	CLE	10:30	8.61	2760

* Acquisition on this date was limited to upslope areas away from the active river channel. The active river channel was acquired entirely on 4/26 meeting the specified flow requirement of less than 2400 cubic feet per second.

2.1 Airborne Survey – Instrumentation and Methods



The LiDAR survey utilized a Leica ALS60 system mounted in a Cessna Caravan 208B. The Leica system was set to acquire ≥105,900 laser pulses per second (i.e. 105.9 kHz pulse rate) and flown from 700 – 900 meters above ground level (AGL) depending on weather and terrain, capturing a scan angle of ±13° to ±15° from nadir. These settings were developed to yield points with an average native pulse density of ≥8 pulses per square meter over terrestrial surfaces. It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return fewer pulses 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.

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

2.2 Ground Survey - Instrumentation and Methods

All monument certification and Public Land Survey oversight for the Cle Elum and Gold Creek LiDAR data collection was performed by WSI Professional Land Surveyor Chris Yotter-Brown (WA PLS #46328). The survey control plan utilized provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. The controls were set prior to the airborne missions. Monument coordinates are provided in Table 2 and shown in Figures 2 and 3.


Trimble GPS survey equipment configured for static collection in the Cle Elum Survey Area

During the airborne data collection missions, WSI conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over the selected monuments. The GNSS data were used to correct the continuous onboard measurements of the aircraft position recorded throughout the mission. 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 refine position accuracy.

2.2.1 Instrumentation

All static surveys were collected either with Trimble model R7 GNSS receivers equipped with a Zephyr Geodetic Model 2 RoHS antenna (OPUS ID: TRM57971.00) or with a Trimble model R8 GNSS receiver (OPUS ID: TRM_R8_GNSS). A Trimble model R8 GNSS unit was also used for collecting check points using real time kinematic (RTK) survey techniques. All GNSS measurements are made with dual frequency L1-L2 receivers with carrier-phase correction.

2.2.2 Monumentation

Established NGS survey benchmarks served as control points during LiDAR acquisition. In addition, one Washington Department of Transportation monument and one monument set by WSI served as additional control. Monuments selected were found to have good visibility and optimal location to support a LiDAR acquisition flight.

[1] Online Positioning User Service (OPUS) is run by the National Geodetic Survey to process corrected monument positions.

Table 2. Base Station control coordinates for the Cle Elum LiDAR data collection

Base Station ID	Datum: NAD83 (CORS96)		GRS80
	Latitude	Longitude	Ellipsoid Z (meters)
STN0053 (NGS)	47° 11′ 47.56652″ N	121° 05′ 01.57474″ W	623.432
STN0056 (NGS)	47° 11′ 41.78997″ N	121° 03′ 11.90775″ W	604.666
WSDOT_1003 (WA DOT)	47° 23′ 30.06615″ N	121° 22′ 57.60490″ W	751.200
GLD_CRK_01 (WSI)	47° 24′ 39.91301″ N	121° 24′ 39.58687″ W	874.556

2.2.3 Monument Accuracy

FGDC-STD-007.2-1998[2] at the 95% confidence level for this project:

Table 3. Federal Geographic Data Committee monument rating

St Dev $_{NE}$:	0.050 m
St Dev $_{Z}$:	0.020 m

2.3 Methodology

All control monuments were observed for a minimum of one survey session lasting no fewer than 4 hours and another session lasting no fewer than 2 hours, resulting in two independent data files to confirm monument location accuracy. Data were collected at a rate of 1Hz using a 10 degree mask on the antenna.

The ground crew uploaded the static data to be reviewed and processed by the WSI Professional Land Surveyor (PLS). Monument positions were triangulated through OPUS Project using 3 or more nearby CORS stations resulting in a fully adjusted position. After multiple sessions had been collected at each monument, accuracy and error ellipses were calculated from the OPUS reports. This resulted in a rating of the monuments, based on FGDC-STD-007.2-1998[3] Part 2 table 2.1 at the 95% confidence level. When a statistical stable position was found, CORPSCON[4] 6.0.1 software was used to convert the UTM positions to geodetic coordinates.

Ground based RTK checkpoints and aircraft mounted GPS measurements were made during periods with PDOP[5] less than or equal to 3.0, with at least 6 satellites in view of both a stationary reference receiver and the roving receiver. Periods of low precision during static sessions were removed during OPUS processing. RTK positions were collected on bare earth locations such as paved or hard packed gravel roads where the ground was clearly visible (and was likely to remain visible) during the data acquisition and RTK measurement period. These checkpoints were taken no closer than one meter to any nearby terrain breaks such as road edges or drop offs.

[2] Federal Geographic Data Committee Draft Geospatial Positioning Accuracy Standards (Part 2 table 2.1)
[3] Federal Geographic Data Committee Draft Geospatial Positioning Accuracy Standards
[4] U.S. Army Corps of Engineers , Army Geospatial Center software
[5]PDOP: Point Dilution of Precision is a measure of satellite geometry, the smaller the number the better the geometry between the point and the satellites.

Figure 2. RTK check points and control monument locations used for Cle Elum acquisition, processing, and accuracy checks.

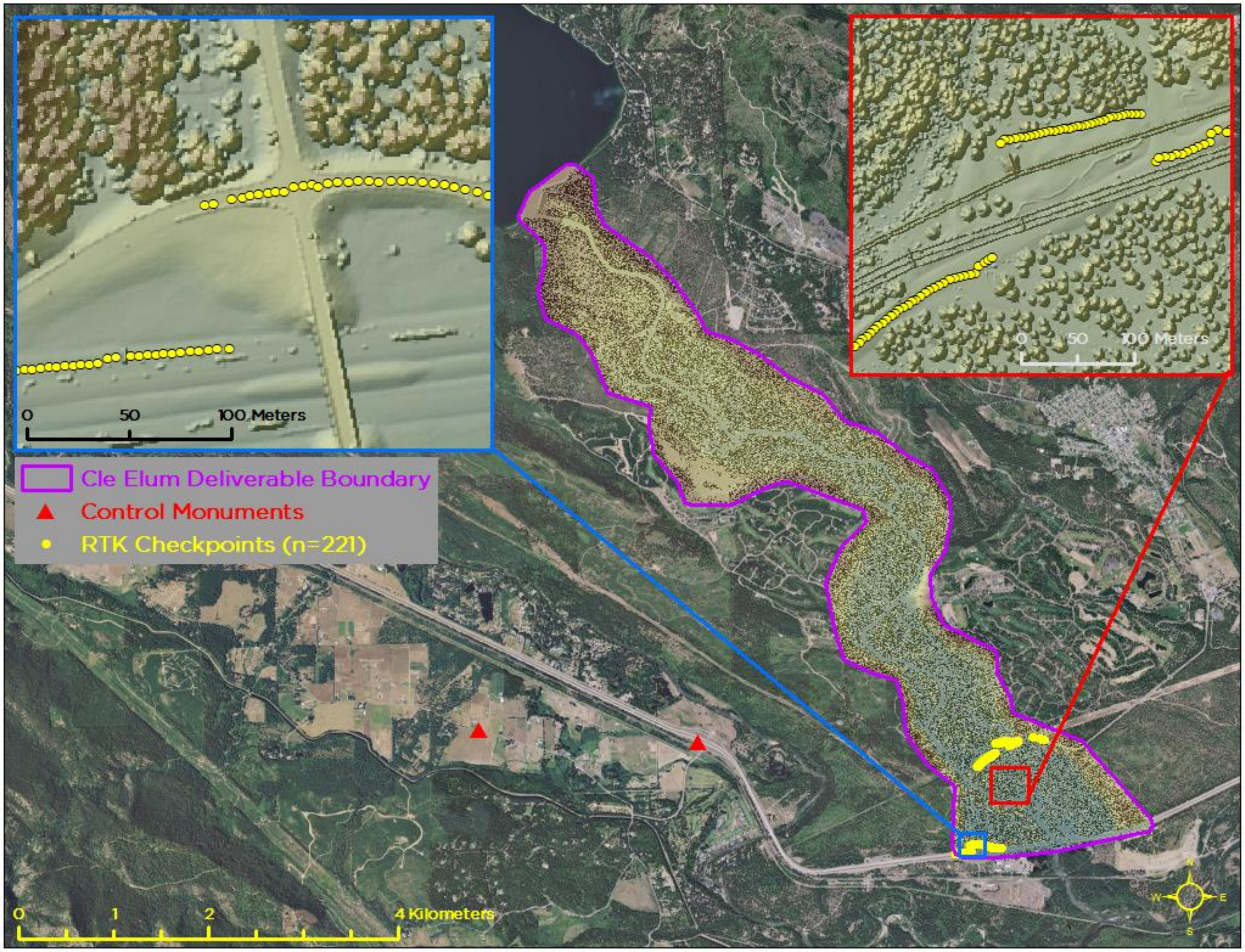
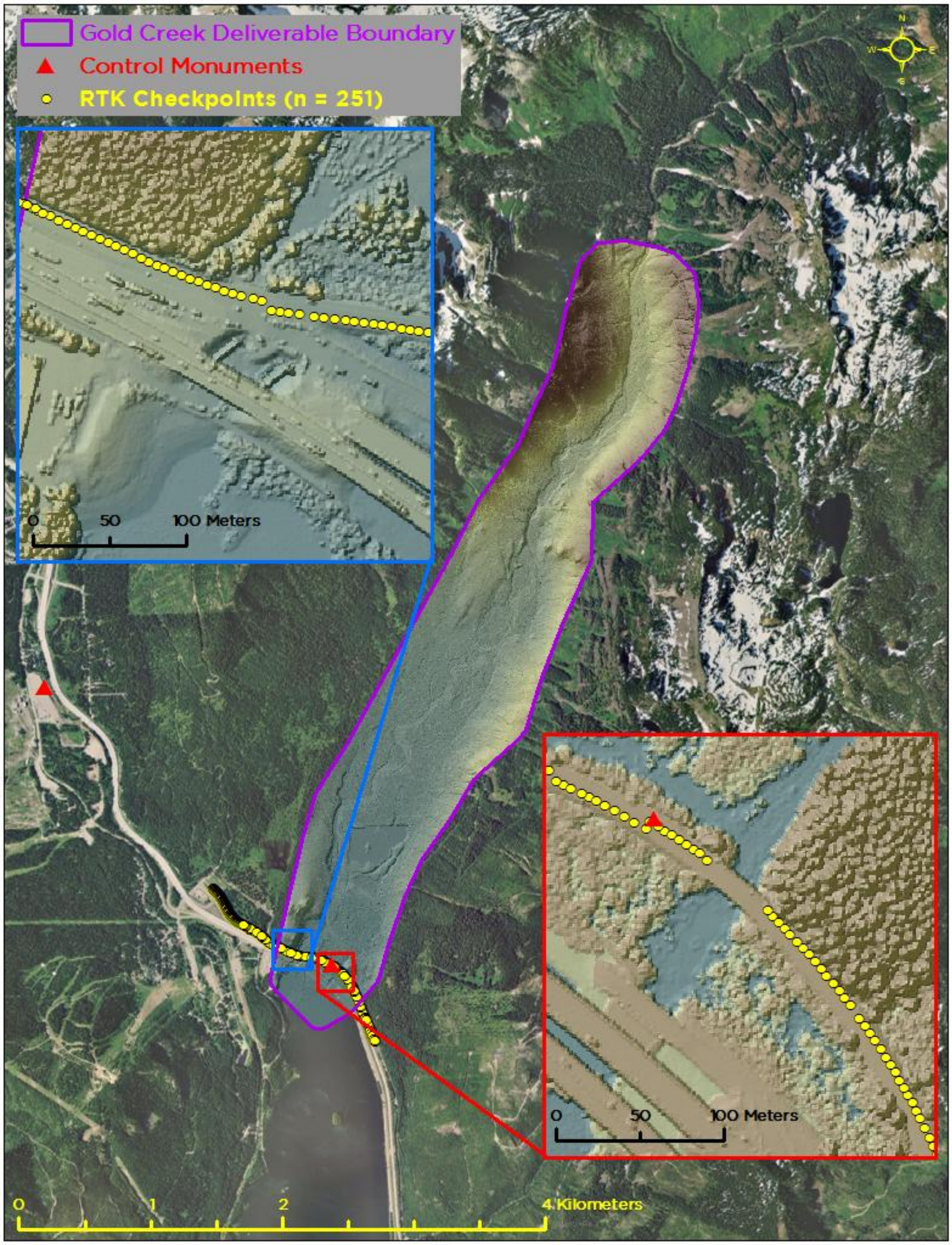


Figure 3. RTK check points and control monument locations used for Gold Creek acquisition, processing, and accuracy checks



3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

Resolved kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.
Software: Waypoint GPS v.8.3, Trimble Business Center v.2.6
Developed a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor head position and attitude were calculated throughout the survey. The SBET data were used extensively for laser point processing.
Software: IPAS TC v.3.1
Calculated laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Created raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format. Data were converted to orthometric elevations (NAVD88) by applying a Geoid09 correction.
Software: ALS Post Processing Software v.2.74
Imported raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter for pits/birds. Ground points were then classified for individual flight lines (to be used for relative accuracy testing and calibration).
Software: TerraScan v.12.004
Using ground classified points per each flight line, the relative accuracy was tested. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations were performed on ground classified points from paired flight lines. Every flight line was used for relative accuracy calibration.
Software: TerraMatch v.12.001
Position and attitude data were imported. Resulting data were classified as ground and non-ground points. Statistical absolute accuracy was assessed via direct comparisons of ground classified points to ground RTK survey data.
Software: TerraScan v.12.004, TerraModeler v.12.002
Bare Earth models were created as a triangulated surface and exported as ArcInfo ASCII grids at a 1-meter pixel resolution. Highest Hit models were created for any class at 1-meter grid spacing and exported as ArcInfo ASCII grids.
Software: TerraScan v.12.004, ArcMap v. 10.0, TerraModeler v.12.002

3.2 Aircraft Kinematic GPS and IMU Data

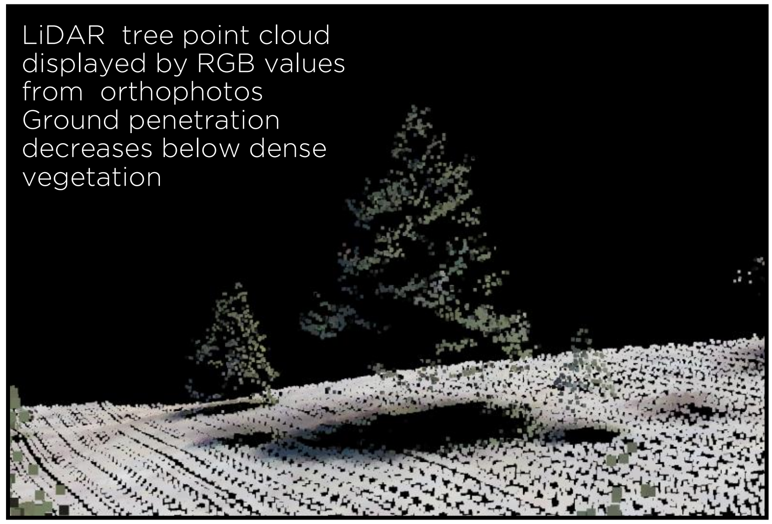
Kinematic corrections for the aircraft were processed in Waypoint GPS v.8.3 and tied to the post-processed control monument locations. IPAS TC v.3.1 was used to develop a trajectory file that includes corrected aircraft position and attitude information. The trajectory data for the entire flight survey session were incorporated into a final smoothed best estimated trajectory (SBET) file that contains accurate and continuous aircraft positions and attitudes.

3.3 Laser Point Processing

Laser point coordinates were computed and returns (first through fourth) were assigned an associated (x, y, z) coordinate along with unique intensity values (0-255). The data were output into large LAS v. 1.2 files with each point maintaining the corresponding scan angle, return number (echo), intensity, and x, y, z (easting, northing, and elevation) information.

These initial laser point files were too large for subsequent processing. To facilitate laser point processing, a gridded tile network was created to divide the dataset into manageable sizes (< 500 MB). Laser point data were imported into the tile network using TerraScan, and manual calibration was performed to assess the system offsets for pitch, roll, heading and scale (mirror flex). Using a geometric relationship developed by WSI, each of these offsets was resolved and corrected if necessary. LiDAR data coverage was subsequently reviewed to ensure adequate density and positional accuracy throughout the Cle Elum River and Gold Creek survey sites.

LiDAR points were then filtered for noise, pits (artificial low points), and birds (true birds as well as erroneously high points) by screening for absolute elevation limits, isolated points and height above ground.



Next, Internal calibration was refined using TerraMatch. Points from overlapping lines were tested for internal consistency and final adjustments were made for system misalignments (i.e., pitch, roll, heading offsets and scale). Automated sensor attitude and scale corrections yielded 3-5 cm improvements in the relative accuracy. Once system misalignments were corrected, vertical GPS drift was then resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy.

TerraScan was then used to classify laser returns into a ground class based on geometric constraints used to identify near earth surface points. The resulting bare earth (ground) model was visually inspected and additional ground point modeling was performed in site-specific areas to improve ground detail. This manual editing of ground often occurs in areas with known ground modeling deficiencies, such as: bedrock outcrops, cliffs, deeply incised stream banks, and dense vegetation. In some cases, automated ground point classification inaccurately included known vegetation (i.e., understory, low/dense shrubs, etc.). These points were manually reclassified as default. In addition, each tile was manually inspected for remaining pits, birds, and spurious points that were consequently removed. In a tile that contained approximately 7.5-9.0 million points, an average of 50-100 points were typically found to be artificially low or high.

4. LiDAR Accuracy Assessment

Laser point absolute accuracy is largely a function of laser noise and relative accuracy. To minimize these contributions to absolute error, a number of noise filtering and calibration procedures were performed (Appendix A). The LiDAR quality assurance process compares the calibrated LiDAR data to the collected RTK check points. The divergence between an RTK check points and the closest ground classified LiDAR point is used to calculate absolute accuracy statistics (Section 5.4). A total of 472 RTK GPS measurements were collected by WSI on hard surfaces distributed among multiple flight swaths.

Statements of statistical accuracy apply to fixed terrestrial surfaces only and may not be applied to areas of dense vegetation or steep terrain.

5. Study Area Results

Summary statistics for accuracy (relative and absolute) and point resolution of the LiDAR data are presented below in terms of central tendency, variation around the mean, and the spatial distribution of the data (for point resolution by delivery tile).

5.1 Data Summary

Table 4. LiDAR Resolution and Accuracy - Specifications and Achieved Values

	Targeted	Achieved
Resolution:	≥ 8 points/m^2	10.40 points/m^2
Vertical Accuracy (RMSE)	<15 cm	2.2 cm

5.2 Data Density/Resolution

The average first-return density of the delivered LiDAR data is 10.40 points per square meter (Table 5). The initial datasets, acquired to be ≥8 points per square meter, were filtered as described previously to remove spurious or inaccurate points. 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 (delivered density) than the laser originally emitted (native density).

Ground classifications were derived from automated ground surface modeling and manual, supervised classifications where it was determined that the automated model had failed. Ground return densities will be lower in areas of dense vegetation, water, or buildings. Figures 8 and 9 show the distribution of average first return and ground point densities for each tile.

Cumulative data resolution for the Cle Elum River and Gold Creek LiDAR data:

Table 5. Native and ground density table for the Cle Elum River and Gold Creek AOIs

	Native	Ground
Cle Elum River	10.76 points/m^2	2.77 points/m^2
Gold Creek	9.71 points/m^2	0.80 points/m^2
Cumulative	10.40 points/m^2	2.08 points/m^2

Figure 4. Cle Elum River density distribution for first return classified laser points

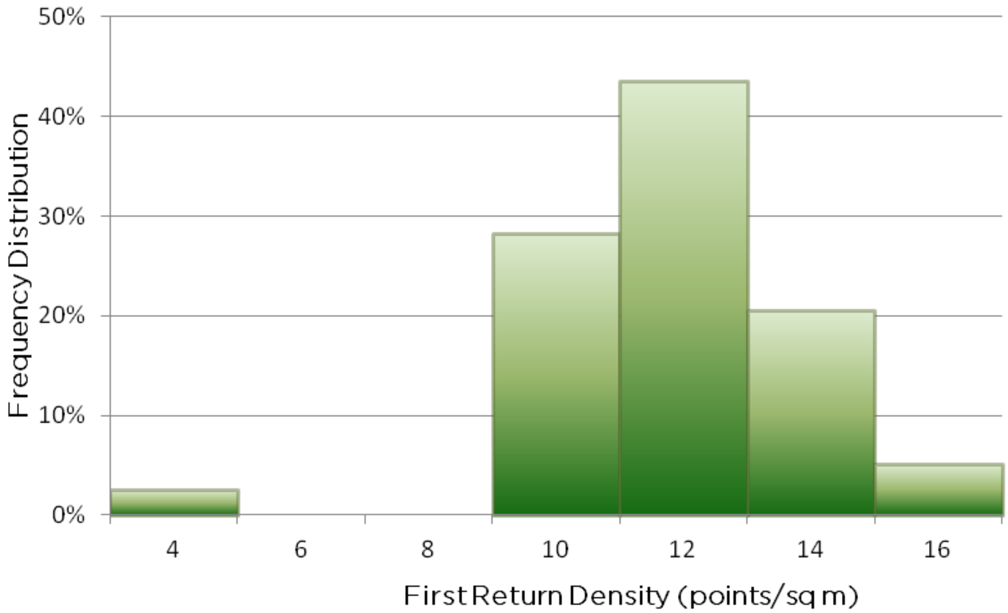


Figure 5. Gold Creek density distribution for first return classified laser points

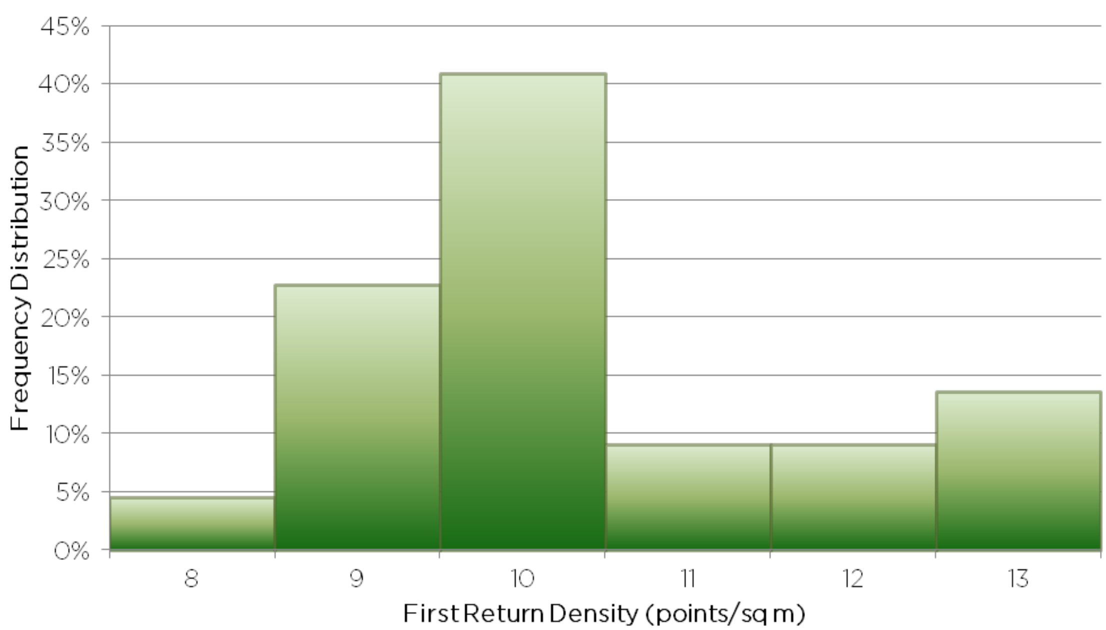


Figure 6. Cle Elum River density distribution for ground classified laser points

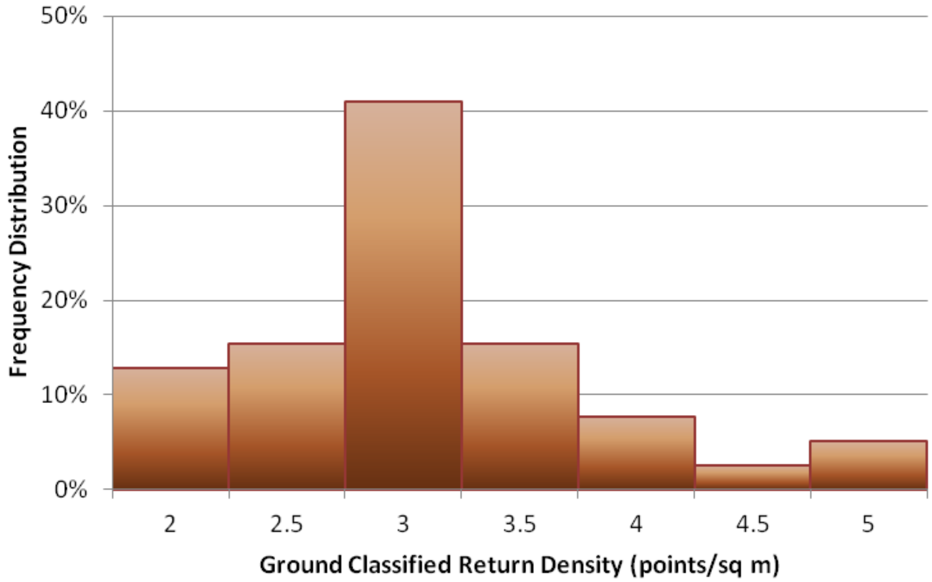


Figure 7. Gold Creek density distribution for ground classified laser points

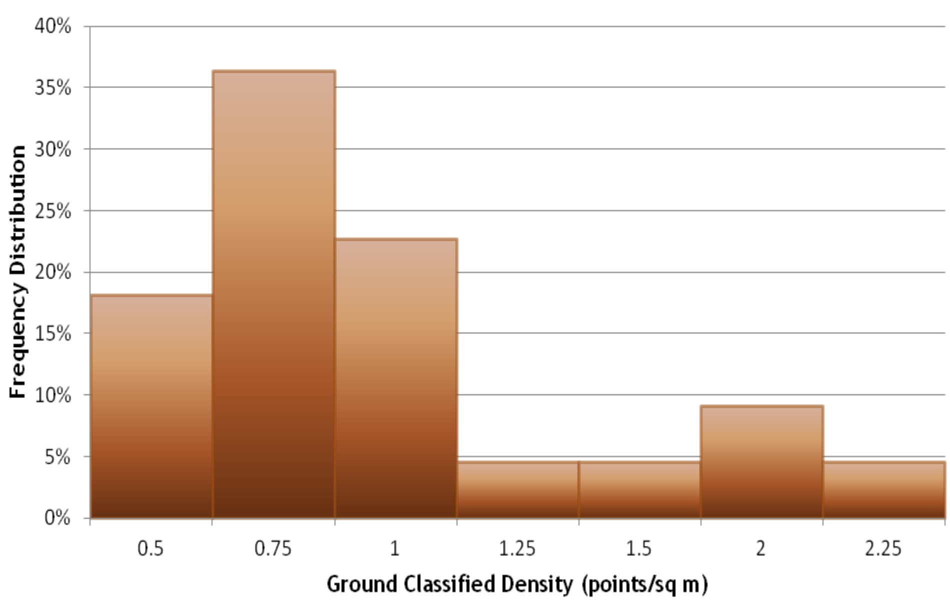


Figure 8. Density distribution map for the Cle Elum River AOI

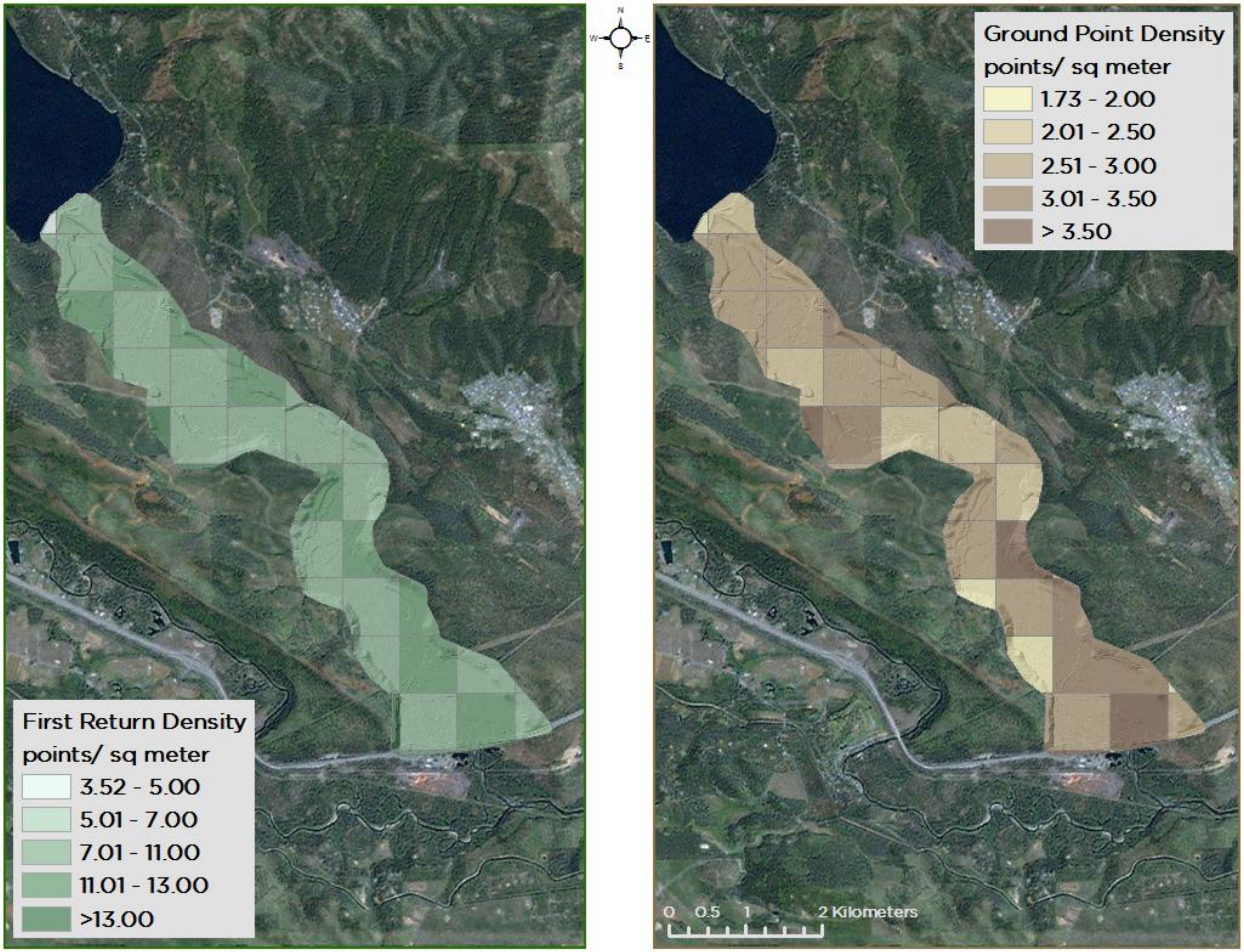
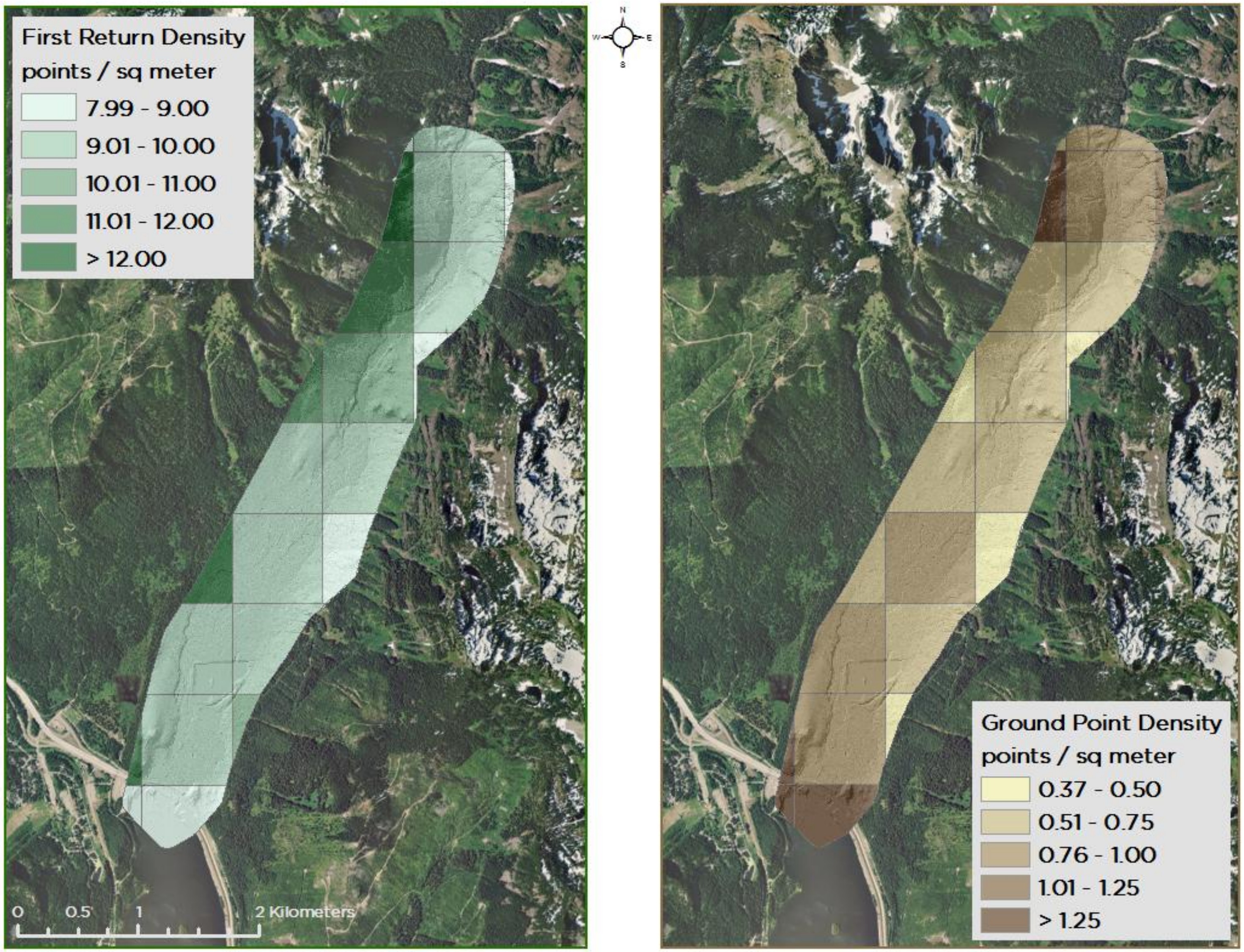


Figure 9. Density distribution map for the Gold Creek AOI



5.3 Relative Accuracy Calibration Results

Relative accuracy statistics for the Cle Elum River and Gold Creek datasets measure the full survey calibration including areas outside the delivered boundary.

	Cle Elum	Gold Creek	Cumulative
Average	0.017	0.063 m	0.027 m
RMSE	0.017	0.070 m	0.043 m
Median	0.017	0.064 m	0.018 m
1 sigma (σ)	0.001	0.016 m	0.026 m
1.96 sigma (σ)	0.002	0.031 m	0.051 m

Figure 10. Distribution of relative accuracies per flight line for Cle Elum River, non slope-adjusted

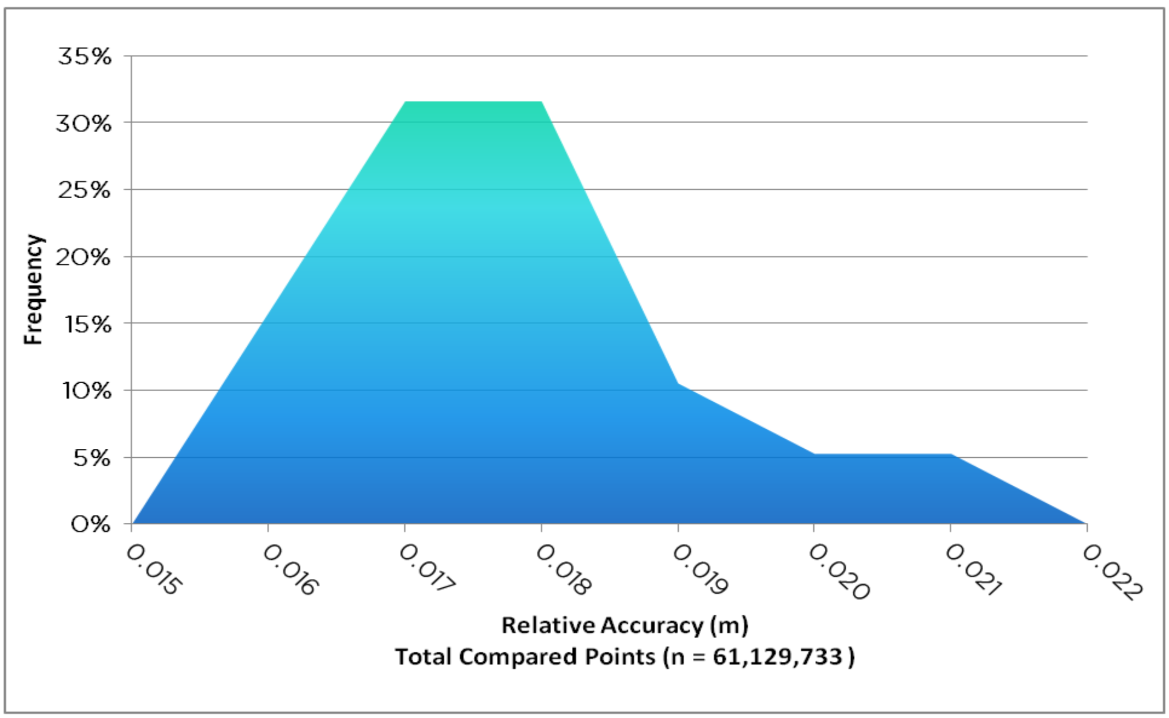
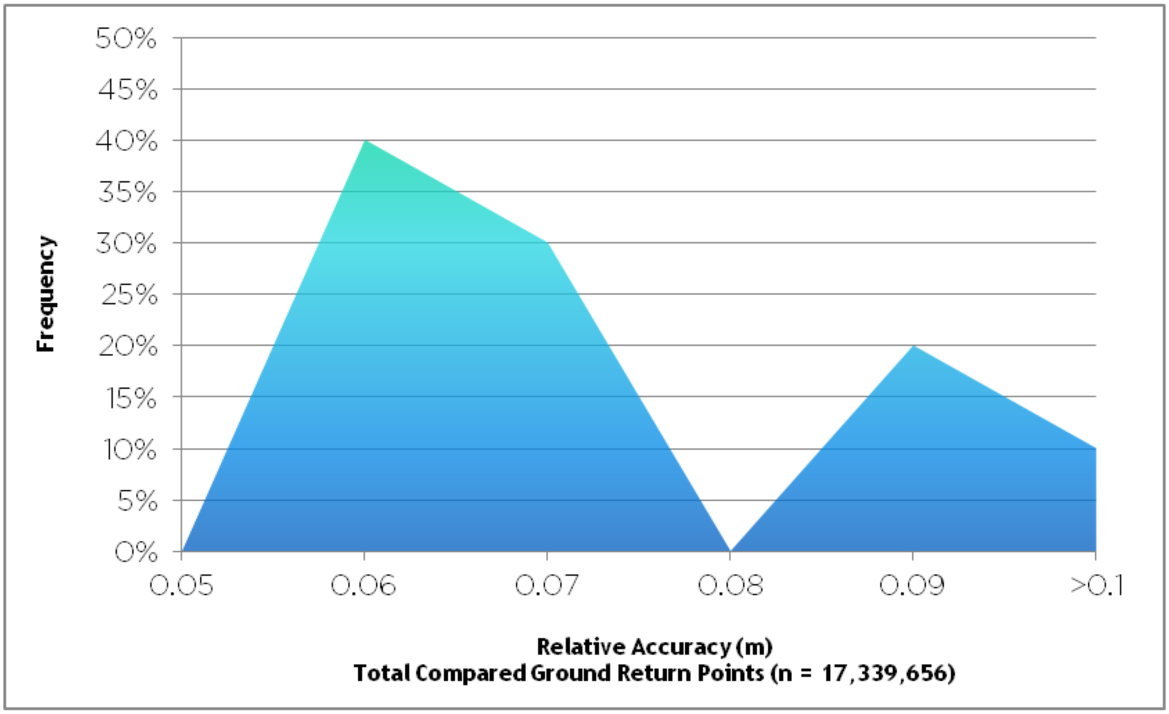


Figure 11. Distribution of relative accuracies per flight line for Gold Creek, non slope-adjusted



5.4 Absolute Accuracy

Absolute accuracies for Cle Elum River and Gold Creek LiDAR:

Table 6. Absolute Accuracy – Deviation between laser points and RTK hard surface survey points

	Cle Elum	Gold Creek	Cumulative
RTK (n)	221	251	472
Average	-0.010 m	-0.001 m	-0.005 m
RMSE	0.019 m	0.029 m	0.022 m
Minimum	-0.057 m	-0.078 m	-0.078 m
Maximum	0.030 m	0.087 m	0.087 m
1 sigma (σ)	0.017 m	0.029 m	0.024 m
1.96 sigma (σ)	0.033 m	0.057 m	0.048 m

Figure 12. Absolute Accuracy - Histogram Statistics for Cle Elum River

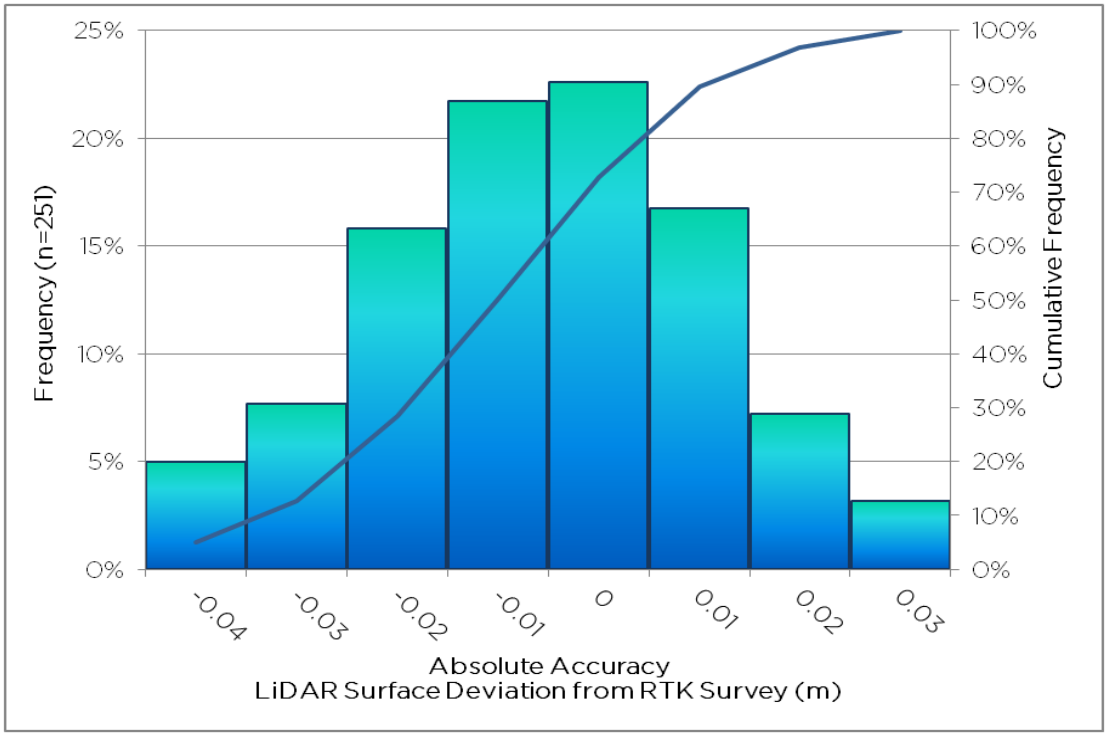
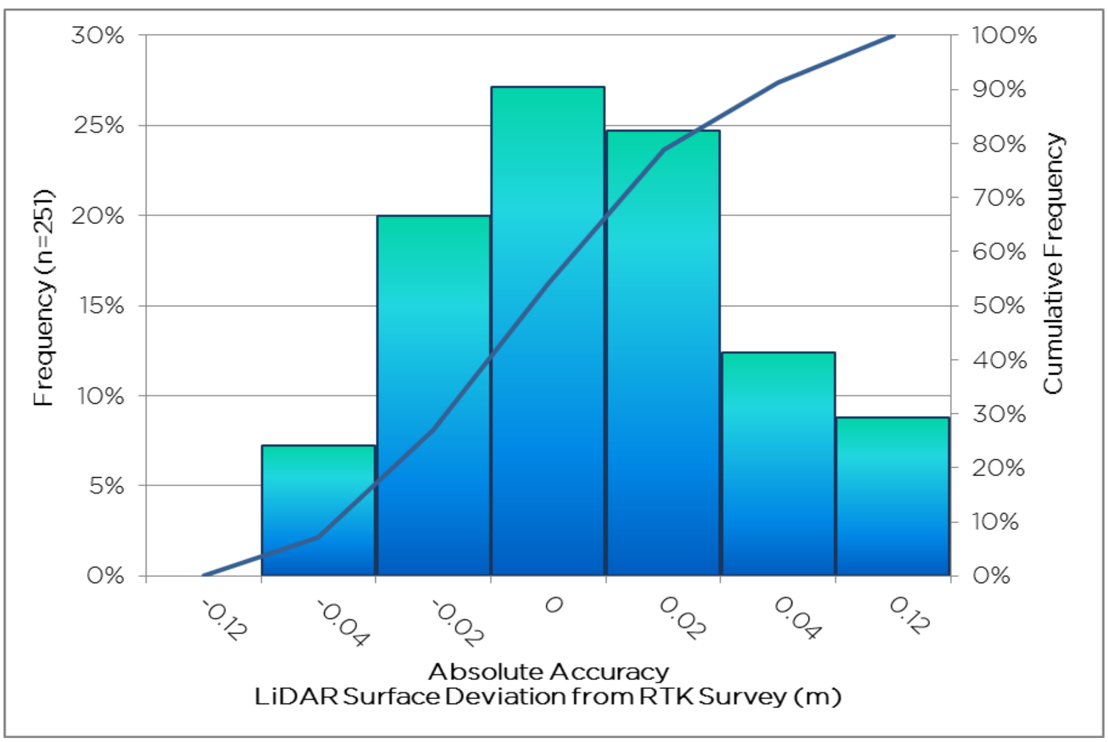


Figure 13. Absolute Accuracy - Histogram Statistics for Gold Creek



6. Projection/Datum and Units

Projection:		UTM Zone 10, Meters
Datum	Vertical:	NAVD88 Geoid09
	Horizontal:	NAD83 (CORS96)
Units:		Meters

7. Deliverables

Point Data:	•All laser returns classified to ground (LAS v. 1.2 format; 750m^2 tile delineation)
Vector Data:	•Total area flown (ESRI shapefile format) •LiDAR Index (ESRI shapefile format)
Raster Data:	•Bare Earth Model (1m ESRI GRID format) •Highest Hit Model (1m ESRI GRID format) •Intensity Image (GeoTIFF format, 0.5m resolution)
Data Report:	•Full report containing introduction, methodology, and accuracy

8. Certifications

WSI provided LiDAR services for the Cle Elum and Gold Creek study area 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 dully 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.

8/16/2012

Christopher W. Yotter-Brown, PLS Oregon & Washington
WSI
Portland, OR 97204

CHRISTOPHER W. YOTTER-BROWN
STATE OF WASHINGTON
46328
REGISTERED
PROFESSIONAL LAND SURVEYOR

Renews: 12/21/2012

9. Selected Images

Figure 14. 3D point cloud colored by 2009 NAIP imagery, looking northwest at the Cle Elum Dam

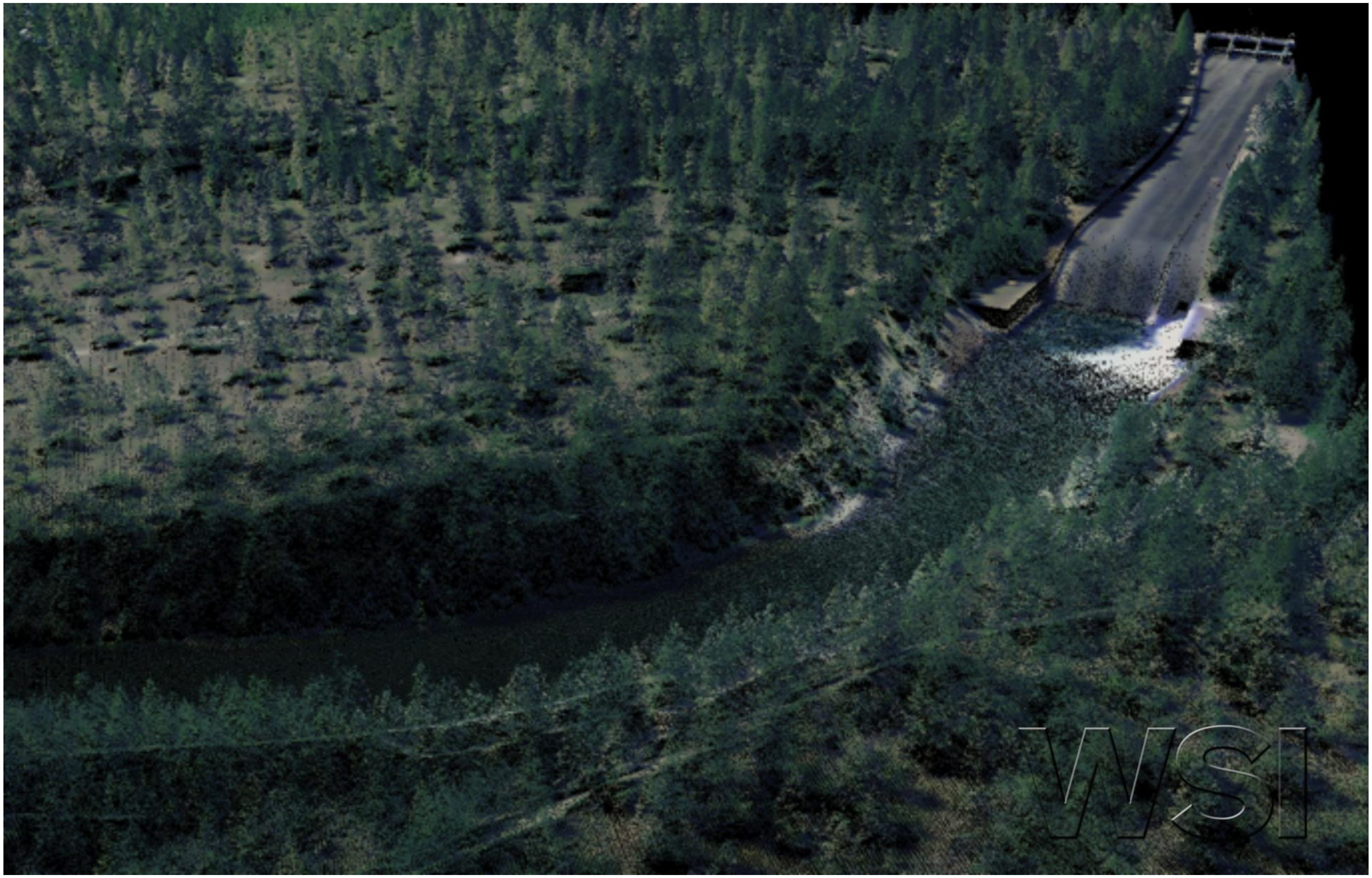


Figure 15. 3D point cloud colored by RGB values extracted from 2009 NAIP imagery, looking south over the Cle Elum River

Figure 16. 3D point cloud colored by 2009 NAIP imagery of the Gold Creek drainage and riparian area looking south toward Gold Creek Road and Trillium Loop.

Figure 17. 3D point cloud colored by 2009 NAIP imagery of an aerial view of Gold Creek and the Gold Creek Valley.

10. Glossary

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

11. Citations

Soininen, A. 2004. TerraScan User's Guide. TerraSolid.

Appendix A

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). See Appendix A for further information on sources of error and operational measures that can be taken to improve relative accuracy.

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 zs are normally distributed, thus we also consider the skew and kurtosis of distributions when evaluating error statistics.

Appendix B

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 315^{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.