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April 11, 2014

Cedar River Watershed & Floodplain, Lake Youngs Reservoir, & SCL/Tolt Reservoir Study Areas LiDAR

Technical Data Report – Delivery 1

Puget Sound Regional Council PSRC

quantum SPATIAL

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Cover Photo: A view looking at the confluence of the Skykomish and Snoqualmie Rivers. The gridded bare earth model is colored by elevation and overlain above ground LiDAR point returns.

INTRODUCTION

This photo taken by QSI acquisition staff shows the mixed conifer landscape in the Cedar Watershed LiDAR site in the Cascade foothills of Washington.

In September 2013, WSI, a Quantum Spatial company (QSI), was contracted by the Puget Sound LiDAR Consortium (PSLC) to collect Light Detection and Ranging (LiDAR) data over three areas of interest (AOIs) in the greater Seattle, Washington area. The individual AOIs include the Cedar River Watershed and Floodplain, Lake Youngs Reservoir, and the SCL/Tolt Reservoir, herein all referred to as the Cedar Watershed LiDAR project (Figure 1). Data were collected to aid PSLC in assessing the topographic and geophysical properties of the study area.

This report accompanies the delivered LiDAR data for a section of the SCL/Tolt Reservoir AOI, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset, including LiDAR accuracy and density. Subsequent data delivery will follow including the remainder of the SCL/Tolt Reservoir AOI, the Cedar River Watershed, and Lake Youngs Reservoir AOIs. Acquisition dates and acreage are shown in Table 1, and a complete list of contracted deliverables provided to PSLC is shown in Table 2.

Table 1: Acquisition dates, acreage, and data types collected on the Cedar Watershed LiDAR site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Cedar Watershed Delivery 1	108,769	111,737	12/11/13, 12/12/13, 12/16/13, and 02/03/14 through 02/06/14	LiDAR

Deliverable Products

Table 2: Products delivered to PSLC for the Cedar Watershed LiDAR site

Cedar Watershed LiDAR Products[1] Projection: Washington State Plane North Horizontal Datum: NAD83 (CORS96) Vertical Datum: NAVD88 (GEOID03) Units: US Survey Feet	
Points	LAS v 1.2 • All Returns Comma Delimited ASCII Files • All Returns (*asc) • Ground Returns(*gnd)
Rasters	3.0 Foot ESRI Grids • Bare Earth Model • Highest Hit Model 1.5 Foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index • DEM Tile Index • Smooth Best Estimate Trajectory (SBETs) • Ground Control Points

**T*he data were created in NAD83 (CORS96), but for GIS purposes are defined as NAD83 (HARN) as per PSLC specifications.*

[1] Additional contracted products will be included with the final delivery, including a hydroflattened and hydroenforced bare earth model and hillshade, and a 3D hydrolines shjapefile.

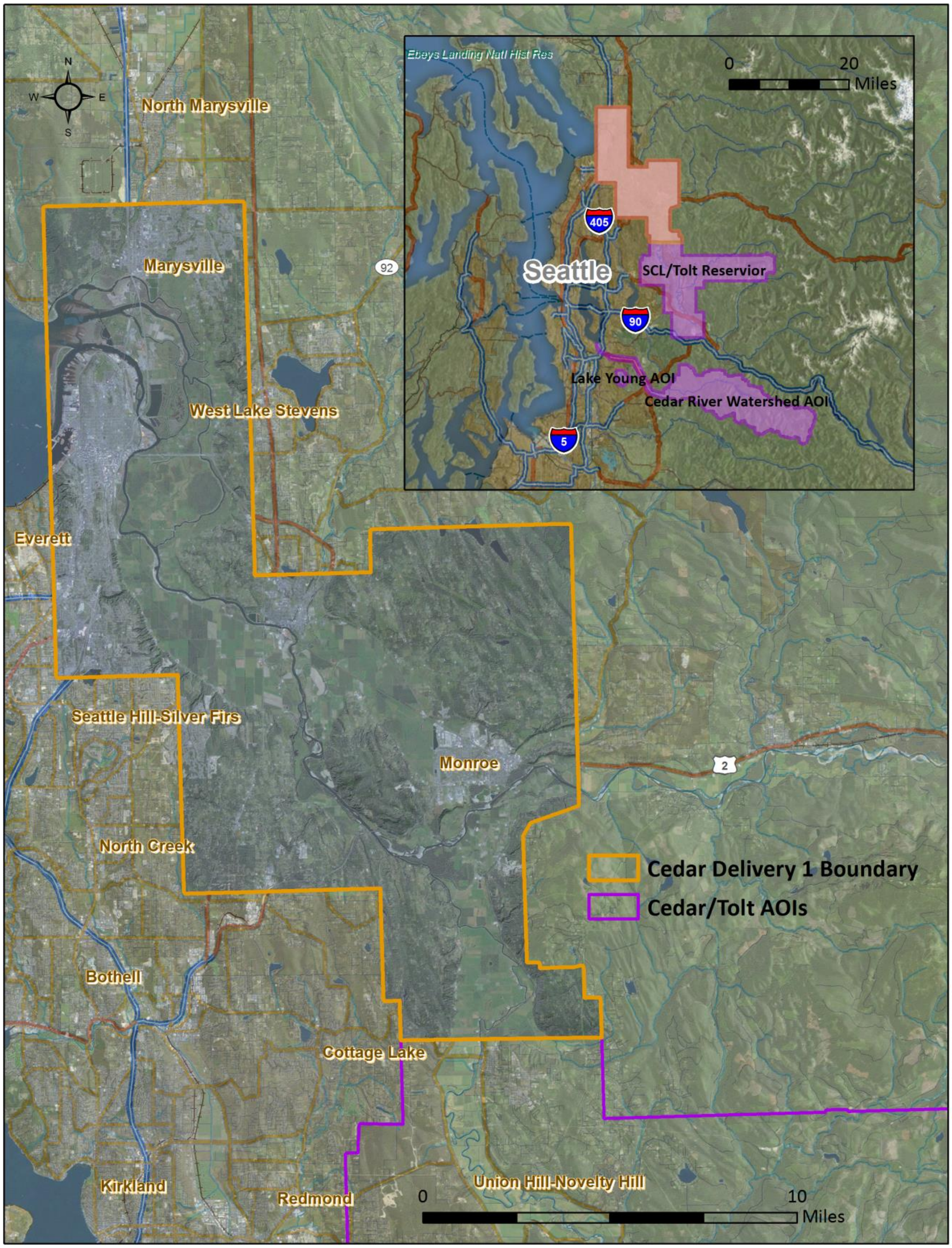

Figure 1: Location map of the Cedar Watershed LiDAR site in Washington

QSI's ground acquisition equipment set up in the Cedar Watershed LiDAR study area.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Cedar Watershed LiDAR study area at the target point density of ≥8.0 points/m^2 (0.74 points/ft^2). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted in order to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including safety, private property access, and decommissioned roads were reviewed.

Ground Control

QSI-Established Monument

Ground control, including monumentation and ground survey points (GSP), are conducted to support the airborne acquisition process. Ground control data are used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data products.

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 survey points using real time kinematic (RTK) and post processed kinematic (PPK) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized two existing monuments and established ten new monuments for the Cedar Watershed LiDAR project (Table 3, Figure 2). New monumentation was set using 5/8” x 30” rebar topped with stamped 2" aluminum caps. QSI’s professional land surveyor, Chris Brown (WA PLS# 46328 LS) oversaw and certified the establishment of all monuments.

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

Monument ID	Latitude	Longitude	Ellipsoid (meters)
ASPI_CP_6	47° 59' 08.15207"	-122° 09' 19.19555"	-21.454
CEDAR_01	47° 22' 19.42501"	-121° 35' 07.03373"	1262.820
CEDAR_02	47° 20' 17.49485"	-121° 36' 25.35834"	1260.978
CEDAR_03	47° 24' 15.79336"	-121° 45' 41.99196"	972.649
CEDAR_04	47° 23' 46.53547"	-121° 46' 37.89910"	1142.593
CEDAR_05	47° 25' 19.90148"	-121° 59' 08.47802"	131.068
CEDAR_06	47° 25' 19.30277"	-122° 04' 52.60433"	119.181
CEDAR_07	47° 41' 11.51397"	-121° 59' 00.88994"	-8.261
CEDAR_08	47° 58' 33.92731"	-122° 10' 27.10333"	-21.965
CEDAR_9	47° 48' 30.30271"	-121° 59' 57.61062"	-11.421
CEDAR_10	47° 48' 48.46508"	-122° 03' 58.91976"	87.133
KNG_05_B	47° 39' 31.49570"	-121° 55' 10.85389"	-4.178

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[2]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

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.[3] 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 is shown in Table 4.

Table 4: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.050 m

For the Cedar Watershed LiDAR project, the monument coordinates contributed no more than 5.4 cm of positional error to the geolocation of the final GSP and LiDAR, with 95% confidence.

Ground Survey Points (GSP)

Ground survey points were collected using real time kinematic (RTK) and post-processed kinematic (PPK) survey techniques. A Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R8 or R10 GNSS receiver. All GSP 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 and PPK data, the rover records data while stationary for five seconds, then calculates 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.

GSP were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSP were collected within as many flightlines as possible, however the distribution of GSP depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

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

[3] 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

Table 5: 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	Static, Rover
Trimble R10	Integrated Antenna R10	TRMR10	Rover

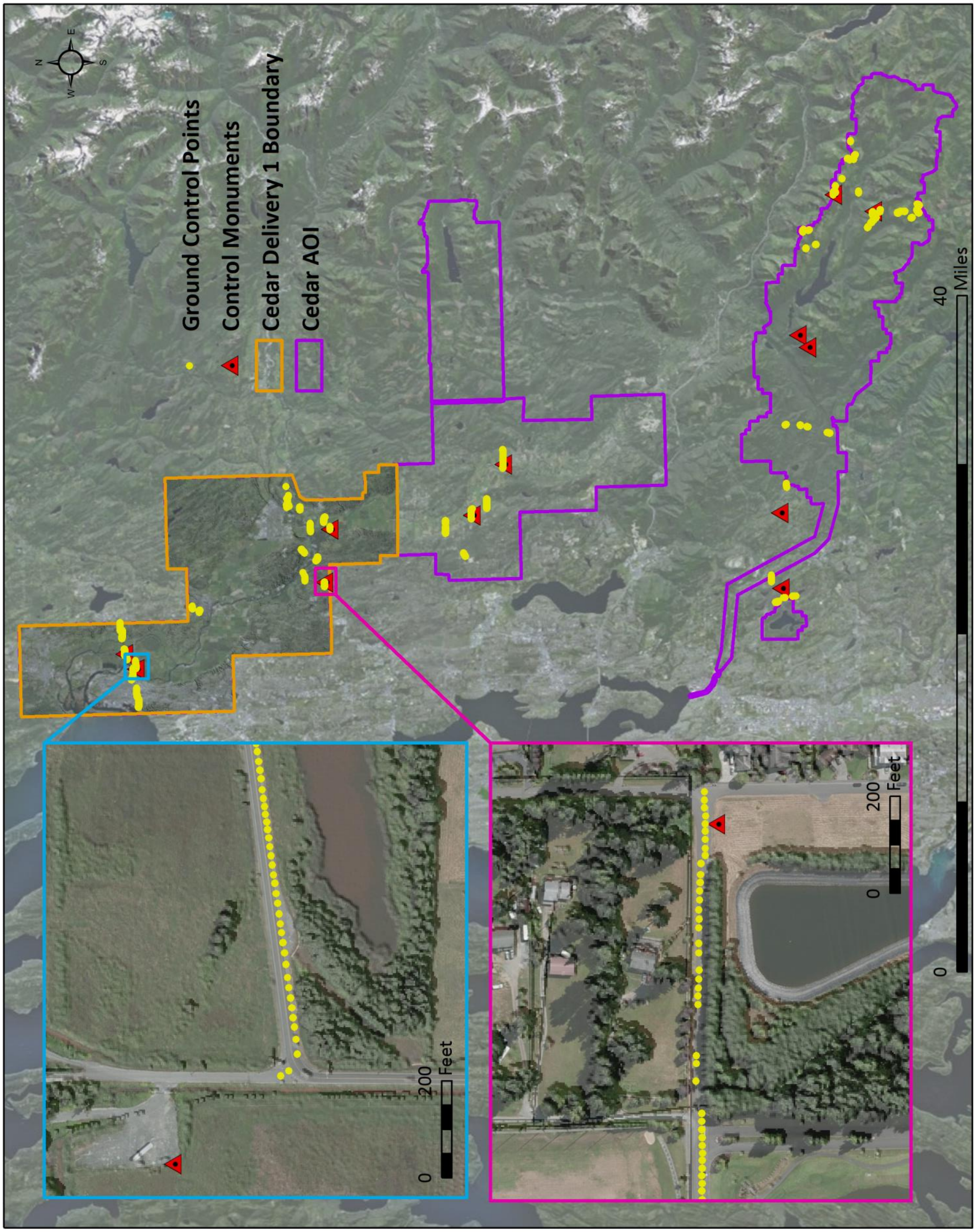


Figure 2: Ground control location map

Airborne Survey

LiDAR

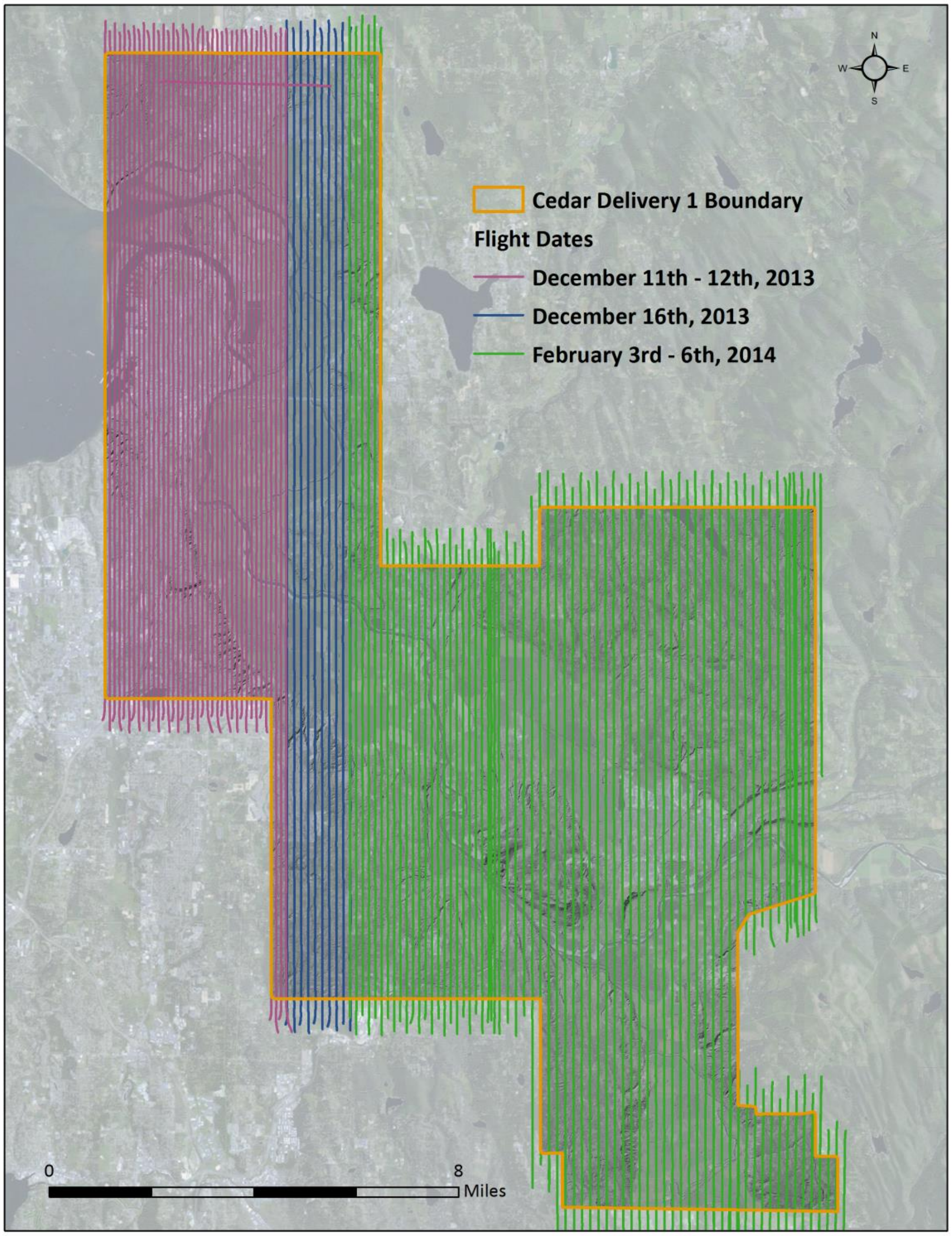
The LiDAR survey was accomplished using a Leica ALS60 system mounted in a Partenavia, and a Leica ALS70 system also mounted in a Partenavia. Table 6 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Cedar Watershed LiDAR project area. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The Leica ALS60 laser system records up to four range measurements (returns) per pulse, and the Leica ALS70 laser system can record unlimited range measurements (returns) per pulse, but typically does not record more than 7 returns per pulse. All discernible laser returns were processed for the output dataset. The discrepancy between native and delivered density will vary depending on terrain, land cover, and the prevalence of water bodies.

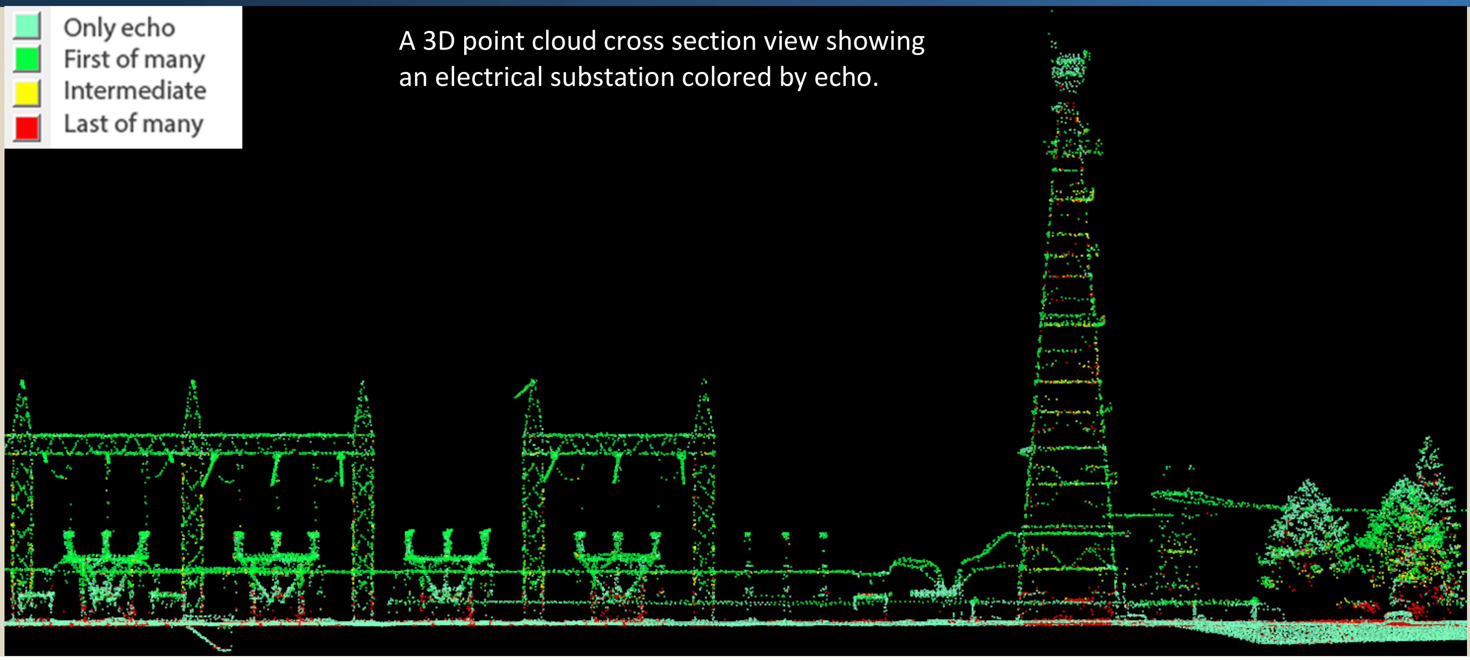
Table 6: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications			
Acquisition Dates	December 11 – 12, 2013	December 16, 2013	February 3 – 6, 2014
Aircraft Used	Partenavia	Partenavia	Partenavia
Sensor	Leica ALS60	Leica ALS60	Leica ALS70
Survey Altitude (AGL)	900 m	1,400 m	1,000 – 1,300 m
Target Pulse Rate	95 – 106 kHz	152 kHz	201 – 275.6 kHz
Sensor Configuration	Single Pulse in Air (SPiA)	Multiple Pulse in Air (MPiA)	Single Pulse in Air (SPiA)
Laser Pulse Diameter	21 cm	32 cm	23 – 30 cm
Mirror Scan Rate	65.9 Hz	66.2 Hz	42.7 – 59.7 Hz
Field of View	26°	24°	30°
GPS Baselines	≤13 nm	≤13 nm	≤13 nm
GPS PDOP	≤3.0	≤3.0	≤3.0
GPS Satellite Constellation	≥6	≥6	≥6
Maximum Returns	4	4	Unlimited
Intensity	8-bit	8-bit	8-bit
Resolution/Density	Average 8 pulses/m^2	Average 8 pulses/m^2	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm	$RMSE_Z$ ≤ 15 cm	$RMSE_Z$ ≤ 15 cm

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time. Flightline paths and dates are shown in Figure 3.

Figure 3: Breakdown of flightlines for delivery 1 of the Cedar Watershed LiDAR site





LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8.

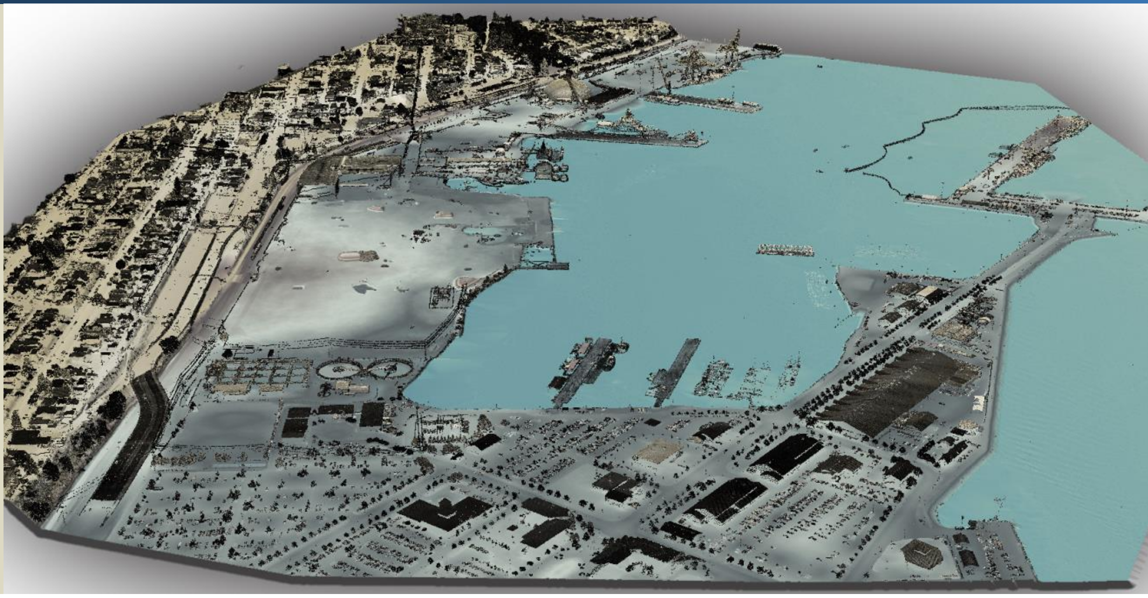
Table 7: ASPRS LAS classification standards applied to the Cedar Watershed LiDAR dataset

Classification Number	Classification Name	Classification Description
1	Default/ Unclassified	Laser returns that are not included in the ground class, composed of vegetation and man-made structures
2	Ground	Bare earth ground, determined by a number of automated and manual cleaning algorithms

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.3.10 Geographic Calculator 2013
Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	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. Convert data to orthometric elevations by applying a geoid03 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. Classify ground points for individual flight lines	TerraScan v.14.001
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.14.001
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 control survey data.	TerraScan v.14.001 TerraModeler v. 14.001
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points Export all surface models as ESRI GRIDs at a 3 foot pixel resolution.	TerraScan v. 14.001 ArcMap v. 10.1 TerraModeler v. 14.001
Export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	TerraScan v. 14.001 ArcMap v. 10.1 TerraModeler v. 14.001

A view looking South at the Everett Naval Station in the Cedar Watershed LiDAR site. The gridded bare earth model is overlain with above ground LiDAR point returns.



LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 points/ft^2). First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse are not considered in first return density analysis. Pulse density distribution will vary within the study area due to laser scan pattern and flight conditions. Additionally, some types of surfaces (e.g., breaks in terrain, water and steep slopes) may return fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return represents the bare earth surface.

The density of ground-classified LiDAR returns was also analyzed for this project. Ground-classified return density is dictated by a combination of variables. Terrain character, land cover, and ground surface reflectivity all influence the density of ground surface returns. In vegetated areas fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of LiDAR data for the Cedar Watershed LiDAR project was 1.15 points/ft^2 (12.41 points/m^2) while the average ground classified density was 0.25 points/ft^2 (2.67 points/m^2) (Table 9). The statistical distribution of first return densities (Figure 4) and classified ground return densities (Figure 5) are portrayed. Also presented are the spatial distribution of average first return densities (Figure 6) and ground return densities (Figure 7) for each 30 m by 30 m cell.

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	1.15 points/ft^2 12.41 points/m^2
Ground Classified	0.25 points/ft^2 2.67 points/m^2

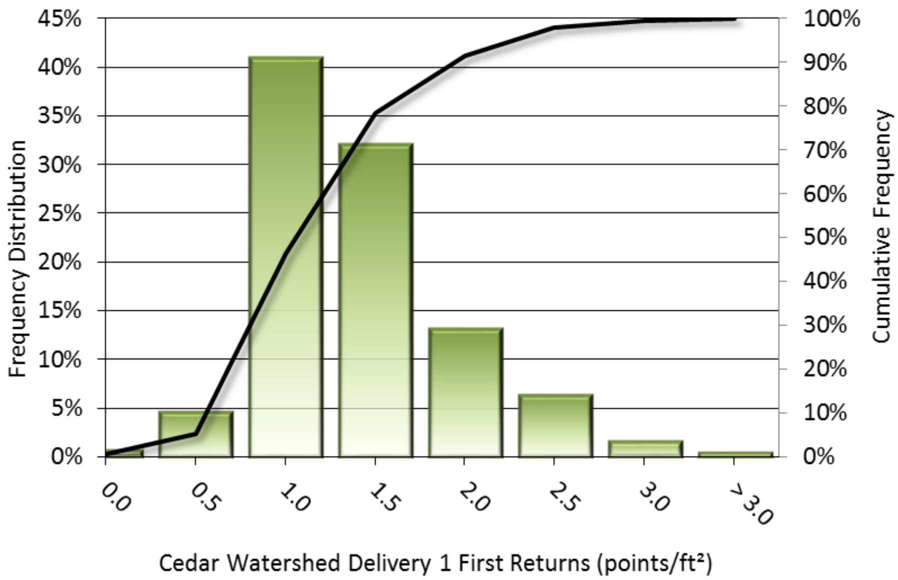


Figure 4: Frequency distribution of first return densities of the 30 x 30 m gridded study area

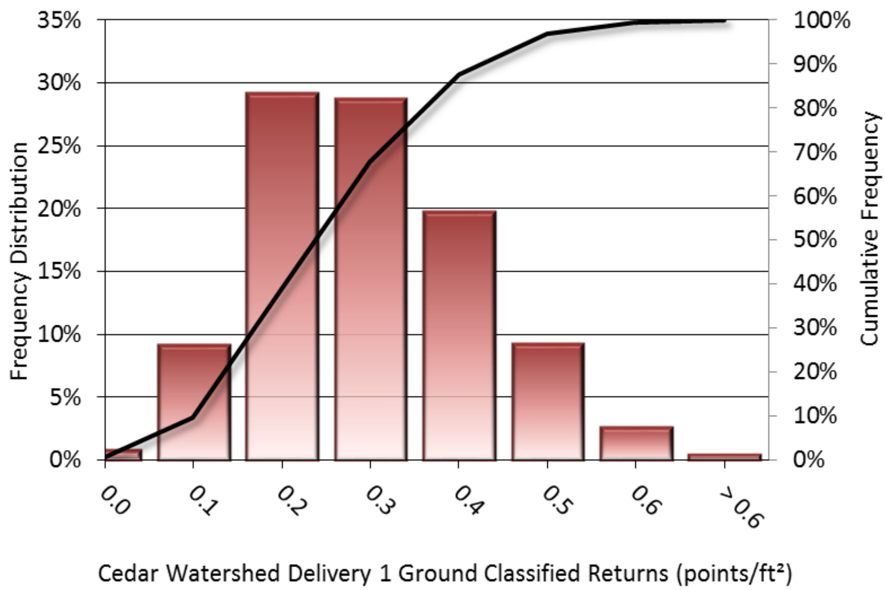


Figure 5: Frequency distribution of ground return densities of the 30 x 30 m gridded study area

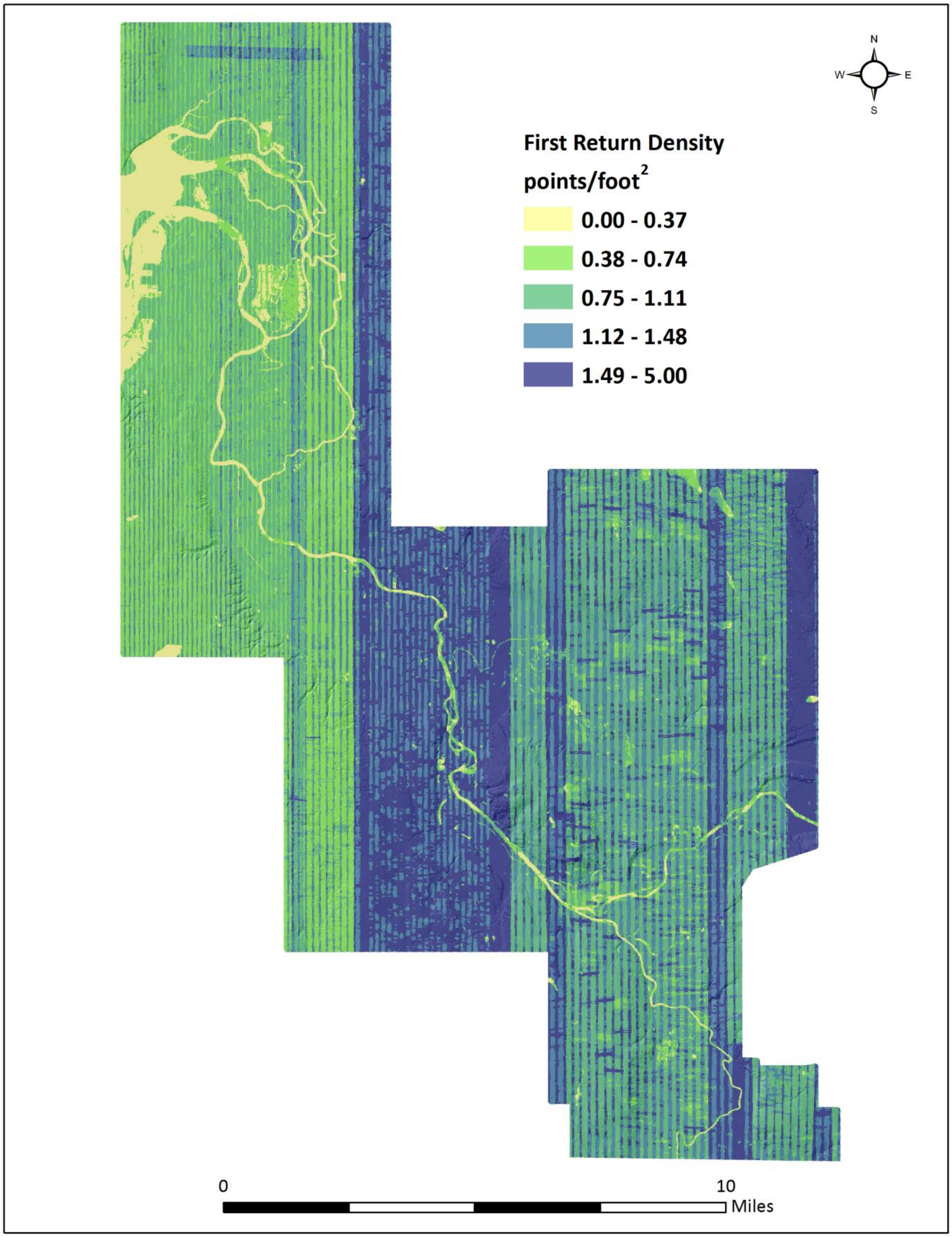


Figure 6: First return density map for the Cedar Watershed LiDAR site (30 m by 30 m cells)

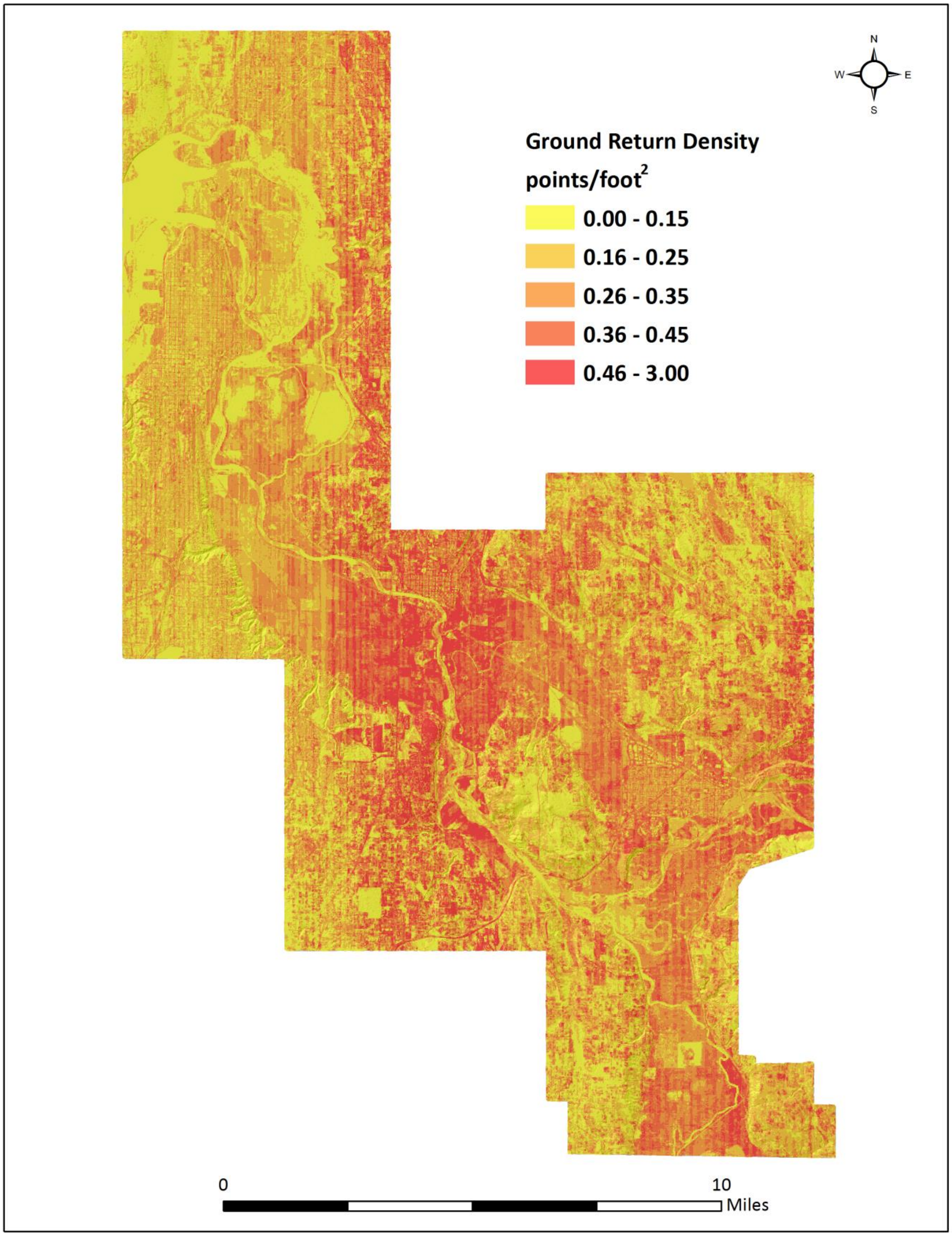


Figure 7: Ground density map for the Cedar Watershed LiDAR site (30 m by 30 m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Absolute Accuracy

Absolute accuracy was assessed using Fundamental Vertical Accuracy (FVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[4]. FVA compares known RTK and PPK ground control point data collected on open, bare earth surfaces with level slope (<20°) 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 * RMSE), as shown in Table 10.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Cedar Watershed LiDAR survey, 1,363 ground survey points were collected in total resulting in an average accuracy of-0.28 feet (-0.009 meters) (Figure 8).

Table 10: Absolute accuracy

Absolute Accuracy	
Sample	1,363 points
FVA (1.96*RMSE)	0.167 ft 0.051 m
Average	-0.028 ft -0.009 m
Median	-0.023 ft -0.007 m
RMSE	0.085 ft 0.026 m
Standard Deviation (1σ)	0.081 ft 0.025 m

[4] 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

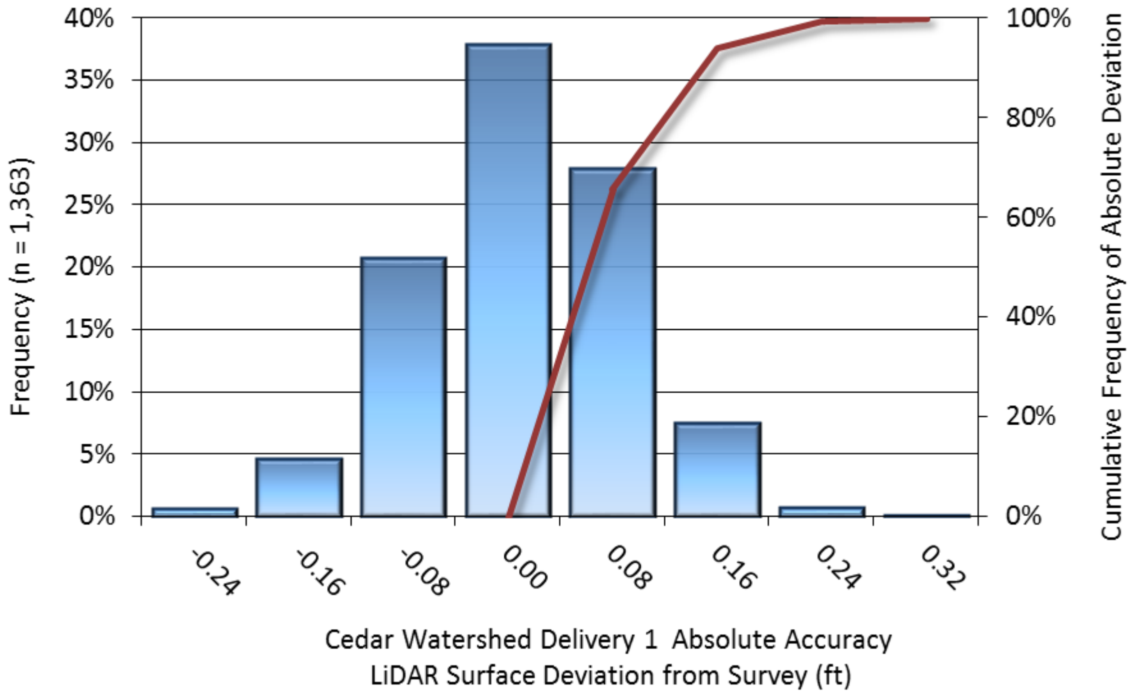


Figure 8: Frequency histogram for LiDAR surface deviation from ground survey point values

LiDAR Vertical Relative Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy 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 Cedar Watershed LiDAR project was 0.122 feet (0.037 meters) (Table 11, Figure 9).

Table 11: Relative accuracy

Relative Accuracy	
Sample	142 surfaces
Average	0.122 ft 0.037 m
Median	0.119 ft 0..036 m
RMSE	0.120 ft 0..037 m
Standard Deviation (1σ)	0.015 ft 0.005 m
1.96σ	0.030 ft 0.008 m

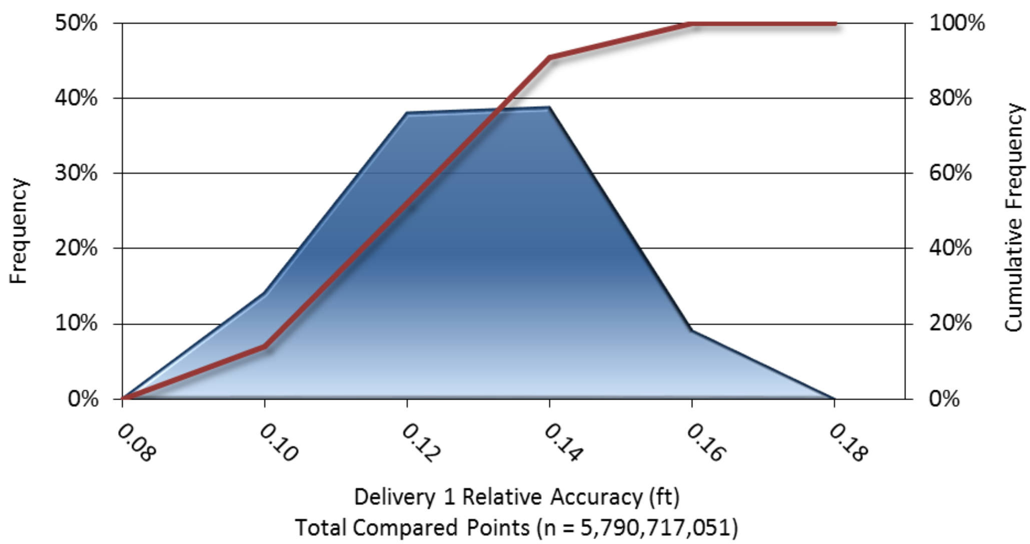


Figure 9: Frequency plot for relative vertical accuracy between flight lines

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

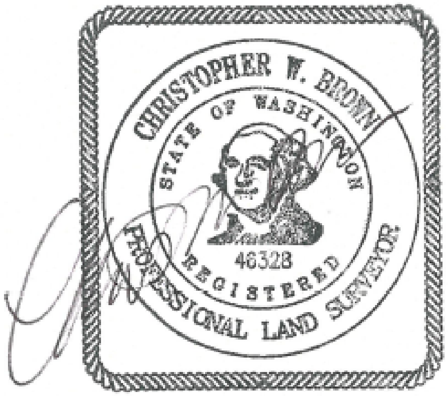
I, Kris Fausti, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Kris Fausti
Operations Manager
WSI a Quantum Spatial Company

I, Christopher W. Brown, being duly registered as a Professional Land Surveyor in and by the state of Washington, say that I hereby certify the methodologies, LiDAR project, Static GNSS occupations on the Base Stations used during airborne flights and RTK survey on hard-surface, were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between October 29, 2013 and January 7, 2014.

Accuracy statistics shown in the Accuracy Section of this Report have been review by me and found to meet the "National Standard for Spatial Data Accuracy".

4/11/2013
Christopher W. Brown, PLS Oregon & Washington
WSI a Quantum Spatial Company
Portland, OR 97204



Renews: 12/21/2014

Figure 10: A view looking at the confluence of the Skykomish and Snoqualmie Rivers. The bottom image is the gridded bare earth model colored by elevation, and the top shows the same image overlain with above ground LiDAR point returns.

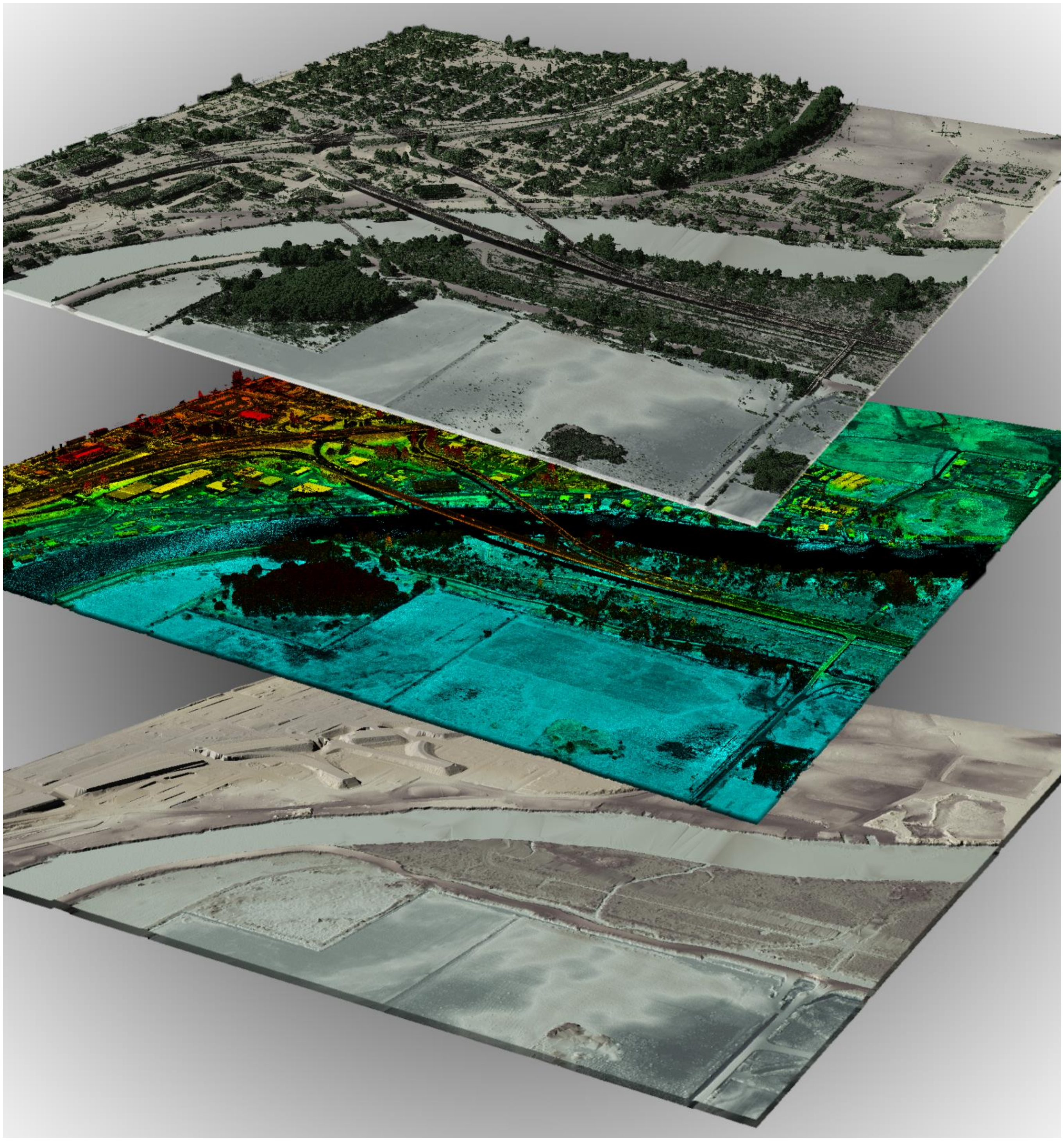


Figure 11: This layered view shows the Route 2 bridge over the Snohomish River. The bottom image is the gridded bare earth model colored by elevation. The middle image shows the 3D LiDAR point cloud colored by intensity. The top image shows the gridded bare earth model overlain with above ground LiDAR point returns.

Figure 12: A view of the Snohomish electric substation. The image is the gridded, bare earth model overlain with above ground LiDAR point returns.

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, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

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

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, calculated as 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., first to last). Lower intensity surfaces (e.g., 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 in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

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.

Native Density: The number of pulses emitted by the LiDAR system, commonly expressed in pulses per square meter (ppsm).

Appendix A - Accuracy Controls

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

LiDAR accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return 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 (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flight Lines: All overlapping flight lines 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.