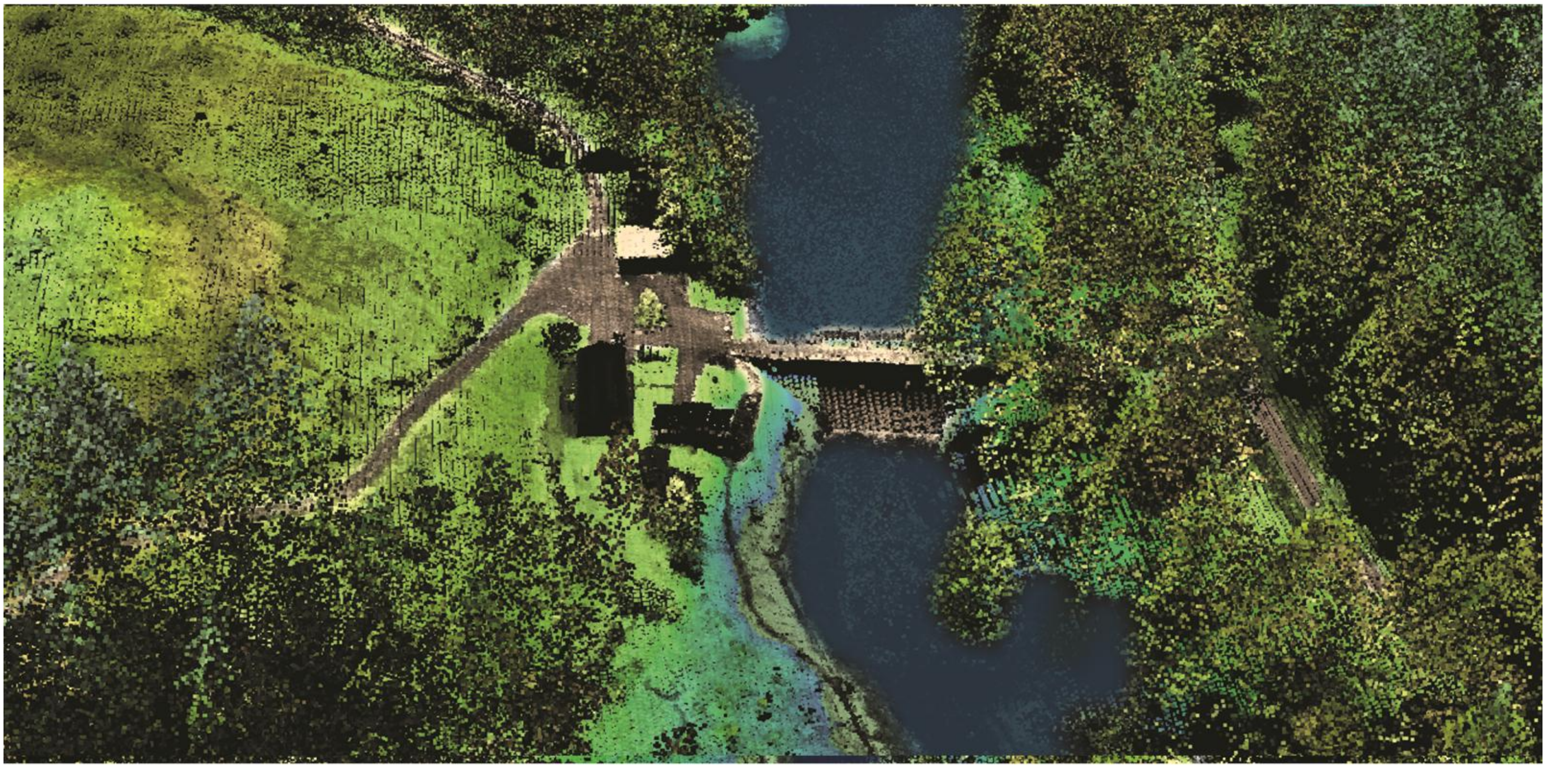
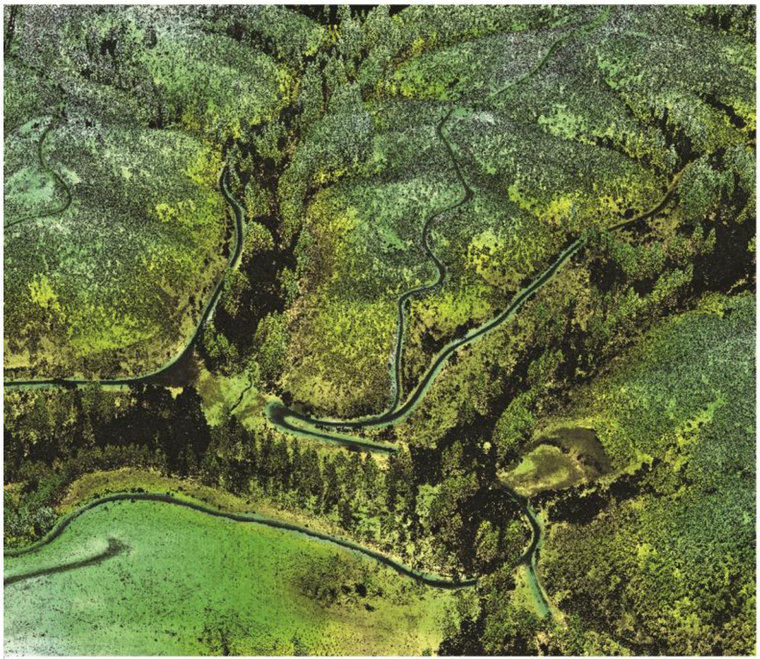
LiDAR REMOTE SENSING

QUINAULT RIVER BASIN (USGS) • WASHINGTON

June 13th, 2012





PUGET SOUND LiDAR CONSORTIUM

DIANA MARTINEZ - 1011 WESTERN AVE, SUITE 500 - SEATTLE, WA 98104

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

LiDAR Remote Sensing Data Collection: Quinault (USGS), Washington

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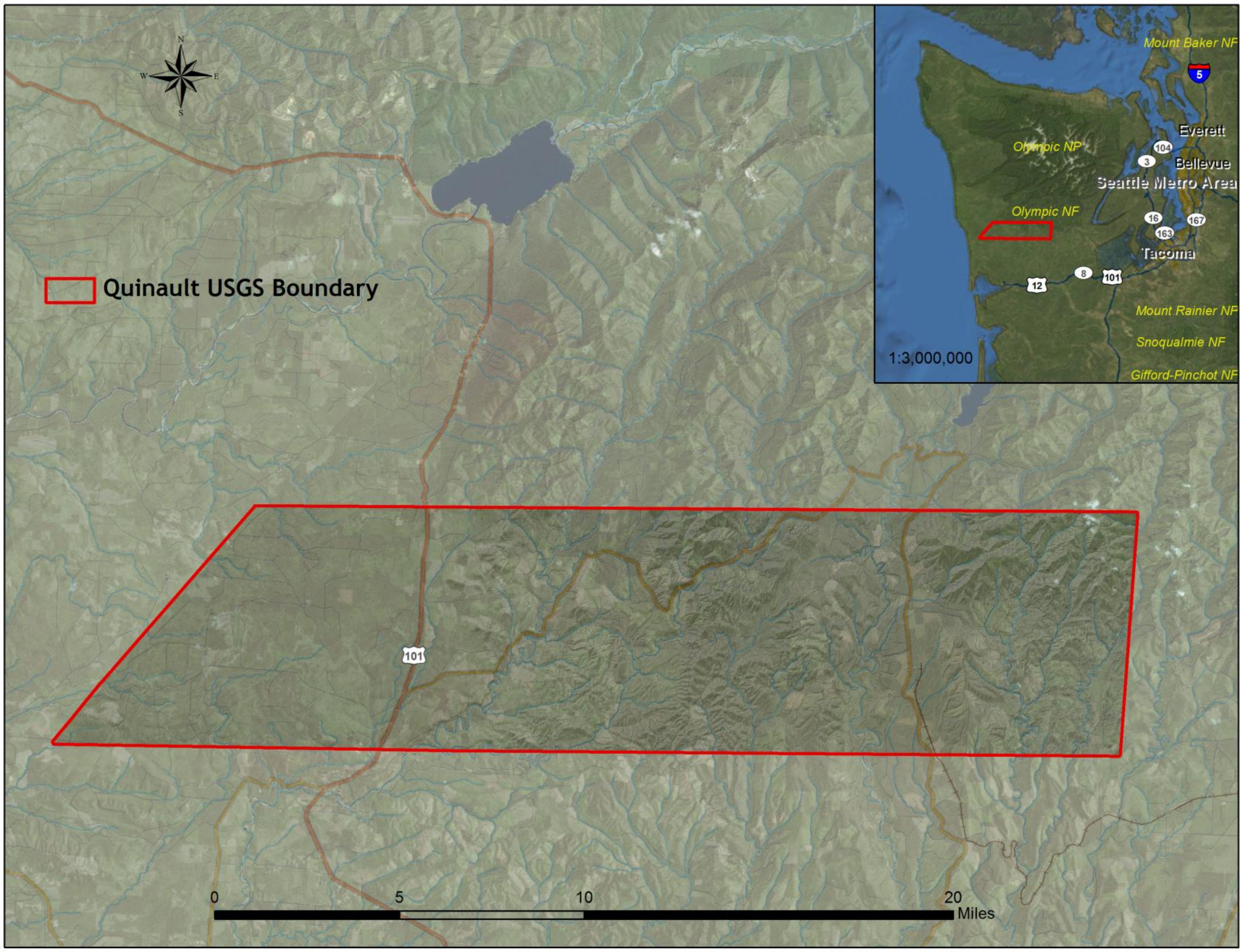
1. Overview

WSI collected Light Detection and Ranging (LiDAR) data on the Quinault River Basin survey area for the Puget Sound LiDAR Consortium and the United States Geological Survey. Data was collected on March 24^{th} – 25^{th}, and April 8^{th} – 9^{th} and 22^{nd}, 2012. This report documents the data acquisition, processing methods, accuracy assessment, and deliverables for the delivered LiDAR data (Figure 1). The requested area is 109,096 acres and was expanded to include a 100m buffer to ensure complete coverage and adequate point densities around survey area boundaries, resulting in 111,786 acres.

***Figure 1**. Quinault USGS area of interest, Washington.*



2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

The LiDAR survey utilized a Leica ALS60 sensor in a Cessna Caravan 208B. Depending on acquisition day, weather, and terrain, the Leica systems were set to acquire 105,000 laser pulses per second (i.e.105 kHz pulse rate) and flown at 900 meters above ground level (AGL), capturing a scan angle of ±14^{o} 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.

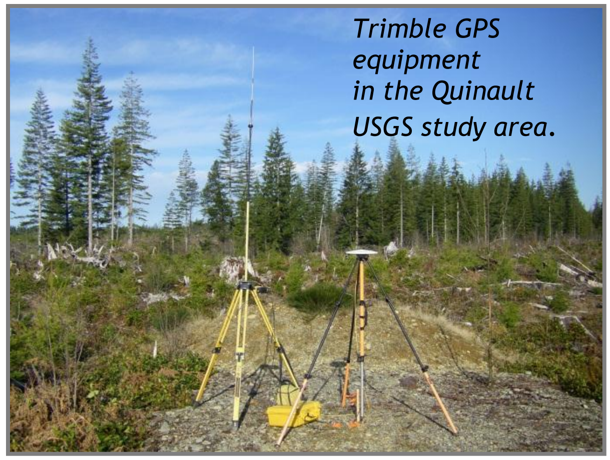
The Cessna Caravan is a stable platform, ideal for flying slow and low for high density projects. The Leica ALS60 sensor head installed in the Caravan is shown on the left.

All areas were surveyed with an opposing flight line side-lap of ≥60% (≥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. Aircraft position 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

During the LiDAR survey, static (1 Hz recording frequency) ground surveys were conducted over set monuments. Monument coordinates are provided in Table 1 and shown in Figure 2. After the airborne survey, the static GPS data are processed using triangulation with Continuously Operating Reference Stations (CORS) and checked using the Online Positioning User Service (OPUS[1]) to quantify daily variance. Multiple sessions are processed over the same monument to confirm antenna height measurements and reported position accuracy.


Trimble GPS equipment in the Quinault USGS study area.

Indexed by time, these GPS data are used to correct the continuous onboard measurements of aircraft position recorded throughout the mission. Control monuments were located within 13 nautical miles of the survey area.

2.2.1 Instrumentation

For this study area, the Trimble GNSS receivers used are listed in Table 1. A Trimble model R7 GNSS unit was used for collecting check points using real time kinematic (RTK) survey techniques. To acquire RTK data, the collector began recording after remaining stationary for 5 seconds then calculating the pseudo range position from at least three epochs with the relative error under 1.5cm horizontal and 2cm vertical. All GPS measurements were made with dual frequency L1-L2 receivers with carrier-phase correction.

***Table 1**. GPS and GNSS Receivers used in the Quinault USGS ground survey.*

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2	TRM55971.00	Static

2.2.2 Monumentation

WSI established four new monuments (Table 1) for this delivery of the Quinault USGS Area. The WSI monumentation was implemented with 5/8" x 30" rebar topped with a metal cap stamped with the project ID and year. Monuments selected were found to have good visibility and optimal location to support a LiDAR acquisition flight. Chris Yotter-Brown (WA-PLS #46328) WSI staff surveyor provided professional supervision and oversight to all survey aspects of this project.

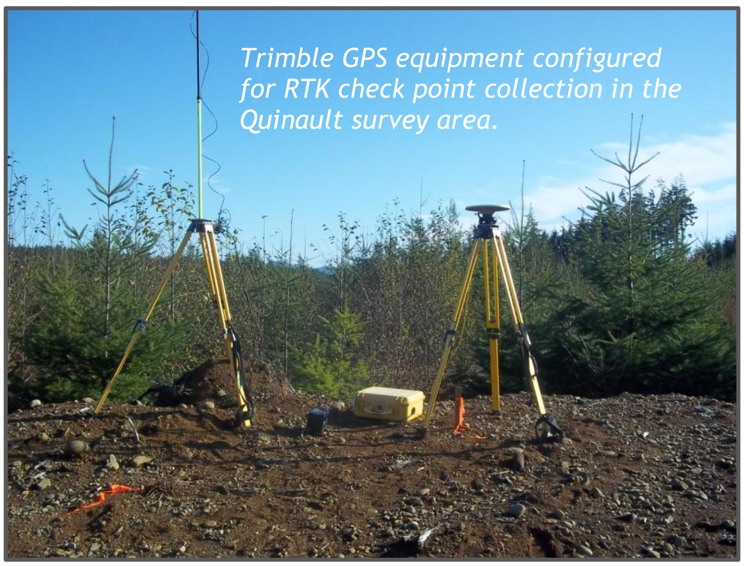
[1] Online Positioning User Service (OPUS) is run by the National Geodetic Survey to process corrected monument positions.

Table 2. Base Station control coordinates for the Quinault USGS study area

Base Station ID	Datum: NAD83 (CORS96)		GRS80
	Latitude	Longitude	Ellipsoid Z (meters)
USGS_QUIN_01	47° 19' 21.96607"	123° 47' 07.17737"	162.134
USGS_QUIN_02	47° 16' 29.14239"	123° 55' 01.13859"	82.000
USGS_QUIN_03	47° 17' 52.21561"	123° 37' 42.98596"	183.855
USGS_QUIN_05	47° 16' 41.24874"	123° 55' 00.98288"	84.502

2.2.3 Methodology

Each aircraft is assigned a ground crew member with two Trimble R7 receivers and an R8 receiver. The ground crew vehicles are equipped with standard field survey supplies and equipment including safety materials. All control monuments are observed for a minimum of one survey session lasting no fewer than 4 hours and another session lasting no fewer than 2 hours. At the beginning of every session the tripod and antenna are reset, resulting in two independent instrument heights and data files. Data is collected at a rate of 1Hz using a 10 degree mask on the antenna.



Trimble GPS equipment configured for RTK check point collection in the Quinault survey area.

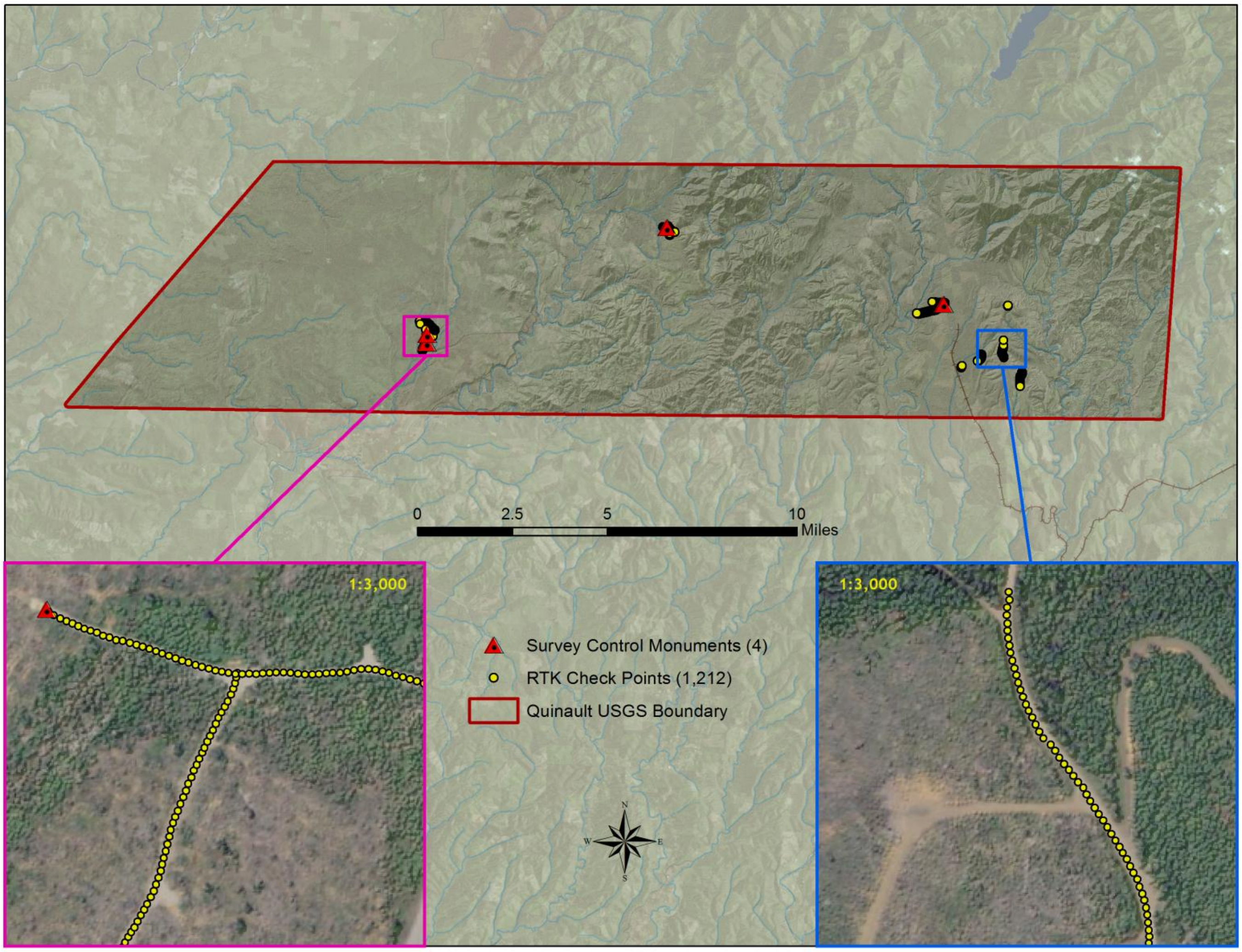
The ground crew uploads the GPS data to an online ftp site on a daily basis for quality control review and processing done by WSI. OPUS processing triangulates the monument position using 3 CORS stations resulting in a fully adjusted position. After multiple days of data have been collected at each monument, accuracy and error ellipses are calculated from the OPUS reports. This information leads to a rating of the monument based on FGDC-STD-007.2-1998[2] at the 95% confidence level (Table 3). When a statistically stable position is found CORPSCON[3] 6.0.1 software is used to convert the UTM positions to geodetic positions. This geodetic position is used for processing the LiDAR data.

RTK and aircraft mounted GPS measurements are made during periods with PDOP[4] less than or equal to 3.0 and with at least 6 satellites in view of both a stationary reference receiver and the roving receiver. Static GPS data collected in a continuous session average the high PDOP into the final solution in the method used by CORS stations. RTK positions are collected on bare earth locations such as paved, gravel or stable dirt roads, and other locations where the

[2] Federal Geographic Data Committee Draft Geospatial Positioning Accuracy Standards (Part 2 table 2.1)
[3] U.S. Army Corps of Engineers , Engineer Research and Development Center Topographic Engineering Center software
[4]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.

ground is clearly visible (and is likely to remain visible) from the sky during the data acquisition and RTK measurement period(s). RTK measurements are not taken on highly reflective surfaces such as center line stripes or lane markings on roads. RTK points were not taken within one meter to any nearby terrain breaks such as road edges or drop offs.

Figure 2. *RTK check point and control monument locations used in the Quinault USGS survey area*



2.2.4 Monument Accuracy

Table 3. *FGDC-STD-007.2-1998[5] at the 95% confidence level for the Quinault USGS survey area*

St Dev $_{NE}$	0.020 m
St Dev $_{z}$	0.020 m

[5] Federal Geographic Data Committee Draft Geospatial Positioning Accuracy Standards (Part 2 table 2.1)

3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

1. Resolved kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.

   Software: Waypoint GPS v.8.10, Trimble Business Center 2.6

2. 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

3. 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 then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction.

   Software: ALS Post Processing Software v.2.74, Corpscon 6

4. 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

5. 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

6. 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

7. Bare Earth models were created as a triangulated surface and exported as ArcInfo ASCII grids at a 3–foot pixel resolution. Highest Hit models were created for any class at 3-foot 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

LiDAR survey datasets were referenced to the 1 Hz static ground GPS data collected over pre-surveyed monuments with known coordinates. While surveying, the aircraft collected 2 Hz kinematic GPS data, and the onboard inertial measurement unit (IMU) collected 200 Hz aircraft attitude data. Waypoint GPS v.8.10 was used to process the kinematic corrections for the aircraft. The static and kinematic GPS data were then post-processed after the survey to obtain an accurate GPS solution and aircraft positions. 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 using the IPAS and ALS Post Processor software suites based on independent data from the LiDAR system (pulse time, scan angle), and aircraft trajectory data (SBET). Laser point 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, bins (polygons) were created to divide the dataset into manageable sizes (< 500 MB). Flightlines and LiDAR data were then reviewed to ensure complete coverage of the survey area and positional accuracy of the laser points.

Laser point data were imported into processing bins in 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 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. Each bin was then manually inspected for remaining pits and birds and spurious points were removed. In a bin containing approximately 7.5-9.0 million points, an average of 50-100 points are typically found to be artificially low or high. Common sources of non-terrestrial returns are clouds, birds, vapor, haze, decks, brush piles, etc.

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.

The TerraScan software suite is designed specifically for classifying near-ground points (Soininen, 2004). The processing sequence began by 'removing' all points that were not 'near' the earth based on geometric constraints used to evaluate multi-return 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 erroneously included known vegetation (i.e., understory, low/dense shrubs, etc.). These points were manually reclassified as default. Ground surface rasters were then developed from triangulated irregular networks (TINs) of ground points.

4. LiDAR Accuracy Assessment

4.1 Laser Noise and Relative Accuracy

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.

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

1. 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.
2. 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.
3. 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.

4.2 Absolute Accuracy

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 prior to evaluating absolute accuracy. The LiDAR quality assurance process uses the data from the real-time kinematic (RTK) ground survey conducted in the AOI. For the Quinault USGS survey area a total of 1,212 GPS measurements were collected on hard surfaces distributed among multiple flight swaths. To assess absolute accuracy the location coordinates of these known RTK ground points were compared to those calculated for the closest ground-classified laser points.

The vertical accuracy of the 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.

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

5. Study Area Results

Summary statistics for point resolution and accuracy (relative and absolute) for Quinault USGS study area are presented below in terms of central tendency, variation around the mean, and the spatial distribution of the data (for point resolution by tile). Laser pulses are absorbed by the water surface or returned at a low intensity; therefore native return densities will be lower in areas of water. In addition, ground densities will be lower in areas of dense vegetation, such as much of the Quinault River Basin survey area.

Data Summary: Quinault USGS Study Area

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

	Targeted	Achieved
Resolution:	≥ 8 points/m^2	0.86 points/ft^2 (9.23 points/m^2)
Vertical Accuracy (1 σ):	<15 cm	2.6 cm (0.08 ft)

5.1 Data Density/Resolution

Combined LiDAR data resolution for the Quinault USGS study area:

- Average Point (First Return) Density = 0.86 points/ft^2 (9.23 points/m^2)
- Average Ground Point Density = .11 points/ft^2 (1.16 points/m^2)

Figure 3. *Density distribution for first return laser points*

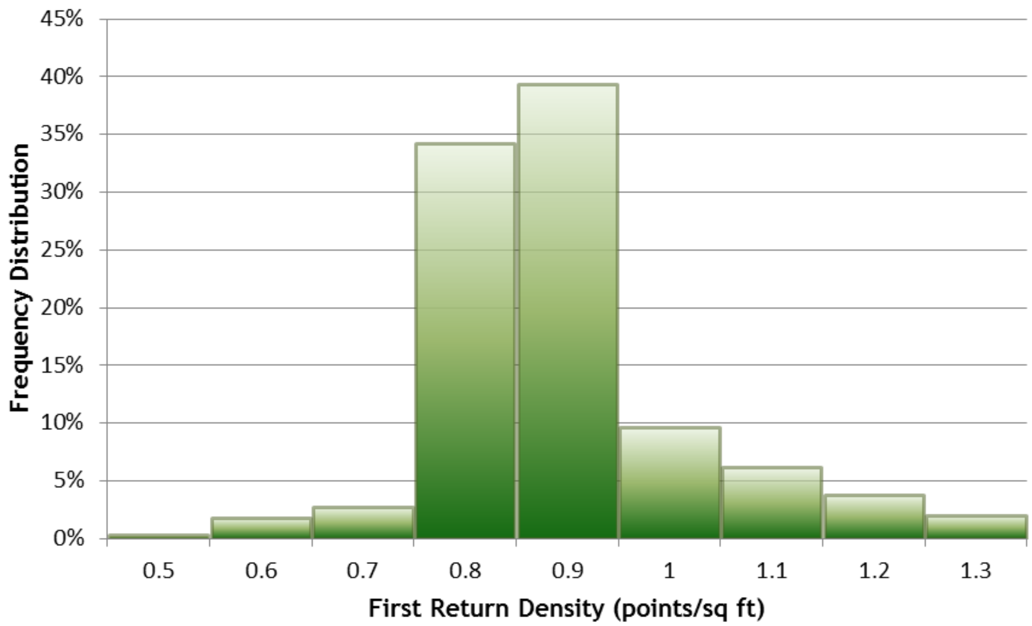


Figure 4. *Density distribution for ground classified laser points*

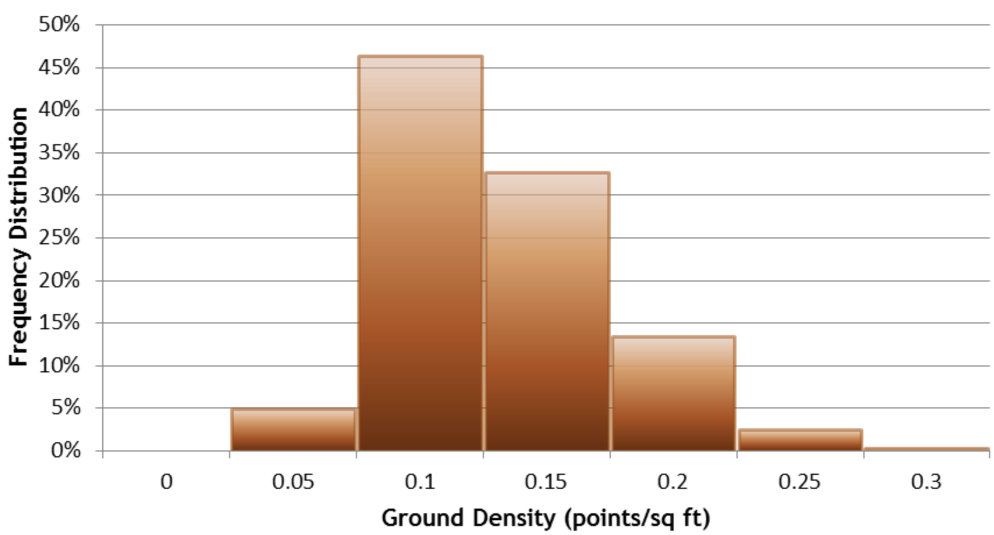
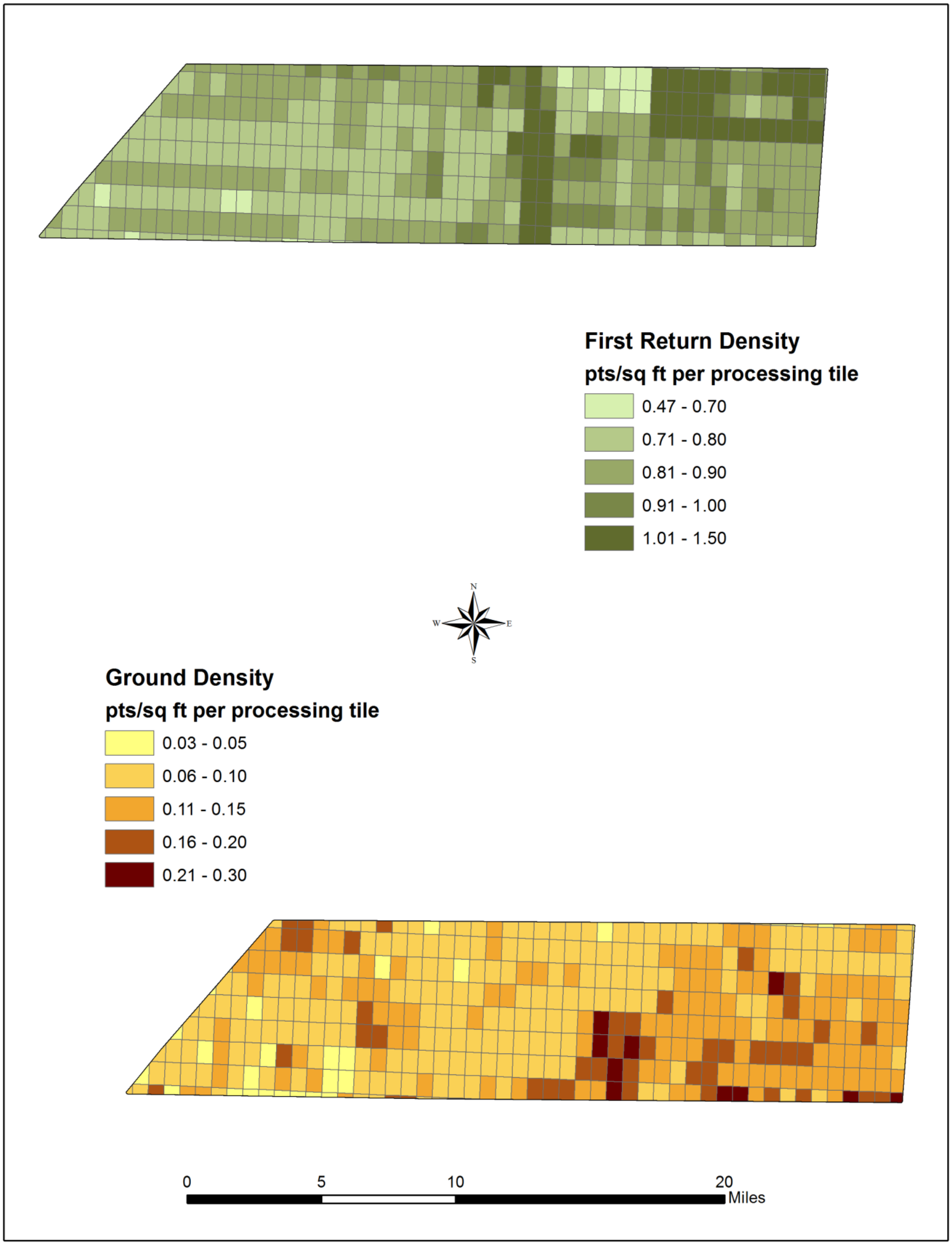


Figure 5. *First return density and ground density by 1/100th USGS tile.*

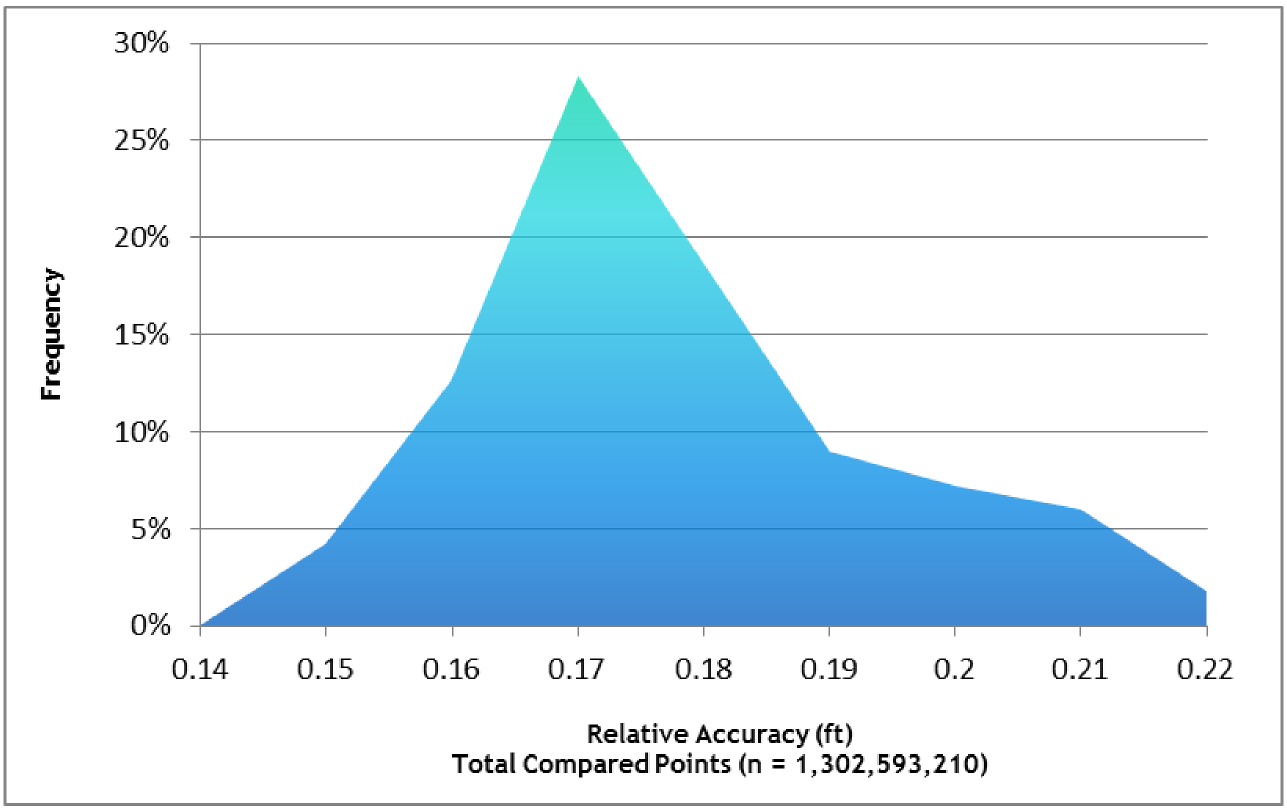


5.2 Relative Accuracy Calibration Results

Combined relative accuracy statistics for the Quinault USGS dataset measure the full survey calibration including areas outside the delivered boundary:

- Project Average = 0.177 ft (0.054 m)
- Median Relative Accuracy = 0.173 ft (0.053 m)
- RMSE = 0.184 ft (0.056 m)
- 1σ Relative Accuracy = 0.029 ft (0.009 m)
- 1.96σ Relative Accuracy = 0.058 ft (0.018 m)

Figure 6. *Distribution of relative accuracies per flight line, non slope-adjusted.*



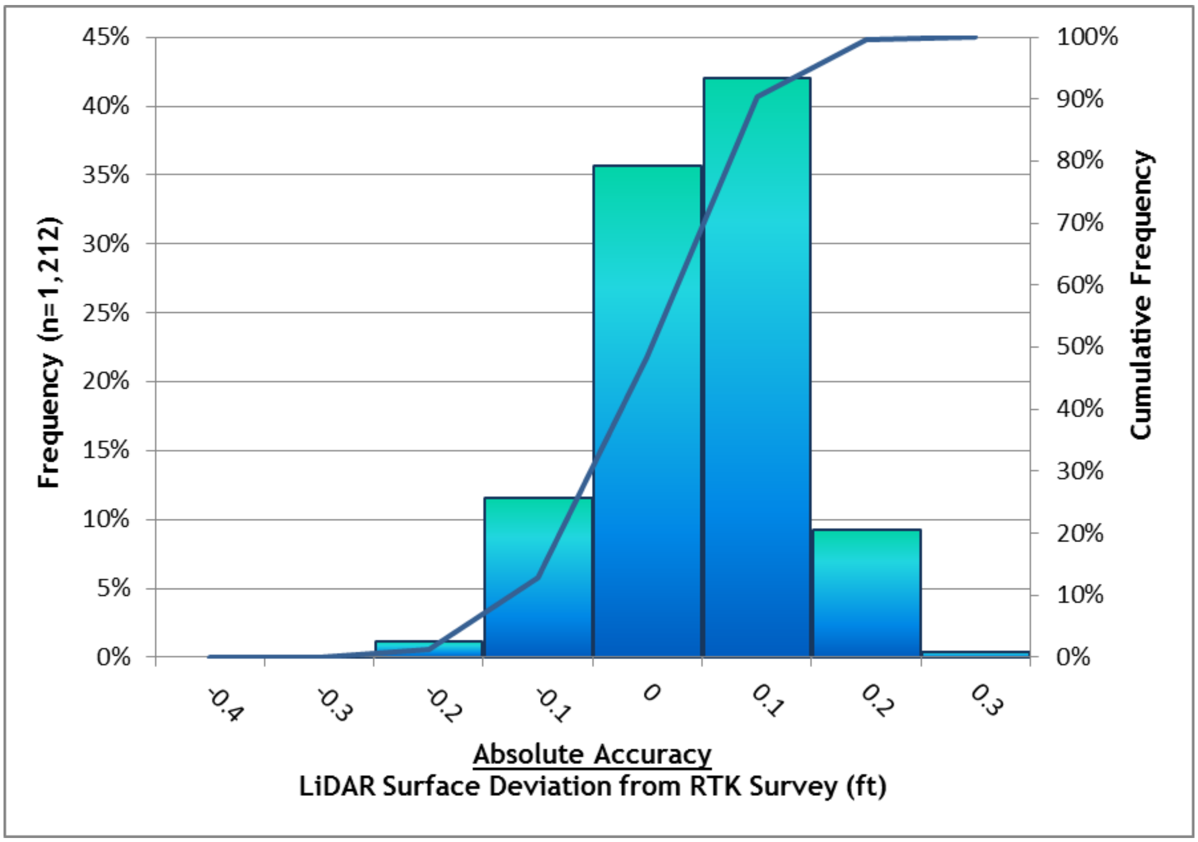
5.3 Absolute Accuracy

Absolute accuracy for the Quinault USGS study area:

Table 5. *Absolute Accuracy – Deviation between laser points and RTK hard surface survey points.*

RTK Survey Sample Size (n): 1,212		
Root Mean Square Error (RMSE) = 0.084 ft (0.026 m)		Minimum Δz = -0.315 ft (-0.096 m)
Standard Deviations		Maximum Δz = 0.256 ft (0.078 m)
1 sigma (σ): 0.084 ft (0.026 m)	1.96 sigma (σ): 0.164 ft (0.050 m)	Average Δz = -0.003 ft (-0.001 m)

Figure 7. *Absolute Accuracy - Histogram Statistics.*



6. Projection/Datum and Units

	Projection:	Washington State Plane South
Datum	**Vertical:**	NAVD88 Geoid03
	Horizontal:	NAD83 (1991 HARN)
	Units:	U.S. Survey Foot

7. Deliverables

Point Data:	• LAS 1.2 format (1/100th USGS quad delineation):
	  o All Returns
	• ASCII text format (1/100th USGS quad delineation):
	  o All Returns
	  o Ground points

Vector Data:	• Tile Index for LiDAR Points (shapefile format) • Tile Index for Rasters (shapefile format) • Total Area Flown (shapefile format) • Area of Interest (shapefile format) • SBETs (ASCII text format)

Raster Data:	• Digital Elevation Models (ESRI GRID format, 3ft resolution, 1/4th USGS quad delineation):
	  o Bare Earth Model
	  o Highest-Hit Model
	• Intensity Images (GeoTIFF format, 1.5ft resolution, (1/100th USGS quad delineation)

Data Report:	• Full report containing introduction, methodology, and accuracy

Point Data (per 1/100th USGS Quad delineation

- LAS v1.1 or ASCII Format

*Note: Delineation based on 1/100th of a full 7.5-minute USGS Quad (0.75-minutes). Larger delineations, such as 1/64th USGS Quads, resulted in unmanageable file sizes due to high data density.

***Figure 8**. Quadrangle naming convention for 1/100th of a 7.5-minute USGS Quad.*

8.Certifications

WSI provided LiDAR services for the Quinault 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.

7/12/2012

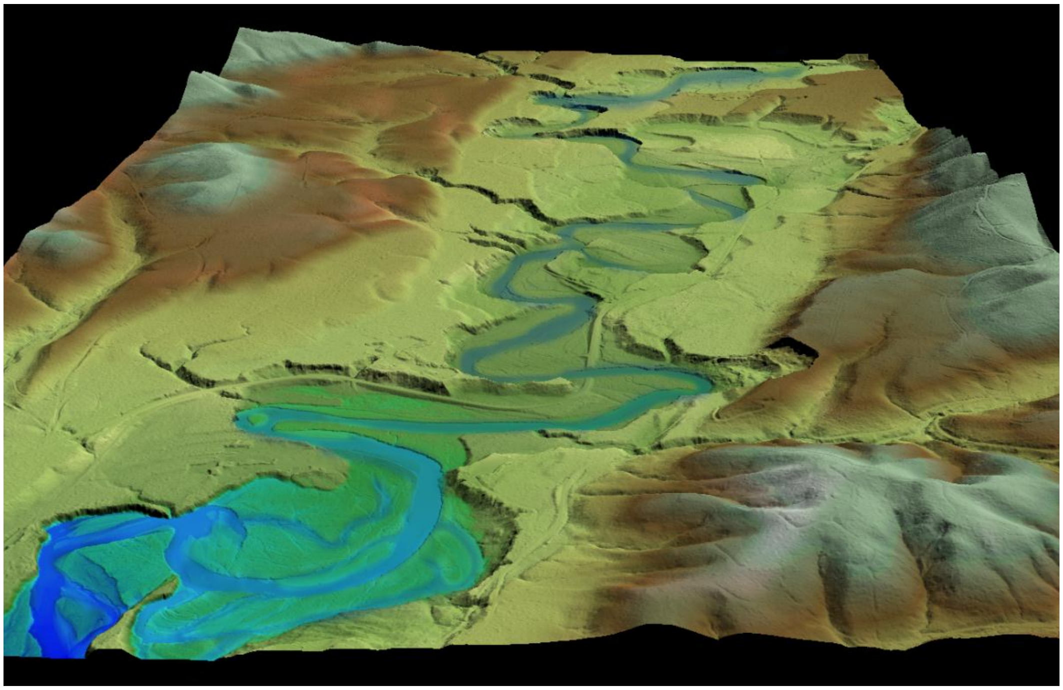
Christopher W. Yotter-Brown, PLS Oregon & Washington
WSI
Portland, OR 97204

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

Renews: 12/21/2012

9. Selected Images

Figure 9*. The top image is a bare earth model colored by elevation, looking north at the West Fork of the Humptulips River and National Forest Develop Road 22 in Grays Harbor County, Washington. The bottom image displays a bare earth model colored by elevation, looking west across the West Fork of the Humptulips River in Grays Harbor County, Washington.*



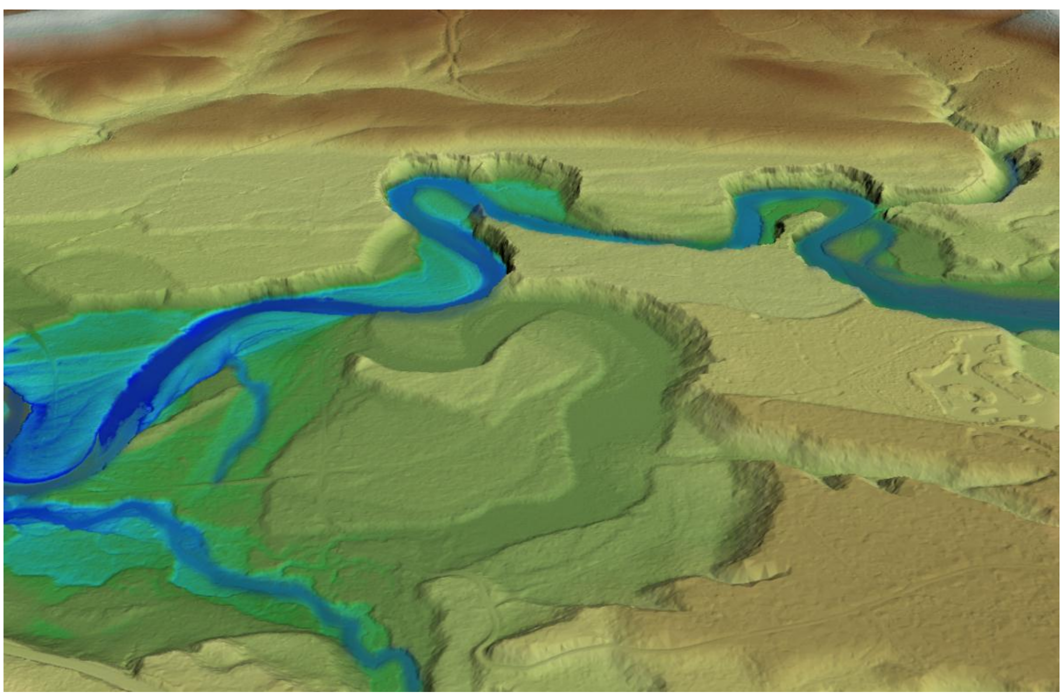


***Figure 10**. The top image is a 3D point cloud looking north at the Malinowski Dam containing the Aberdeen Reservoir in Grays Harbor County, Washington, colored by height and intensity. The bottom image is a 3D point cloud looking south at the lower part of the Aberdeen Reservoir in Grays Harbor County, Washington, colored by height and intensity.*

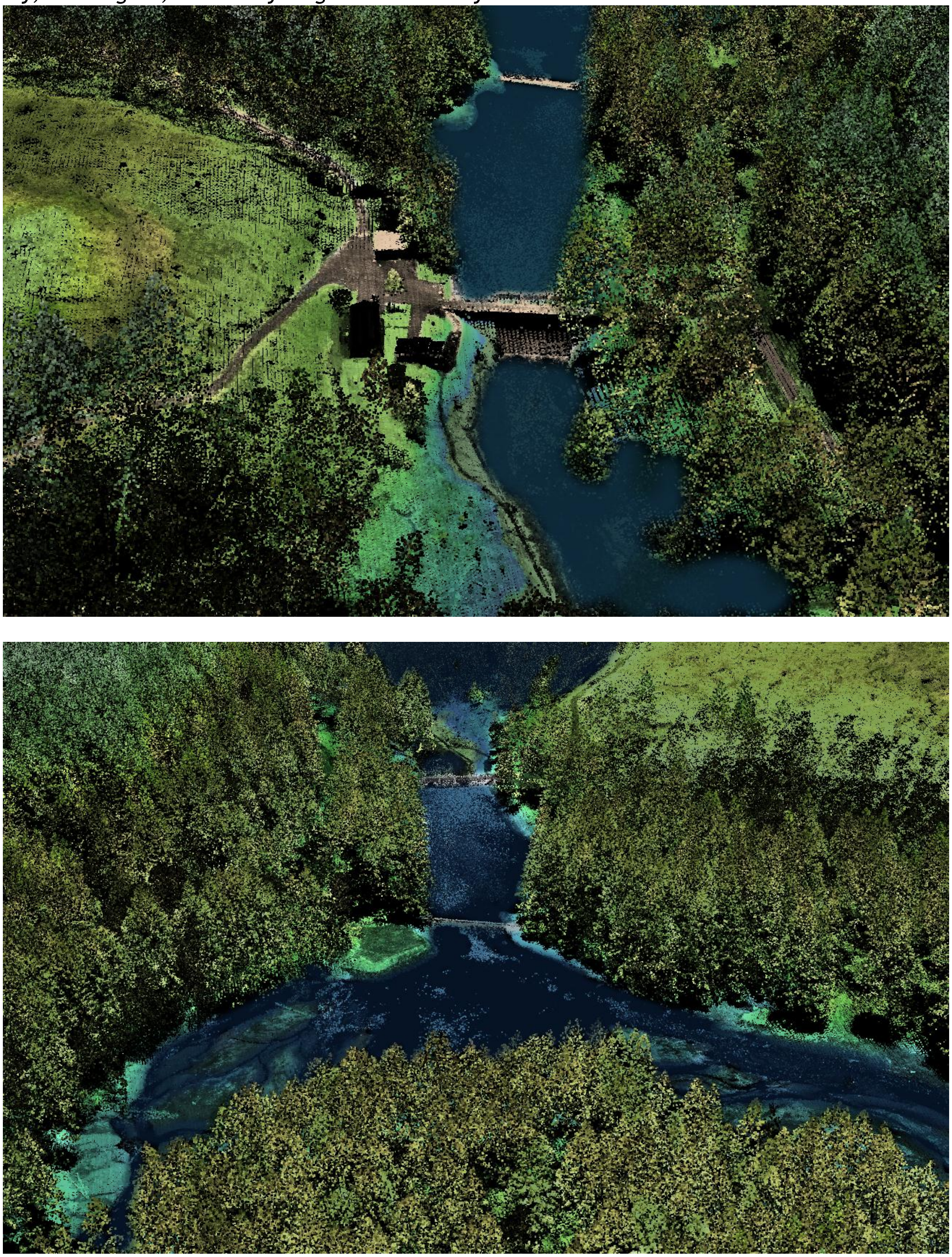
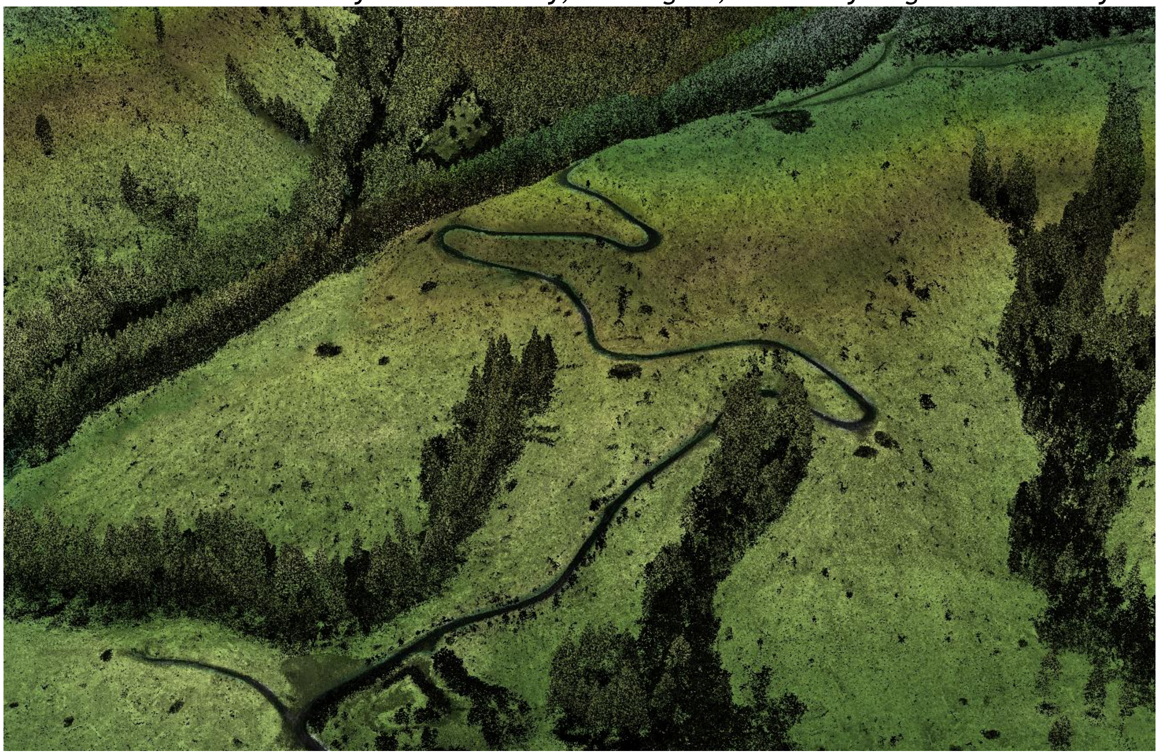


Figure 11*. The top image is a 3D point cloud looking northeast at the National Forest Develop Road leading up toward Reed Hill in Grays Harbor County, Washington, colored by height and intensity. The bottom image is a 3D point cloud looking northeast at the National Forest Develop Roads to the west of the Aberdeen Reservoir in Grays Harbor County, Washington, colored by height and intensity.*



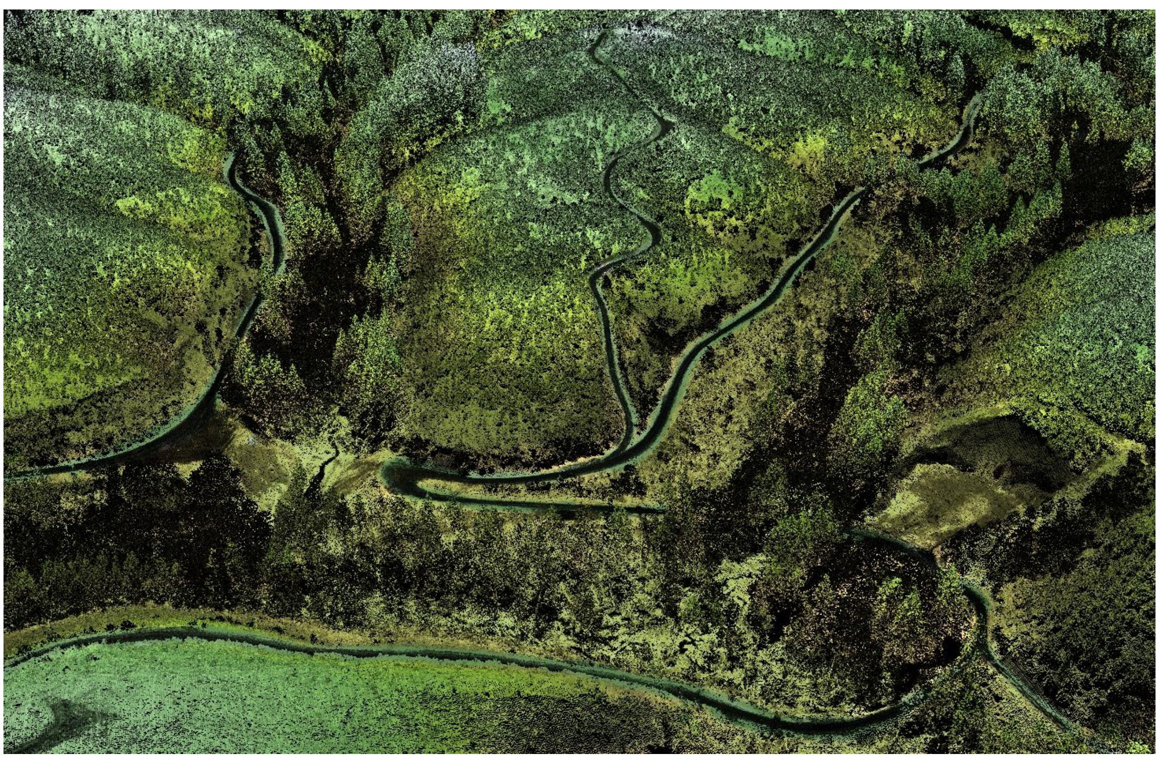
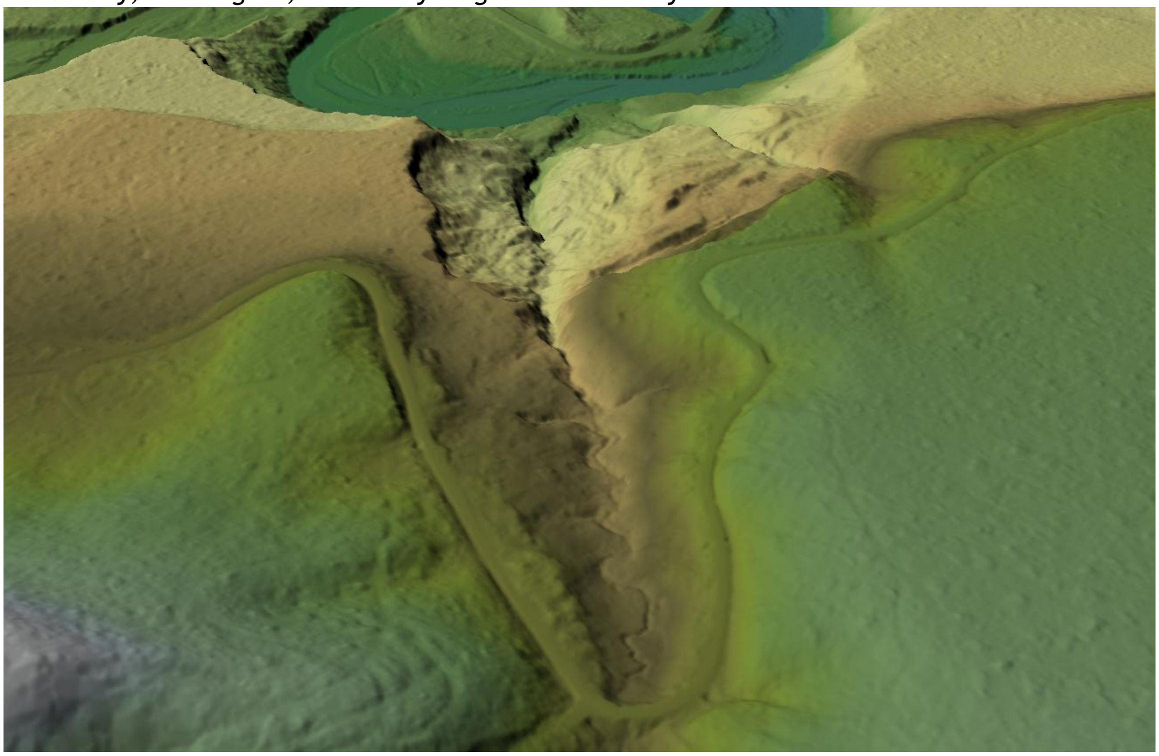
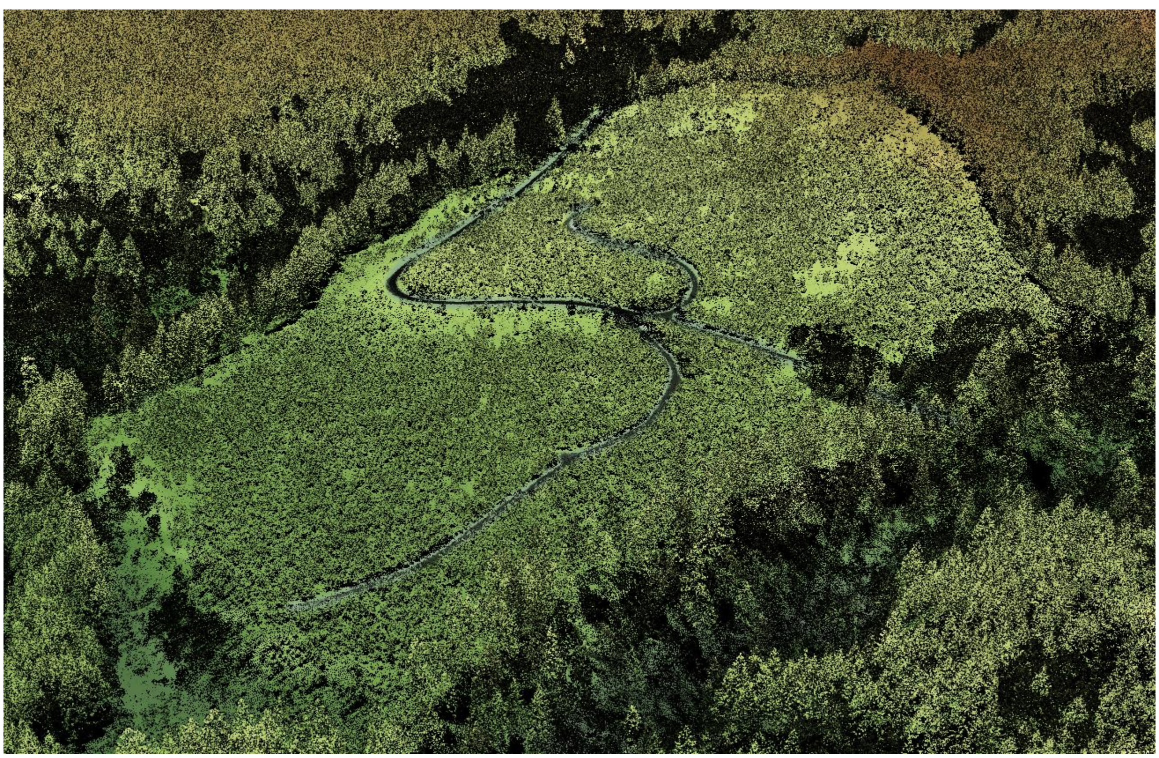


Figure 12*. The top image is a bare earth model colored by elevation, looking southeast at the National Forest Develop Road 2152 and the Canyon River in Grays Harbor County, Washington. The bottom image is a 3D point cloud looking north at the National Forest Develop Road 2152 in Grays Harbor County, Washington, colored by height and intensity.*





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

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:

1. 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., ~ $1/3000^{th}$ AGL flight altitude).
2. 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.
3. Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 15^{o}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. 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.
5. 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.
6. 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.
7. 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.