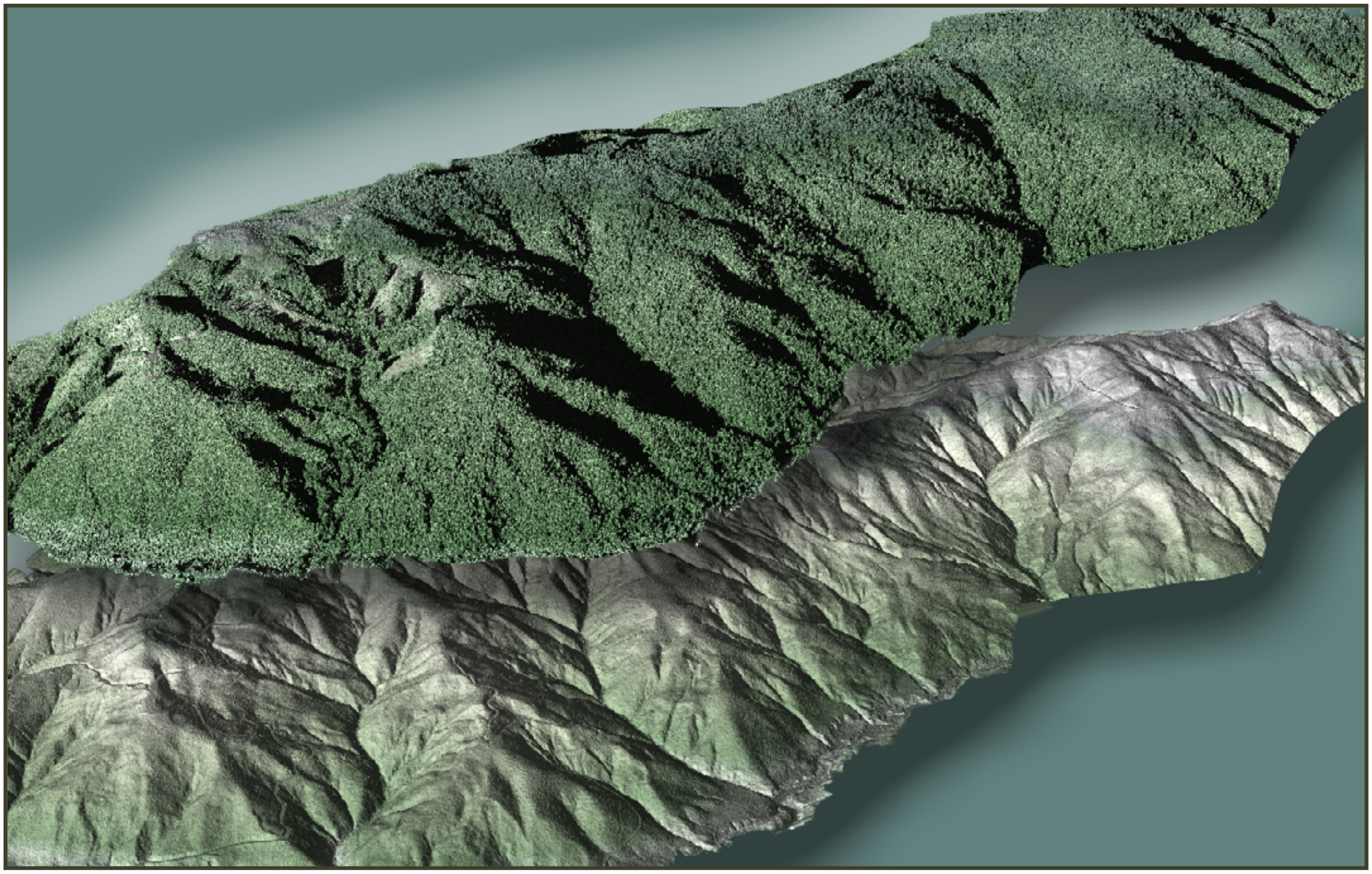
November 23, 2015



WA DNR Lands
Puget Sound LiDAR Consortium

Technical Data Report

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Cover Photo: View of Calawah Ridge looking North. The image was created from the gridded LiDAR surface colored by elevation and overlaid with the 3-DLiDAR point cloud.

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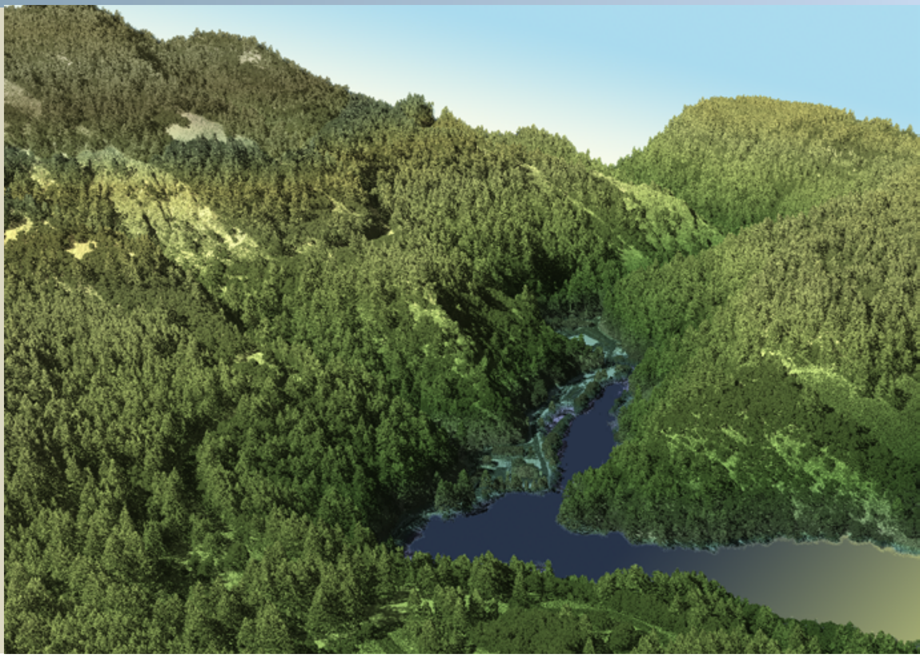
Introduction



View looking northeast at the mouth of the Little White Salmon River. The image was created from the gridded LiDAR surface colored by elevation and overlaid with the 3-D LiDAR point cloud.

In June 2014, WSI, a Quantum Spatial Inc. (QSI) company, was contracted by the Puget Sound LiDAR Consortium (PSLC) to collect Light Detection and Ranging (LiDAR) data for the Washington Department of Natural Resources (WA DNR) Lands in western Washington. Data were collected to aid the WA DNR in assessing the topographic and geophysical properties of the study area.

This report accompanies the delivered LiDAR data and derivative products, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to Puget Sound LiDAR Consortium is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the WA DNR Lands site

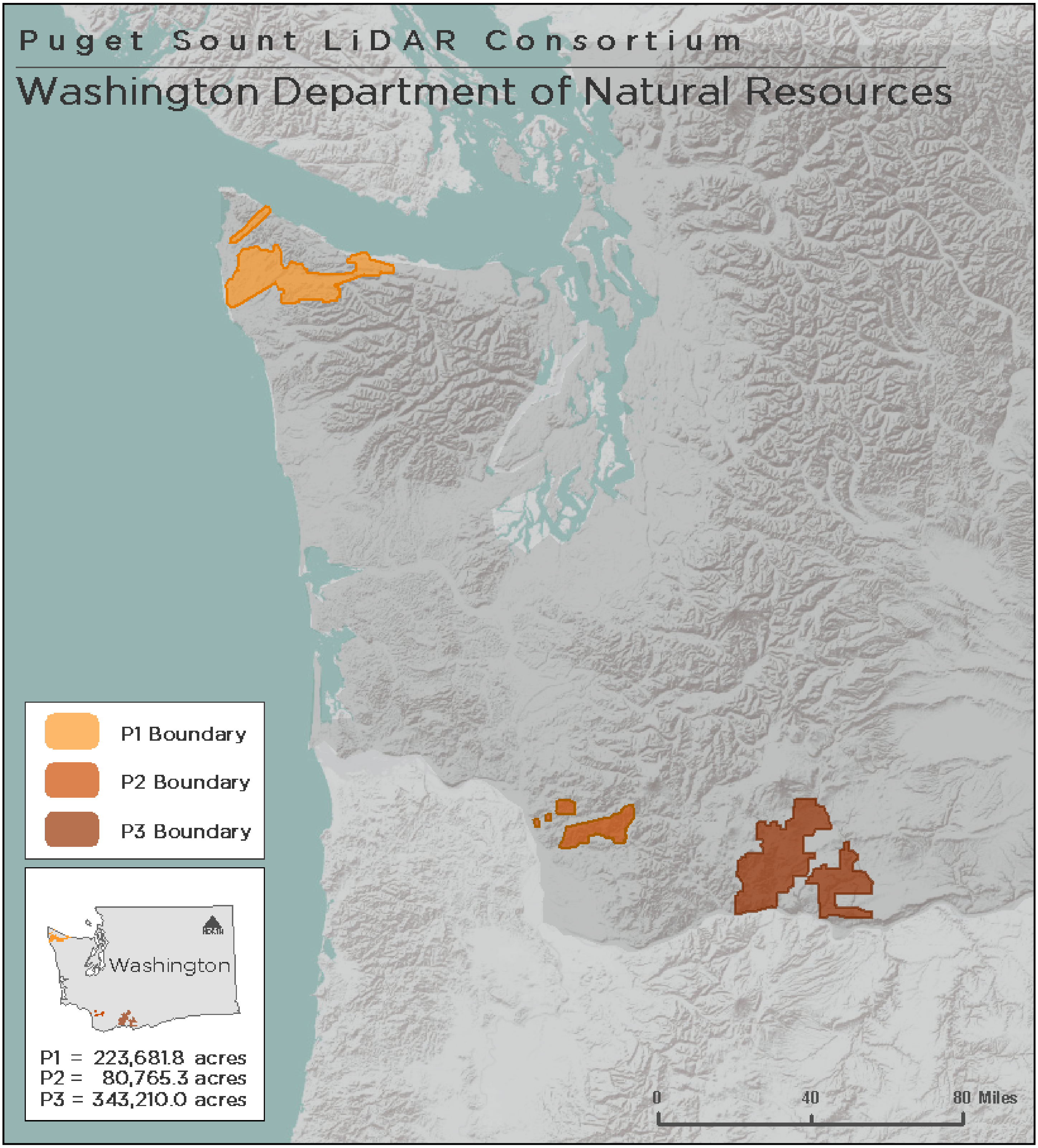
Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
P1 Area	216,827	223,681.8	12/31/2014 - 3/6/2015	LiDAR
P2 Area	77,827	80,765.3	1/8/2015 - 1/20/2015	LiDAR
P3 Area	316,221	330,385	10/17/14 - 3/13/2015	LiDAR

Deliverable Products

Table 2: Products delivered to PSLC for the WA DNR Lands site

Puget Sound LiDAR Consortium WA DNR Lands Products Projection: Washington State Plane South Horizontal Datum: NAD83 (CORS 96) Vertical Datum: NAVD88 (GEOID 03) Units: US Survey Feet	
Points	LAS v 1.2 and ASCII • All Returns ASCII • Ground Point List
Rasters	3.0 Feet ESRI Grid • Bare Earth Model • Highest Hit Model 1.5 Feet GeoTiffs • Normalized Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index (*.dgn and *.shp) • DEM Tile Index • Ground Survey Points • Aircraft Trajectories (SBET files) at one-second intervals

Figure 1: Location map of the WA DNR Lands study areas in Washington.



Acquisition

QSI Cessna Grand Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the WA DNR Lands 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 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 private property access and potential air space restrictions were reviewed.

Ground Control

Ground control surveys, including monumentation, and ground survey points (GSPs), were conducted to support the airborne acquisition. Ground control data were 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's staff surveyor, Christopher Glantz (WA PLS#48755) reviewed and certified the established monuments. See Appendix C for a list of ground control monumentation.

Trimble R7 unit set up in the WA DNR P3 survey area.

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*) 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**. 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 3.

Table 3: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev NE:	0.02 m
1.96 * St Dev z:	0.05 m

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

** 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

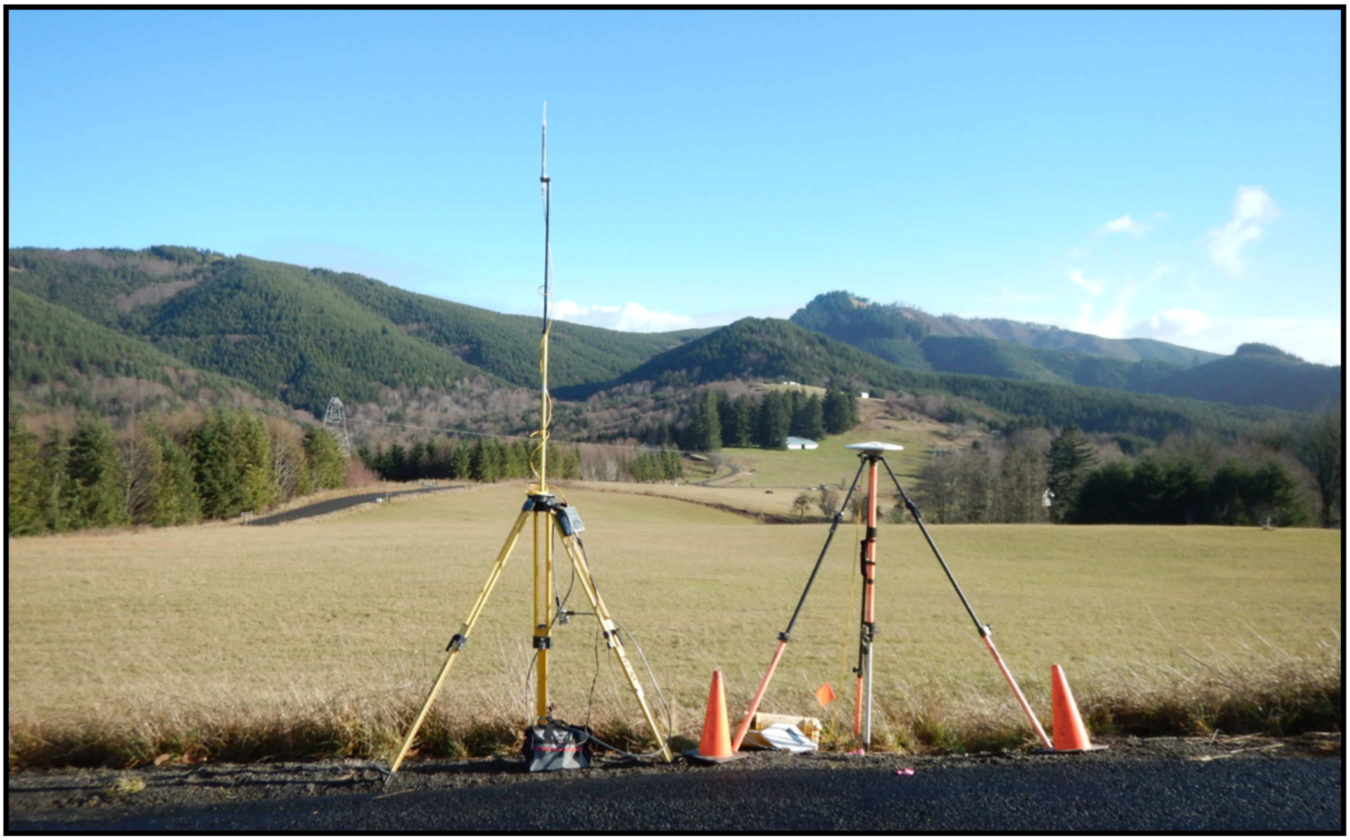
Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic and post-processed kinematic survey techniques. A Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R6, 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 any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. 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 4 for Trimble unit specifications.

GSPs were collected in areas where good satellite visibility was achieved on paved 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. GSPs were collected within as many flightlines as possible, however the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

Table 4: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R6 GNSS	Integrated GNSS Antenna R6	TRM_R6	RTK
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8 GNSS	Integrated Antenna R8 Model 2	TRM_R8_GNSS	Rover
Trimble R10 GNSS	Integrated GNSS Antenna R10	TRM_R10	RTK



Above: Trimble R7 unit set up in the WA DNR P1 survey area.

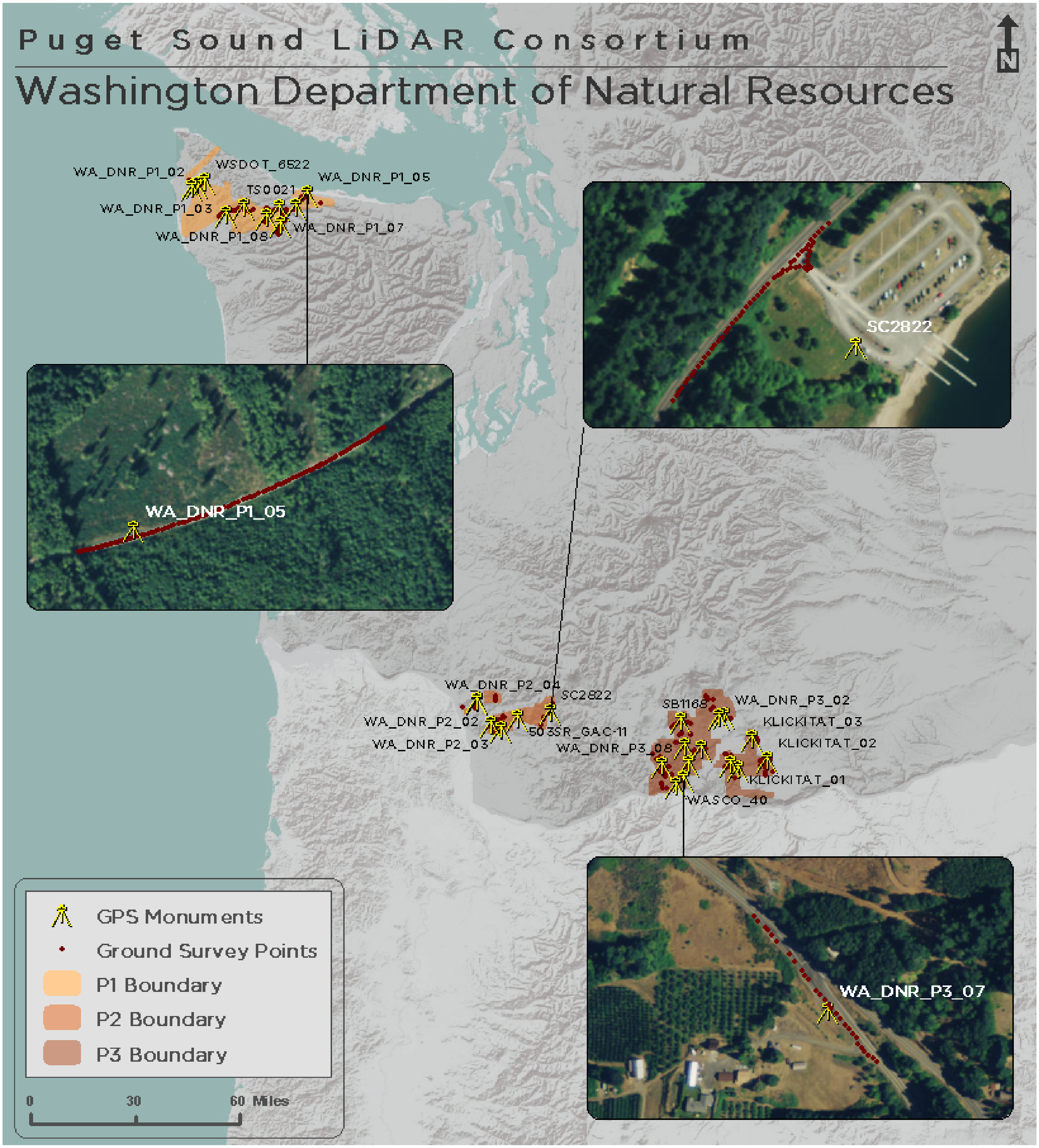


Figure 2: Ground control location map

Airborne Survey

LiDAR

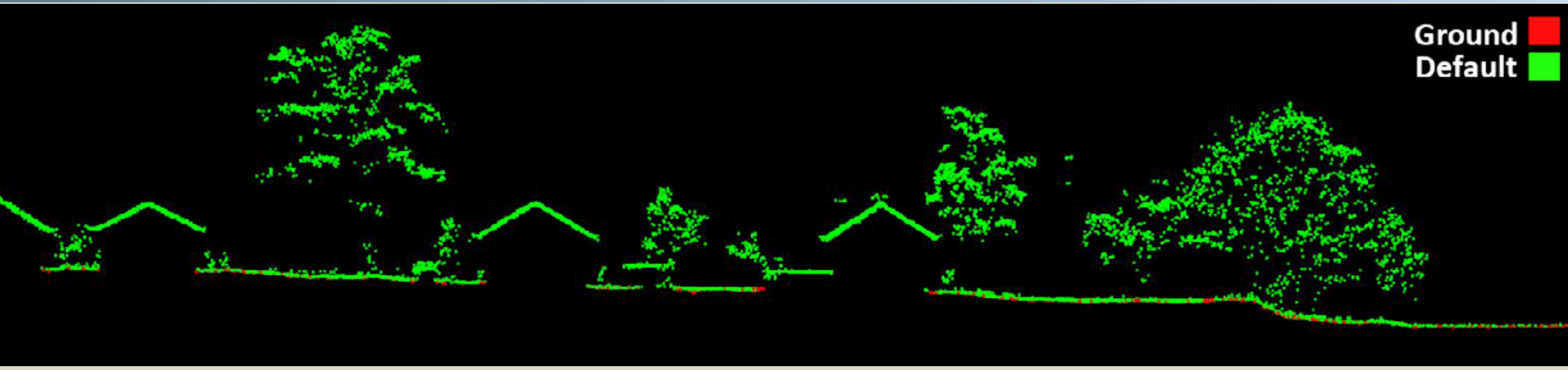
The LiDAR survey was accomplished using a Leica ALS70 and a Leica ALS80 system mounted in a Cessna Grand Caravan. Table 5 summarizes the settings used to yield an average pulse density of 8 pulses/m² over the WA DNR Lands project area; figure 5 shows acquisition flightlines. The Leica ALS70 and ALS80 systems can record unlimited measurements (returns) per pulse, but typically do not record more than five returns per pulse. 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 discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 5: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	10/17/2014 - 3/13/2015
Aircraft Used	Cessna Grand Caravan
Sensor	Leica ALS70 & ALS80
Survey Altitude (AGL)	1,400 m
Target Pulse Rate	198 kHz / 195 kHz
Pulse Mode	Single Pulse in Air (SPiA)
Mirror Scan Rate	41.1 Hz / 58.4 Hz
Field of View	30°
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	Unlimited, but typically not more than five
Intensity	8-bit
Resolution/Density	Average 8 pulses/m2
Accuracy	RMSEz ≤ 15 cm

Leica ALS70 LiDAR sensor

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



View of a neighborhood in Klickitat, Washington. The image was created from a 3 meter cross section of the 3-D LiDAR point cloud colored by point class.

LiDAR Data

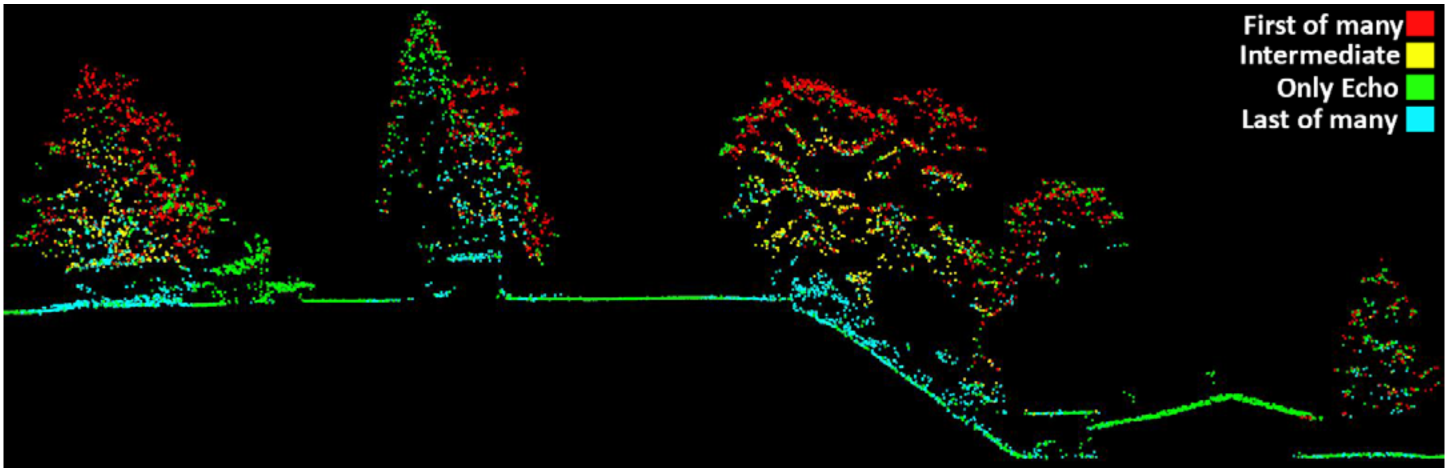
Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 6). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 7.

Table 6: ASPRS LAS classification standards applied to the WA DNR Lands dataset

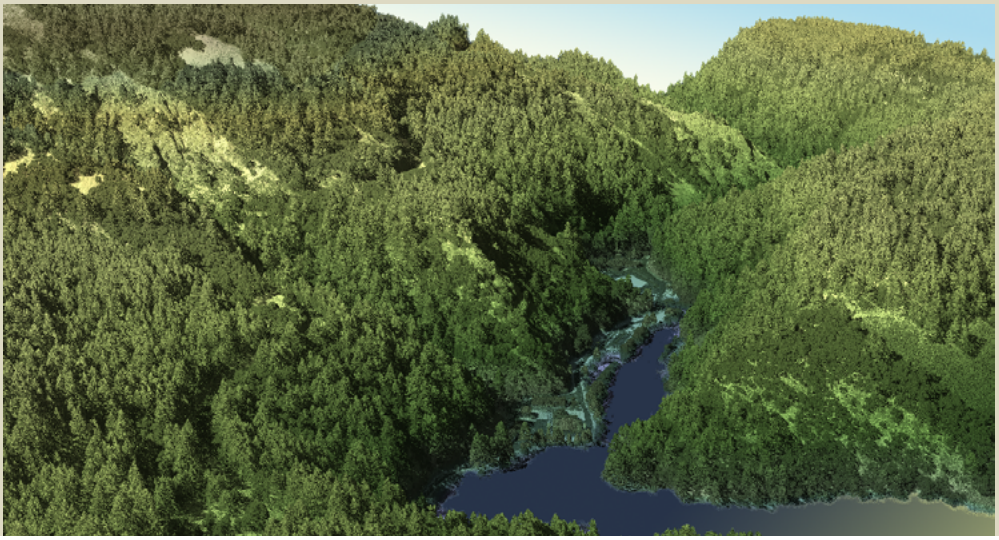
Classification Number	Classification Name	Classification Description
1	Default/ Unclassified	Laser returns that are not included in the ground class, composed of vegetation and man-made structures
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms

Table 7: LiDAR processing workflow

Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. 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 Waypoint Inertial Explorer v.8.5
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 geoid correction.	ALS Post Processing Software v.2.75
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.15
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.15
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.15 TerraModeler v.15
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 in EDRAS Imagine (.img) format at a 1 meter pixel resolution.	TerraScan v.15 TerraModeler v.15 ArcMap v. 10.1
Correct intensity values for variability and export intensity images as GeoTIFFs at a 0.5-meter pixel resolution.	TerraScan v.15 TerraModeler v.15 ArcMap v. 10.1



View of a building under a vegetated hillside near the Klickitat River in Klickitat, Washington. The image was created from a 3 meter cross section of the 3-D LiDAR point cloud colored by laser echo.



View looking northeast at the mouth of the Little White Salmon River. The image was created from the gridded LiDAR surface colored by elevation and overlaid with the 3-D LiDAR point cloud.

LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m² (0.74 points/ft²). 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 were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned 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 will be the only echo and represents the bare earth surface.

The density of ground-classified LiDAR returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced 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 and classified ground return density values of LiDAR data for each of the three WA DNR study ares are included in Table 8. The statistical distributions of first return densities and classified ground return densities per 30 m x 30 m cells are portrayed in Figures 3 through 8. Spatial distribution of density values is portrayed in Figures 9 through 12.

Table 8: Average LiDAR point densities

Classification	Point Density		
	P1	P2	P3
First-Return	17.45 points/m²	21.77 points/ m²	20.11 points/m²
	1.62 points/ft²	2.02 points/ ft²	1.87 points/ ft²
Ground Classified	1.30 points/m²	1.78 points/ m²	2.21m² points/m²
	0.12 points/ft²	0.17 ft² points/ft²	0.21 ft² points/m²

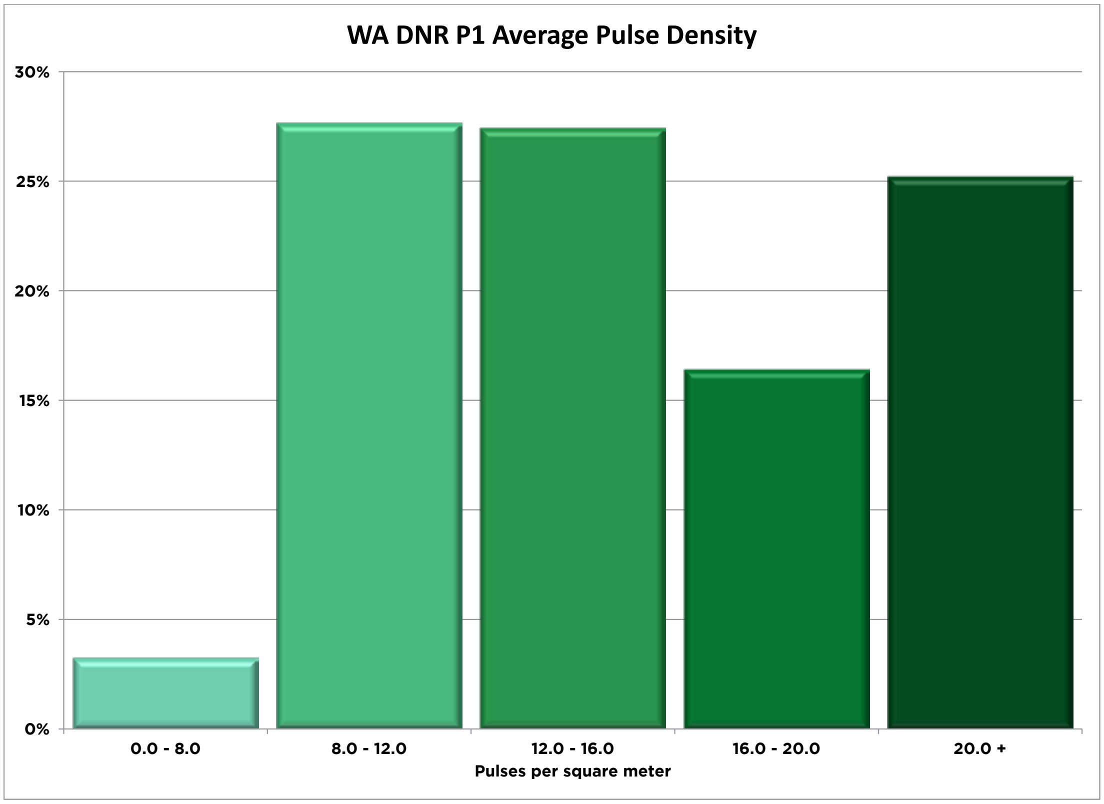


Figure 3: Frequency distribution of first return densities per 30 m X 30 m cell

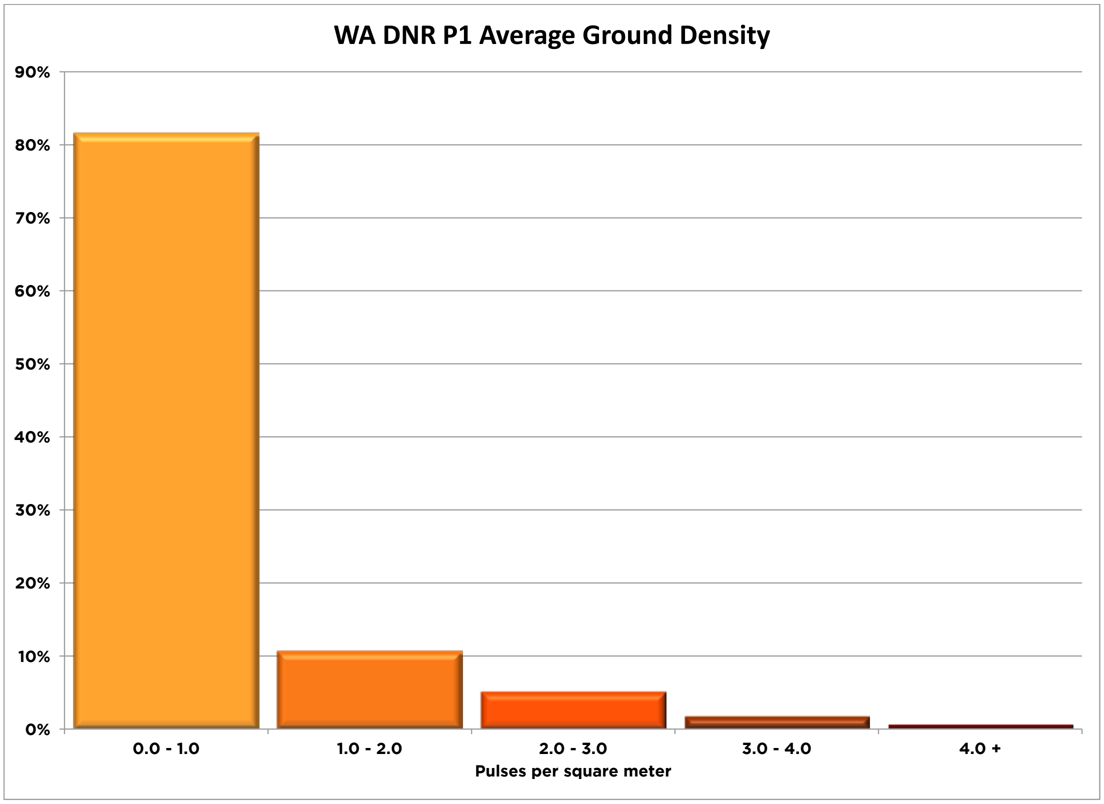


Figure 4: Frequency distribution of classified ground point densities per 30 m X 30 m cell

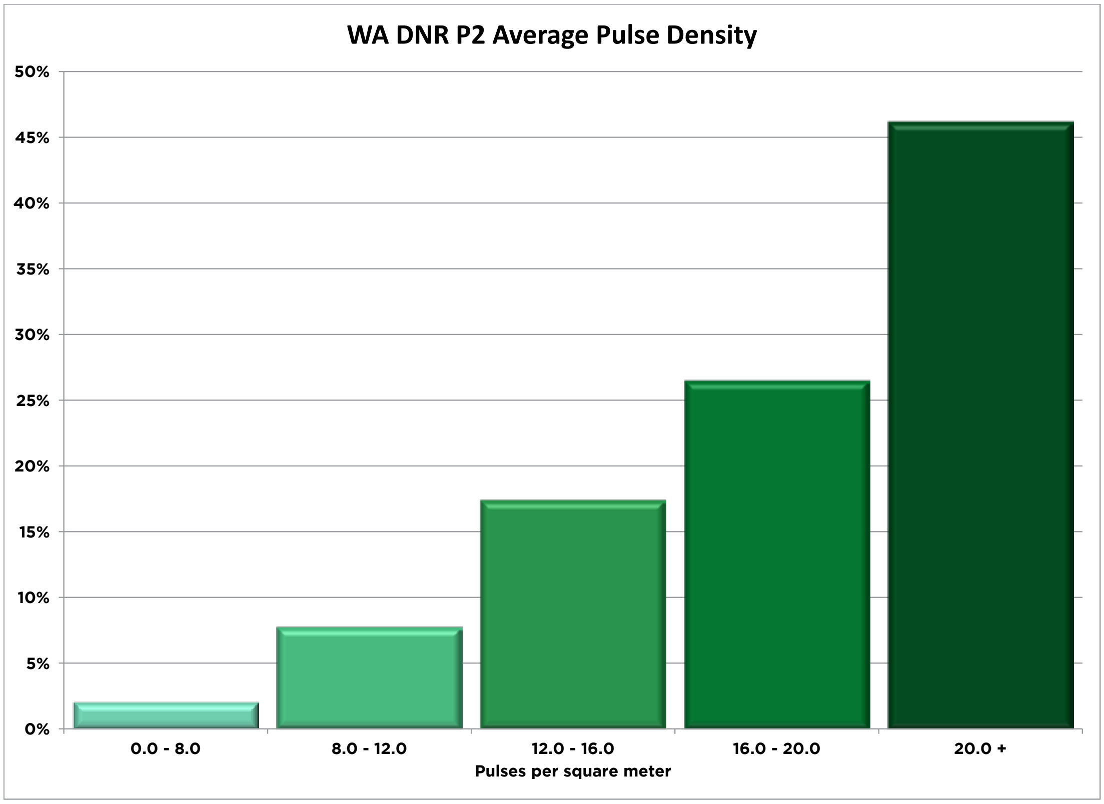


Figure 5: Frequency distribution of first return densities per 30 m X 30 m cell

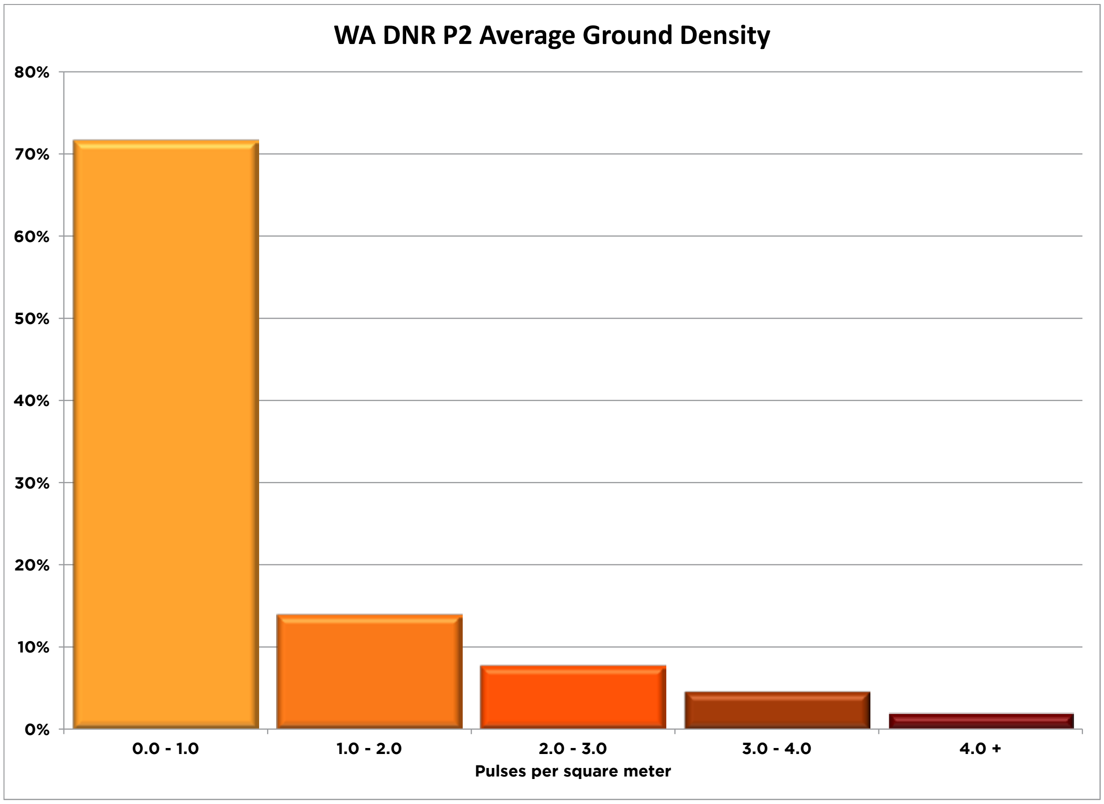


Figure 6: Frequency distribution of classified ground point densities per 30 m X 30 m cell

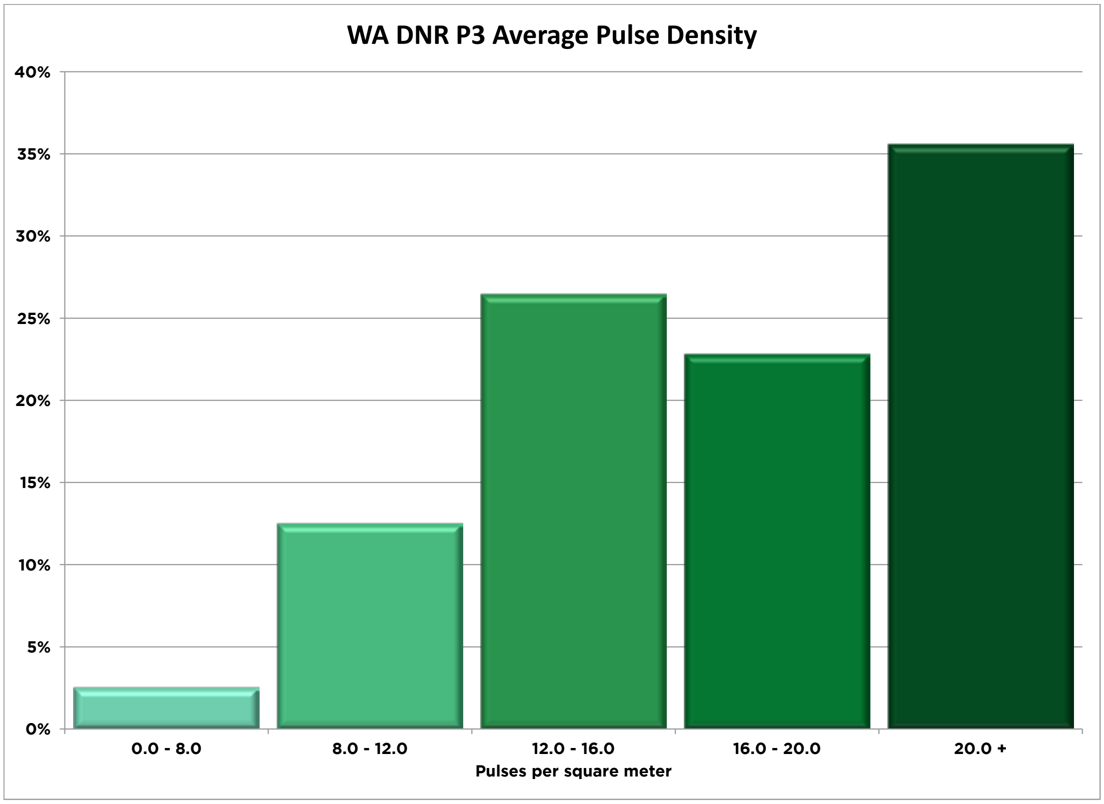


Figure 7: Frequency distribution of first return densities per 30 m X 30 m cell

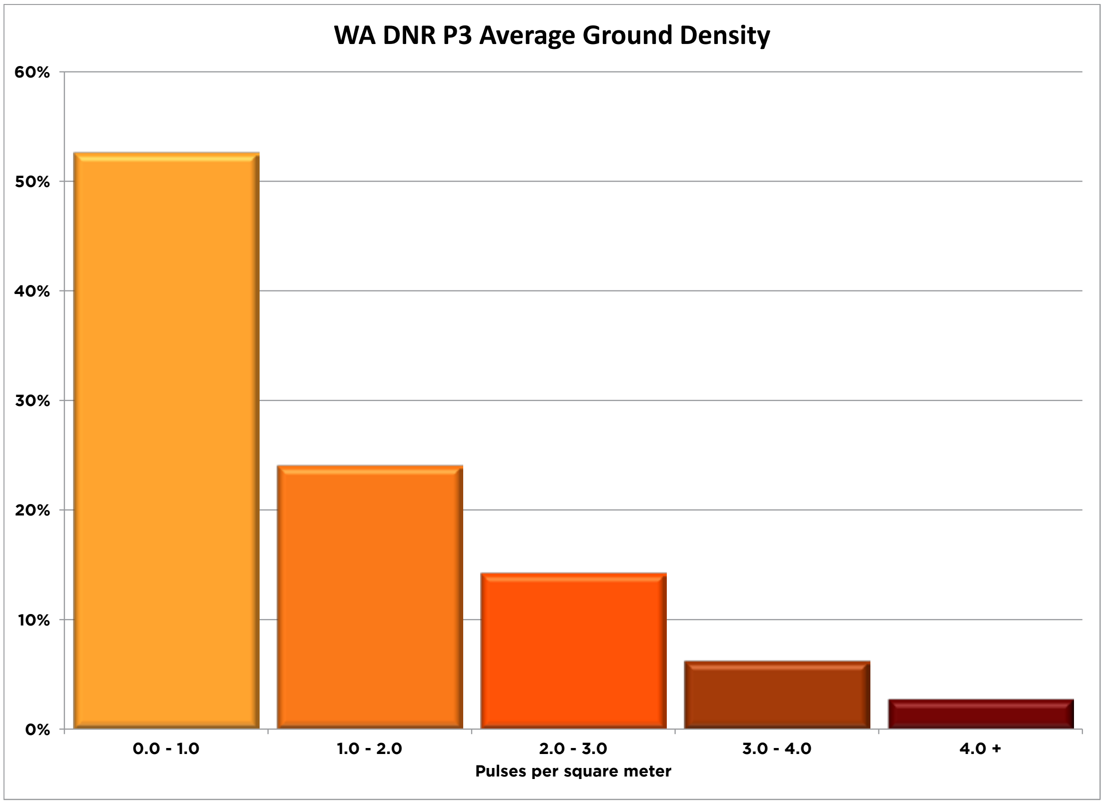


Figure 8: Frequency distribution of classified ground point densities per 30 m X 30 m cell

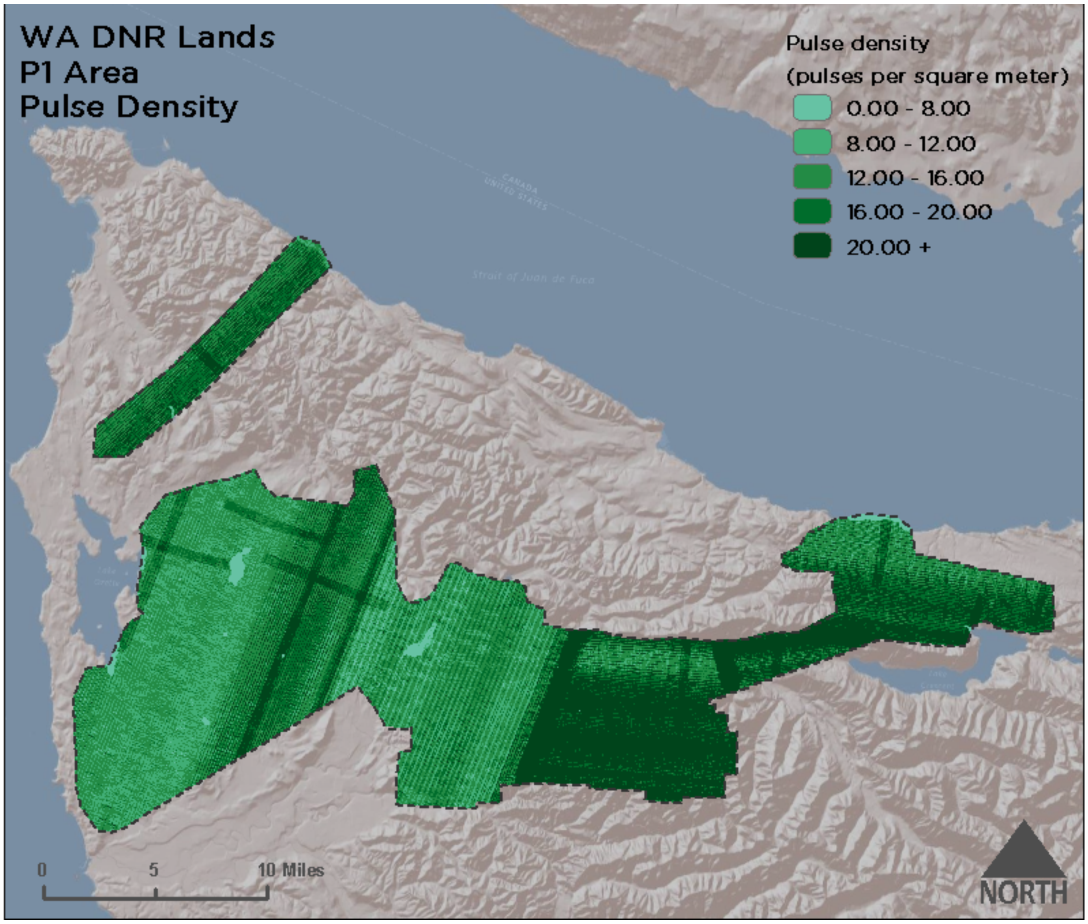


Figure 9: Map of first return densities per 30 m X 30 m cell

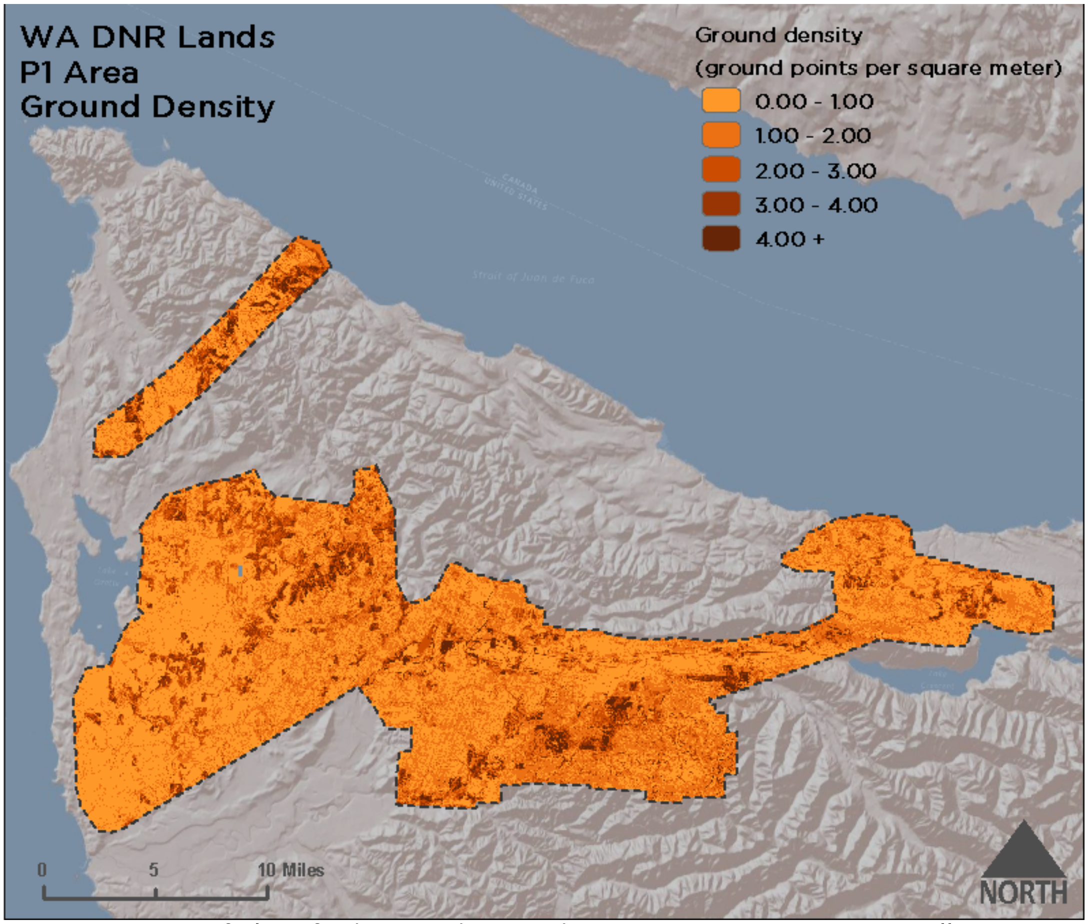


Figure 10: Map of classified ground point densities per 30 m X 30 m cell

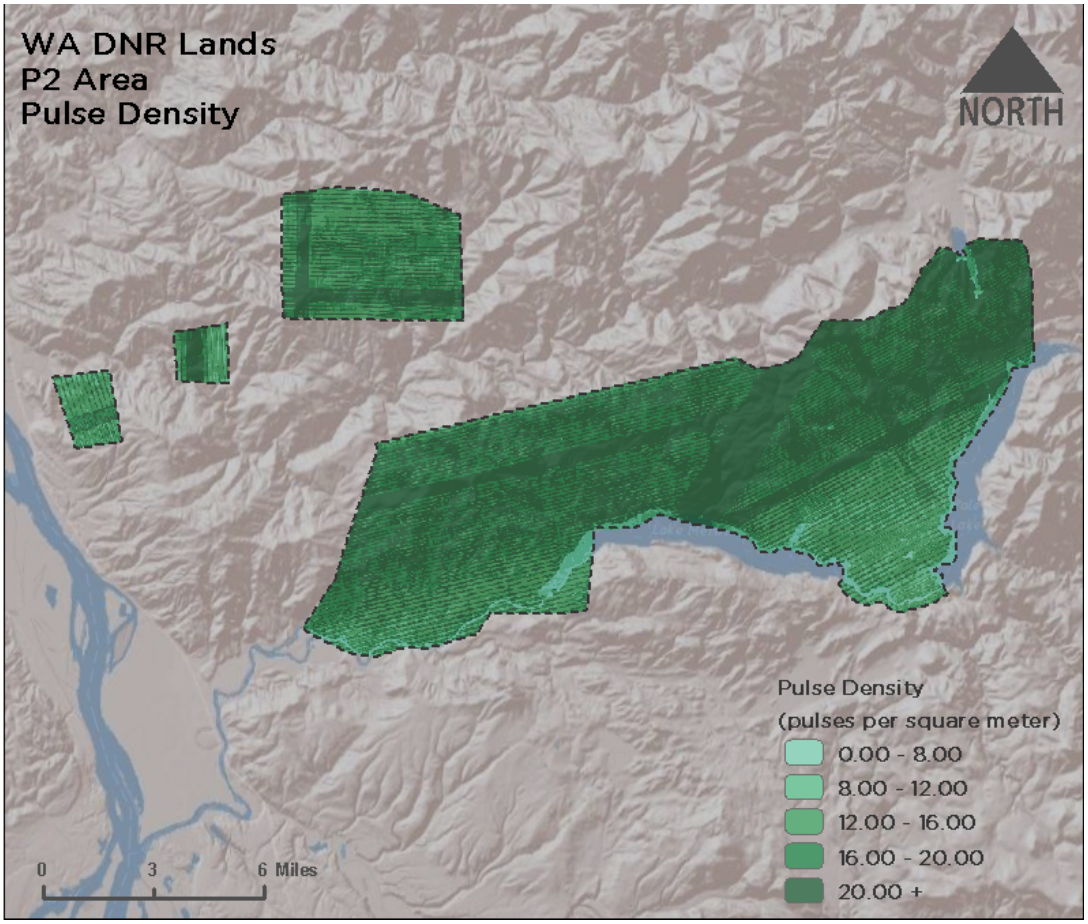


Figure 11: Map of first return densities per 30 m X 30 m cell

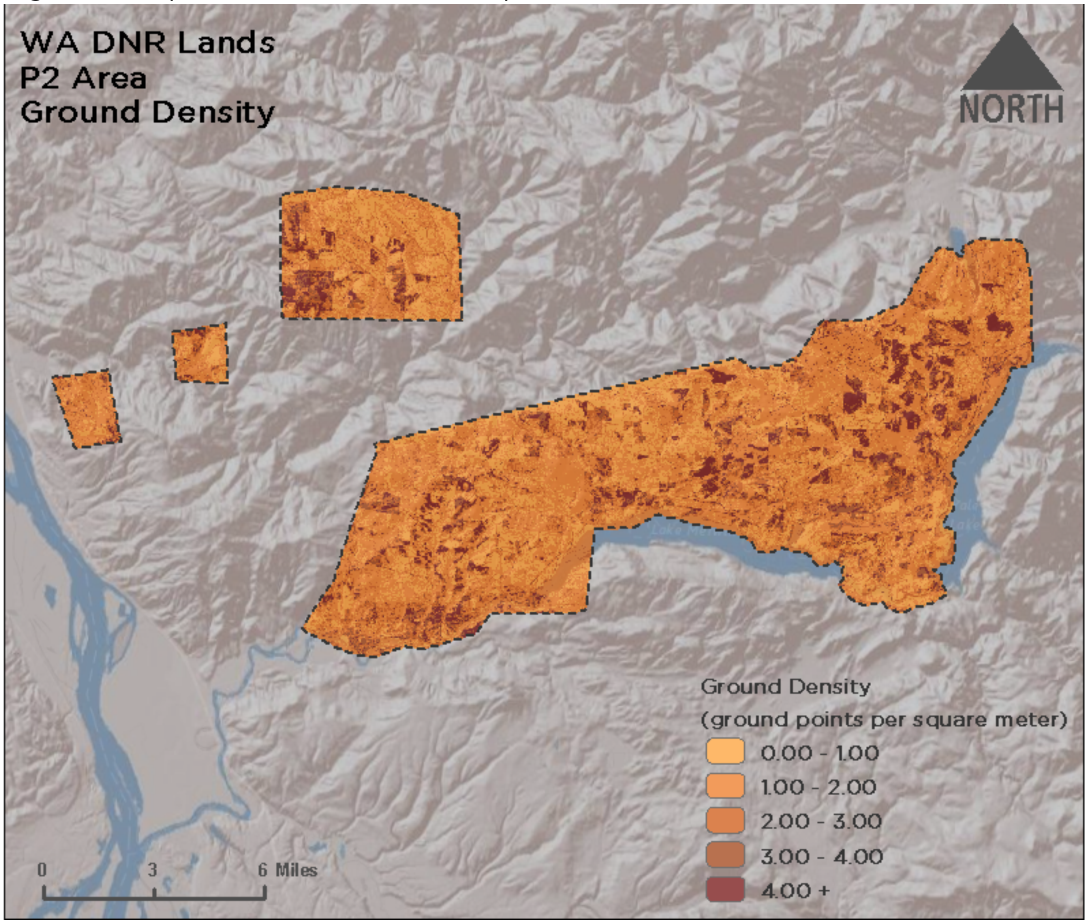


Figure 12: Map of classified ground point densities per 30 m X 30 m cell

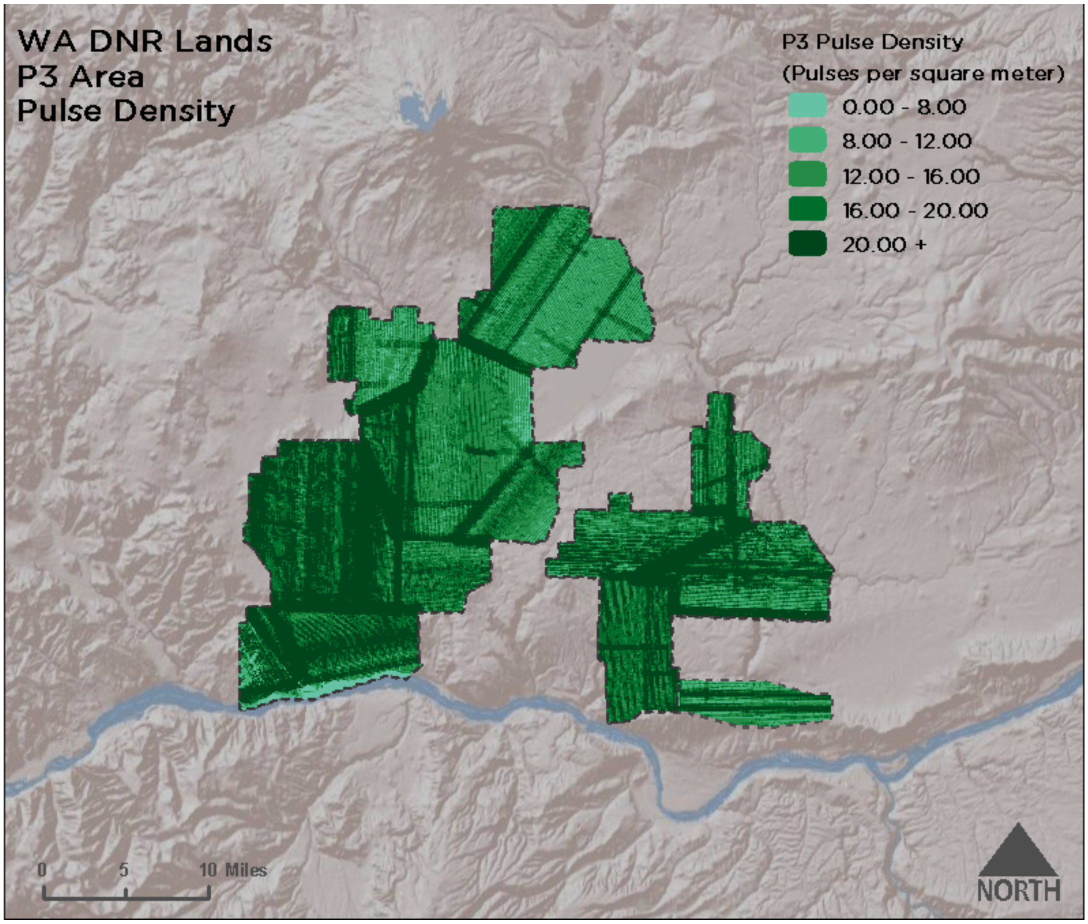


Figure 13: Map of first return densities per 30 m X 30 m cell

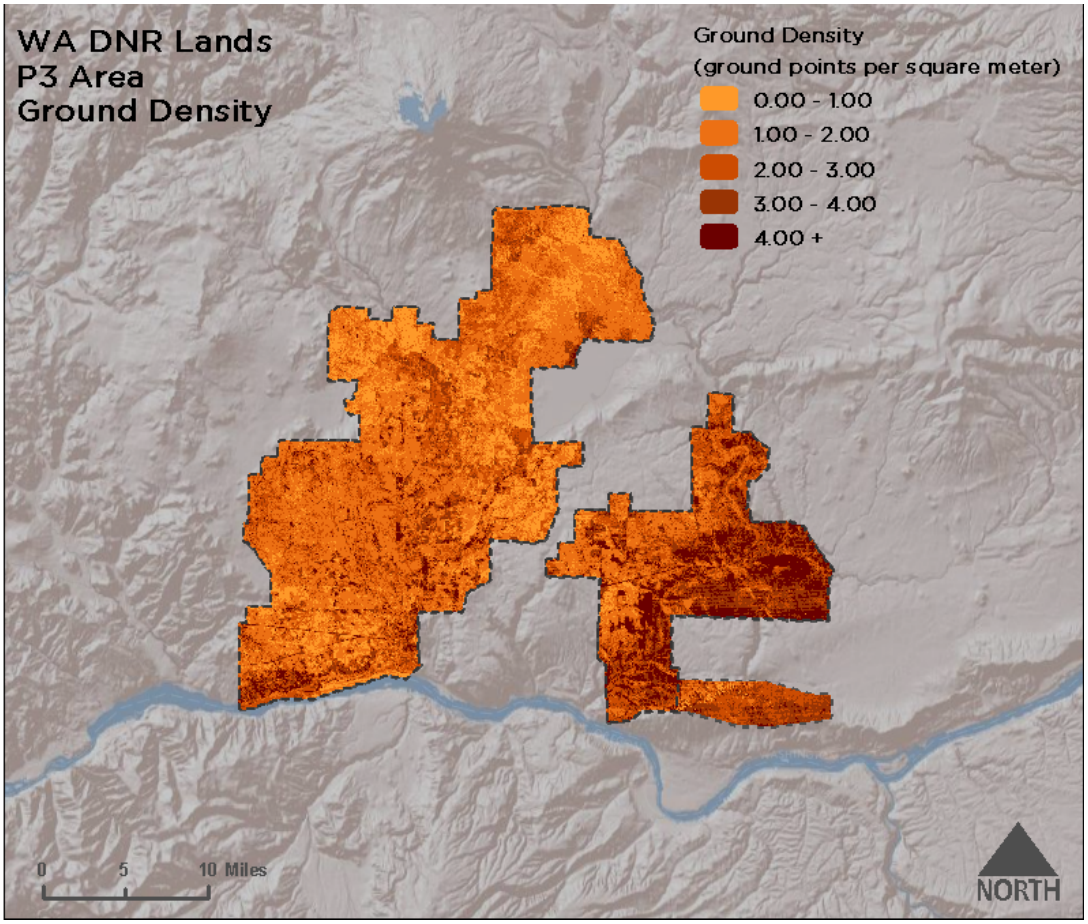


Figure 14: Map of classified ground point densities per 30 m X 30 m cell

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. FVA compares known RTK ground check point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated 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 high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 10. Absolute vertical accuracy was also assessed using ground control point data used in the calibration process project and can be found in Appendix B.

The mean and standard deviation (sigma s) 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 WA DNR Lands survey, 265 ground check points were withheld from the calibration and post-processing of the LiDAR (Table 9, Figure 14).

Table 9: Absolute accuracy

Withheld Check Point Accuracy			
	P1	P2	P3
Sample	n=96	n=27	n=142
FVA (1.96*RMSE)	0.162 m 0.532 ft.	0.061 m 0.200 ft.	0.088 m 0.289 ft.
Average	0.075 m 0.245 ft.	0.026 m 0.085 ft.	-0.020 m -0.066 ft.
Median	-0.023 m -0.075 ft.	-0.012 m -0.041 ft.	-0.014 m -0.047 ft.
RMSE	0.083 m 0.272 ft.	0.031 m 0.102 ft.	0.045 m 0.147 ft.
Standard Deviation (1σ)	0.091 m 0.298 ft.	0.032 m 0.104 ft.	0.040 m 0.132 ft.

*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

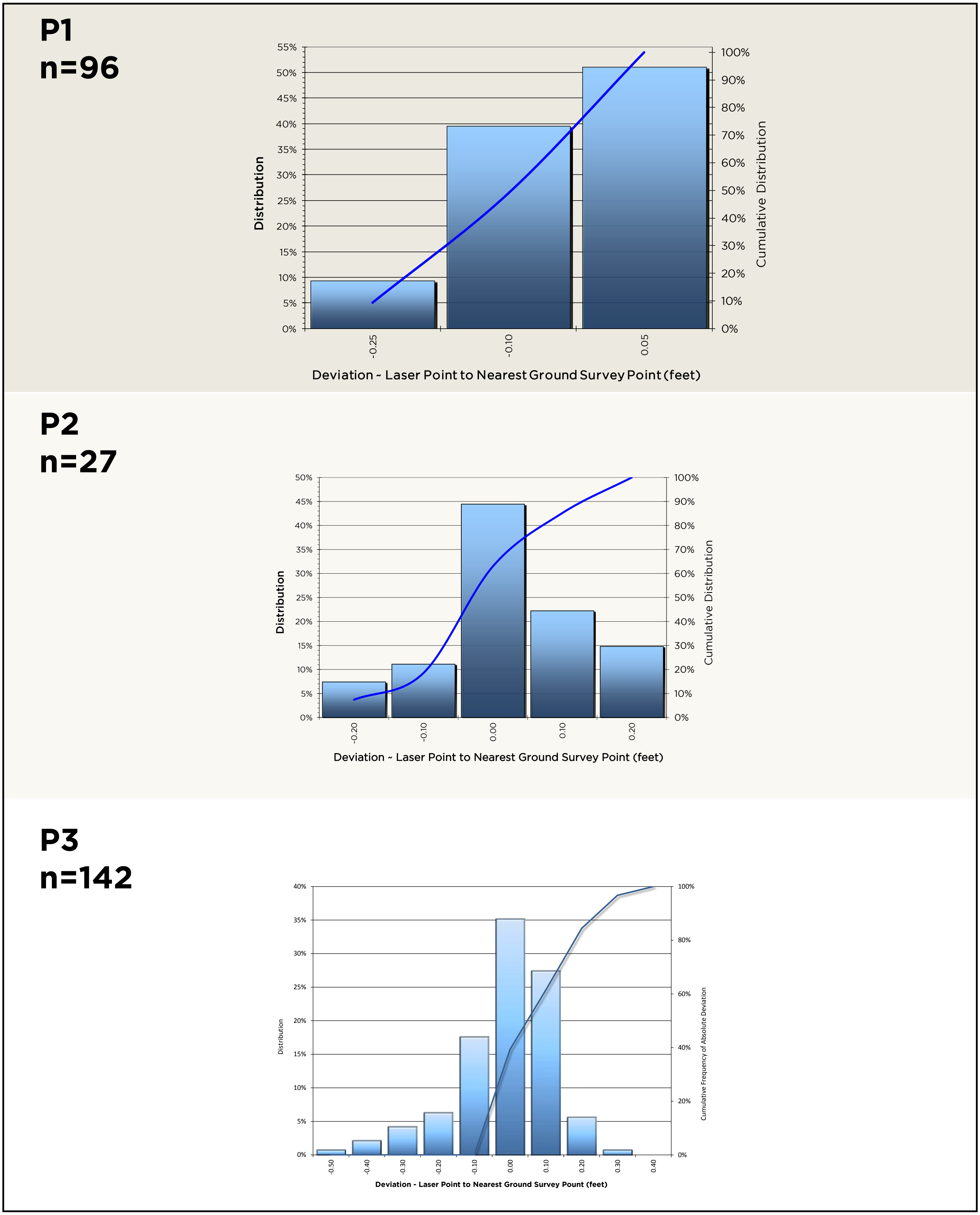


Figure 14. Frequency histogram for LiDAR surface deviation from reserved ground survey control point data.

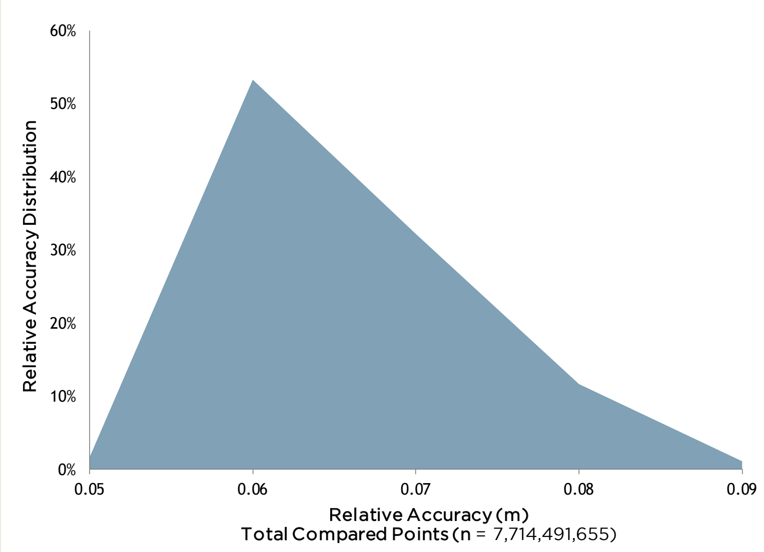
LiDAR Vertical Relative Accuracy

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 was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The relative accuracy was assessed for each AOI within the WA DNR project. (Table 10, Figure 15).

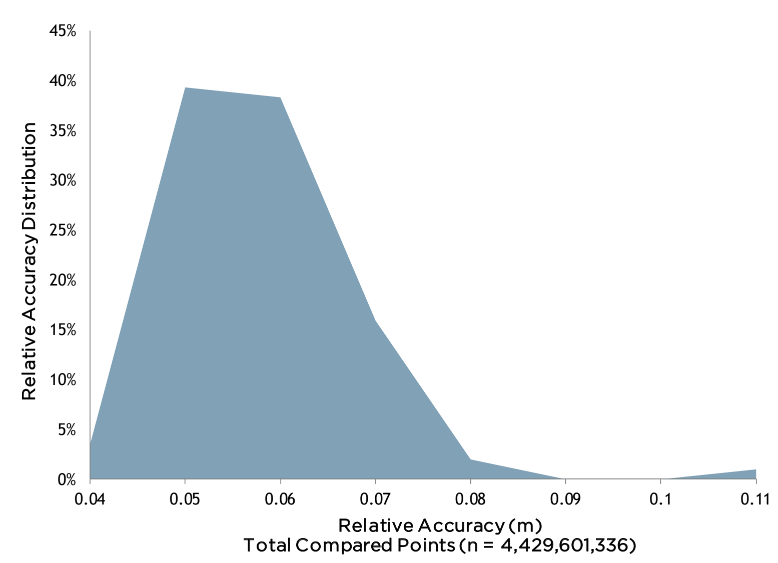
Table 10. Relative accuracy

Relative Accuracy	P1	P2	P3
Surfaces	351	201	1,320
Average	0.062 m	0.053 m	0.049 m
	0.204 ft.	0.173 ft.	0.160 ft.
Median	0.060 m	0.051 m	0.047 m
	0.198 ft	0.168 ft.	0.154 ft.
Standard Deviation (1σ)	0.065 m	0.054 m	0.053 m
	0.212 ft	0.178 ft.	0.172 ft.
1.96σ	0.126 m	0.106 m	0.103 m
	0.415 ft	0.349 ft.	0.242 ft.

P1
351 Surfaces



P2
201 Surfaces



P3
1,830 Surfaces

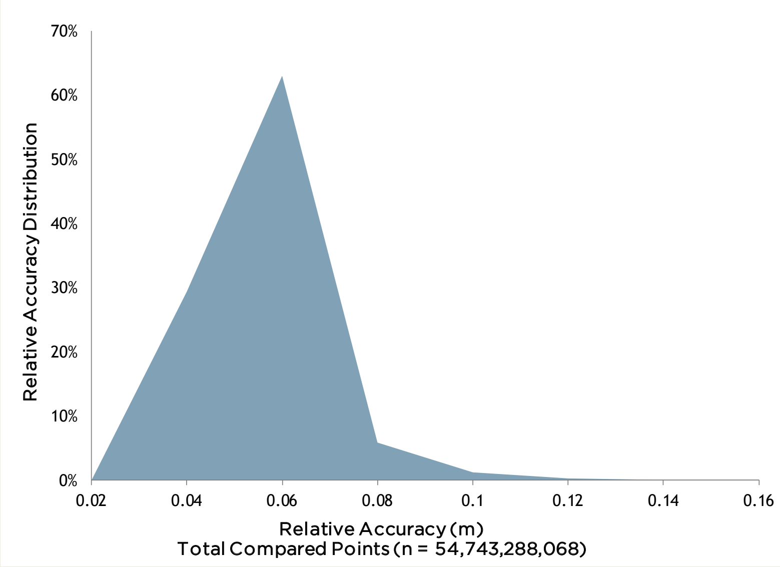
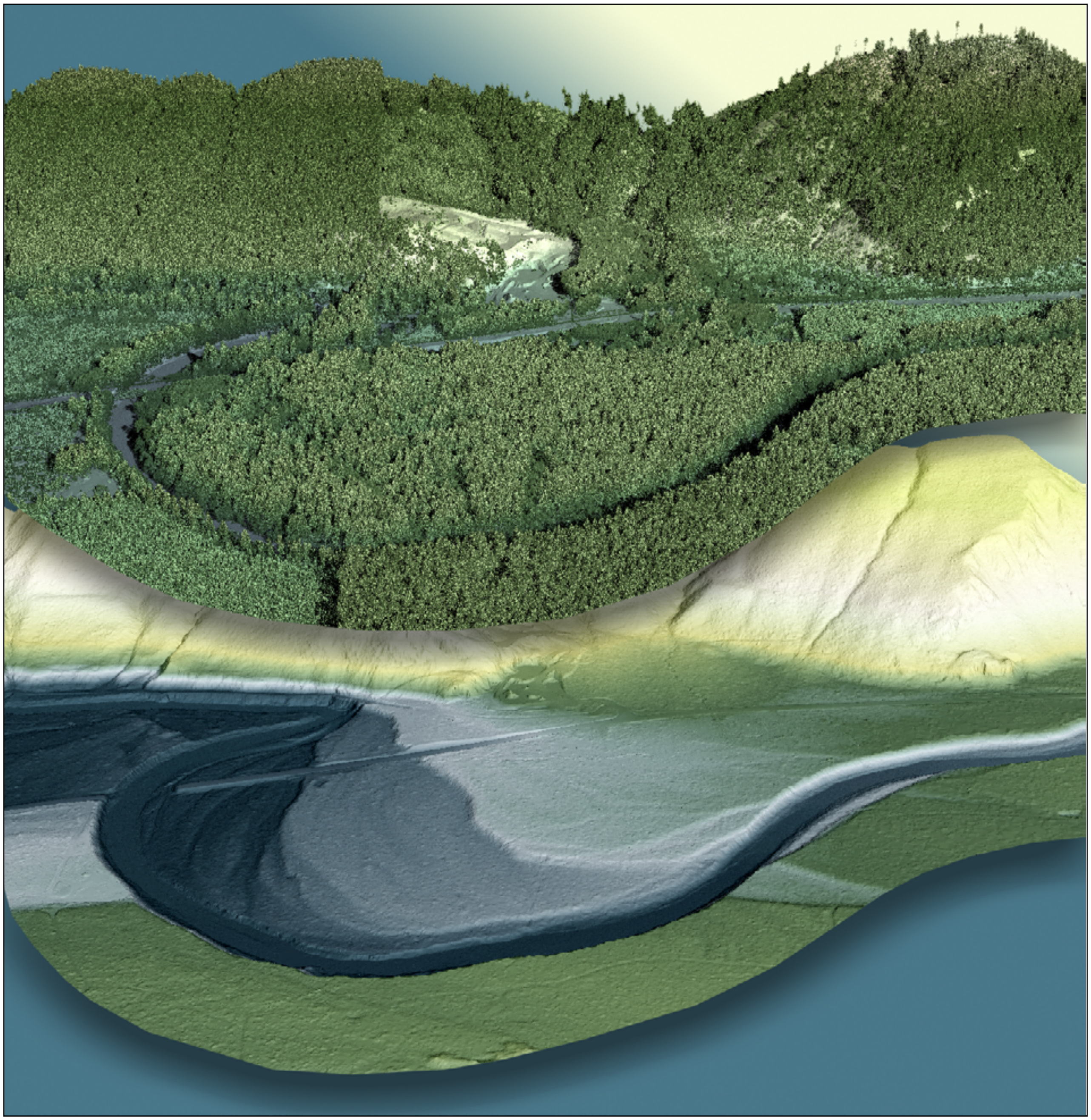
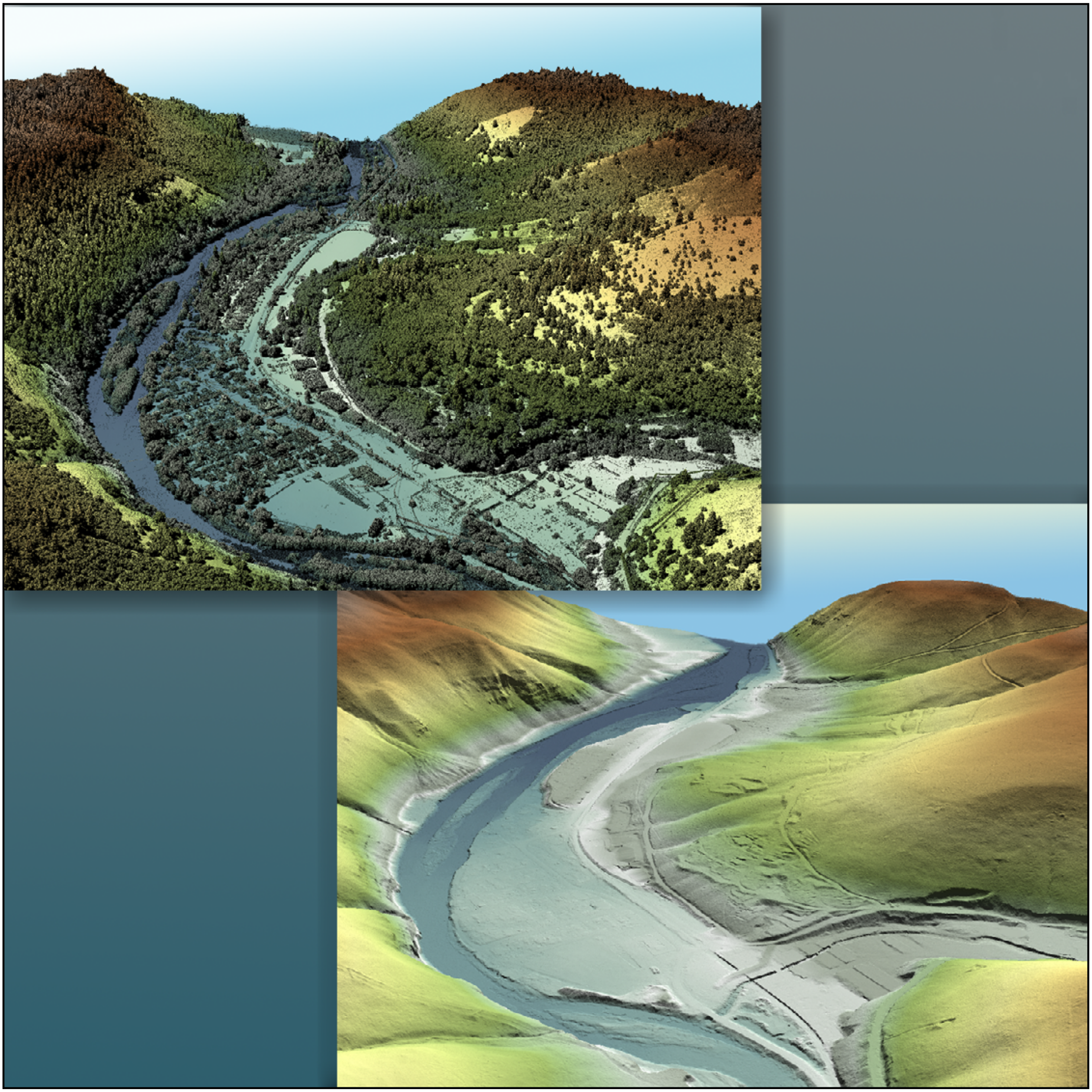


Figure 15: Frequency plot for relative vertical accuracy between WA DNR Lands flightlines



View looking West at an intersection of highway 101 and the Sol Duc River. The image was created from the gridded LiDAR surface colored by elevation and overlaid with the 3-D LiDAR point cloud.



View looking West over Klickitat, Washington. The images were created from the gridded LiDAR surface colored by elevation with the 3-D LiDAR point cloud overlaid in the upper left image.

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 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Fundamental Vertical Accuracy (FVA) reporting.

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 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 the skew and kurtosis of distributions are also considered 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.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

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 (i.e., echos) 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.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. 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.

Native LiDAR Density: The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

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 (i.e., intensity) 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 312o 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 13 nm 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 have opposing directions. 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.

Appendix B - Control Point Accuracy

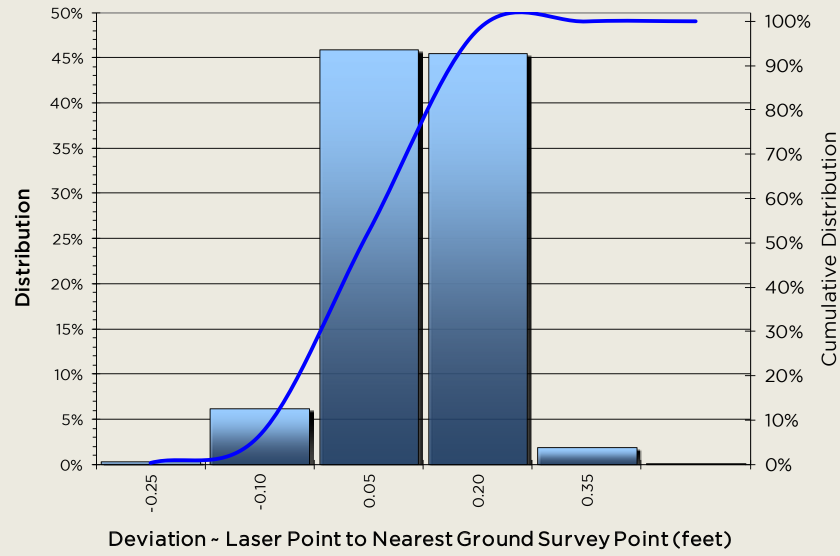
For the WA DNR Lands project, absolute vertical accuracy was also assessed using ground control point data. Although ground control points are used in the calibration and post-processing of the LiDAR data, they still provide a good indication of the overall accuracy of the LiDAR dataset.

For the WA DNR Lands survey each AOI was assessed separately. (Figure 11).

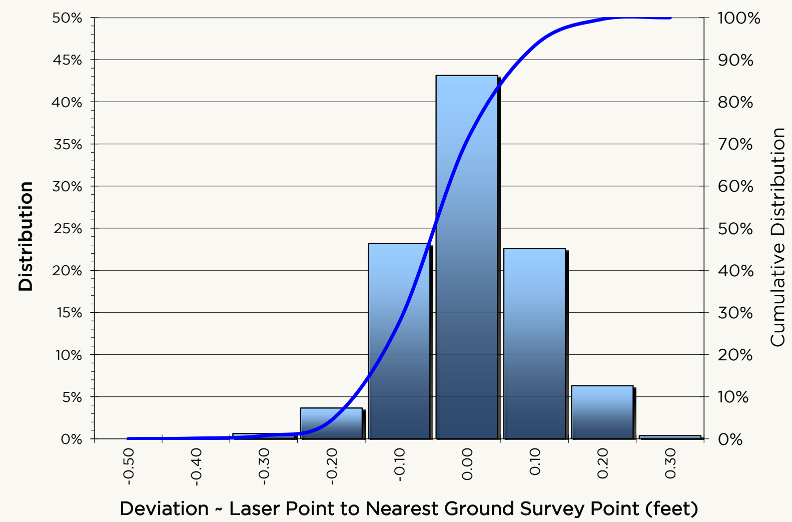
Table 11: Absolute accuracy

Absolute Accuracy			
	P1	P2	P3
Sample	n=3,045	n =793	n=4,070
Average	0.001 m 0.002 ft	0.025 m 0.081 ft.	-0.018 m -0.059 ft.
Median	0.004 m 0.013 ft	-0.076 m -0.248 ft.	-0.010 m -0.034 ft
RMSE	0.022 m 0.072 ft	0.043 m 0.097 ft.	0.044 m 0.146 ft
Standard Deviation (1σ)	0.022 m 0.072 ft	0.031 m 0.101 ft.	0.041 m 0.133 ft.

P1



P2



P3

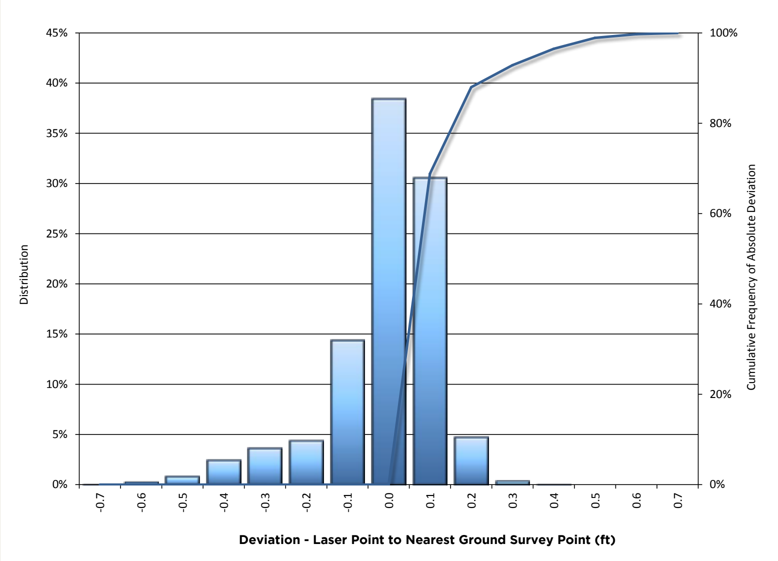


Figure 11: Frequency histogram for LiDAR surface deviation from ground survey point data for P1, P2 and P3.

Appendix C - GPS Monuments

Monuments occupied for the WA DNR Lands acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2010.00. NAVD88 heights were calculated using Geoid03.

Monument ID	Latitude	Longitude	Ellipsoid (meters)	NAVD88 Height (meters)
503SR_GAC-11	45° 59' 47.98922"	-122° 30' 38.64487"	136.086	157.532
KLICKITAT_01	45° 48' 01.49781"	-121° 11' 57.55716"	361.450	382.473
KLICKITAT_02	45° 50' 27.75781"	-121° 01' 44.28768"	306.713	327.654
KLICKITAT_03	45° 55' 47.30244"	-121° 07' 10.55029"	309.968	330.680
SB1168	46° 00' 00.49959"	-121° 32' 30.77556"	577.147	597.413
SC2822	46° 01' 34.14545"	-122° 19' 05.11321"	130.111	151.166
TS0021	48° 04' 18.73797"	-124° 16' 44.81808"	122.729	144.435
WA_DNR_P1_01	48° 09' 03.63327"	-124° 34' 26.07773"	7.582	29.791
WA_DNR_P1_02	48° 08' 09.55238"	-124° 36' 24.10654"	20.579	42.975
WA_DNR_P1_03	48° 02' 08.64807"	-124° 23' 04.71375"	90.223	112.522
WA_DNR_P1_04	48° 04' 10.32636"	-124° 03' 36.65212"	259.821	280.676
WA_DNR_P1_05	48° 08' 11.26267"	-123° 53' 14.92542"	136.573	156.856
WA_DNR_P1_06	48° 04' 44.24585"	-123° 57' 37.83944"	335.539	356.031
WA_DNR_P1_07	48° 00' 07.09715"	-124° 02' 36.56590"	870.305	891.278
WA_DNR_P1_08	48° 01' 59.57728"	-124° 08' 03.80410"	638.814	660.126
WA_DNR_P2_01	45° 56' 44.13946"	-122° 36' 29.36128"	53.921	75.747
WA_DNR_P2_02	46° 03' 27.89800"	-122° 45' 22.19293"	298.922	320.505
WA_DNR_P2_03	45° 57' 52.96098"	-122° 39' 56.77907"	358.873	380.632
WA_DNR_P2_04	46° 03' 45.14116"	-122° 45' 18.81678"	321.506	343.071
WA_DNR_P3_01	45° 49' 24.88857"	-121° 14' 39.67594"	687.578	708.452
WA_DNR_P3_02	46° 01' 11.71163"	-121° 16' 52.95509"	556.687	577.166
WA_DNR_P3_03	46° 00' 56.94469"	-121° 18' 38.72732"	552.883	573.337
WA_DNR_P3_04	45° 53' 06.12609"	-121° 25' 04.65882"	597.059	617.796
WA_DNR_P3_05	45° 53' 45.69374"	-121° 30' 51.41932"	346.915	367.602
WA_DNR_P3_06	45° 49' 13.37756"	-121° 29' 17.84023"	143.466	164.545
WA_DNR_P3_07	45° 45' 24.03344"	-121° 31' 10.47366"	137.926	159.263
WA_DNR_P3_08	45° 48' 51.86996"	-121° 38' 43.34016"	408.387	429.372
WASCO_40	45° 43' 43.90530"	-121° 33' 54.44315"	315.198	336.649
WSDOT_6522	48° 09' 58.22077"	-124° 31' 49.58540"	22.342	44.310

Appendix D - PLS Certification

I, Christopher Glantz, PLS, being duly registered as a Professional Land Surveyor in and by the state of Washington, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between October 16, 2014 and March 13, 2015.

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

11/16/2015

Christopher Glantz, PLS
Professional Land Surveyor
Quantum Spatial, Inc.