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Olympic Peninsula, Washington 3DEP LiDAR - Area 1 Technical Data Report

Contract No. G16PC00016, Task Order No. G17PD00827

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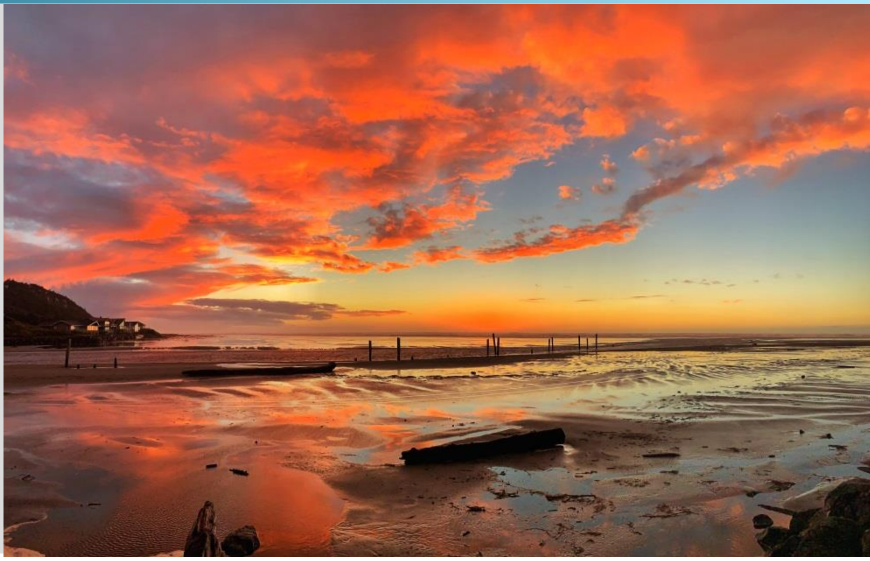
Cover Photo: A view of the Dosewallips River in the Olympic Mountains in Washington State. This image was created with the LiDAR derived elevation surface colored by imagery.

INTRODUCTION

This photo taken by QSI acquisition staff shows a scenic view within the Olympic Peninsula 3DEP project area in Washington.



In August 2017, Quantum Spatial (QSI) was contracted by the United States Geological Survey (USGS) to collect Light Detection and Ranging (LiDAR) data for the Olympic Peninsula 3DEP QL1 LiDAR project site in the state of Washington. The Olympic Peninsula 3DEP LiDAR project area covers approximately 3.4 million acres in northwestern Washington, split into four areas. This delivery includes Area 1, which covers 1.4 million acres in Grays Harbor, Mason, Jefferson and Clallam counties in northwest Washington. Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area to support the 3DEP mapping initiative.

This report accompanies the delivered LiDAR data, 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 USGS 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 Olympic Peninsula sites

Project Site	Total Acres	Acquisition Dates	Data Type
Olympic Peninsula Area 1	1,449,550	• September 14, 2017 – December 12, 2017 • January 14, 2018 – April 25, 2018 • June 19, 2018 • July 12 – July 24, 2018 • October 11, 2018 • December 3, 2018 – December 6, 2018 • January 30, 2019 • April 25, 2019	High Resolution QL1 LiDAR

Deliverable Products

Table 2: Products delivered to USGS for the Olympic Peninsula Priority Area 3 site

Olympic Peninsula 3DEP LiDAR Products Projection: Washington State Plane South Horizontal Datum: NAD83 (CORS96), Labeled HARN* Vertical Datum: NAVD88 (GEOID03) Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns • Unclassified Flightline Swaths
Rasters	3.0 Foot ESRI GRID • Hydroflattened Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM) • Ground Density 3.0 Foot GeoTiffs (*.tif) • Intensity Images
Vectors	Index Shapefiles (*.shp) • Site Boundary • Deliverable Sites Diagram • LAS Tile Index (1/100th USGS Quadrangles) • DEM Tile Index (1/4 USGS Quadrangles) • Breaklines (Water's Edge and Bridges) • Flightline Index Ground Survey Shapefiles (*.shp) • Non-Vegetated Ground Check Points • Vegetated Ground Check Points • Ground Control Points • Ground Base Stations

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

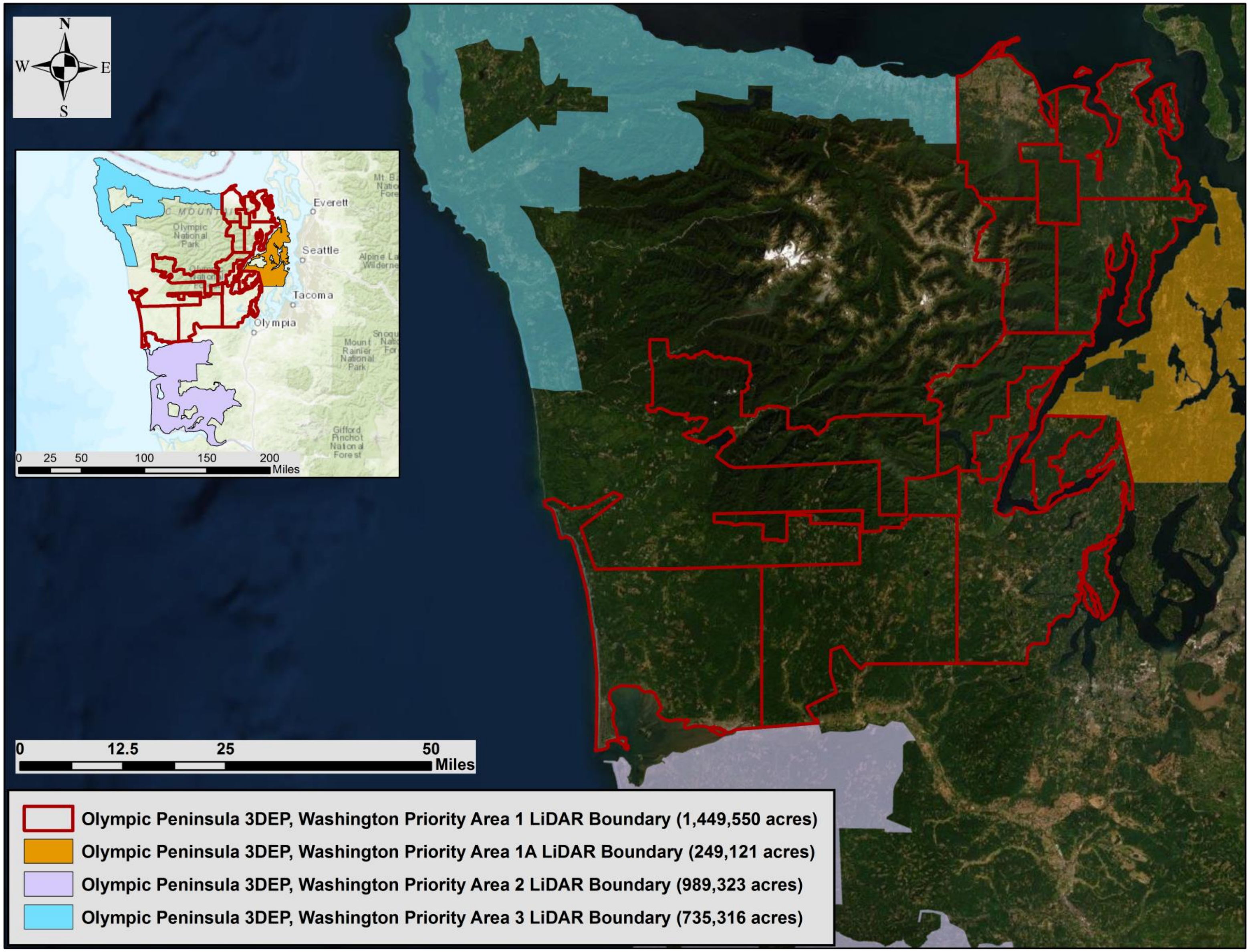


Figure 1: Location map of the Olympic Peninsula 1 site in Washington

ACQUISITION

QSI's ground acquisition equipment set up in the Olympic Peninsula LiDAR study area.

Planning

Quantum Spatial, in collaboration with Airborne Imaging and Eagle Mapping, developed specialized flight plans to ensure complete coverage of the Olympic Peninsula Area 1 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 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 flights 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.

Airborne LiDAR Survey

The LiDAR surveys were accomplished by three different vendors. The northern portion of Area 1 was acquired with a Leica ALS80 or Riegl VQ-1560i sensor system mounted in QSI's Cessna Caravan, while the majority of the central and southern portions of Area 1 were flown by Eagle Mapping and Airborne Imaging, respectively (Figure 2). Airborne imaging utilized a Riegl Q-1560 or Riegl VQ-1560i sensor system mounted in a Piper Navajo, while Eagle Mapping acquired data using a Riegl LMS-Q780, also mounted in a Piper Navajo. Table 3 summarizes the various settings used to yield an average pulse density of ≥8 pulses/m^2 over the Olympic Peninsula 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 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.

All areas were surveyed with an opposing flightline 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.

Scenic photo of a neighborhood overlooking Liberty Bay in the Area 1 Olympic Peninsula site taken by QSI acquisition staff

Table 3: Survey Settings & Specifications

LiDAR Survey Settings & Specifications				
Operating Company	**Airborne Imaging**	**Eagle Mapping**	**QSI**	**QSI**
Acquisition Dates	12/10/17 – 12/12/17, 3/31/18, 4/2/18, 4/20/18, 4/23/18, 4/25/18, 12/3/18 – 12/6/18	10/15/17, 10/28/17, 1/14/18, 1/15/18, 6/19/18, 7/12/18, 7/13/18, 10/11/18, 1/30/19	9/14/17 – 9/16/17, 9/24/17, 9/27/17 – 9/28/17, 10/4/17 – 10/6/17, 3/7/18, 3/10/18, 3/11/18, 3/16/18, 7/22/18 – 7/24/18	2/13/18, 2/19/18, 2/21/18, 12/5/18, 4/25/19
Aircraft Used	Piper Navajo	Piper Navajo	Cessna Caravan	Cessna Caravan
Sensor	Riegl	Riegl	Leica	Riegl
Laser	Q1560 or VQ-1560i	LMS-Q780	ALS80	VQ-1560i
Maximum Returns	Unlimited	Unlimited	Unlimited	Unlimited
Nominal Pulse Density	Average 4 pulses/m^2	Average 4 pulses/m^2	Average 4 pulses/m^2	Average 4 pulses/m^2
Aggregate Nominal Pulse Density	Average 8 pulses/m^2	Average 8 pulses/m^2	Average 8 pulses/m^2	Average 8 pulses/m^2
Nominal Pulse Spacing	0.70 m	0.70 m	0.70 m	0.70 m
Aggregate Nominal Pulse Spacing	0.35 m	0.35 m	0.35 m	0.35 m
Survey Altitude (AGL)	1,200 m	1,300 m	1,550 m	1,650 m
Survey speed	170 knots	140 knots	120 knots	140 knots
Field of View	58.5°	58.5°	40°	58.5°
Mirror Scan Rate	107 lines per second	207 lines per second	48.0 Hz	Auto Calculated
Target Pulse Rate	400 kHz	400 kHz	341.6 kHz	500 kHz per channel
Pulse Length	3 ns	3 ns	2.5 ns	3 ns
Laser Pulse Footprint Diameter	30 cm	32.5 cm	34 cm	41 cm
Central Wavelength	1064 nm	1064 nm	1064 nm	1064 nm
Pulse Mode	MTA (Multiple-Time-Around)	MTA (Multiple-Time-Around)	Multi-Pulse in Air (2PiA)	MTA (Multiple-Time-Around)
Beam Divergence	0.25 mrad	0.25 mrad	0.22 mrad	0.25 mrad
Swath Width	1,344 m	1,456 m	1,128 m	1,848 m
Swath Overlap	60%	60%	60%	60%
Intensity	16-bit	16-bit	8-bit, scaled to 16-bit	16-bit
Accuracy Requirement	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm NVA (95% Confidence Level) ≤ 19.6 cm VVA (95^{th} Percentile) ≤ 29.4 cm			

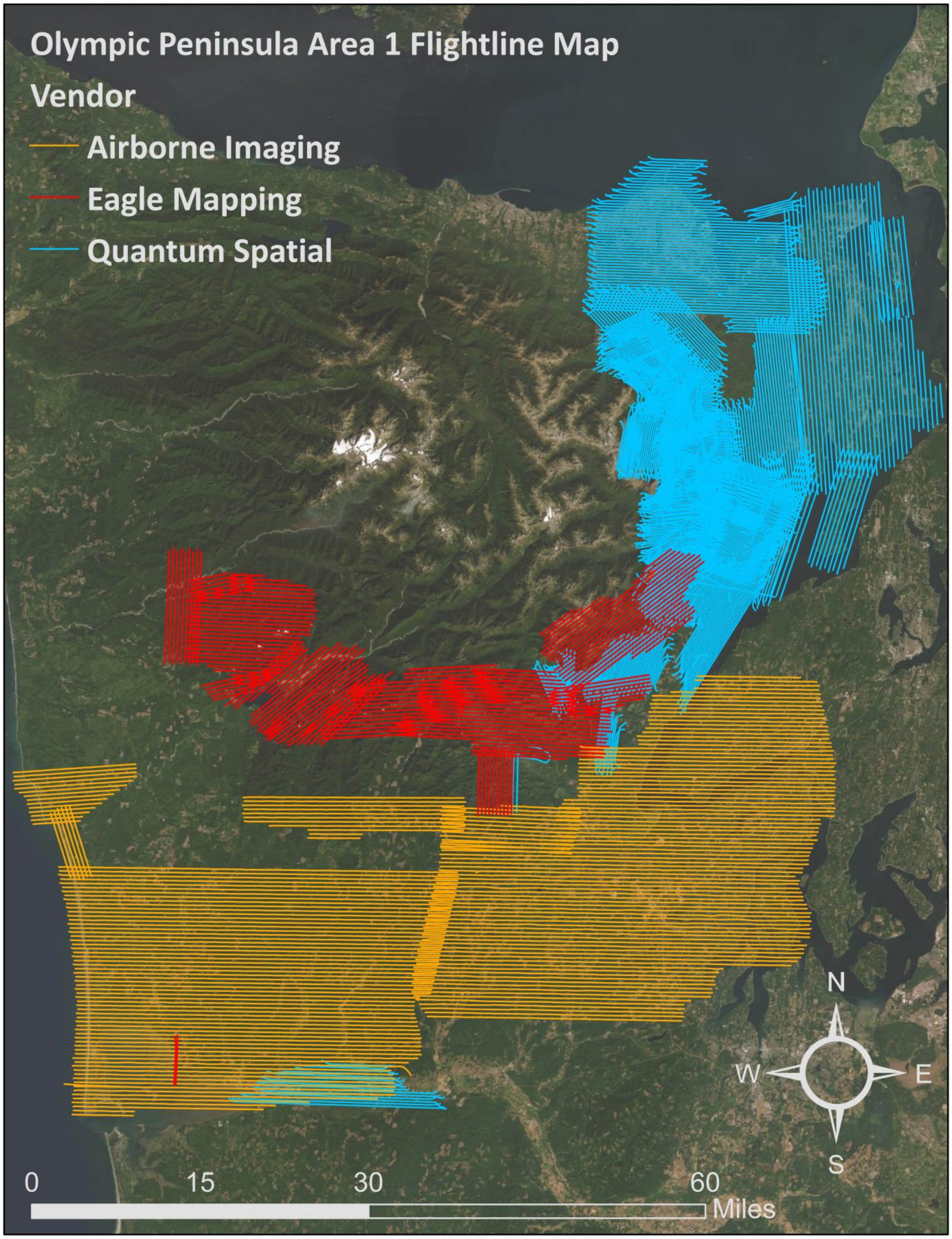


Figure 2: Olympic Peninsula Area 1 Flightline Map

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.

Base Stations

The spatial configuration of ground control monuments and base stations provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments and base stations were also used for collection of ground survey points using real time kinematic (RTK), post-processed kinematic (PPK), and fast static (FS) survey techniques. Base station locations were selected with consideration for satellite visibility, field crew safety, RTN availability and optimal location for GSP coverage.

QSI utilized one previously QSI-established monument and set five new monuments for the Olympic Peninsula LiDAR project. New monuments were set with 2-inch aluminum caps on 5/8-inch rebar. In addition, QSI utilized 16 permanent GNSS stations from the Washington State Reference Network (WSRN) for kinematic processing and GSP collection. See Table 4 for a full listing of monuments and WSRN stations (Figure 3).

Table 4: Base Stations utilized for the Olympic Peninsula Area 1 acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00.

Base Station ID	Source	Latitude	Longitude	Ellipsoid (meters)
CHCM	WSRN	48° 00' 38.20717"	-122° 46' 33.06166"	20.726
CUSH	WSRN	47° 25' 24.02222"	-123° 13' 11.66726"	217.377
DEEJ	WSRN	47° 28' 07.79482"	-123° 55' 34.05703"	103.908
ELSR	WSRN	47° 29' 51.35881"	-122° 45' 38.04349"	115.503
GHCC	WSRN	46° 57' 09.29564"	-123° 48' 07.36046"	32.653
LNGB	WSRN	47° 13' 07.61168"	-122° 45' 29.87670"	2.813
MONT	WSRN	46° 58' 58.26044"	-123° 36' 12.74612"	8.346
OCEN	WSRN	46° 57' 08.51949"	-124° 09' 34.91408"	-17.062
OLAR	WSRN	46° 57' 40.28713"	-122° 54' 30.41541"	41.412
OLMP	WSRN	47° 02' 41.43320"	-122° 53' 42.72587"	2.955
OLY_PEN_01	QSI	47° 49' 29.34910"	-122° 55' 39.26721"	232.004
OLY_PEN_02	QSI	47° 45' 20.86369"	-122° 57' 27.82766"	821.68
OLY_PEN_03	QSI	47° 34' 11.45469"	-123° 02' 47.48419"	176.327
OLY_PEN_04	QSI	47° 31' 55.34925"	-123° 04' 55.73886"	149.183
OLY_PEN_05	QSI	47° 24' 27.62996"	-123° 10' 52.44215"	172.664
OLYMPIC_01	QSI	47° 29' 00.20214"	-123° 49' 31.15323"	38.224
P400	WSRN	47° 30' 48.03996"	-123° 48' 44.75945"	65.358
SEQM	WSRN	48° 05' 29.08134"	-123° 06' 48.69404"	35.017

Base Station ID	Source	Latitude	Longitude	Ellipsoid (meters)
TACO	WSRN	47° 13' 43.90565"	-122° 28' 17.36765"	81.457
UFDA	WSRN	47° 45' 18.01711"	-122° 40' 02.63841"	76.922
WAMS	WSRN	46° 58' 39.27571"	-123° 36' 08.49095"	-8.729
WAPO	WSRN	47° 48' 12.51325"	-122° 34' 08.96520"	20.104

QSI utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 5.

Table 5: Federal Geographic Data Committee monument rating for network accuracy

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

For the Olympic Peninsula LiDAR project, the monument coordinates contributed no more than 2.8 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), post-processed kinematic (PPK), fast-static (FS), and total station (TS) survey techniques.

- For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical.
- PPK surveys compute these corrections during post-processing to achieve comparable accuracy.
- 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.

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

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

- FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines for post-processing.
- Forested check points were collected using total stations in order to measure positions under dense canopy. Total station backsight and setup points were established using FS survey techniques.

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. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 6 for QSI equipment specifications.

GSPs 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. 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 3).

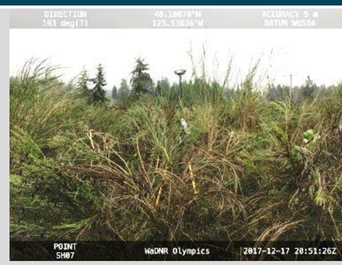
Table 6: QSI equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R6	Integrated GNSS Antenna R6	TRM_R6	Rover
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	Static, Rover
Trimble R10	Integrated Antenna R10	TRMR10	Rover
Nikon NPL-322+ 5” P		n/a	Total Station
Trimble S7 3” DR+		n/a	Total Station

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the LiDAR derived ground models across land cover classes (Table 7, see LiDAR Accuracy Assessments, page 20).

Table 7: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrub	SHRUB		Areas dominated by lowland brush and woody vegetation	VVA
Tall Grass	TALL_GRASS		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FOREST		Forested areas dominated by trees	VVA
Bare Earth	BARE, BE		Areas of bare earth surface	NVA
Urban	URBAN		Areas dominated by urban development, including parks	NVA

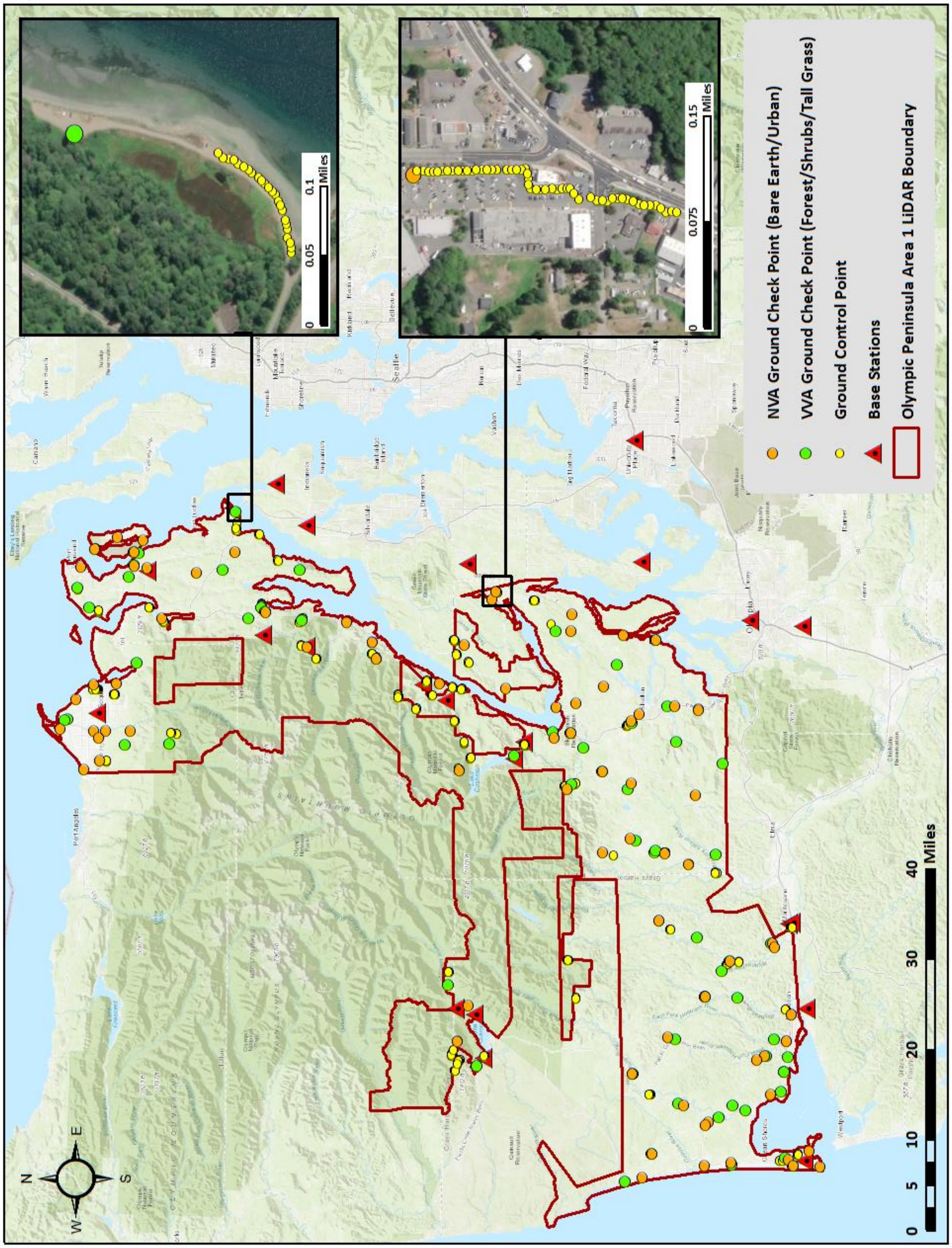
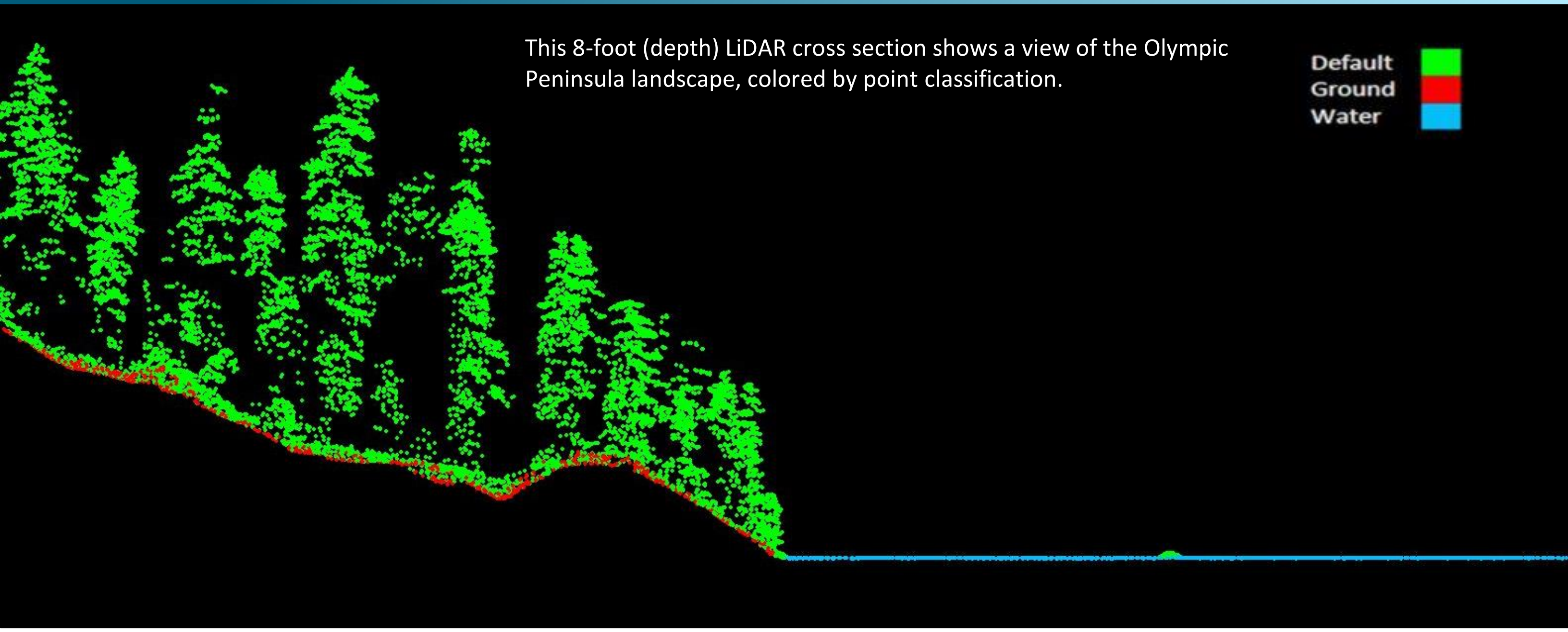


Figure 3: Ground survey location map



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 8). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9.

Table 8: ASPRS LAS classification standards applied to the Olympic Peninsula dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-O	Overlap/Edge Clip	Flightline edge clip that is withheld because it does not contribute to the utility of the dataset, but may be maintained as a reference
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7	Noise	Laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface

Classification Number	Classification Name	Classification Description
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	Bridge decks
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for breakline-enforced model creation

Table 9: LiDAR processing workflow

LiDAR Processing Step	Software Used
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.	POSPac 8.1 – 8.3
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. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	RiProcess 1.8.4 – 1.8.5 RiWorld 5.1.3 – 5.1.4 SDC Import 2.2.5 – 2.3.12
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.17 - 18
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.17 - 18
Classify resulting data to ground and other client designated ASPRS classifications (Table 8). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.17 - 19 TerraModeler v.17 - 19
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 format at a 3.0 foot pixel resolution.	Las Product Creator 3.1 (QSI Proprietary) ArcMap v. 10.3.1
Export intensity images as GeoTIFFs at a 3.0 foot pixel resolution.	Las Product Creator 3.1 (QSI Proprietary)

Feature Extraction

Hydroflattening and Water's Edge Breaklines

The coastal waters surrounding the Olympic Peninsula project area, rivers nominally wider than 30 meters, and water bodies within the project area greater than 2 acres were flattened to a consistent water level. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary.

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered LiDAR returns to create the final 3D breaklines. Lakes were assigned a consistent elevation for an entire polygon while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge.

Tidal and Temporal Changes

The Olympic Peninsula Area 1 project area is bounded by miles of coastline and includes many tidally influenced lakes and river deltas. Since the project was acquired over many months, it is expected that there is data captured at varying tide levels which lends issues to the hydroflattening process. To accommodate these tidal and temporal differences, it is not uncommon to "stair-step" the flattened water surface to most accurately reflect the different missions in the project while capturing as much ground as permitted (Figure 4). Please reference section C.1.c.(ii).(d) of the task order and the Hydroflattening section of the USGS LiDAR Base Specification, V. 1.2 for more information.

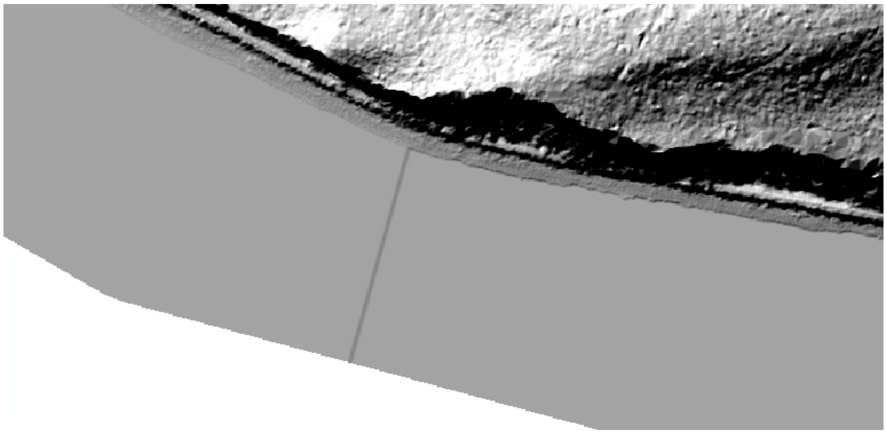
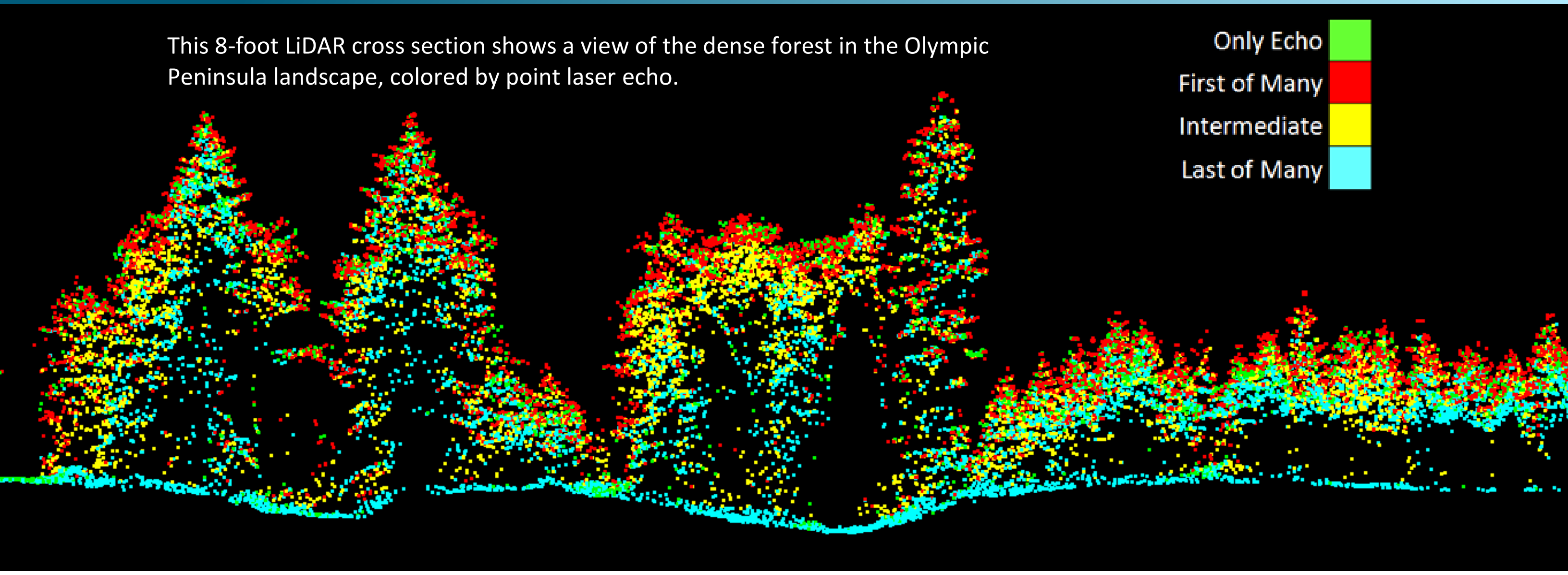


Figure 4: Example of a "stair step" in the hydroflattened coastline of Olympic Peninsula Area 1



This 8-foot LiDAR cross section shows a view of the dense forest in the Olympic Peninsula landscape, colored by point laser echo.

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 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 (Figure 7).

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 of LiDAR data for the Olympic Peninsula Area 1 project was 1.37 points/ft^2 (14.71 points/m^2) while the average ground classified density was 0.17 points/ft^2 (1.84 points/m^2) (Table 10). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 5 through Figure 8.

Table 10: Average LiDAR point densities

Classification	Point Density
First-Return	1.37 points/ft^2 14.71 points/m^2
Ground Classified	0.17 points/ft^2 1.84 points/m^2

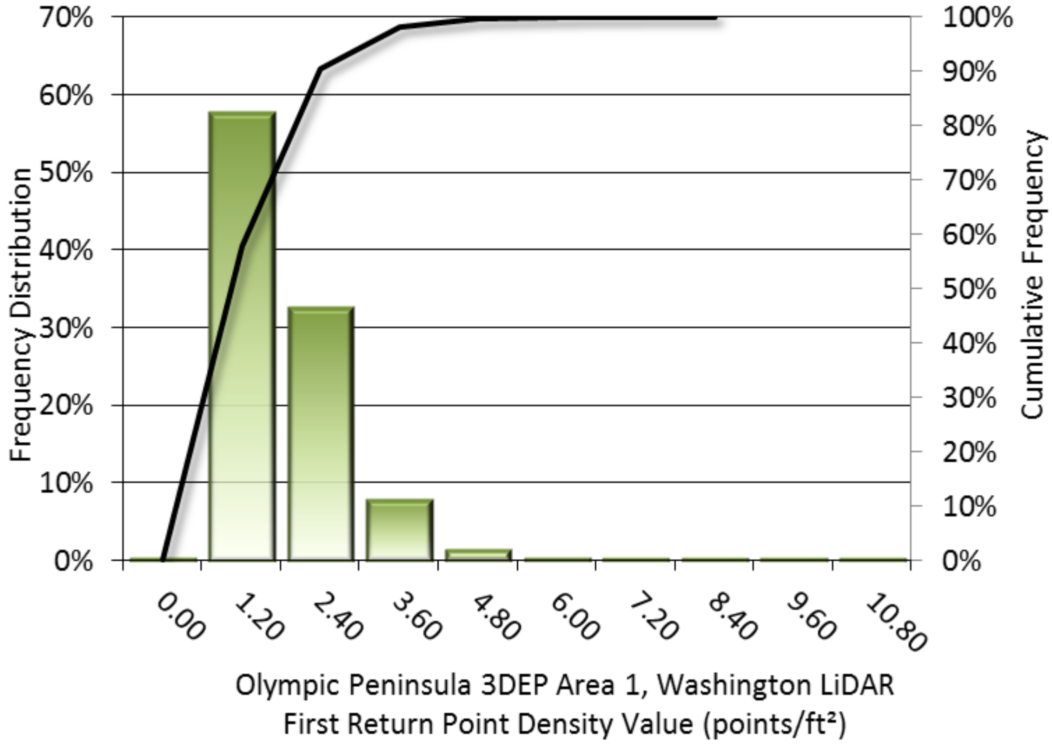


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

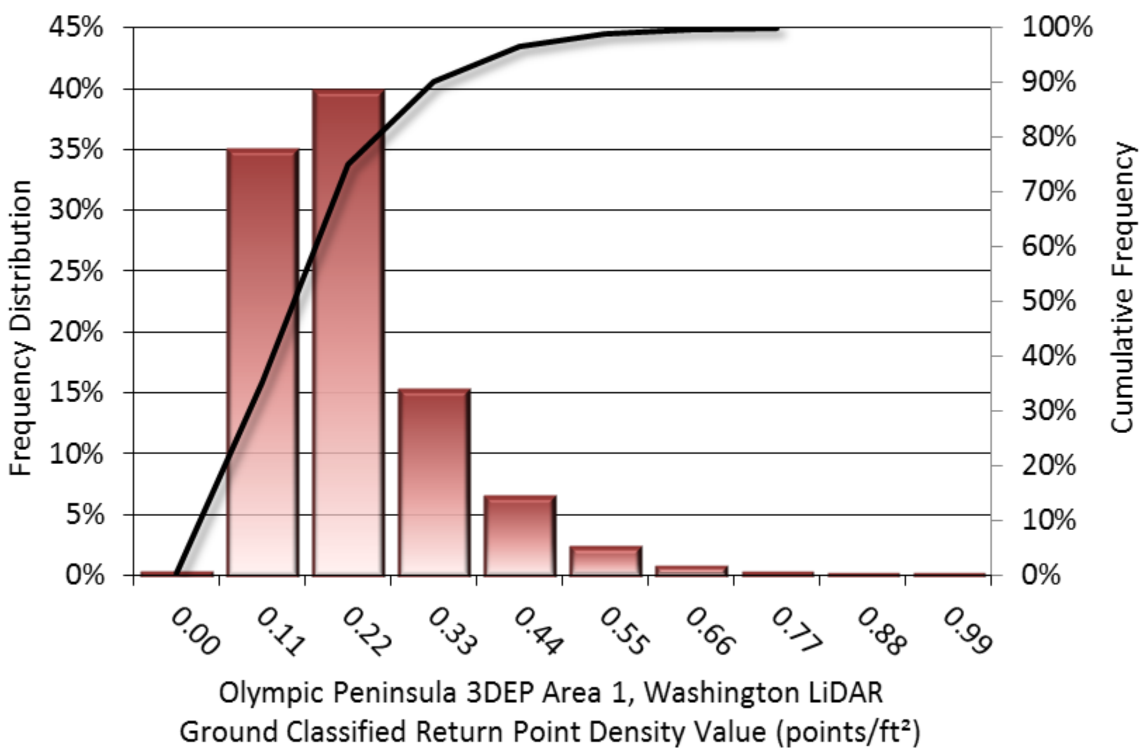


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

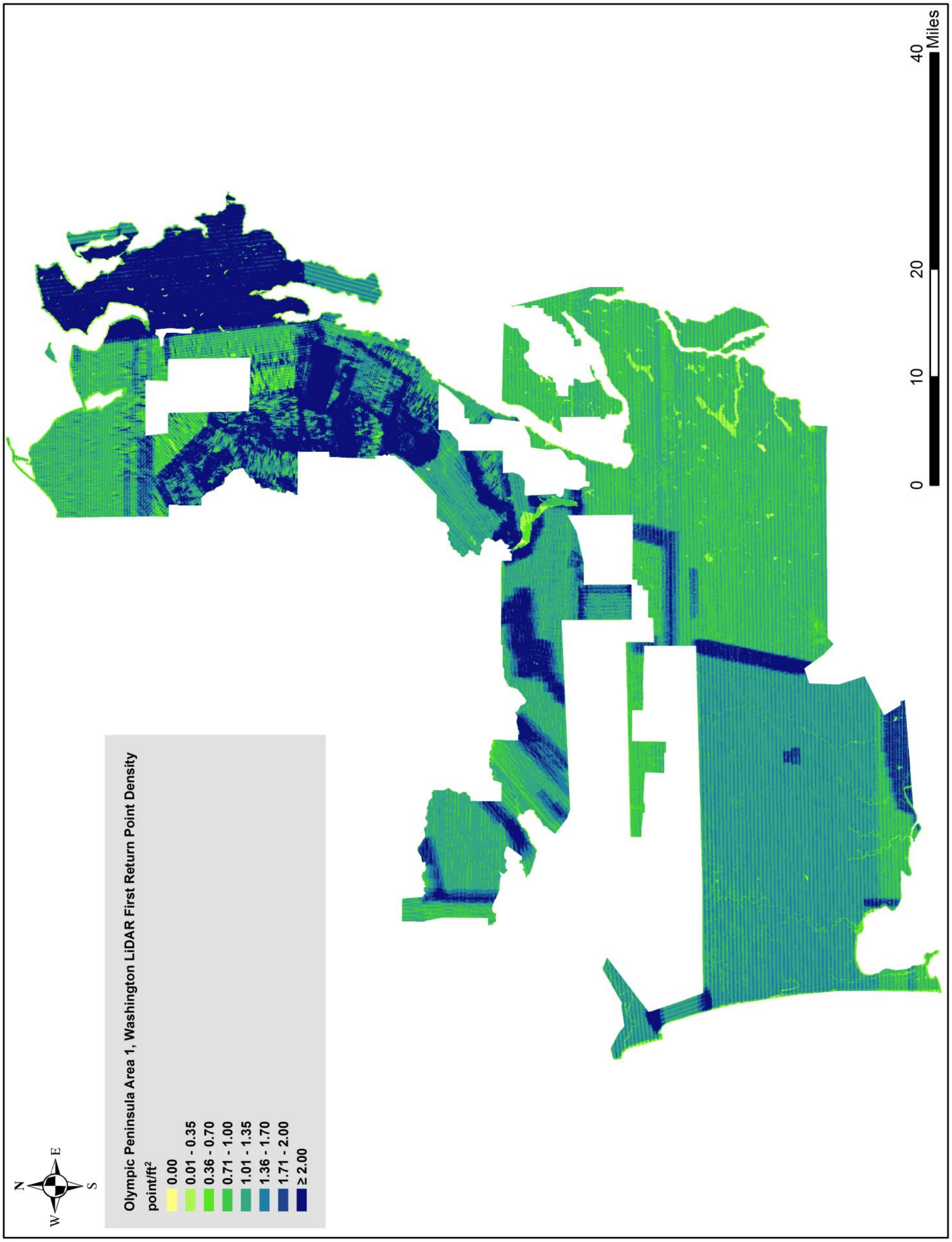


Figure 7: First return point density map for the Olympic Peninsula Area 3 site (100 m x 100 m cells)

Figure 8: Ground classified point density map for the Olympic Peninsula Area 1 site (100 m x 100 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 Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the LiDAR point cloud to the triangulated surface generated by the unclassified LiDAR point cloud as well as the derived gridded bare earth DEM. NVA 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 11.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground check 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 Olympic Peninsula Area 1 survey, 82 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.337 feet (0.103 meters) as compared to unclassified LAS, and 0.271 feet (0.083 meters) as compared to the bare earth DEM, with 95% confidence (Table 11, Figure 9, Figure 10).

QSI also assessed absolute accuracy using 3,515 supplemental ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 11 and Figure 11.

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[3] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

Table 11: Absolute accuracy results

Absolute Accuracy			
	Quality Assurance Points (NVA), as compared to unclassified LAS	Quality Assurance Points (NVA), as compared to the Bare Earth DEM	Supplemental Ground Control Points
Sample	82 points	82 points	3,515 points
NVA (1.96*RMSE)	0.337 ft 0.103 m	0.271 ft 0.083 m	0.246 ft 0.075 m
Average	0.124 ft 0.038 m	-0.050 ft -0.015 m	-0.009 ft -0.003 m
Median	0.126 ft 0.039 m	-0.037 ft -0.011 m	-0.007 ft -0.002 m
RMSE	0.172 ft 0.052 m	0.138 ft 0.042 m	0.126 ft 0.038 m
Standard Deviation (1σ)	0.119 ft 0.036 m	0.129 ft 0.039 m	0.125 ft 0.038 m

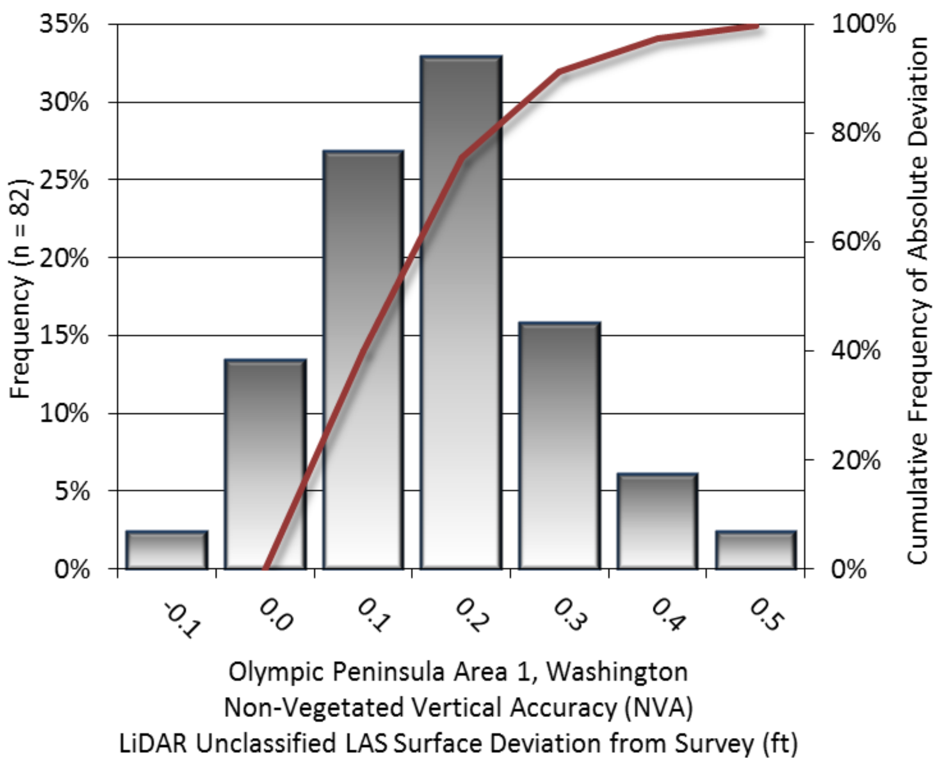

Figure 9: Frequency histogram for LiDAR unclassified point deviation from non-vegetated quality assurance point values

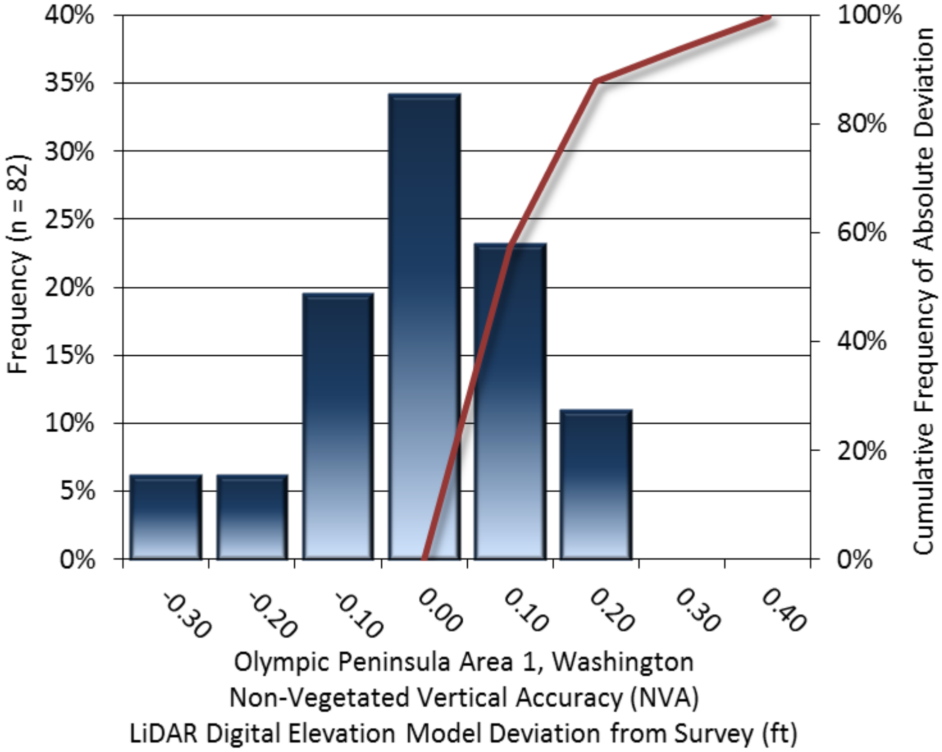

Figure 10: Frequency histogram for LiDAR DEM surface deviation from non-vegetated quality assurance point values

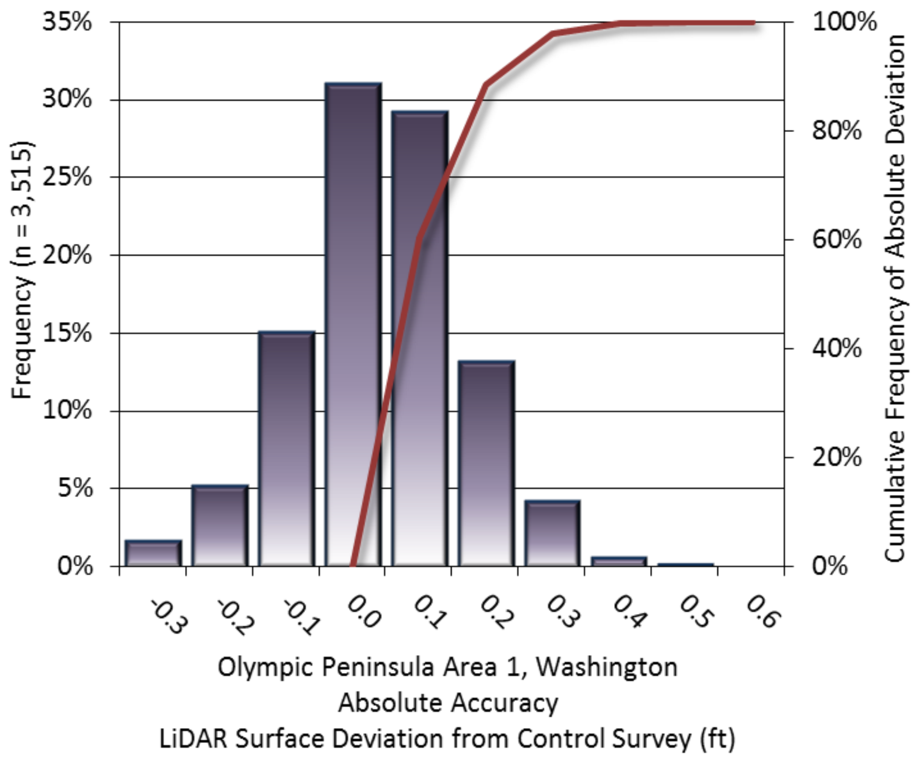

Figure 11: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI assessed vegetated vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces to the LiDAR derived bare earth surface model. For the Olympic Peninsula Area 1 survey, 63 vegetated quality assurance points tested 0.681 feet (0.207 meters) vertical accuracy at the 95th percentile (Table 12, Figure 12).

Table 12: Vegetated Vertical Accuracy for the Olympic Peninsula Project

Vegetated Vertical Accuracy (VVA)	
Sample	63 points
95th Percentile	0.681 ft 0.207 m
Average Dz	-0.301 ft -0.092 m
Median	-0.308 ft -0.094 m
RMSE	0.394 ft 0.120 m
Standard Deviation (1σ)	0.256 ft 0.078 m

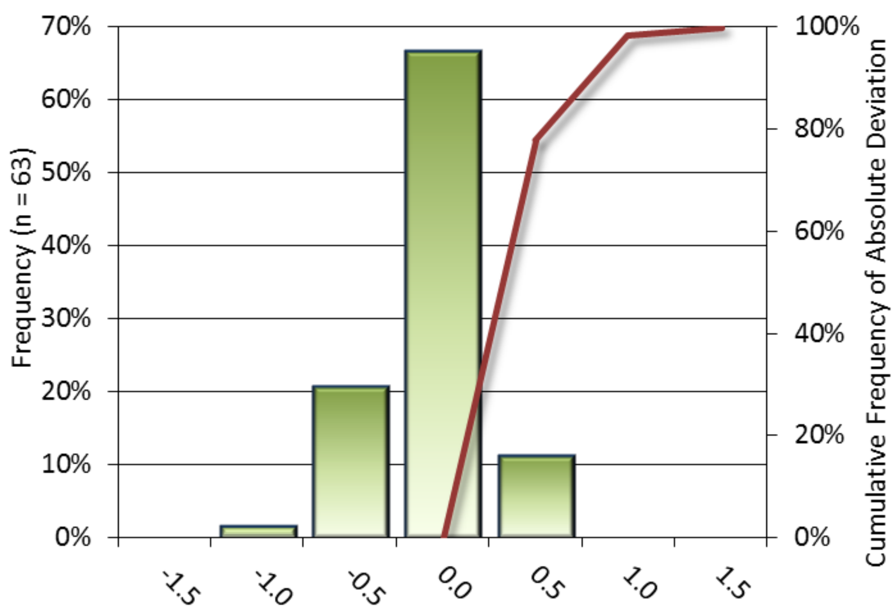

Figure 12: Frequency histogram for LiDAR surface deviation from all land cover class point values (VVA)

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flightlines, 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 flightline with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Olympic Peninsula LiDAR project was 0.167 feet (0.051 meters) (Table 13, Figure 13).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	1,246 surfaces
Average	0.167 ft 0.051 m
Median	0.222 ft 0.068 m
RMSE	0.237 ft 0.072 m
Standard Deviation (1σ)	0.085 ft 0.026 m
1.96σ	0.167 ft 0.051 m

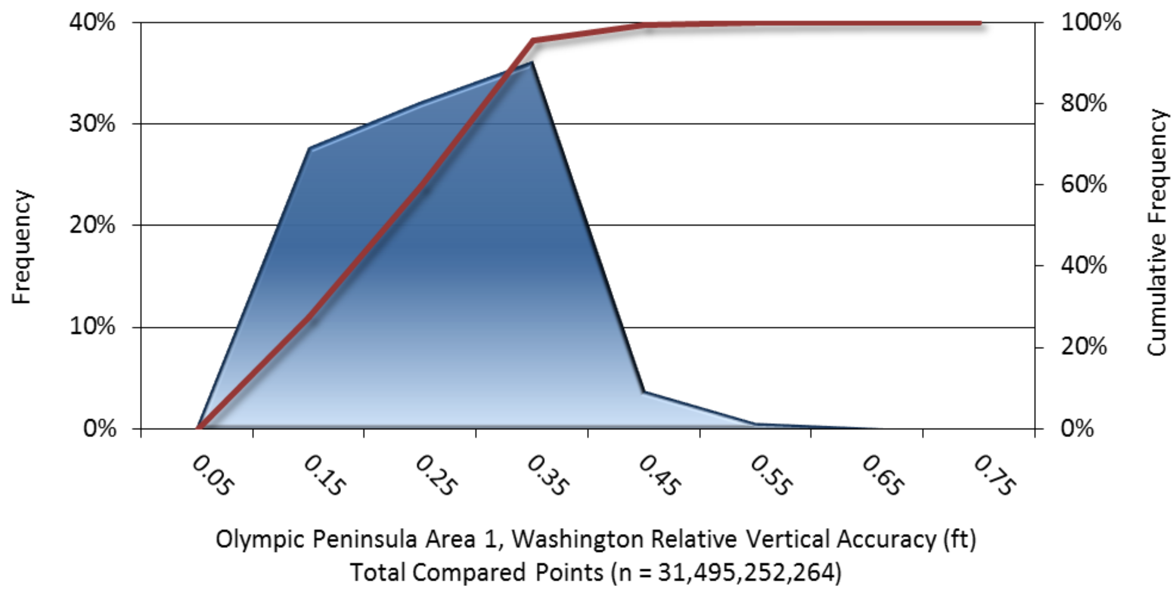

Figure 13: Frequency plot for relative vertical accuracy between flightlines

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the Olympic Peninsula project as described in this report.

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

Tucker Selko
Tucker Selko (Nov 4, 2019) Nov 4, 2019

Tucker Selko
Project Manager
Quantum Spatial, Inc.

I, Evon P. Silvia, 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 September 13, 2017 and April 25, 2019.

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".

Evon P. Silvia Nov 4, 2019

Evon P. Silvia, PLS
Quantum Spatial, Inc.
Corvallis, OR 97333

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 Non-vegetated Vertical Accuracy (NVA) 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 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 flightlines, 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 flightlines within an overlapping area. Divergence is most apparent when flightlines 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 flightline.

Overlap: The area shared between flightlines, 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., echoes) 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 flightline 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 ±29.25^{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 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 flightlines 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 flightline coincides with the swath edge portion of overlapping flightlines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flightlines: All overlapping flightlines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flightline(s), making misalignments easier to detect and resolve.