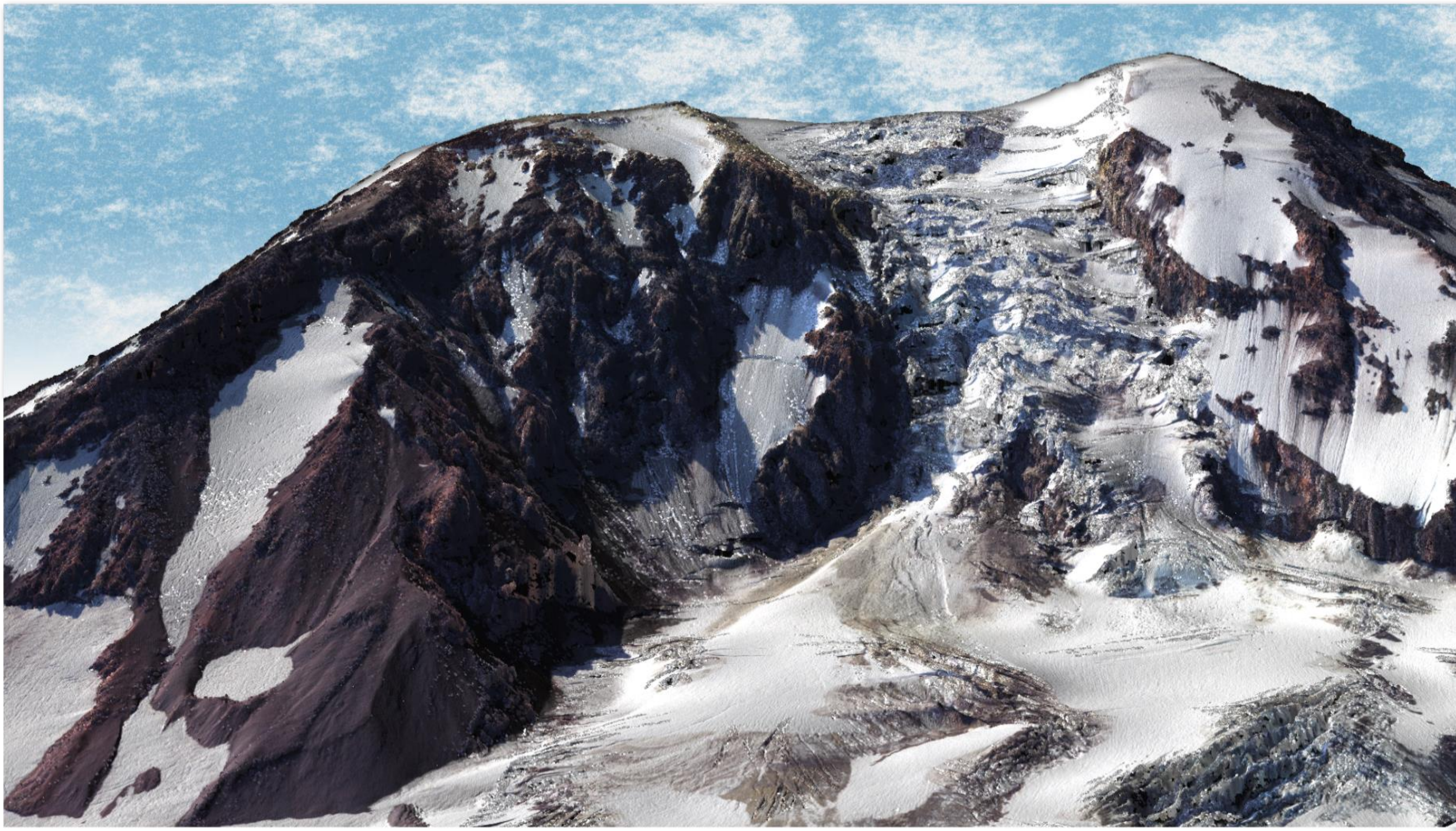
April 21, 2017



Mount Adams, Washington USGS 3DEP

LiDAR Technical Data Report, Task Order G16PD00796

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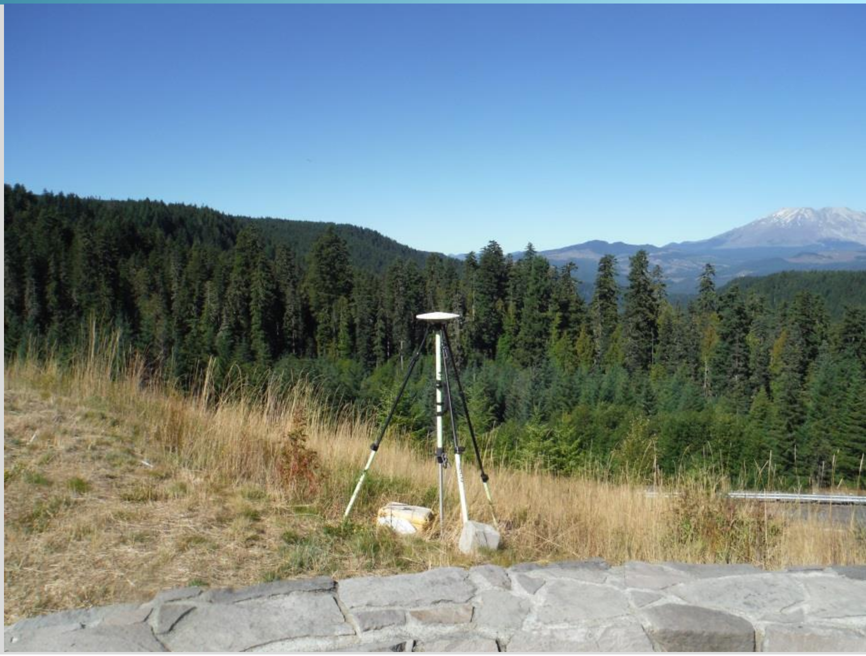
Cover Photo: A view looking southeast at Mount Adams. This image was created from the gridded bare earth LiDAR surface, colored using NAIP imagery.

INTRODUCTION



This photo taken by QSI acquisition staff shows a view of GNSS equipment set up over monument MT_ADAMS_04 to the southwest of Mount Adams.

In July 2016, Quantum Spatial (QSI) was contracted by the United States Geological Survey (USGS) to collect high resolution QL1 Light Detection and Ranging (LiDAR) data between August and September 2016 for the Mount Adams site in Washington. QSI provided the Pilot delivery of an area encompassing 4,942 acres on December 21, 2017. This data delivery includes the entire extent of the Mount Adams project site. Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area and to support seismic hazard modeling of impacts posed from the potentially active stratovolcano to the surrounding landscape.

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 for the Mount Adams, Washington site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
USGS Mount Adams 3DEP LiDAR	550,643	560,563	8/15/16 - 8/21/16, 8/23/16, 8/25/16 – 8/29/16, 9/08/16 – 9/10/16, 9/12/16 – 9/16/16, 9/25/16 – 9/26/16	LiDAR

Deliverable Products

Table 2: Products delivered to USGS for the Mount Adams, Washington site

USGS Mount Adams, Washington LiDAR Products Projection: UTM Zone 10 North Horizontal Datum: NAD83 (HARN)* Vertical Datum: NAVD88 (GEOID03) Units: Meters	
Points	LAS v 1.4 Point Record Format 6 • All Classified Returns • Raw Calibrated Flightline Swaths
Rasters	1.0 Meter ERDAS Imagine Files (*.img) • Hydroflattened Bare Earth Model 1.0 Meter GeoTiffs • 8-Bit Intensity Images
Vectors	Shapefiles (*.shp) • Full Site Boundary • Full Site LiDAR Tile Index • Full Site DEM Tile Index • Full Site LAS Tile Index • Smoothed Best Estimate Trajectories • Flightline Index • Ground Survey Points, Quality Assurance Points, and Monuments • Water's Edge Breaklines With Elevation Values • Bridge Breaklines With Elevation Values

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

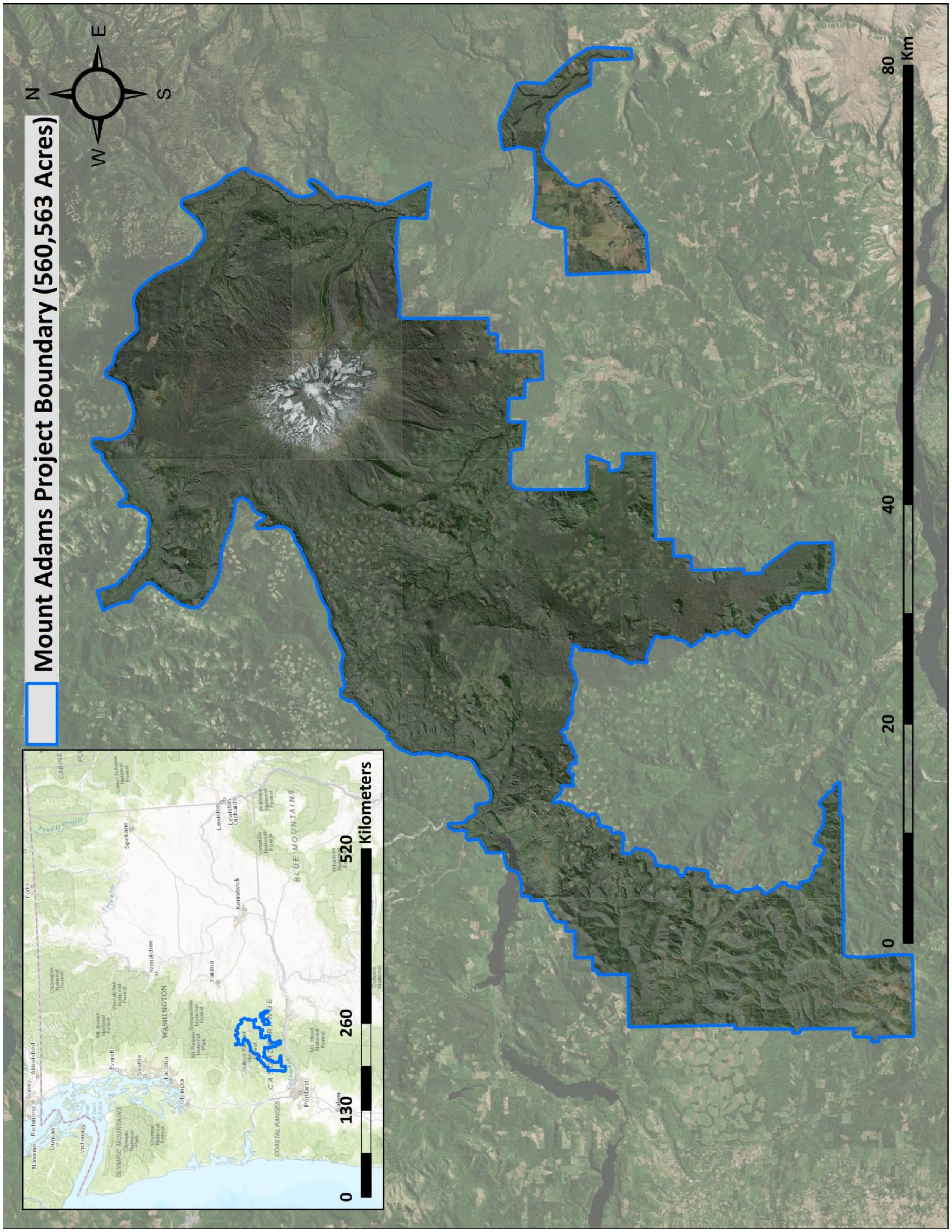


Figure 1: Location map of the Mount Adams, Washington project area

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Mount Adams, Washington QL1 LiDAR study area at the target point density of ≥8.0 points/m^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, including orographic lift caused by the Mount Adams cone, which stands at 12,280 feet; the third highest in the Cascade Range (Table 3). In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in QSI's Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥ 8 pulses/m^2 over the Mount Adams, Washington project area. The Leica laser system can return unlimited range measurements (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 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications		
	All Areas Flight Settings	**Mt. Adams Cone Flight Settings**
Acquisition Dates	8/15/16 - 8/21/16, 8/23/16, 8/25/16 – 8/29/16, 9/08/16 – 9/10/16, 9/12/16 – 9/16/16, 9/25/16 – 9/26/16	08/15/16, 08/16/16
Aircraft Used	Cessna Caravan 208B	Cessna Caravan 208B
Sensor	Leica ALS80	Leica ALS80
Survey Altitude (AGL)	1,600 m	1,700 m
Swath Width	857 m	661 m
Target Pulse Rate	340 kHz	315 kHz
Pulse Mode	Two Pulse in Air (SPiA)	Two Pulse in Air (SPiA)
Laser Pulse Diameter	35 cm	37 cm
Mirror Scan Rate	56 Hz	56 Hz
Field of View	30^o	22^o
GPS Baselines	≤13 nm	≤13 nm
GPS PDOP	≤3.0	≤3.0
GPS Satellite Constellation	≥6	≥6
Maximum Returns	Unlimited	Unlimited
Intensity	8-bit, scaled to 16-bit	8-bit, scaled to 16-bit
Resolution/Density	Average 8 pulses/m^2	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 10 cm	$RMSE_Z$ ≤ 10 cm

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

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.

Existing Monument WASCO_46

QSI-Established Monument MT_ADAMS_10

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), post-processed kinematic (PPK), and fast-static (FS) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized five existing monuments and established ten new monuments for the Mount Adams, Washington LiDAR project (Table 4, Figure 2). New monumentation was set using 5/8" x 30" rebar topped with stamped 2 ½ " aluminum caps. QSI's professional land surveyor, Evon Silvia (WAPLS#53957) oversaw and certified the establishment of all monuments.

Table 4: Monuments established for the Mount Adams, Washington acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
WA_DNR_P3_02	46° 01' 11.71130"	-121° 16' 52.95463"	556.679
WASCO_42	45° 54' 07.67148"	-121° 50' 17.85853"	834.285
WASCO_43	45° 55' 54.71394"	-121° 53' 11.33812"	758.663
WASCO_46	45° 54' 42.14943"	-122° 04' 08.39241"	1231.016
WASCO_48	45° 50' 51.59932"	-122° 01' 33.99909"	563.200
MT_ADAMS_01	46° 06' 46.57905"	-121° 31' 31.46435"	1293.834
MT_ADAMS_02	46° 07' 58.25902"	-121° 29' 57.20636"	1631.297
MT_ADAMS_03	46° 05' 33.62380"	-121° 45' 50.25657"	1280.139
MT_ADAMS_04	46° 02' 25.40320"	-121° 55' 10.60312"	743.135
MT_ADAMS_05	46° 13' 29.51752"	-121° 19' 35.96054"	1413.486
MT_ADAMS_06	46° 12' 43.02368"	-121° 19' 27.86629"	1431.326
MT_ADAMS_07	46° 17' 49.84811"	-121° 39' 18.40374"	1250.196
MT_ADAMS_08	46° 19' 16.10426"	-121° 28' 47.30172"	1485.874
MT_ADAMS_09	45° 47' 54.09917"	-121° 44' 31.92429"	840.376
MT_ADAMS_10	45° 50' 39.35829"	-122° 05' 48.41131"	1175.124

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[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 Mount Adams, Washington 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), and fast-static (FS) survey techniques. A Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R6 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. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines for post-processing. 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 Trimble unit 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 2).

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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

Table 6: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R6	Integrated GNSS Antenna R6	TRM_R6	Static, Rover
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static

Land Cover Class Accuracy Check Points

Land cover class check points were collected throughout the study area over five land cover types, to support non-vegetated and vegetated vertical accuracy assessment (see page 20). Individual accuracies were calculated for each land cover type to assess confidence in the LiDAR derived ground models across land cover types. Land cover types and descriptions are shown in Table 7.

Table 7: Land Cover Types and Descriptions

Land cover type	Land cover code	Description	Accuracy Type
Mixed Forest	DEC_FOR EVER_FOR FOREST MX_FOR	Forested areas, fully covered by trees, including hardwoods, conifers, and mixed forests.	VVA
Shrub and Brushland	SHRUB	Areas dominated by brush or shrubland.	VVA
Tall Grass	TALL GRASS	Areas characterized by grasses, legumes, or natural and semi-natural grasslands.	VVA
Bare Earth/Open Terrain	BARE DRT	Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material.	NVA
Urban	URBAN	Urban areas that may include anthropogenic structures.	NVA

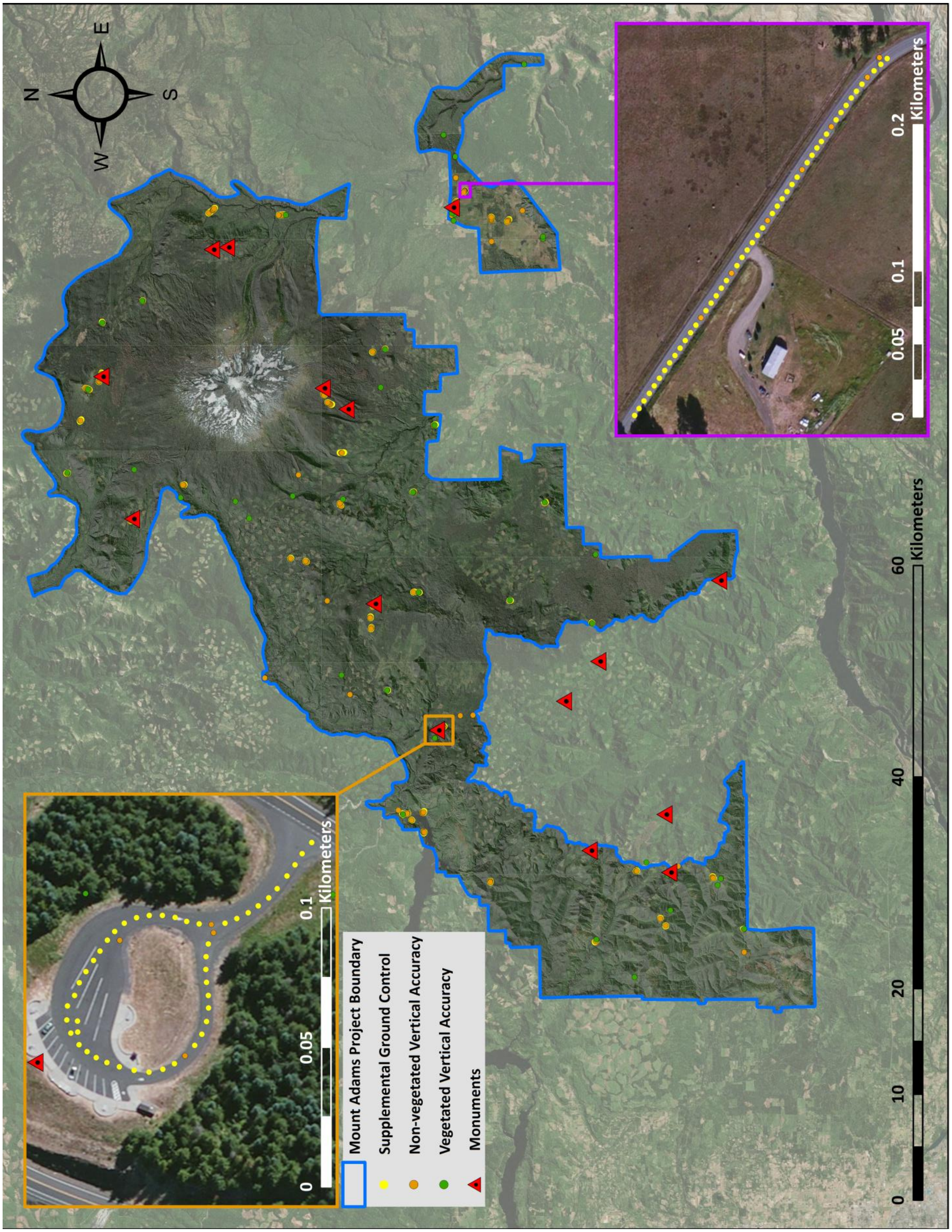
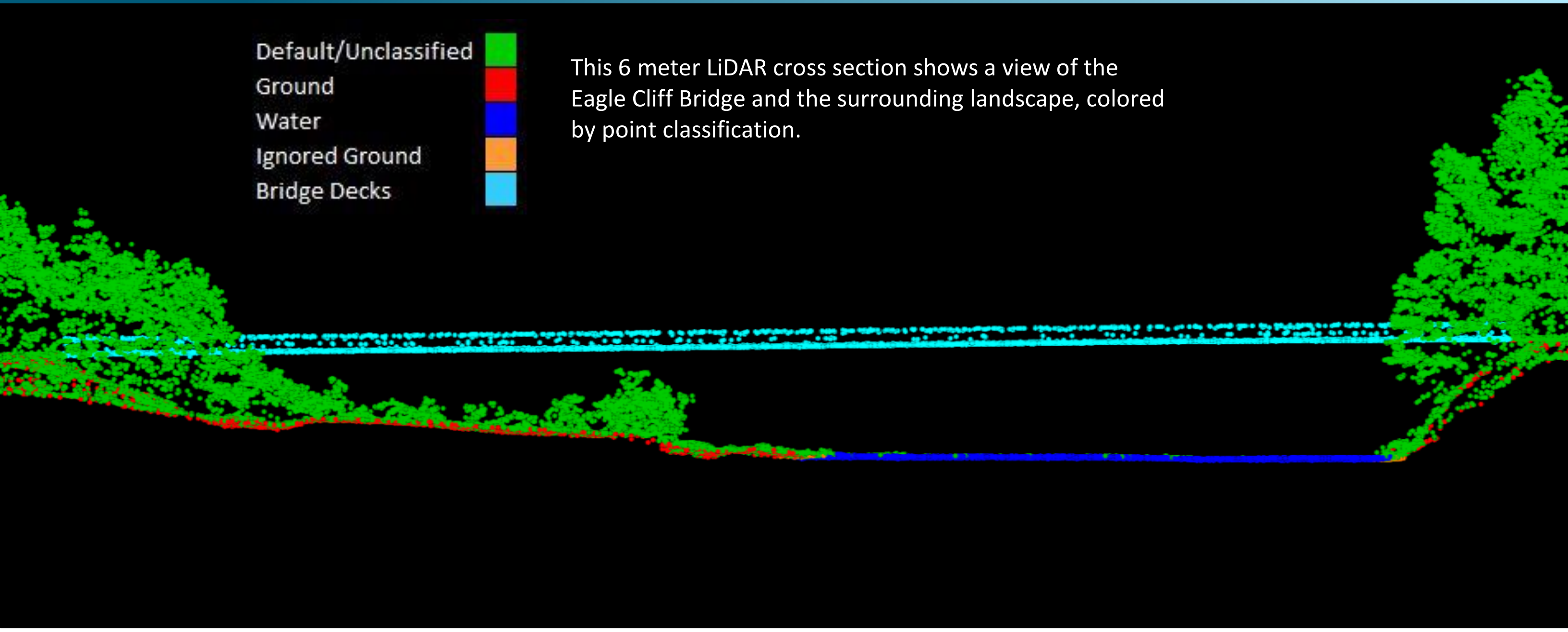


Figure 2: Ground survey location map



This 6 meter LiDAR cross section shows a view of the Eagle Cliff Bridge and the surrounding landscape, colored by point classification.

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 Mount Adams, Washington 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
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.
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms

Classification Number	Classification Name	Classification Description
10	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation
17	Bridge Decks	Permanent bridge decks

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.	Waypoint Inertial Explorer v.8.6
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.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.2
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.16
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.16
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.16 TerraModeler v.16
Generate hydroflattened bare earth models as triangulated surfaces. Export all surface models in EDRAS Imagine (.img) format at a 1 meter pixel resolution.	TerraScan v.16 TerraModeler v.156 ArcMap v. 10.2
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1 meter pixel resolution.	Las Monkey 2.2.1SP2 (QSI proprietary) LAS Product Creator 1.5 (QSI proprietary) ArcMap v. 10.2

Feature Extraction

Hydroflattening and Water's Edge Breaklines

All water bodies within the Mount Adams, Washington project area above USGS specified tolerance thresholds were flattened to a consistent water level. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 100 feet, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. 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 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. (Figure 3).

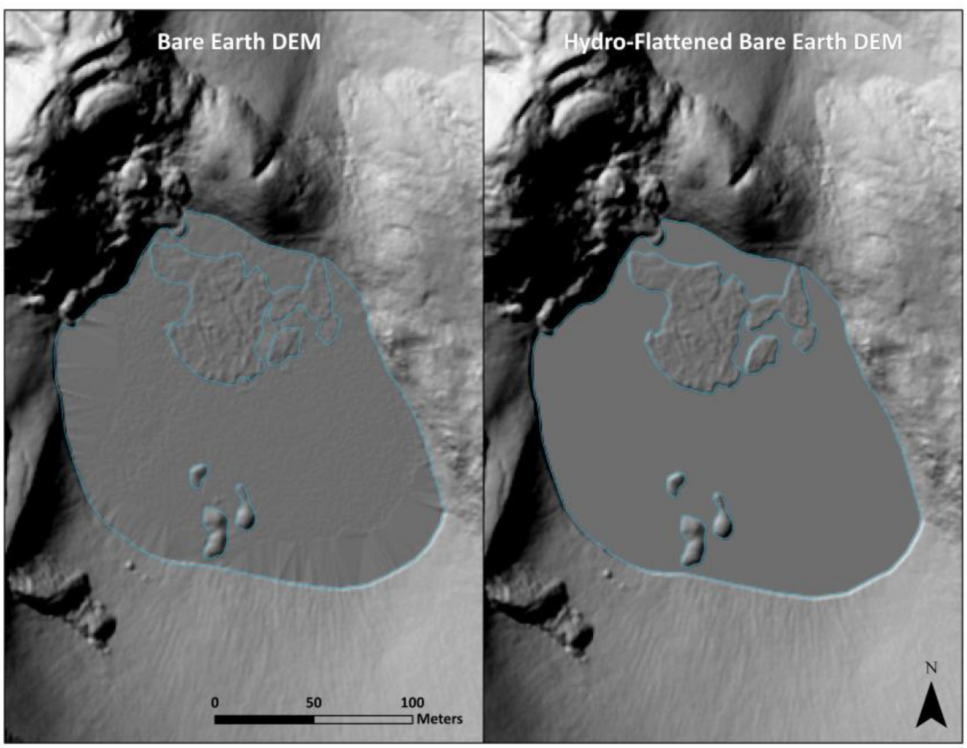
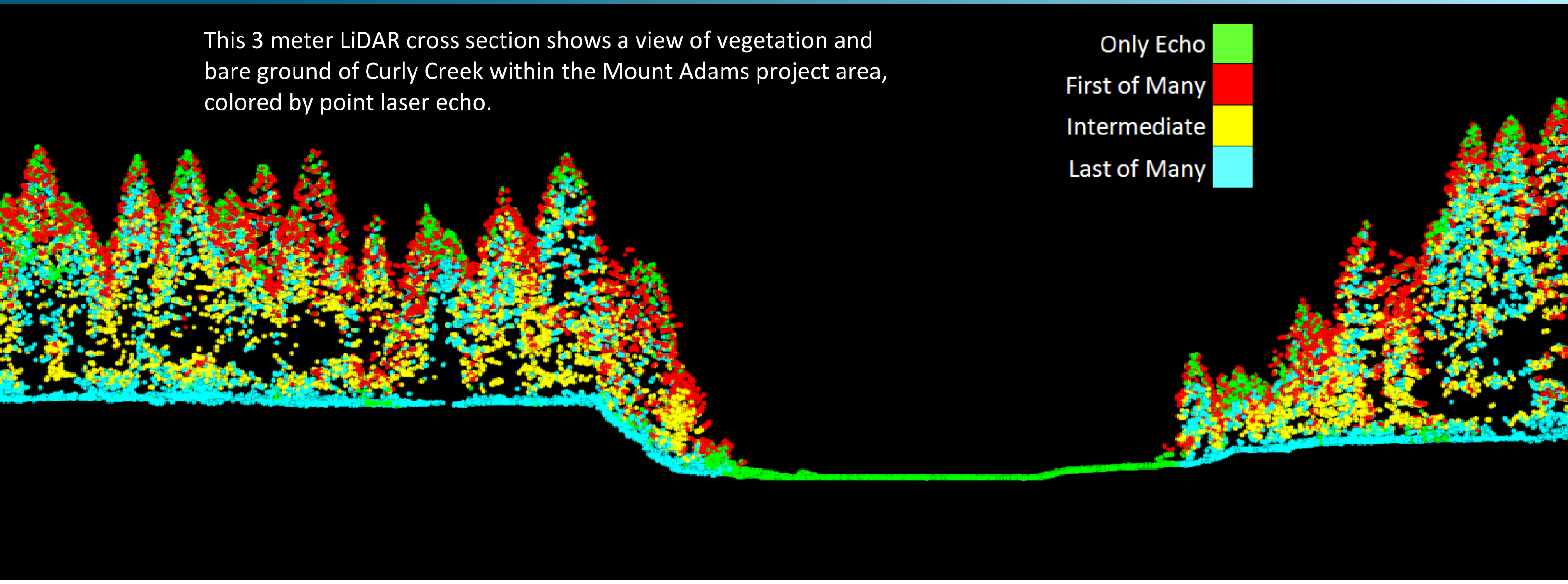


Figure 3: Example of hydro-flattening in the Mount Adams, Washington LiDAR dataset



LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^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.

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 Mount Adams, Washington project was 17.42 points/m^2 while the average ground classified density was 1.88 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 4 through Figure 7.

Table 10: Average LiDAR point densities

Classification	Point Density
First-Return	17.42 points/m^2
Ground Classified	1.88 points/m^2

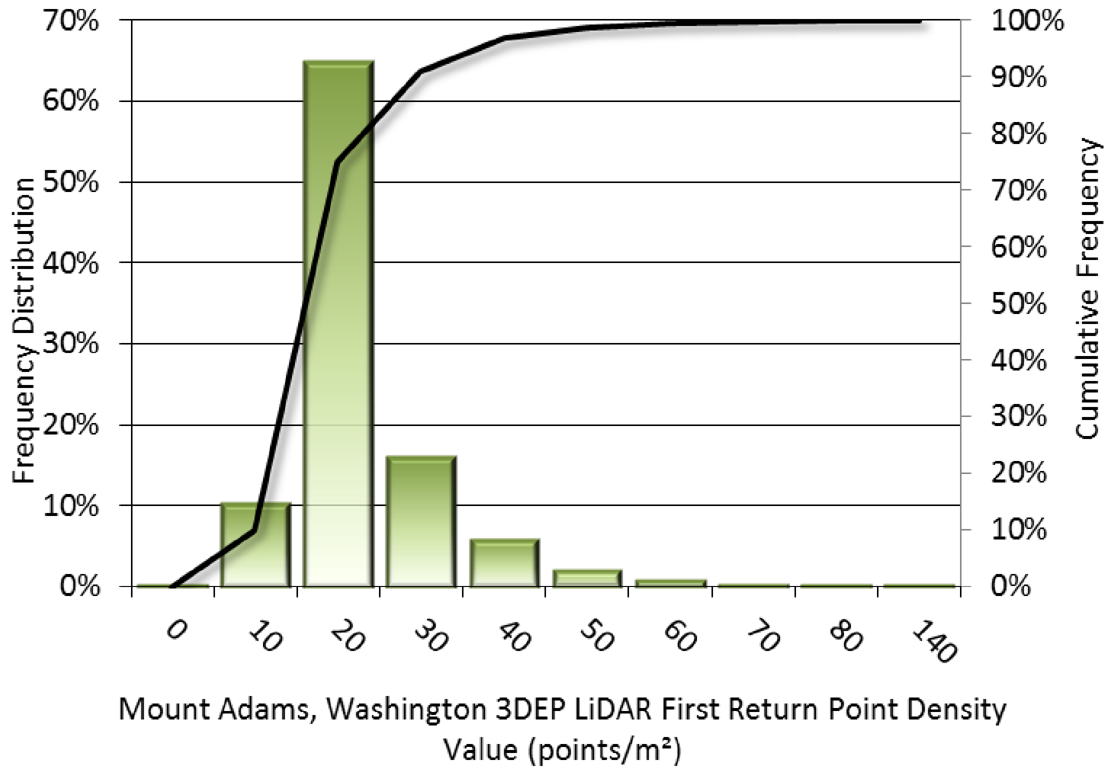


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

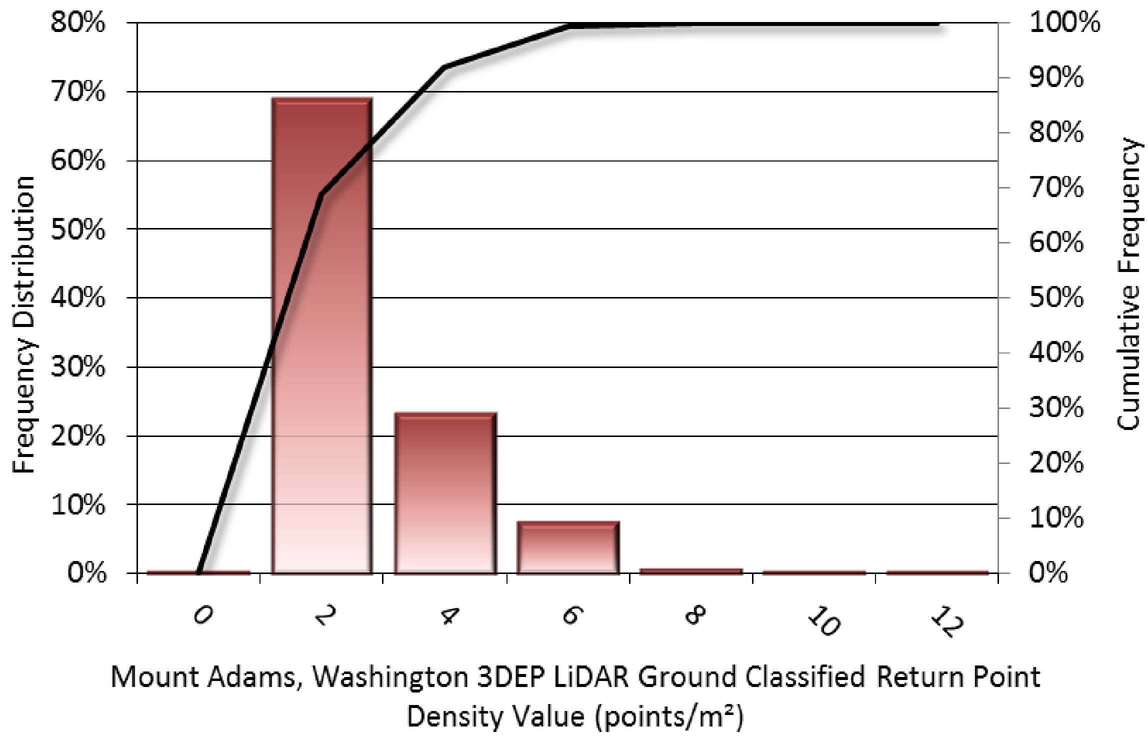


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

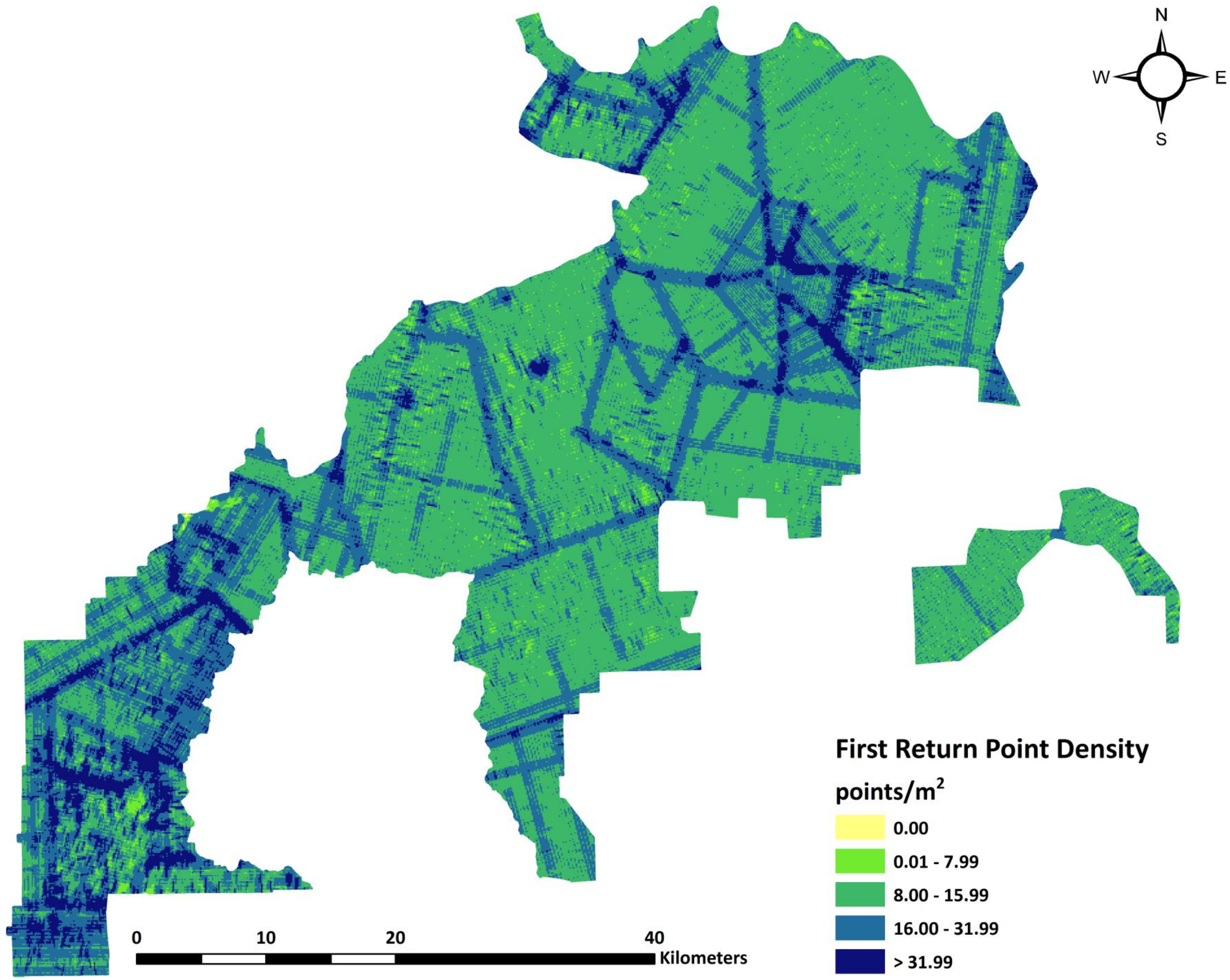


Figure 6: First return point density map for the Mount Adams, Washington site (100 m x 100 m cells)

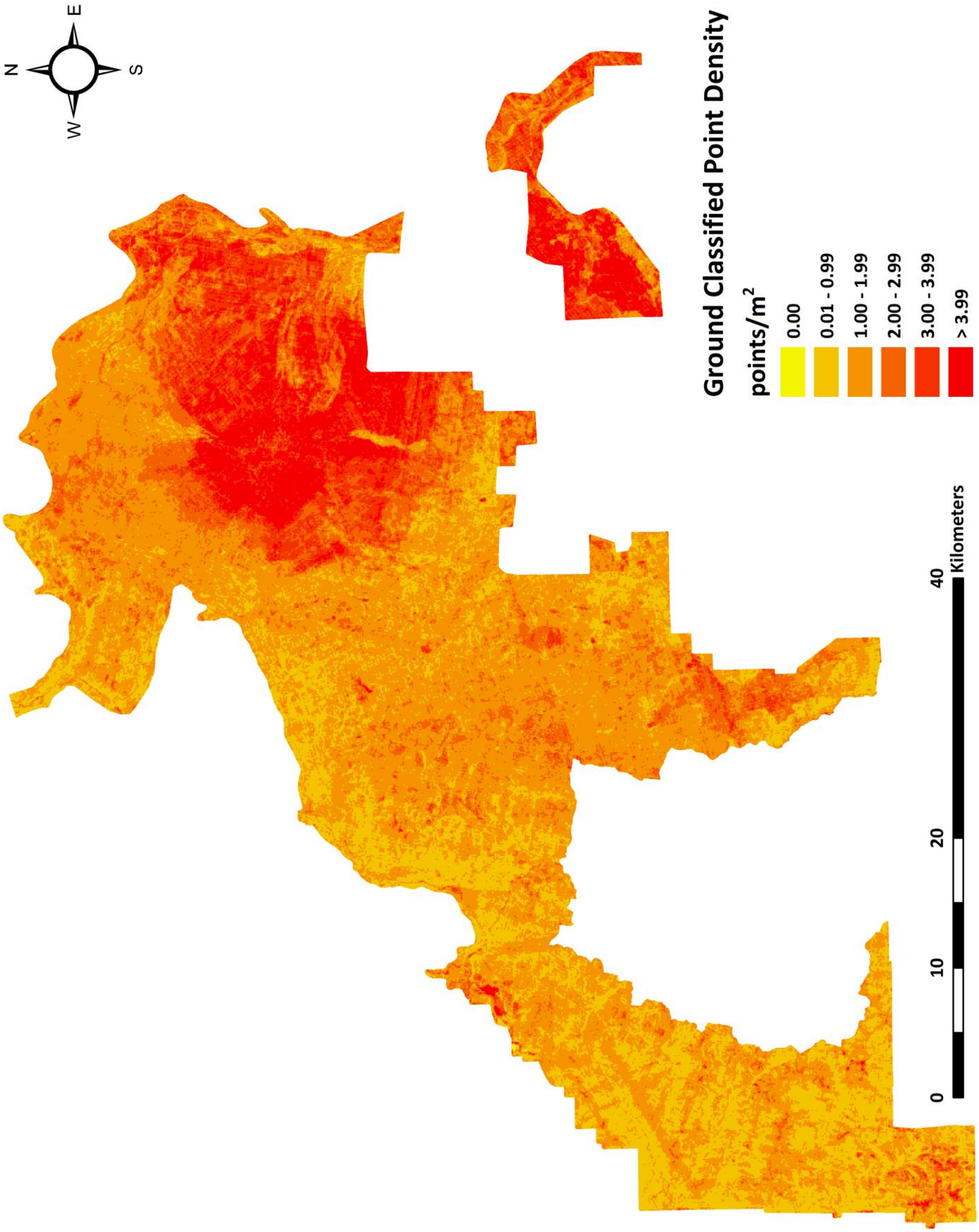


Figure 7: Ground point density map for the Mount Adams, Washington site (100 m x 100 m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute vertical accuracy (the consistency of the data with external data sources) and relative vertical 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 vertical 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] (NSSDA). NVA compares known ground quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. 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 quality assurance 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 Mount Adams, Washington survey, 179 quality assurance points were withheld from ground survey points, in combination with bare earth and urban land class check points; 179 quality assurance points tested 0.063 meters vertical accuracy at 95 percent confidence level as compared to the bare earth DEM. As compared to the unclassified point cloud, 179 quality assurance points tested 0.069 meters vertical accuracy at 95 percent confidence level (Figure 8).

QSI also assessed absolute accuracy using 2,054 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 9.

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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 Bare Earth DEM	Quality Assurance Points (NVA), as compared to unclassified LAS	Supplemental Ground Control Points
Sample	179 points	179 points	2,054 points
NVA (1.96*RMSE)	0.063 m	0.069 m	0.050 m
Average	0.005 m	0.023 m	0.004 m
Median	0.006 m	0.026 m	0.005 m
RMSE	0.032 m	0.035 m	0.025 m
Standard Deviation (1σ)	0.032 m	0.026 m	0.025 m

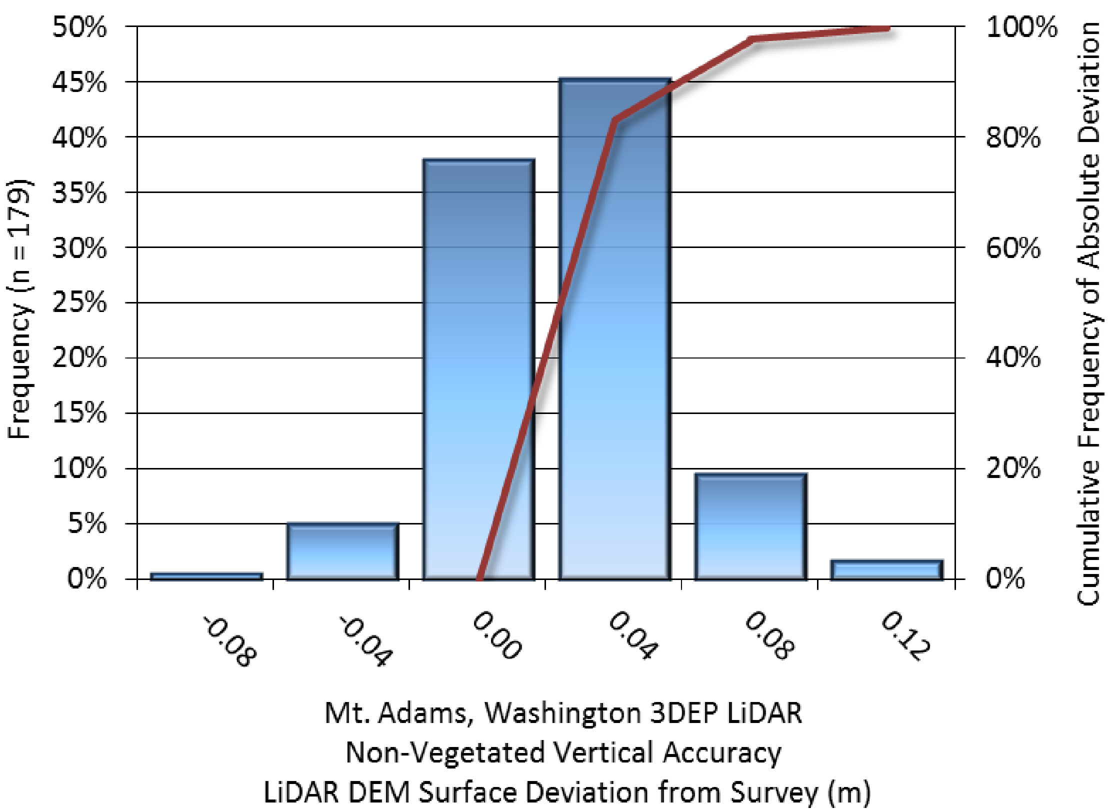

Figure 8: Frequency histogram for LiDAR DEM surface deviation from non-vegetated quality assurance point values

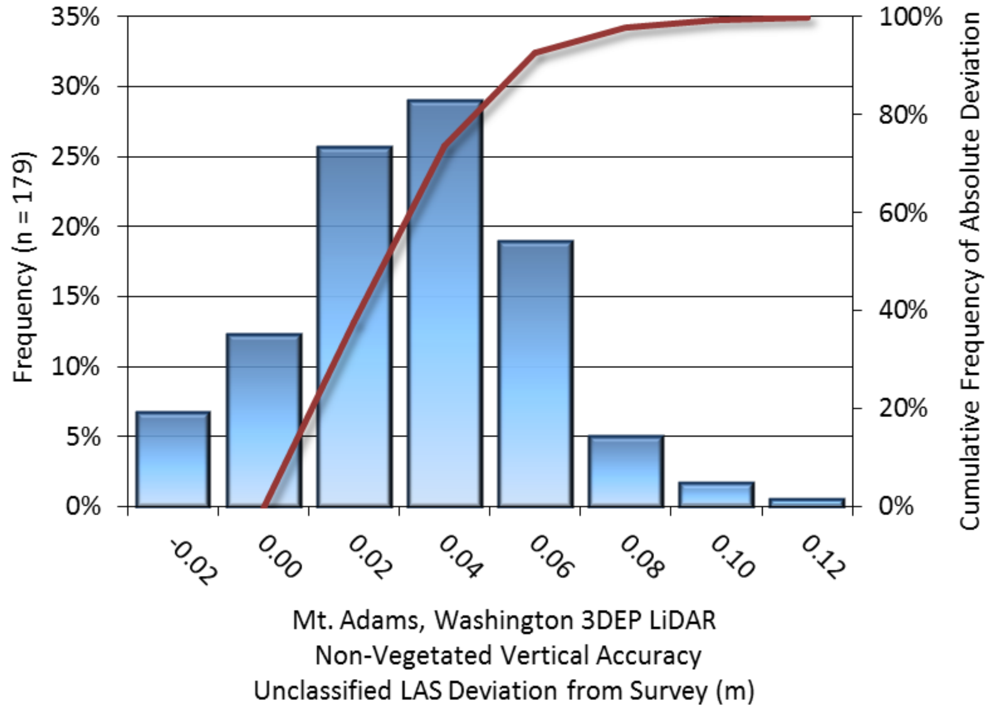

Figure 9: Frequency histogram for LiDAR unclassified point deviation from non-vegetated quality assurance point values

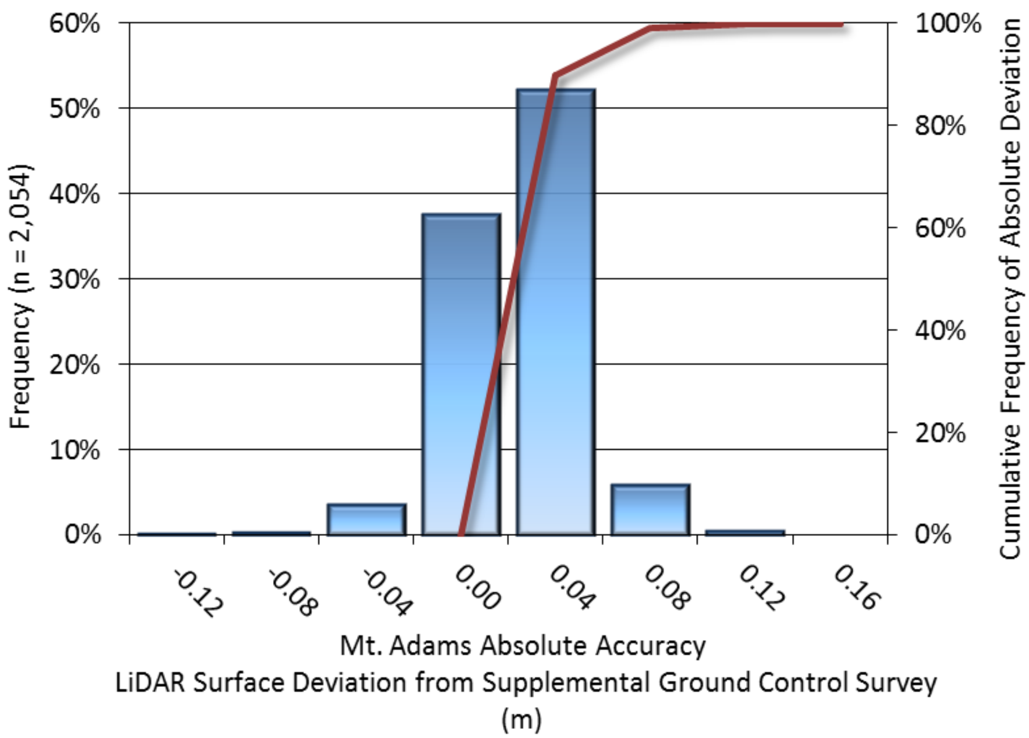

Figure 10: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground quality assurance point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified LiDAR points. For the Mount Adams, Washington survey, 60 vegetated quality assurance points tested 0.209 meters vertical accuracy at the 95th percentile (Table 12, Figure 11).

Table 12: Vegetated Vertical Accuracy for the Mount Adams, Washington Project

Vegetated Vertical Accuracy (VVA)				
Sample	**Mixed Forest**	**Shrub and Brushland**	**Tall Grass**	**Cumulative (VVA)**
	43 points	11 points	6 points	60 points
Average Dz	-0.005 m	0.148 m	0.050 m	0.029 m
Median	-0.004 m	0.146 m	0.050 m	0.011 m
RMSE	0.083 m	0.193 m	0.097 m	0.113 m
Standard Deviation (1σ)	0.083 m	0.130 m	0.091 m	0.110 m
95th Percentile	0.184 m	0.338 m	0.174 m	0.209 m

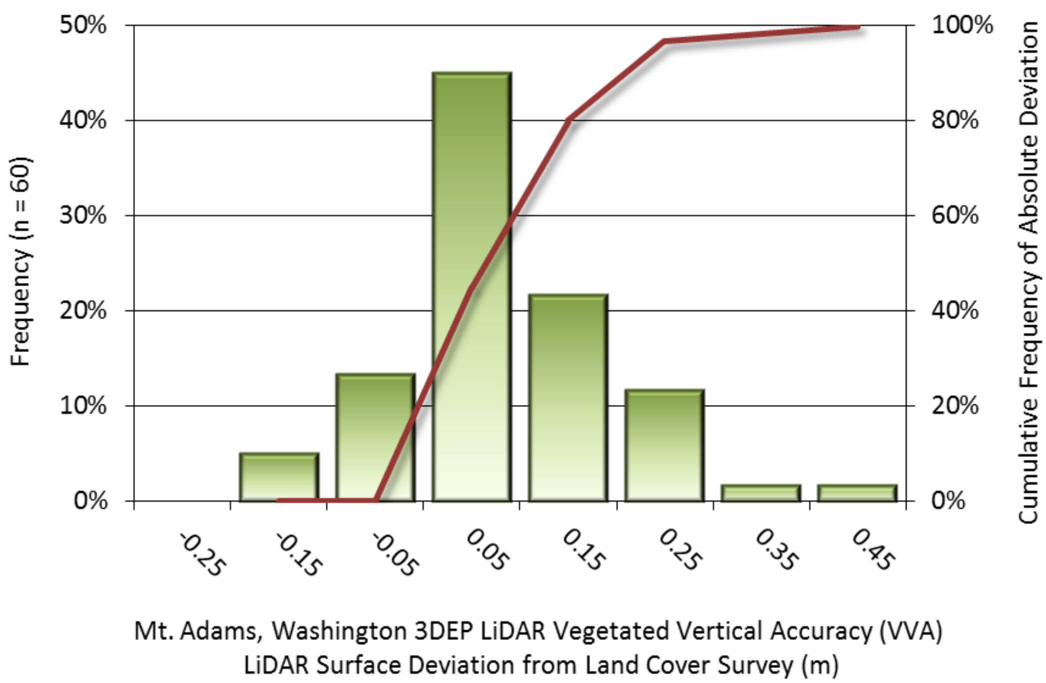

Figure 11: Frequency histogram for LiDAR surface deviation from all land cover class point values (VVA)

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 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 average (mean) line to line relative vertical accuracy for the Mount Adams, Washington LiDAR project was 0.046 meters (Table 13, Figure 12).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	1,387 surfaces
Average	0.046 m
Median	0.049 m
RMSE	0.058 m
Standard Deviation (1σ)	0.019 m
1.96σ	0.038 m

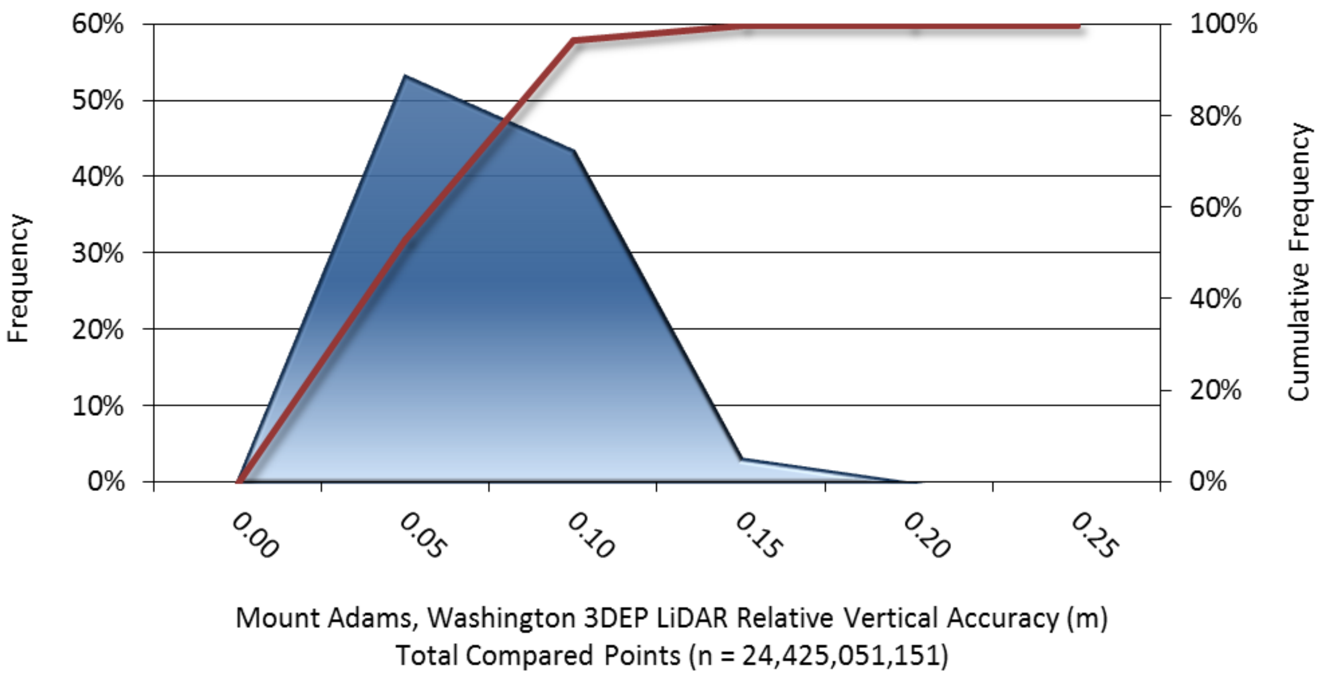

Figure 12: Frequency plot for relative vertical accuracy between flight lines

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the Mount Adams, Washington 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 (Apr 21, 2017) Apr 21, 2017

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 August 15 and September 26, 2016.

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 Apr 21, 2017

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

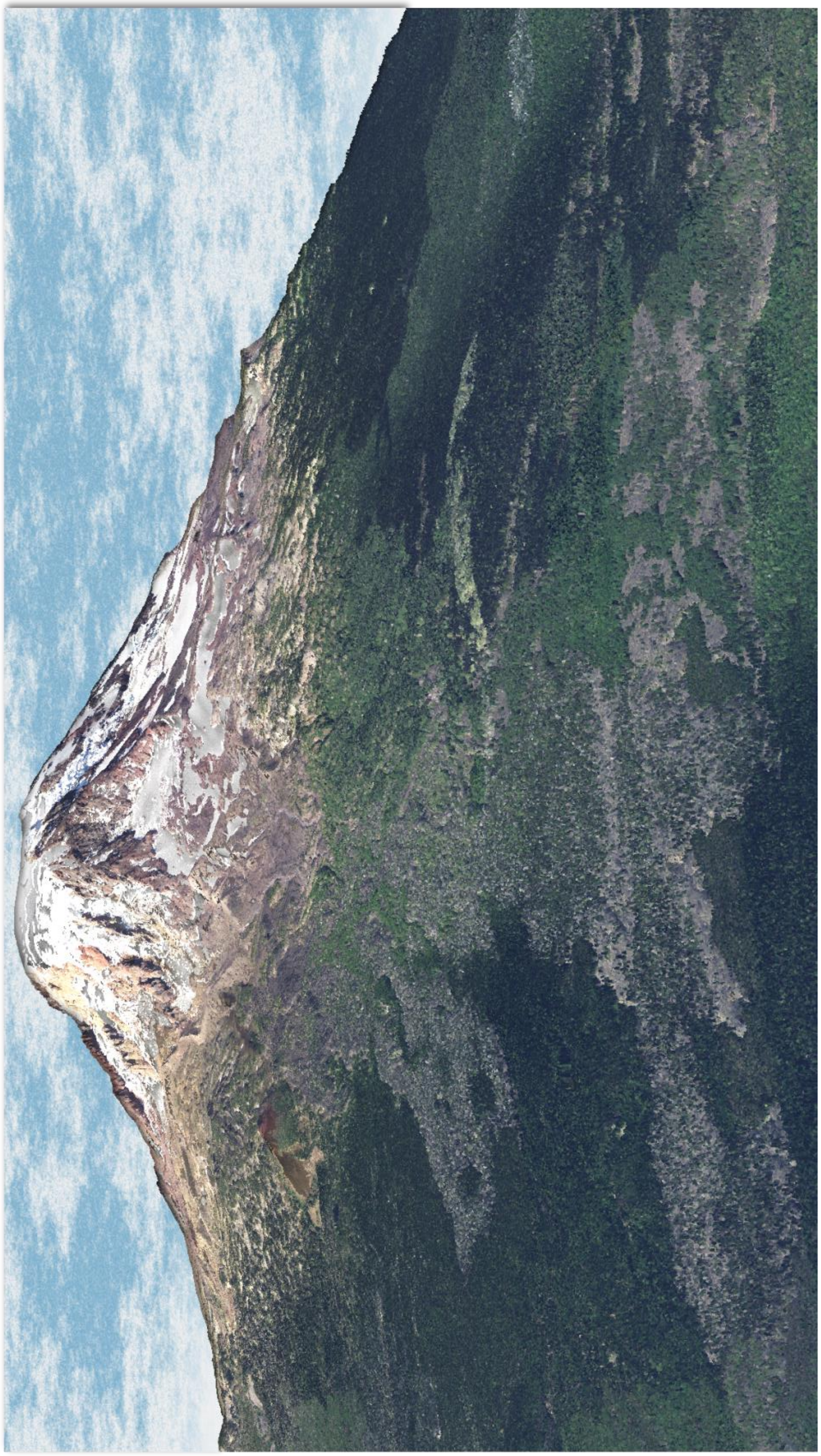

Figure 13: A view looking southwest over lava flows in the Mount Adams, Washington project area. This image was created from the gridded bare earth surface, colored using NAIP imagery.

Figure 14: A view looking southeast over lava flows in the Mount Adams, Washington project area. This image was created from the gridded bare earth surface, colored using NAIP imagery.

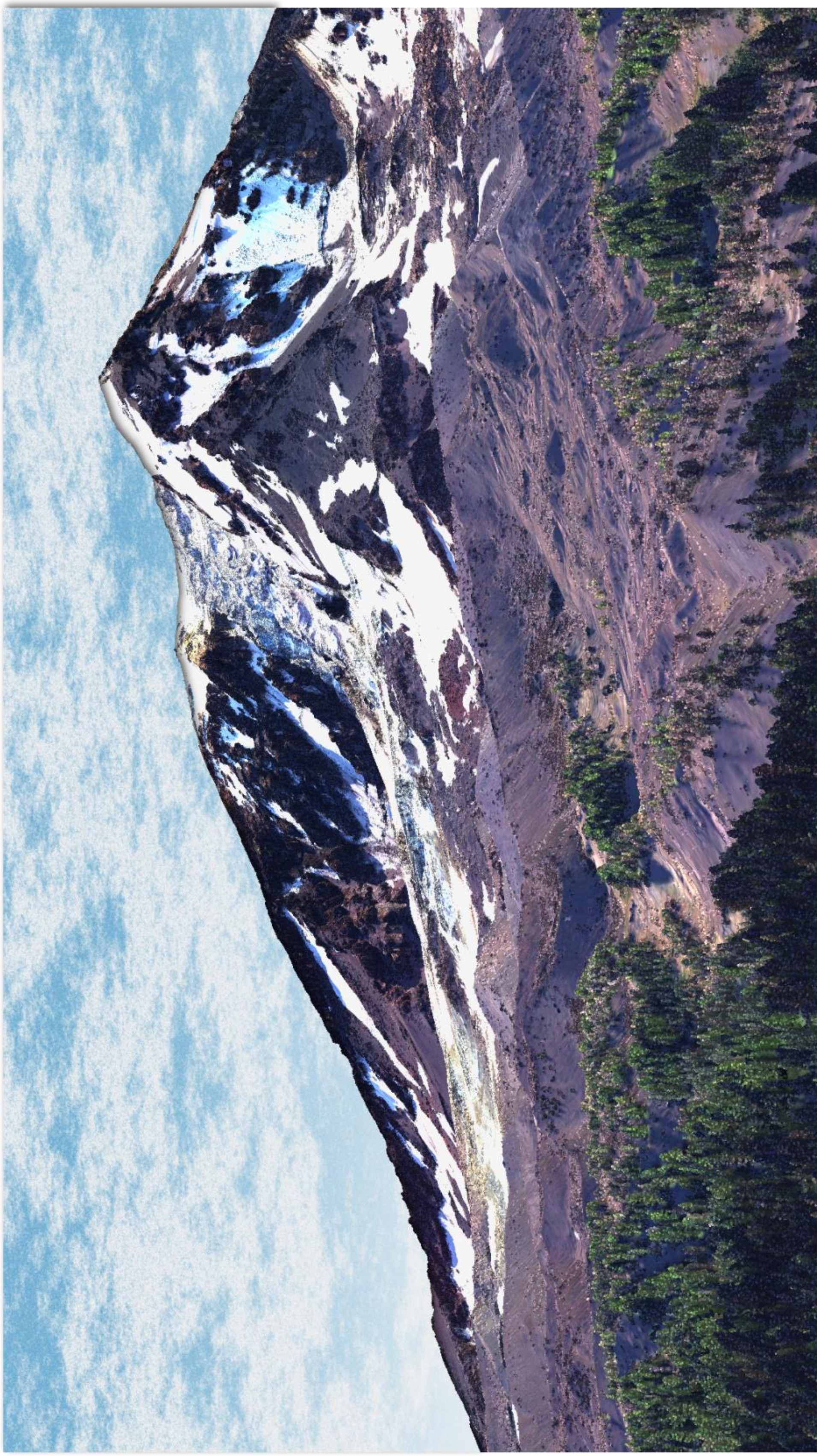

Figure 15: A view looking west at Mount Adams. This image was created from the gridded bare earth surface, colored using NAIP imagery.

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 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.

Appendix A - Accuracy Controls

Relative Accuracy Calibration Methodology:

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

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

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

LiDAR accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

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

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (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 ±15^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 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.