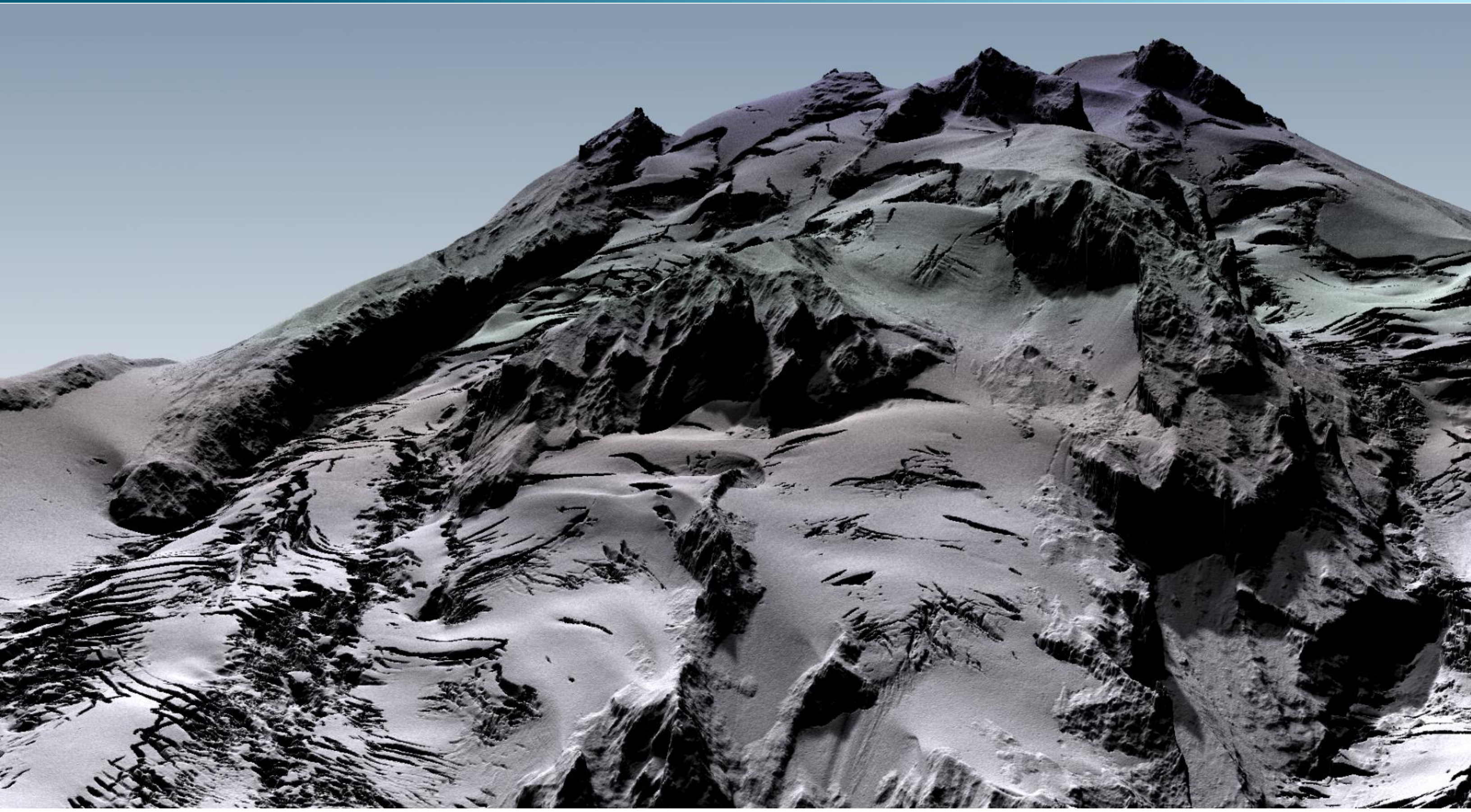
December 18, 2015



Glacier Peak, WA LiDAR

Technical Data Report, USGS Task Order G14PD00776

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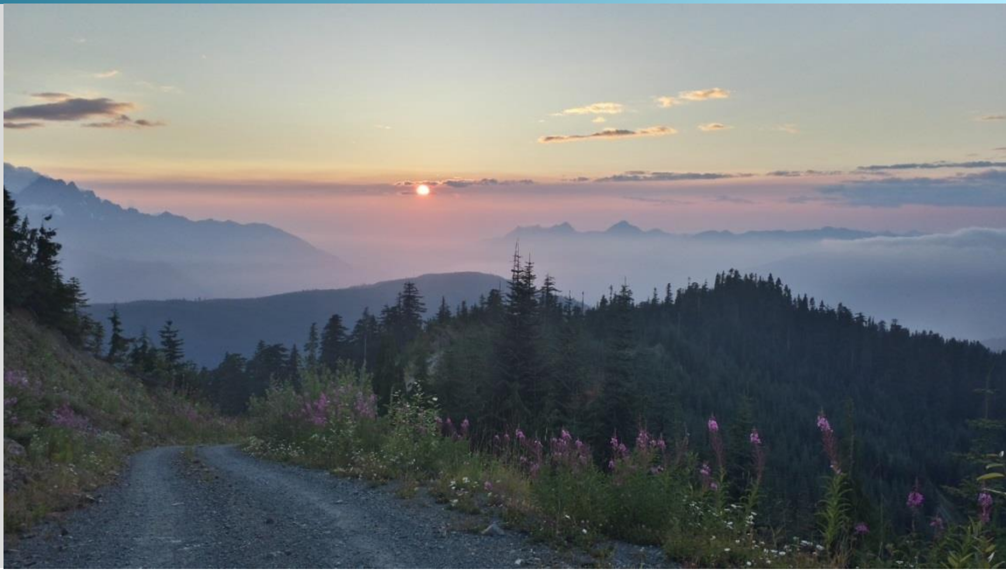
Cover Photo: This image shows a view looking toward the summit of Glacier Peak from the southwest. The image was created from the gridded bare earth model colored by elevation.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the sunrise over the Glacier Peak project area.



In August 2014, Quantum Spatial (QSI) was contracted by the United States Geological Survey (USGS) under task order G14PD00776, to collect Light Detection and Ranging (LiDAR) data for an area encompassing Glacier Peak in the Washington Cascade Mountains, approximately 60 miles northeast of Seattle (Figure 1). Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area in order to plan for the placement of additional seismometers on Glacier Peak to monitor potentially hazardous seismic activity.

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 Glacier Peak sites

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Glacier Peak AOI	304,148	308,475	08/25/14 – 08/27/14, 09/05/14 – 09/07/14, 09/10/14 – 09/12/14, 09/14/14 – 09/17/14, 09/20/14 – 09/21/14, 09/28/14, 10/02/14 – 10/03/14, 10/09/14, 11/15/14 – 11/19/14, 06/06/15 – 06/11/15, 06/13/15 – 06/14/15, 06/18/15, 06/21/15 – 06/24/15	LiDAR
Monte Cristo AOI	4,356	5,257	06/23/2015, 06/24/2015	LiDAR

Deliverable Products

Table 2: Products delivered to USGS for the Glacier Peak sites

Glacier Peak Products Projection: UTM Zone 10 North Horizontal Datum: NAD83 (CORS96)* Vertical Datum: NAVD88 (GEOID03) Units: Meters	
Points	LAS v 1.2 • All Returns • Unclassified Flightline Swaths
Rasters	1.0 Meter ERDAS Imagine Files (*.img) • Hydroflattened Bare Earth Model 1 Meter GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index • Base Station Control • Supplemental Ground Control and Check Points • Water's Edge Breaklines

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

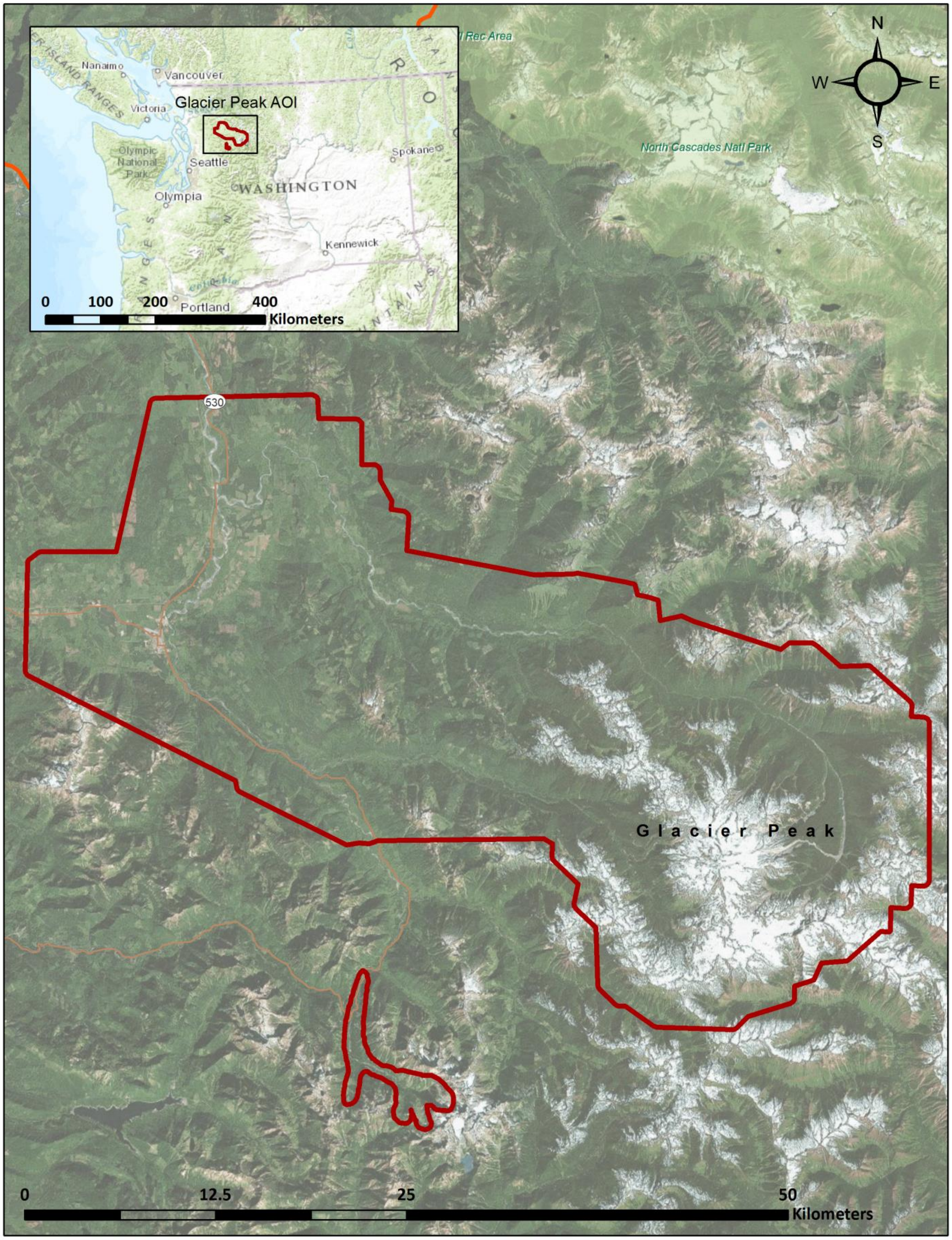


Figure 1: Location map of the Glacier Peak site in Washington

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 Glacier Peak 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 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.

Due to the remote and challenging nature of the Glacier Peak site, airborne and ground operations required detailed planning during all phases of acquisition. Weather windows and access constraints required the coordination of acquisition over several months, from August 2014 to June 2015.

Airborne Survey

LiDAR

The LiDAR survey was accomplished using a Leica ALS70 system mounted in a Cessna Caravan 208B, Partenavia, or Piper Navajo aircraft. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Glacier Peak project area. The Leica ALS70 laser system can record unlimited range measurements (returns) per pulse, but typically does not record more than 5 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	
Acquisition Dates	08/25/2014 – 06/24/2015
Aircraft Used	Cessna Caravan 208B, Piper Navajo, Partenavia
Sensor	Leica ALS70
Survey Altitude (AGL)	1,650 m
Speed	105 kts
Target Pulse Rate	160 - 172 kHz
Pulse Mode	Single Pulse in Air (SPiA)
Laser Pulse Diameter	41.25 cm
Mirror Scan Rate	38.5 Hz
Field of View	24^o
GPS Baselines	≤17 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	Unlimited, but typically not more than 5
Intensity	8-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm

Leica ALS70 LiDAR sensor

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 Survey

Ground control surveys, including base station control and supplemental ground control (SGC), were conducted to support the airborne acquisition. Supplemental ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data.

Existing DOT Monument

QSI-Established Monument

Base Station Control Monuments

The spatial configuration of base station control provided redundant control within 17 nautical miles of the mission areas for LiDAR flights. Base stations were also used for collection of supplemental ground control points using real time kinematic (RTK) and post processed kinematic (PPK) survey techniques.

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized seven existing monuments and established eight new monuments for the Glacier Peak LiDAR project (Table 4, Figure 2). New monuments were set using 5/8” x 30” rebar topped with stamped 2" aluminum caps. QSI’s professional land surveyor, Christopher Glantz (WA PLS#48755) oversaw and certified the establishment of all base stations.

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

Monument ID	Latitude	Longitude	Ellipsoid (meters)
GP_02	48° 01' 50.70724"	-121° 17' 30.00994"	692.132
GP_03	48° 15' 21.03029"	-121° 16' 14.20142"	364.500
GP_05_RTK	48° 10' 21.87214"	-121° 28' 16.32379"	266.733
GP_06_RTK	48° 22' 38.33430"	-121° 26' 43.97054"	1255.749
GP_07	48° 15' 20.86132"	-121° 16' 14.21944"	364.530
GP_RI1	48° 13' 35.86714"	-121° 27' 45.60345"	1313.179
GP_RTK_MON	48° 01' 50.92707"	-121° 26' 16.46215"	665.291
P442	48° 15' 37.71111"	-121° 36' 55.91920"	147.239
GP_08	48° 15' 28.05390"	-121° 36' 51.89186"	147.350
GP_09	48° 18' 16.81205"	-121° 31' 22.79695"	138.085
GP_10	48° 13' 35.82504"	-121° 27' 45.78741"	1312.983
WSDOT_7632	48° 16' 09.05120"	-121° 40' 26.00701"	124.221
GP_11	48° 04' 04.57300"	-121° 30' 52.91495"	501.462
GP_11_NAIL	48° 04' 04.42730"	-121° 30' 52.72444"	501.361

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 $_{z}$:	0.050 m

For the Glacier Peak LiDAR project, the monument coordinates contributed no more than 5.4 cm of positional error to the geolocation of the final ground survey points and LiDAR, with 95% confidence.

Supplemental Ground Control Points (SGCs)

Control points (both supplemental ground control and quality check points,) were collected using real time kinematic and post-processed kinematic (PPK) survey techniques. A Trimble R6, R7, or R8 base unit was positioned at a nearby base station to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All SGC 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 SGC 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.

SGCs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. SGC 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. SGCs were collected within as many flightlines as possible; however the distribution of SGCs depended on ground access constraints and base station locations and may not be equitably distributed throughout the study area (Figure 2).

[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
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	Static, Rover

Ground Control Quality Check Points

Ground Control Quality Check Points (QCPs) were collected throughout the study area to support accuracy assessment and reporting. Individual accuracies were calculated for each land cover type to assess confidence in the LiDAR derived ground models across land cover classes. Land cover types and descriptions are shown in Table 7.

Table 7: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description
Bare Earth/Open Terrain	BARE		Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material.
Brushlands and Trees	BRUSH SH_GRASS SHRUB		Areas dominated by brush or shrubland.
Tall Weeds and Crops	GRASS TRACK PAST/HAY TALL GRASS		Areas characterized by grasses, legumes, or natural and semi-natural grasslands.

Land cover type	Land cover code	Example	Description
Forested and Fully Grown	DEC_FOR EVER_FOR FOREST MX_FOR		Forested areas, fully covered by trees, including hardwoods, conifers, and mixed forests.
Urban	PARK/URBAN/REC	n/a	Urban areas that may include tall, dense man-made structures.

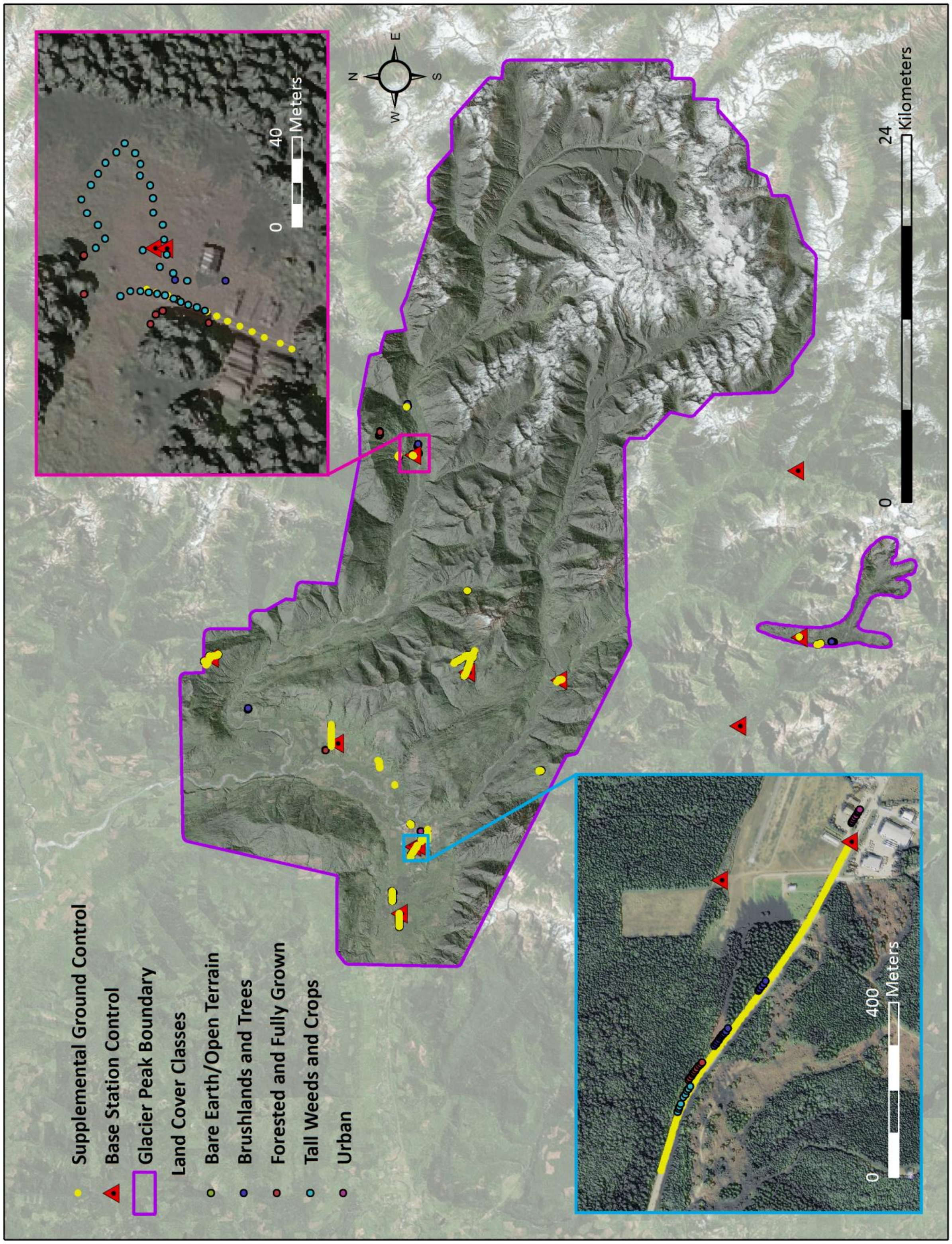
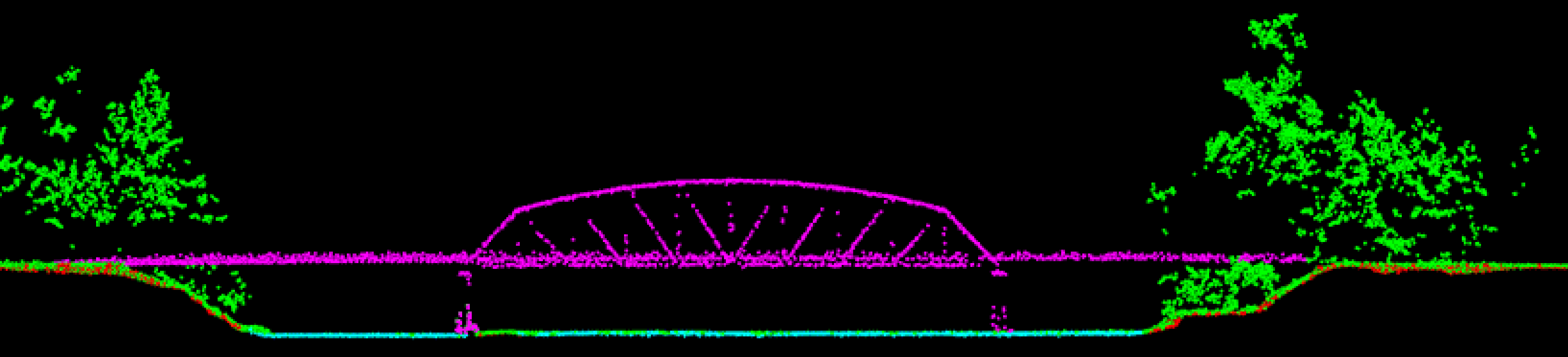


Figure 2: Ground survey location map

This 2 meter LiDAR cross section shows a view of the Glacier Peak point cloud colored by classification. Ground returns are displayed in red, default in green, water in blue, and bridge/decks in pink.



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 Glacier Peak 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.
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.
10	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation.
17	Bridge Decks	Permanent structures such as bridges and 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 geoid03 correction.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.1
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 8). 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 in EDRAS Imagine (.img) format at a 1 meter pixel resolution.	TerraScan v.15 TerraModeler v.15 ArcMap v. 10.1
Export intensity images as GeoTIFFs at a 1 meter pixel resolution.	DZOrtho Creator TerraScan v.15 TerraModeler v.15 ArcMap v. 10.1

Feature Extraction

Hydro-flattening and Water's edge breaklines

Water bodies within the Glacier Peak project area 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 30 meters, and select smaller bodies of water as feasible. The hydro-flattening 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.

Hydro-flattening 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 hydro-flattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 3).

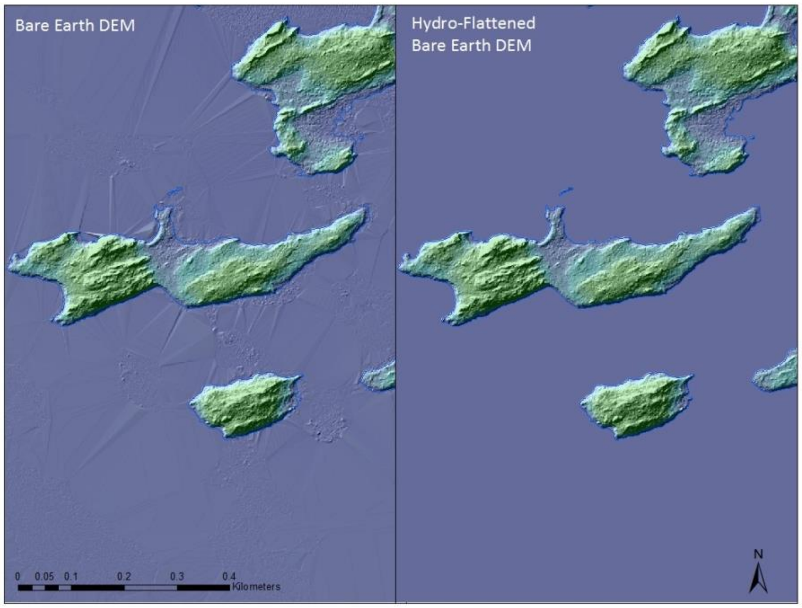
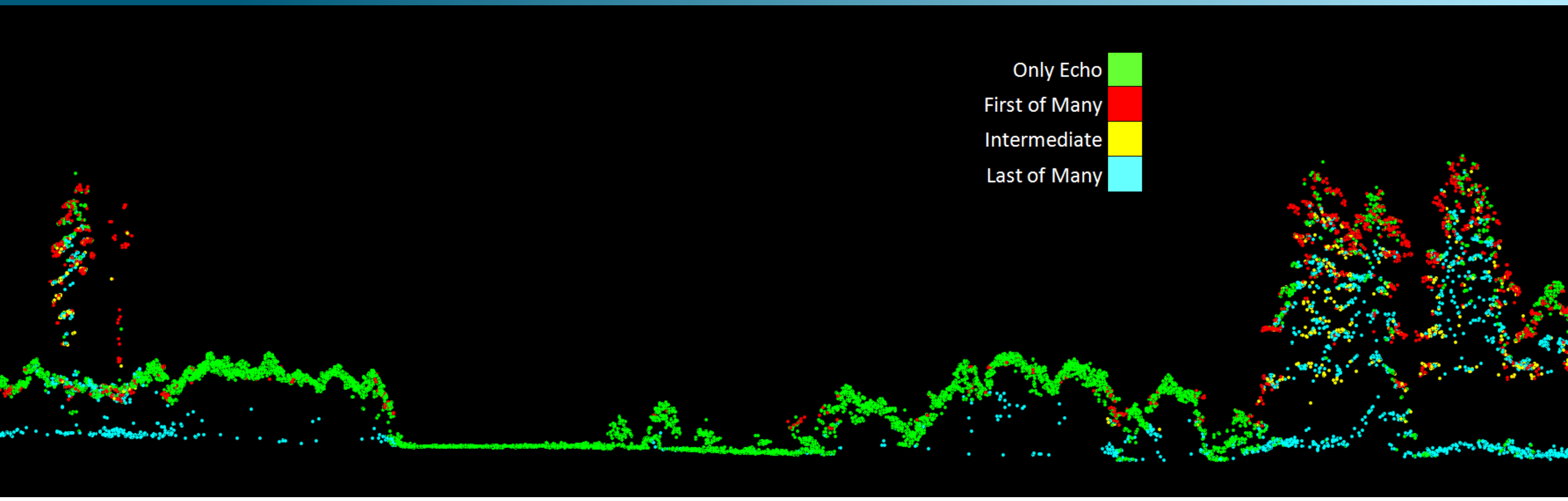


Figure 3: Example of hydro-flattening



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 Glacier Peak project was 27.05 points/m^2 while the average ground classified density was 2.86 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	27.05 points/m^2
Ground Classified	2.86 points/m^2

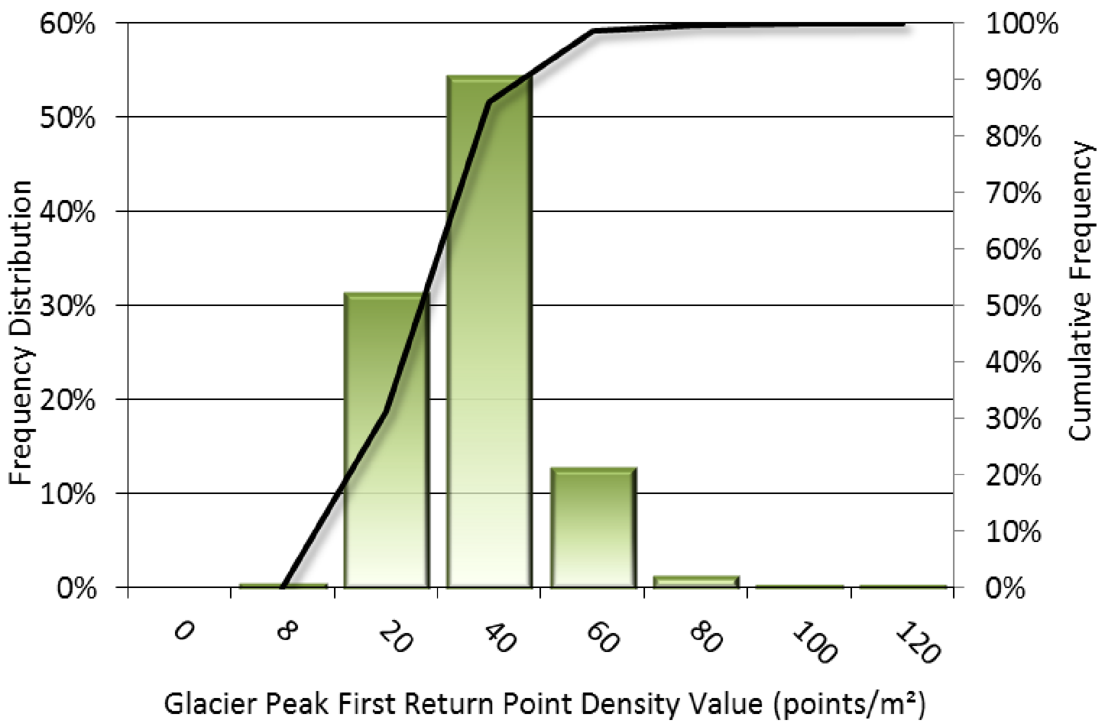


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

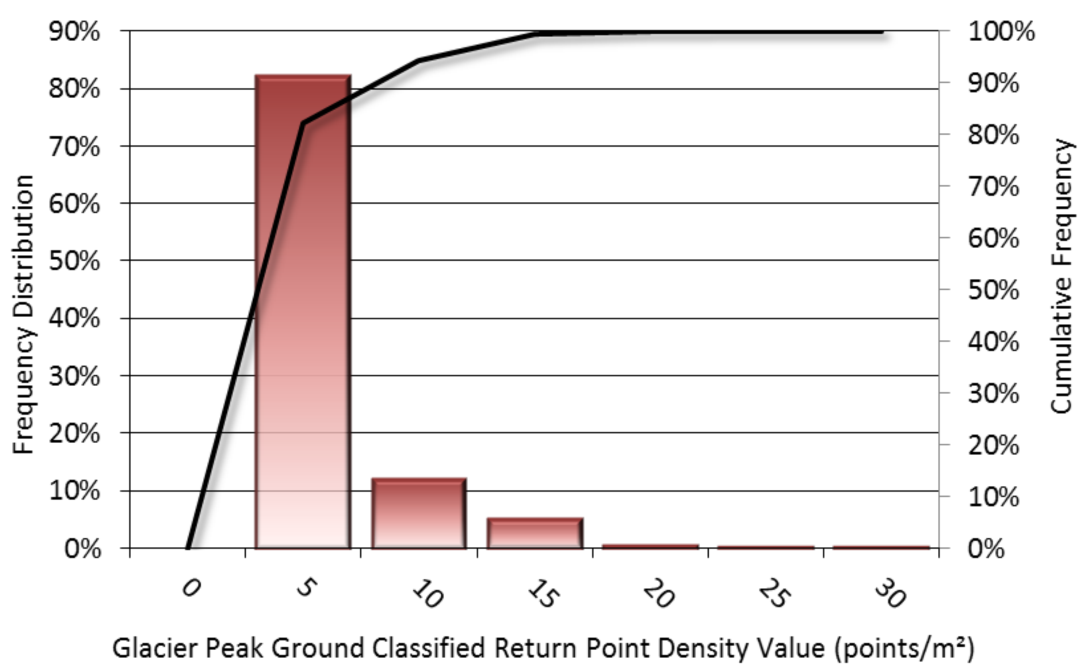


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

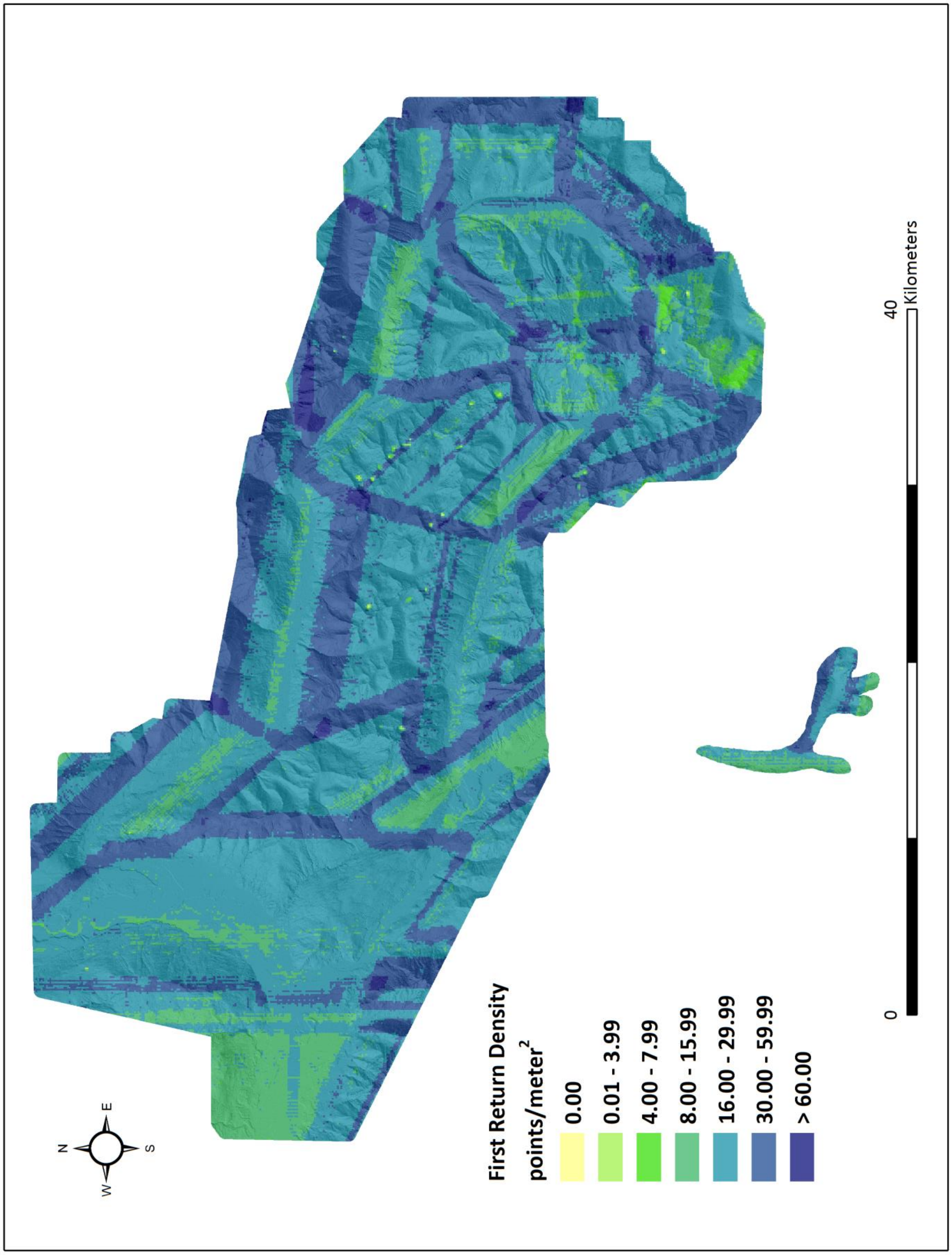


Figure 6: First return point density map for the Glacier Peak site (100 m x 100 m cells)

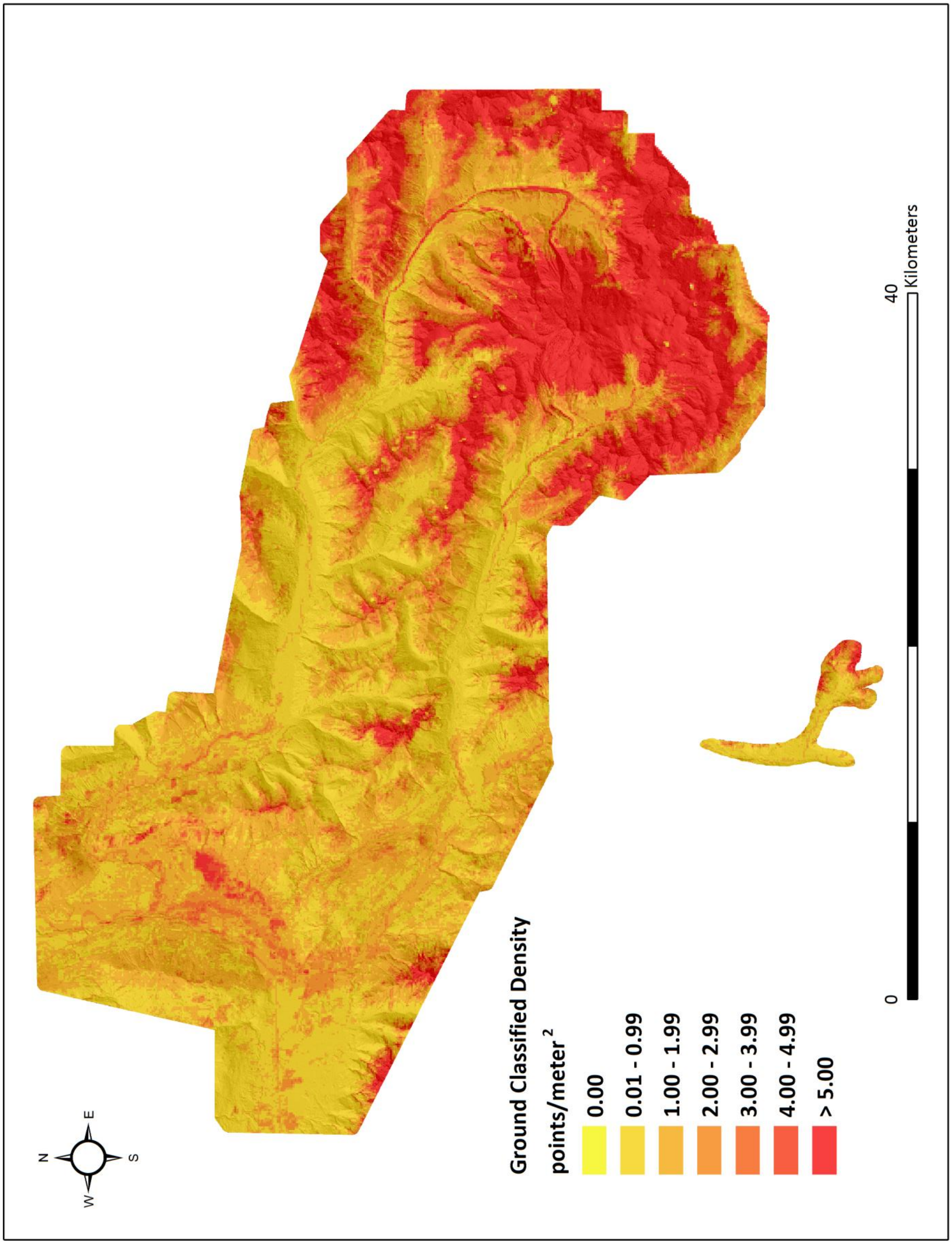


Figure 7: Ground point density map for the Glacier Peak site (100 m x 100 m cells)

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 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[3]. FVA compares known 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 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 Glacier Peak survey, 54 bare earth points were collected in total resulting in a fundamental vertical accuracy of 0.94 meters (Figure 8).

QSI also assessed absolute accuracy using 1,611 ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they may still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 11 and Figure 9.

Table 11: Absolute accuracy results

Absolute Accuracy		
	Bare Earth Points (FVA)	**Ground Control Points**
Sample	54 points	1,611 points
FVA (1.96*RMSE)	0.094 m	0.056 m
Average	-0.015 m	-0.006 m
Median	-0.006 m	-0.004 m
RMSE	0.048 m	0.028 m
Standard Deviation (1σ)	0.046 m	0.028 m

[3] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.3-1998). Part 3: National Standard for Spatial Data Accuracy. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

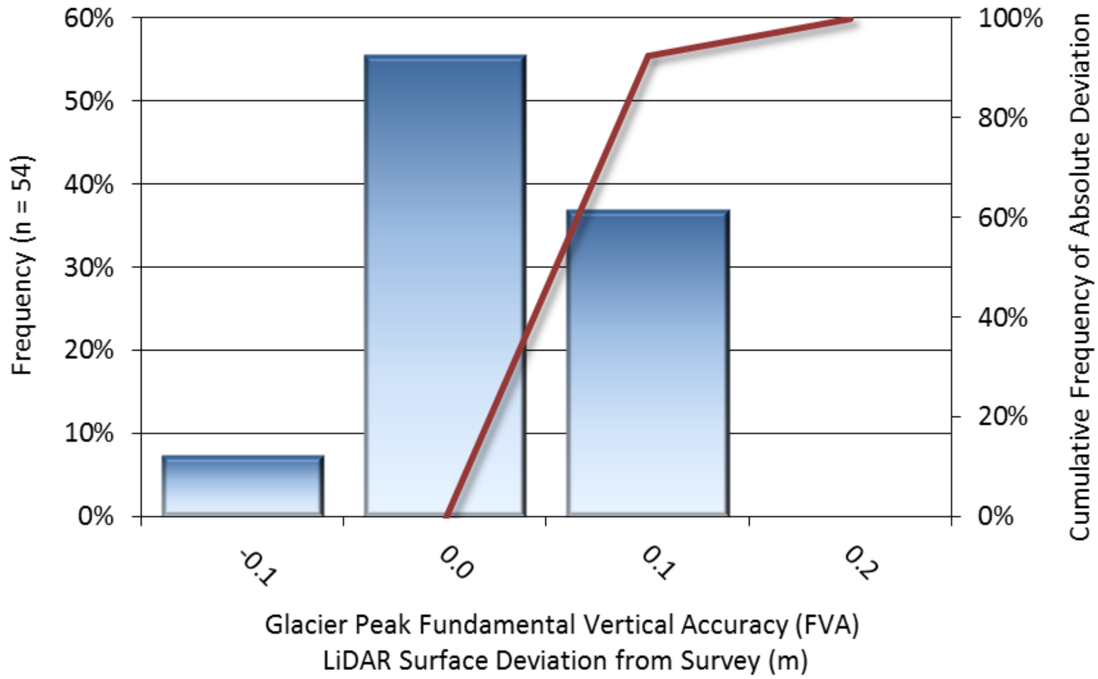


Figure 8: Frequency histogram for LiDAR surface deviation from bare earth check point values

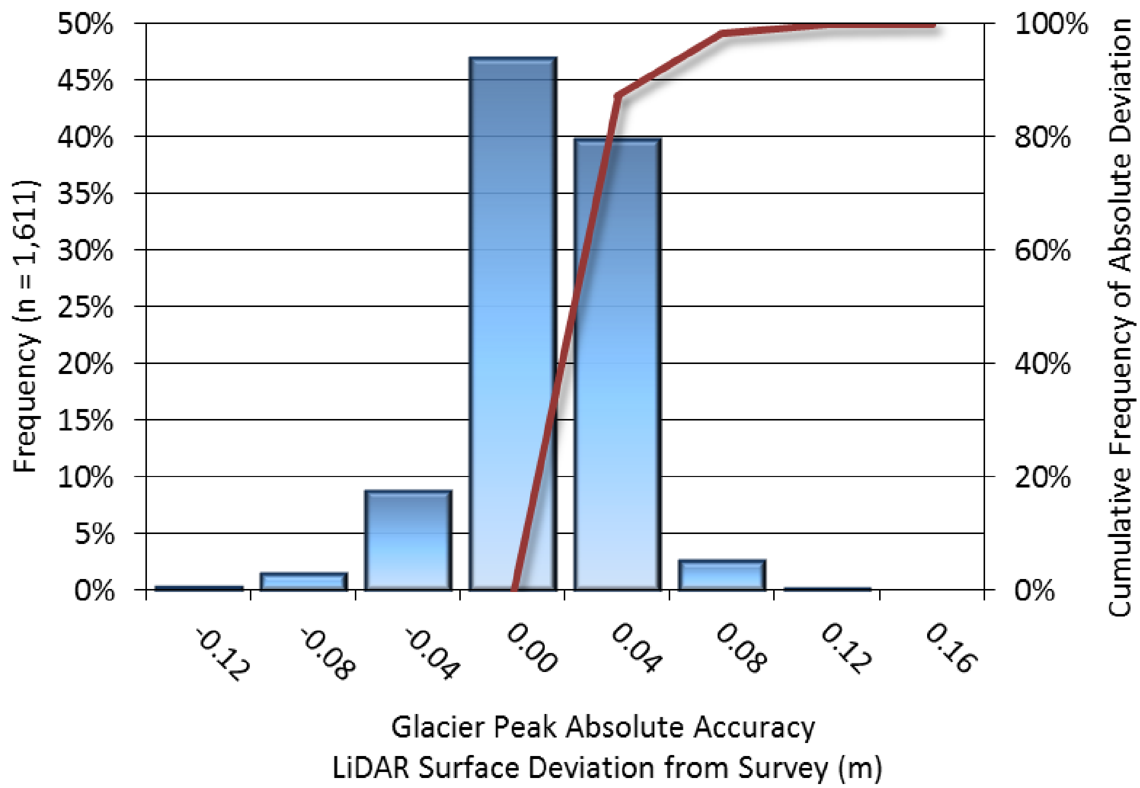


Figure 9: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Supplemental and Consolidated Vertical Accuracies

QSI also assessed vertical accuracy using Supplemental Vertical Accuracy (SVA) and Consolidated Vertical Accuracy (CVA) reporting. SVA compares known ground check point data within individual land cover class categories to the triangulated ground surface generated by the ground classified LiDAR points while CVA compares known ground check points within all land cover classes. SVA and CVA are evaluated at the 95th percentile, as shown in Table 12.

Table 12: Supplemental and Consolidated Vertical Accuracies for the Glacier Peak Project

Supplemental and Consolidated Vertical Accuracies						
	SVA					CVA
Land Cover Class	**Bare Earth**	**Brushlands/ Trees**	**Tall Weeds and Crops**	**Forested/Fully Grown**	**Urban**	**All Land Cover Classes**
Sample	54 points	152 points	54 points	70 points	23 points	353
Average Dz	-0.015 m	0.047 m	0.038 m	0.036 m	-0.004 m	0.031 m
Median	-0.006 m	0.043 m	0.014 m	0.024 m	0.004 m	0.019 m
RMSE	0.048 m	0.086 m	0.099 m	0.079 m	0.026 m	0.079 m
Standard Deviation (1σ)	0.046 m	0.072 m	0.093 m	0.071 m	0.026 m	0.073 m
95th Percentile	0.107m	0.184 m	0.237 m	0.170 m	0.050 m	0.179 m

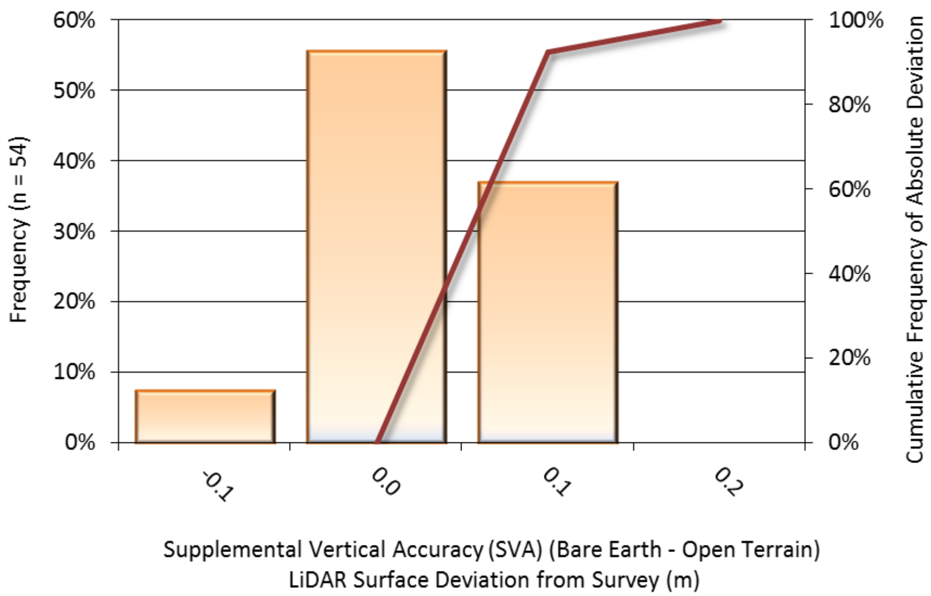


Figure 10: Frequency histogram for LiDAR surface deviation from "Bare Earth" land cover class point values

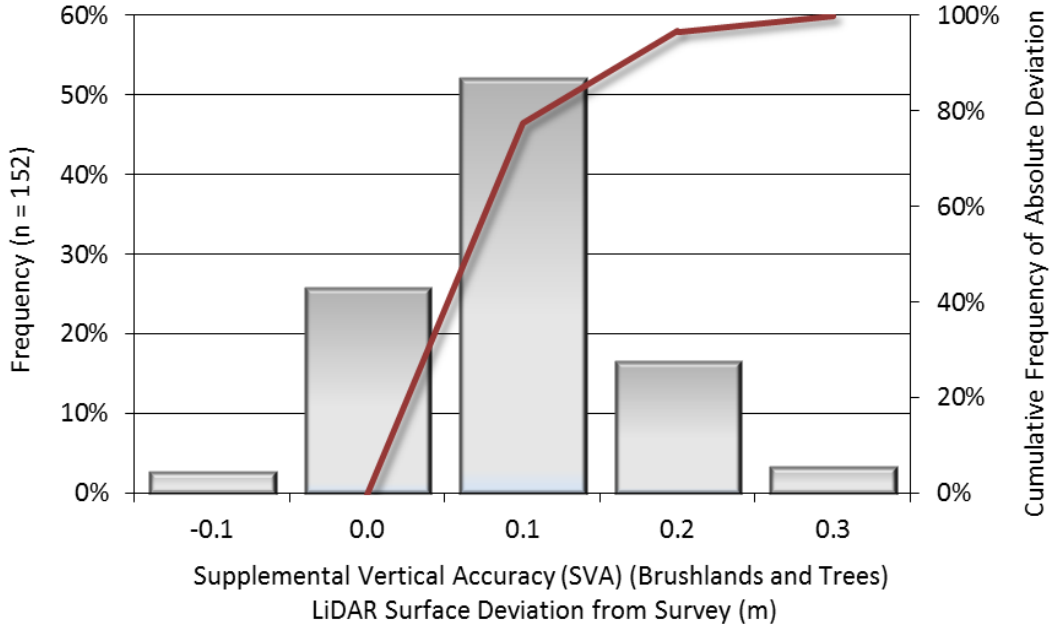


Figure 11: Frequency histogram for LiDAR surface deviation from "Brushlands and Trees" land cover class point values

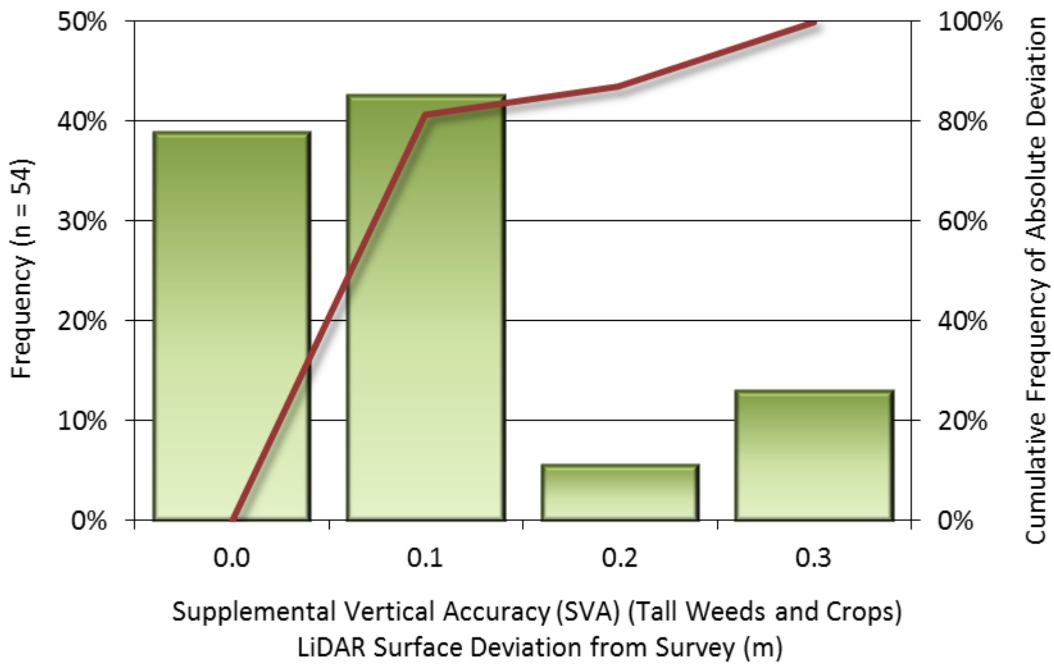


Figure 12: Frequency histogram for LiDAR surface deviation from "Tall Weeds/Crops" land cover class point values

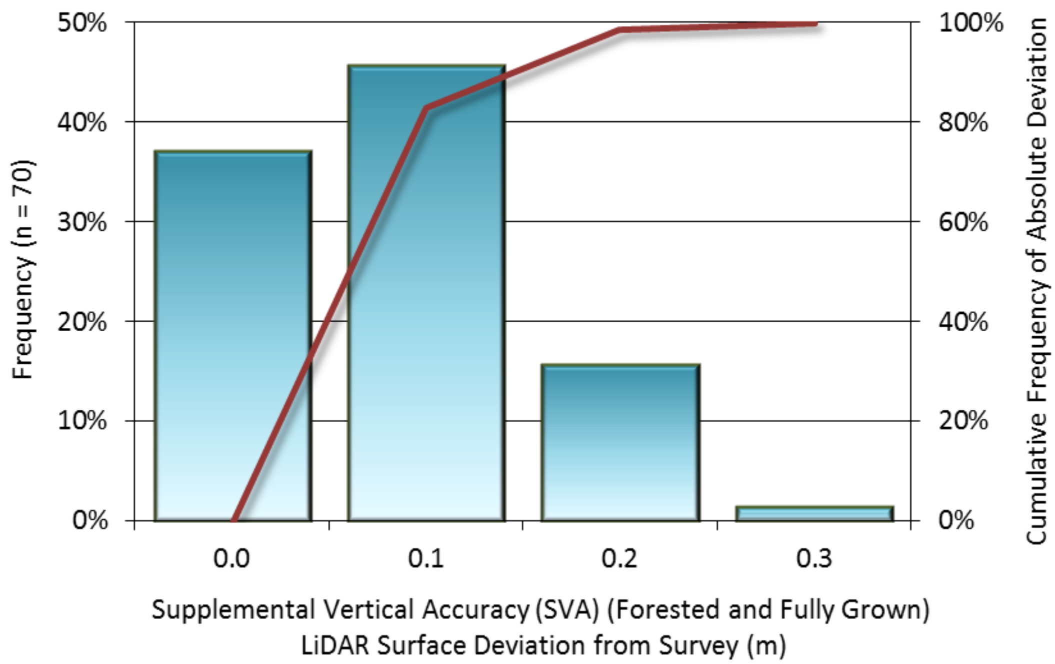


Figure 13: Frequency histogram for LiDAR surface deviation from "Forested and Fully Grown" land cover class point values

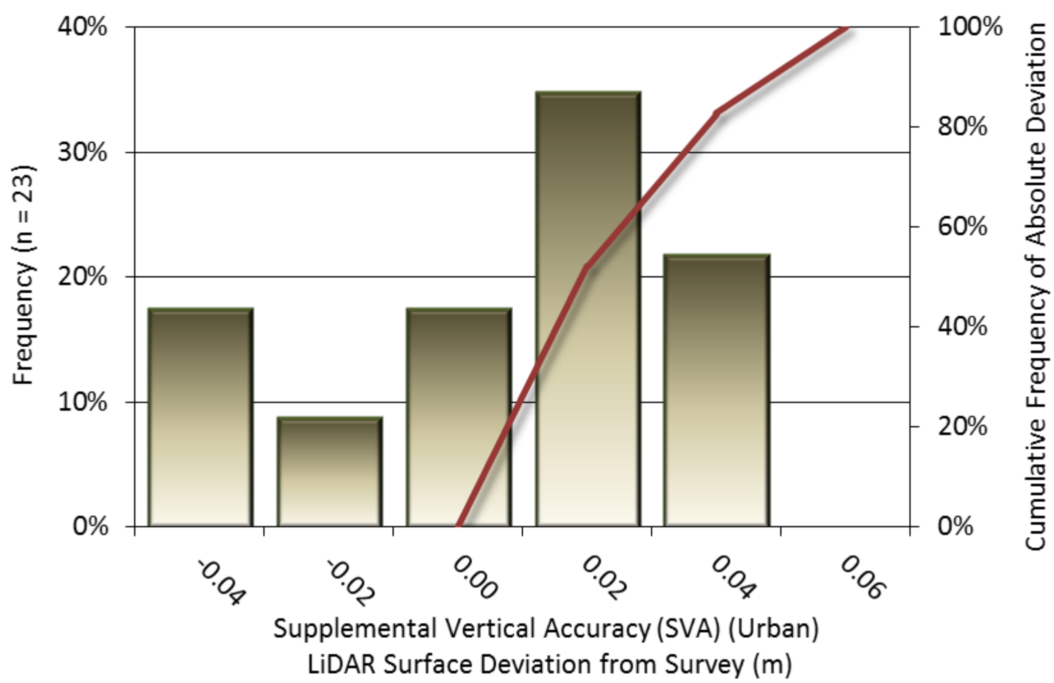


Figure 14: Frequency histogram for LiDAR surface deviation from "Urban" land cover class point values

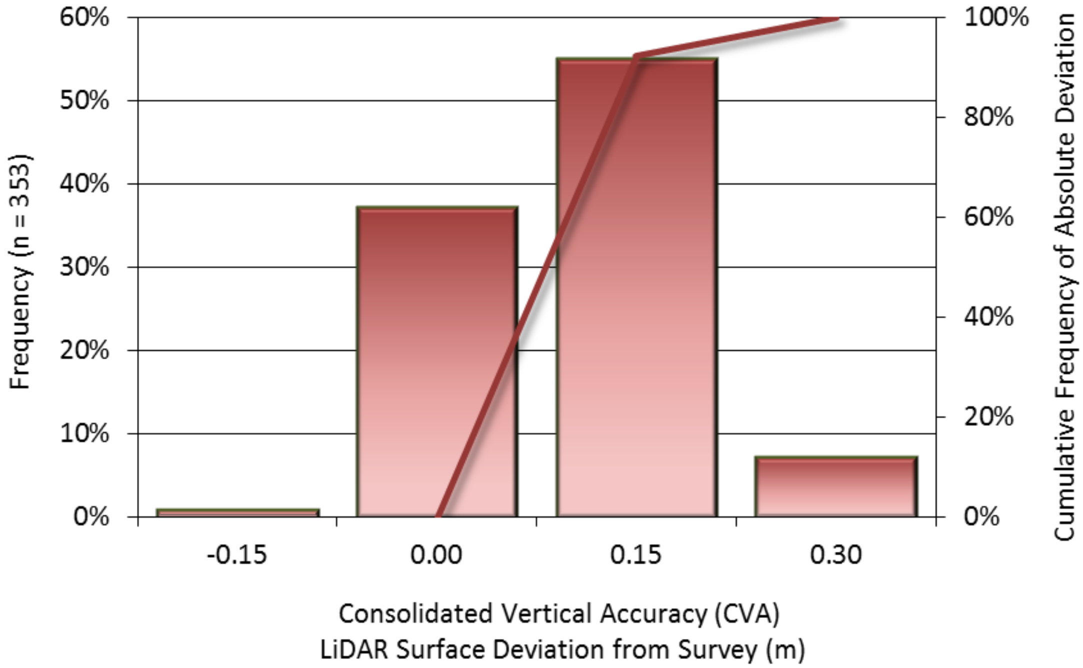


Figure 15: Frequency histogram for LiDAR surface deviation from all land cover class point values (CVA)

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 Glacier Peak LiDAR project was 0.072 meters (Table 13, Figure 16).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	1,290 surfaces
Average	0.072 m
Median	0.069 m
RMSE	0.075 m
Standard Deviation (1σ)	0.019 m
1.96σ	0.037 m

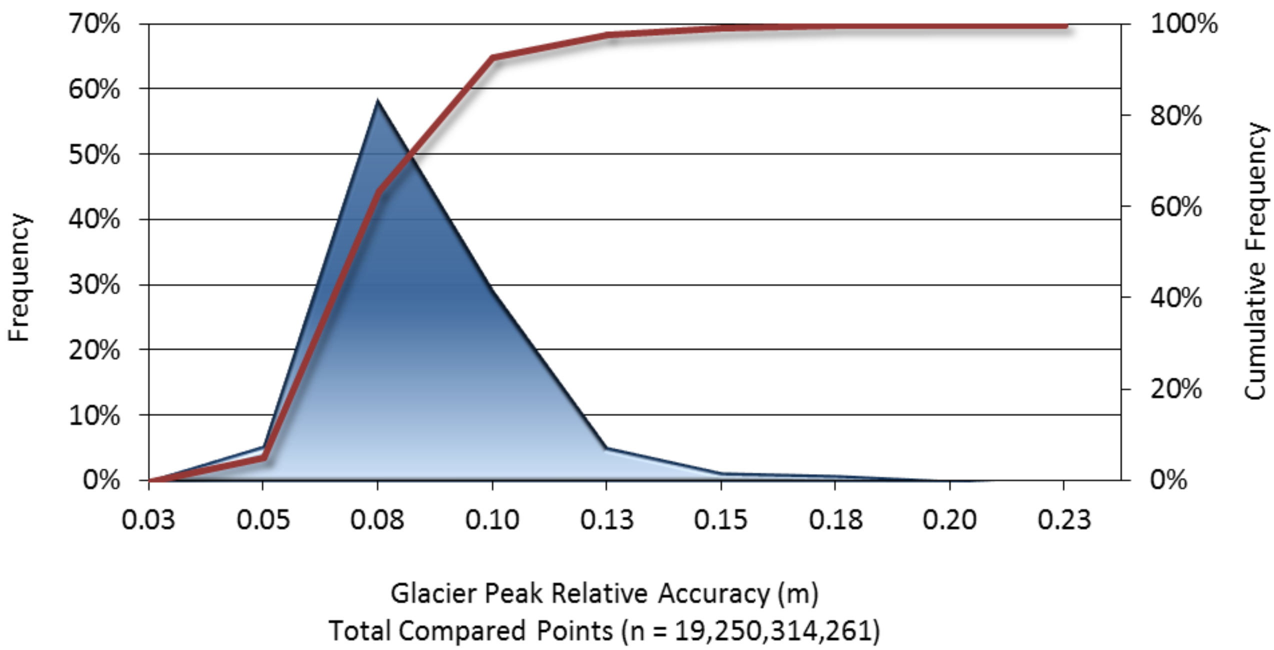


Figure 16: Frequency plot for relative vertical accuracy between flight lines

CERTIFICATIONS

Quantum Spatial provided LiDAR services for the Glacier Peak LiDAR project as described in this report.

I, Christopher Glantz, 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 between August 15, 2014 and June 30, 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".

12/18/2015

Christopher Glantz, PLS
Survey Manager
Quantum Spatial, Inc.

SELECTED IMAGES

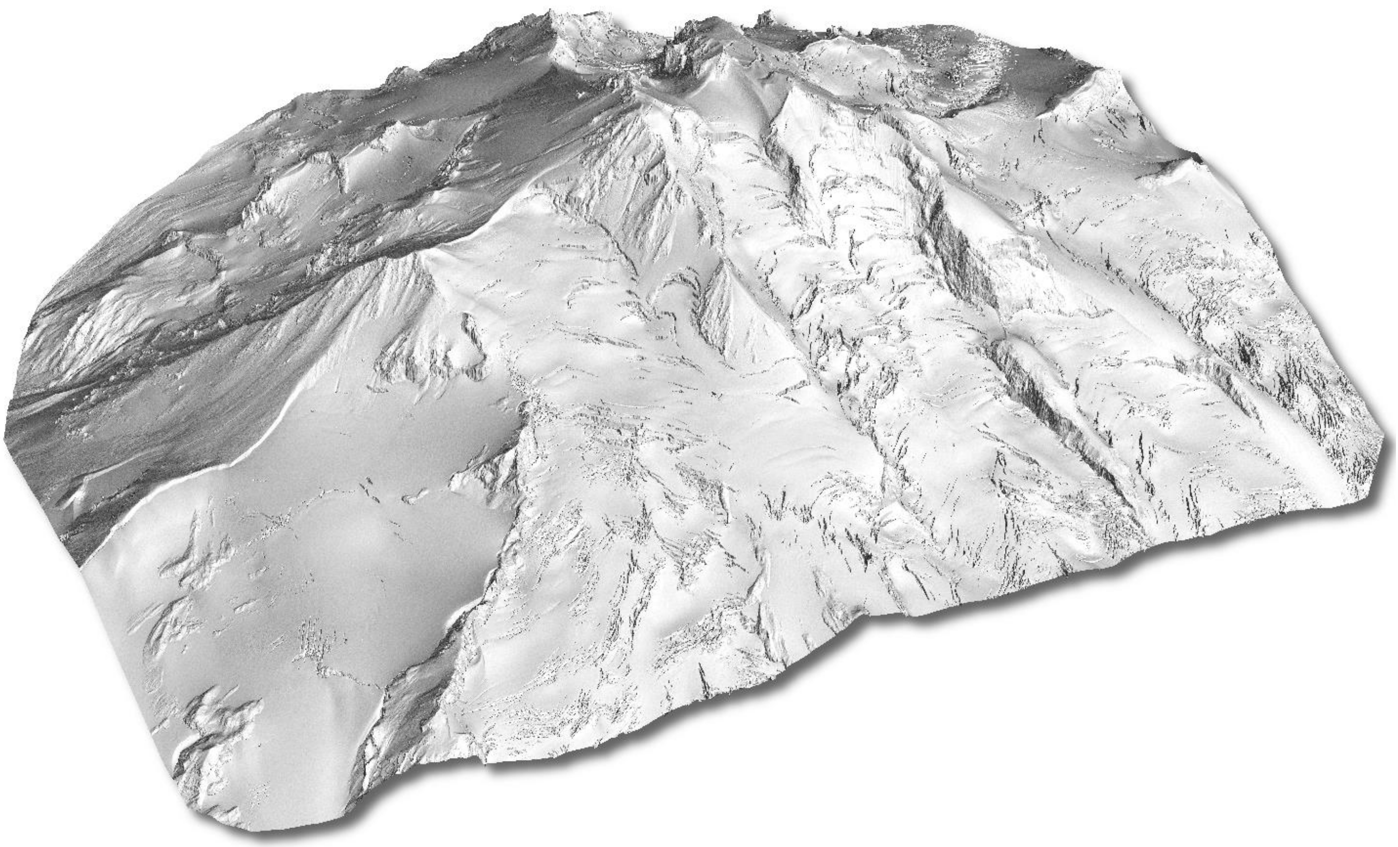


Figure 17: This image shows a detailed view of Glacier Peak as a whole, and was created from the gridded bare earth surface, colored to look like snowpack.

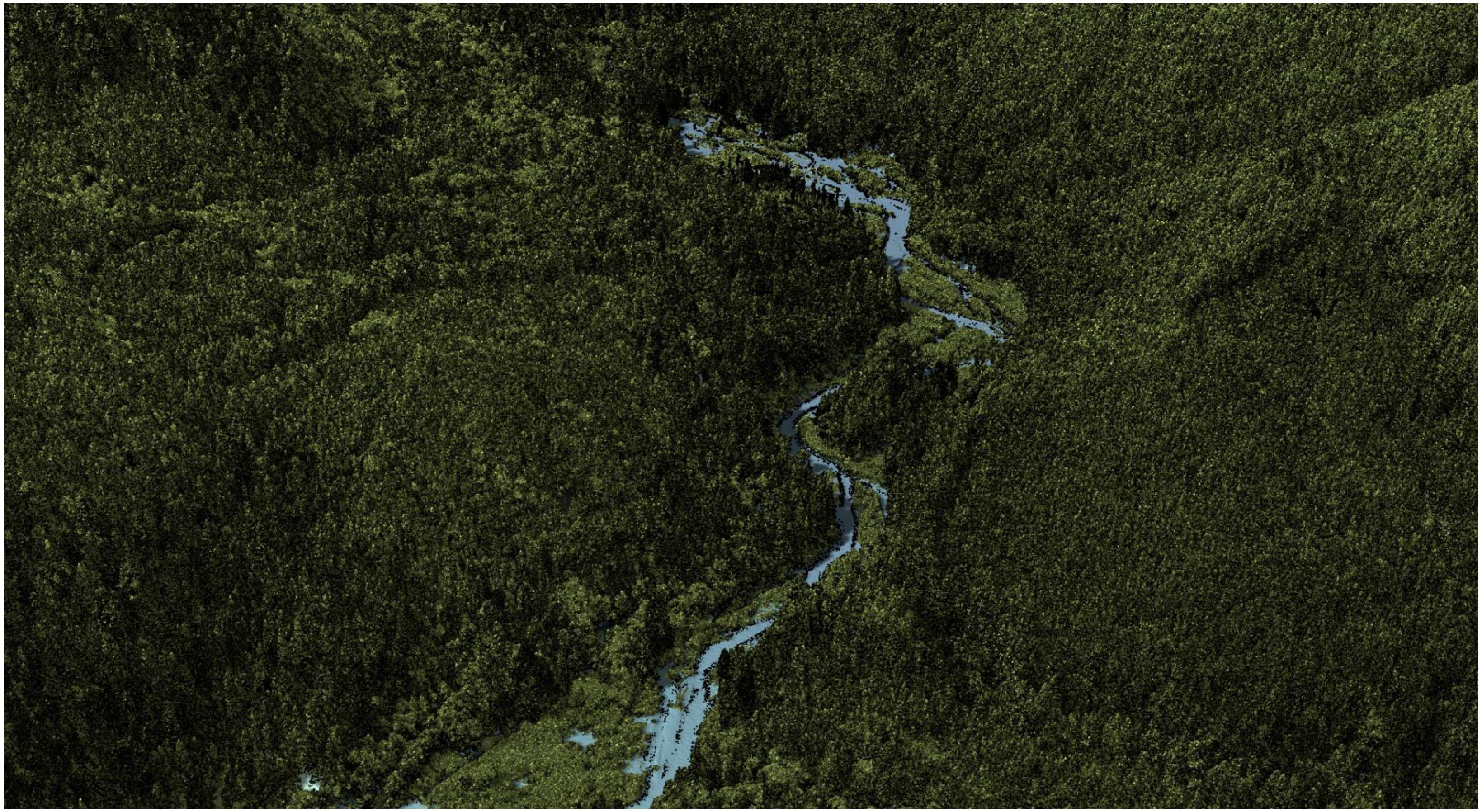


Figure 18: This image shows a view of the Sauk River peeking through the dense vegetation captured by the above-ground LiDAR point cloud.

Figure 19: This image shows another view of the Sauk River, overlaid by the above-ground LiDAR returns colored by elevation

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 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.

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 $\pm 12^{o}$ 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.