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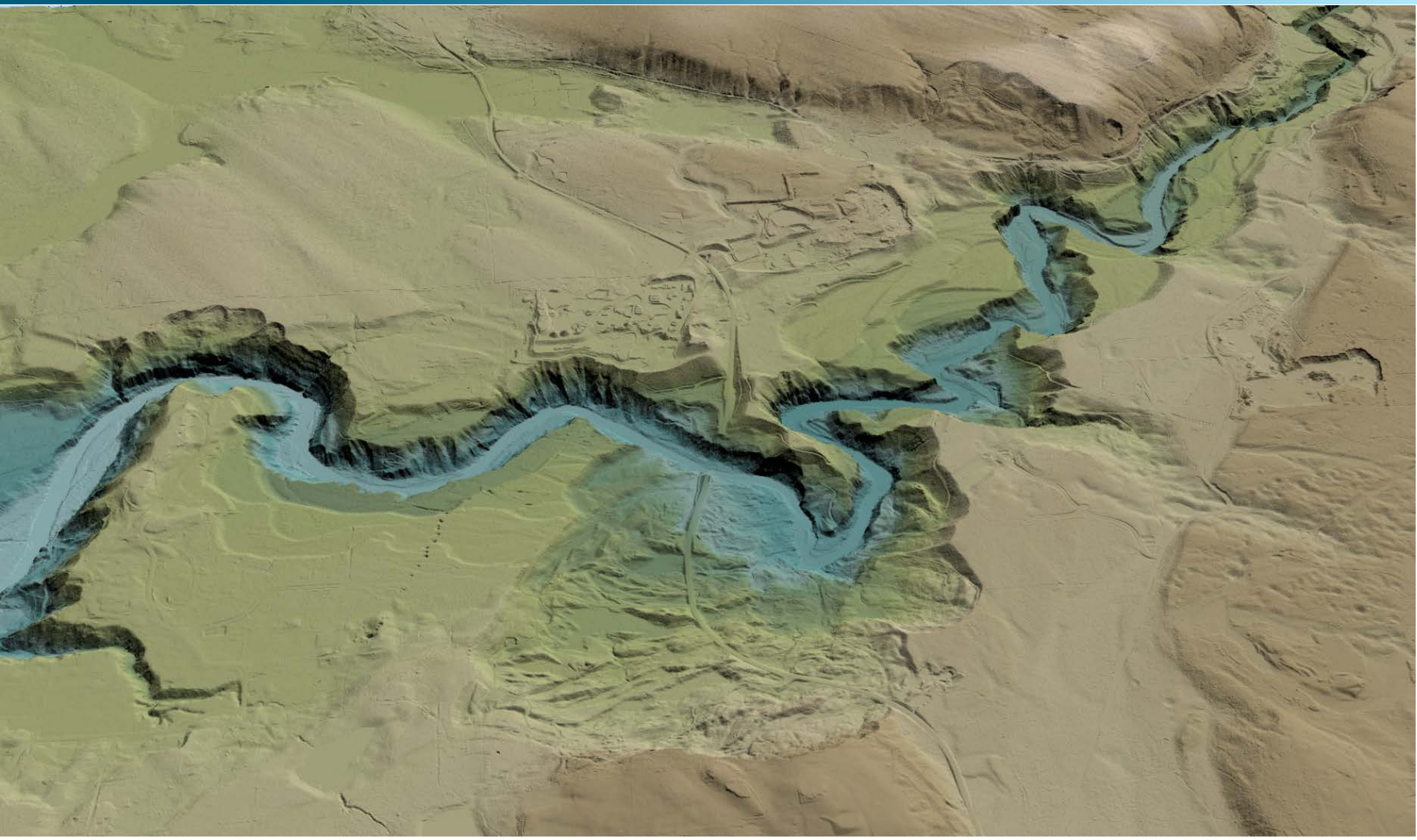

PSLC King County LiDAR

Technical Data Report

Puget Sound Regional Council
PSRC

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Cover Photo: A view looking north east at the Green River Gorge. The image was created from the LiDAR bare earth model colored by elevation.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the Green River along the Auburn Golf Course within the PSLC King County sites in Washington.

In February 2016, Quantum Spatial (QSI) was contracted by the Puget Sound LiDAR Consortium (PSLC) in association with the Kitsap County Department of Emergency Management to collect Light Detection and Ranging (LiDAR) data in early 2016 for the PSLC King County sites in Washington. Data were collected to aid PSLC in assessing the topographic and geophysical properties of the study area to support a variety of tasks including municipal planning, change detection and geomorphic mapping, and hazard mitigation.

This report accompanies the King County Delivery 3 LiDAR data and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy and density. The Delivery 1, Delivery 2, and Delivery 3 acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to PSLC 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 Deliveries 1, 2, & 3 King County sites

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Delivery 1	180,108	185,031	02/24/2016 - 02/26/2016, 03/02/2016, 03/05/2016, 03/08/2016, 03/11/2016, 03/18/2016, 03/19/2016, and 03/28/2016	LiDAR
Delivery 2	118,589	121,690	02/25/2016, 03/08/2016, 03/11/2016, 03/18/2016, 03/19/2016, 03/28/2016	LiDAR
Delivery 3	181,919	184,695	03/02/2016, 03/05/2016, 03/11/2016, 03/17/2016, 03/19/2016, 03/26/2016, 03/29/2016	LiDAR

Deliverable Products

Table 2: Products delivered to PSLC for the King County sites

King County Delivery 3 Products Projection: Washington State Plane North Horizontal Datum: NAD83 (HARN)* Vertical Datum: NAVD88 (GEOID03) Units: US Survey Feet	
Points	LAS v 1.2 • All Returns Comma Delimited ASCII Files • All Returns (*asc) • Ground Returns (*gnd)
Rasters	3 Foot ESRI Floating Point Grid • Bare Earth Model • Highest Hit Model 1.5 Foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index • DEM Tile Index • Ground Control and Check Points • Ground Control Monuments • Smooth Best Estimate Trajectory (SBETs)

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

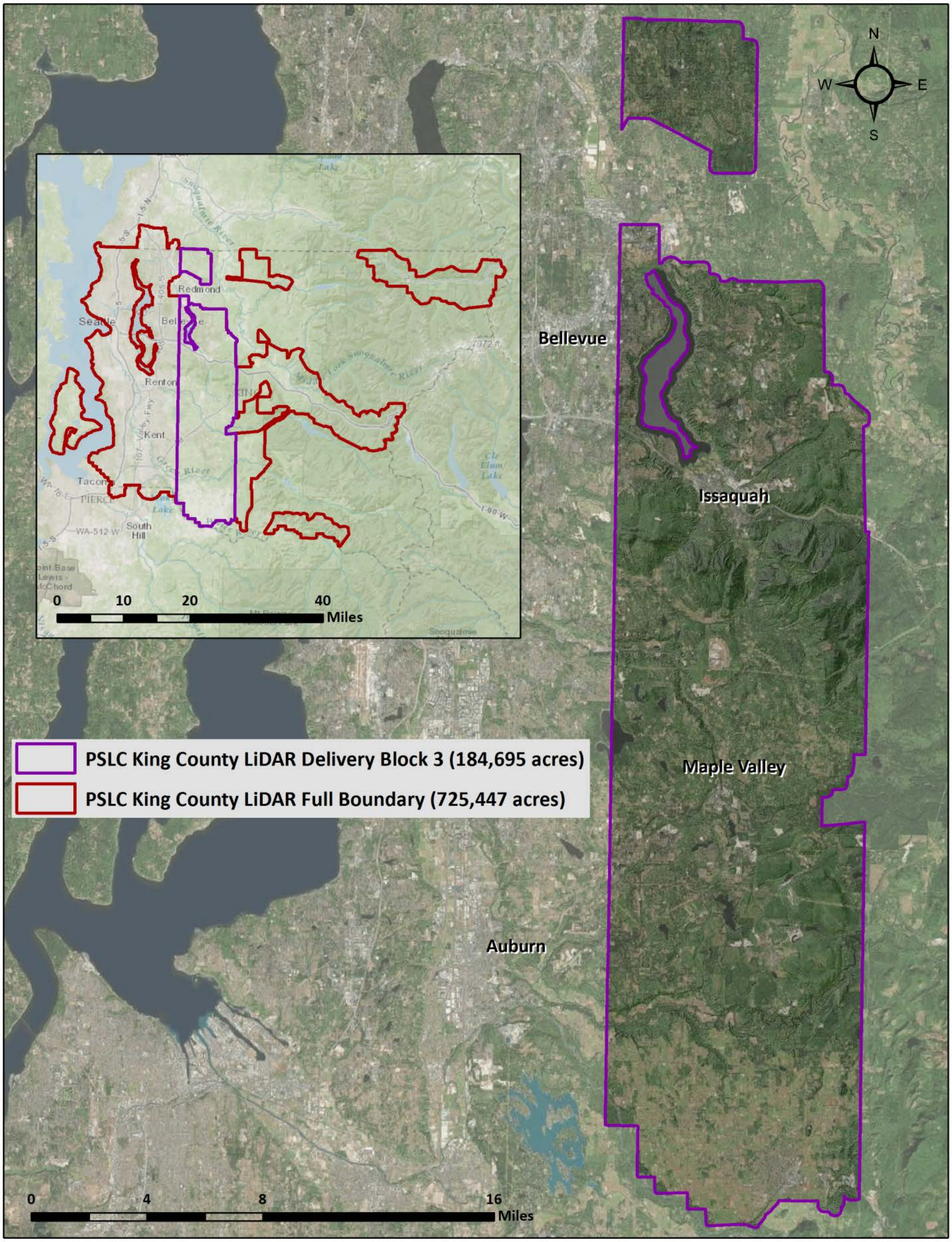

Figure 1: Location map of the King County Delivery 3 site in Washington.

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 King County 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 survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan. Table 3 summarizes the Delivery 3 and previous project delivery settings used to yield an average pulse density of ≥8 pulses/m^2 (0.74 pulses/ft^2) over the King County Delivery 1, 2 and 3 project areas. The Leica ALS80 laser system can record 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 for Deliveries 1, 2, & 3

LiDAR Survey Settings & Specifications for Deliveries 1, 2, & 3		
Acquisition Dates	03/08/2016, 03/11/2016, 03/19/2016, 03/26/2016	02/24/2016-02/26/2016, 03/02/2016, 03/05/2016, 03/17/2016, 03/18/2016, 03/28/2016, 03/29/2016
Aircraft Used	Cessna Caravan 208B	Cessna Caravan 208B
Sensor	Leica ALS80	Leica ALS80
Survey Altitude (AGL)	1200 m	1600 m
Swath Width	874 m	857 m
Target Pulse Rate	400 kHz	340 kHz
Pulse Mode	Multi Pulse in Air (MPiA)	Multi Pulse in Air (MPiA)
Laser Pulse Diameter	26 cm	35 cm
Mirror Scan Rate	53 Hz	53 Hz
Field of View	40°	30°
GPS Baselines	≤13 nm	≤13 nm
GPS PDOP	≤3.0	≤3.0
GPS Satellite Constellation	≥6	≥6
Maximum Returns	Unlimited	Unlimited
Intensity	8-bit	8-bit
Resolution/Density	Average 8 pulses/m^2	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm	$RMSE_Z$ ≤ 15 cm

All areas were surveyed with an opposing flight line side-lap of ≥63% (≥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

PSLC_KNG 14
QSI-Established Monument

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.

Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground survey points using real time kinematic (RTK) and post processed kinematic (PPK) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. In addition to the seven new monuments and four existing monuments used for Deliveries 1 & 2, QSI established three new monuments and utilized four existing monuments for the King County Delivery 3 LiDAR project areas (Table 4, Figure 2). New monumentation was set using 5/8” x 30” rebar topped with stamped 2 ½" aluminum caps).

Table 4: Monuments used for the King County Delivery 1, 2, & 3 acquisitions. Coordinates are on the NAD83 (HARN) datum

Monument ID	Latitude	Longitude	Ellipsoid (meters)
CEDAR_9	47° 48' 30.30271"	-121° 59' 57.61062"	-11.421
KCJJ_01	47° 17' 01.32634"	-122° 03' 10.77785"	31.851
KCJJ_02	47° 35' 09.70140"	-121° 57' 15.17980"	11.943
KNG_11	47° 20' 23.65277"	-122° 12' 27.27308"	-5.038
KNG_CO_01	47° 24' 42.01975"	-122° 16' 37.11827"	-12.535
MGRC_SOOS_01	47° 19' 44.52155"	-122° 09' 54.37518"	127.153
PSLC_KNG_07	47° 40' 08.43367"	-122° 04' 44.58168"	-2.92
PSLC_KNG_08	47° 39' 37.71847"	-122° 06' 25.05828"	-11.009
PSLC_KNG_09	47° 36' 02.74424"	-122° 17' 07.36536"	-14.428
PSLC_KNG_10	47° 35' 32.19072"	-122° 18' 12.28435"	27.116
PSLC_KNG_11	47° 38' 28.04519"	-122° 18' 40.28866"	-15.545
PSLC_KNG_12	47° 38' 48.10630"	-122° 20' 17.49197"	-13.211
PSLC_KNG_13	47° 35' 31.59330"	-121° 57' 30.81496"	8.39
PSLC_KNG_14	47° 27' 49.89049"	-122° 29' 32.44791"	45.903

Monument ID	Latitude	Longitude	Ellipsoid (meters)
PSLC_KNG_15	47° 24' 24.79988"	-122° 19' 21.88588"	21.086
PSLC_KNG_16	47° 50' 20.37391"	-122° 12' 54.69201"	60.916
SY0513	47° 20' 43.06372"	-122° 07' 15.11845"	82.18

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 King County LiDAR project area, 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.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic and post-processed kinematic (PPK) survey techniques. A Trimble R7 base unit was positioned at a nearby monument to broadcast kinematic corrections to roving Trimble R6 or Trimble R8 GNSS receiver. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK and PPK data, the rover records data while stationary for five seconds, then calculates the pseudorange position using at least three one-second epochs. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 6 for Trimble unit specifications.

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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

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).

Table 6: Trimble equipment identification

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

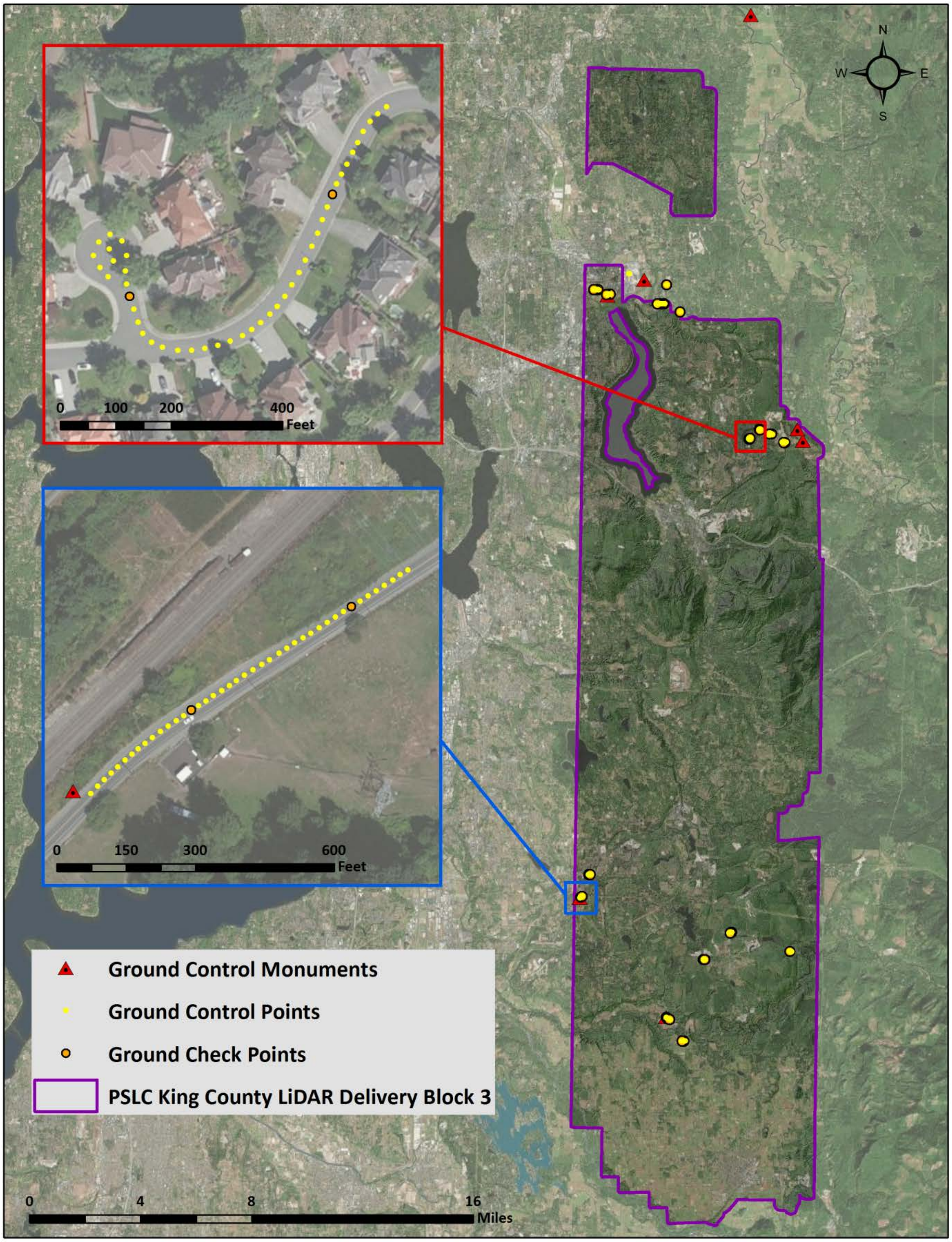
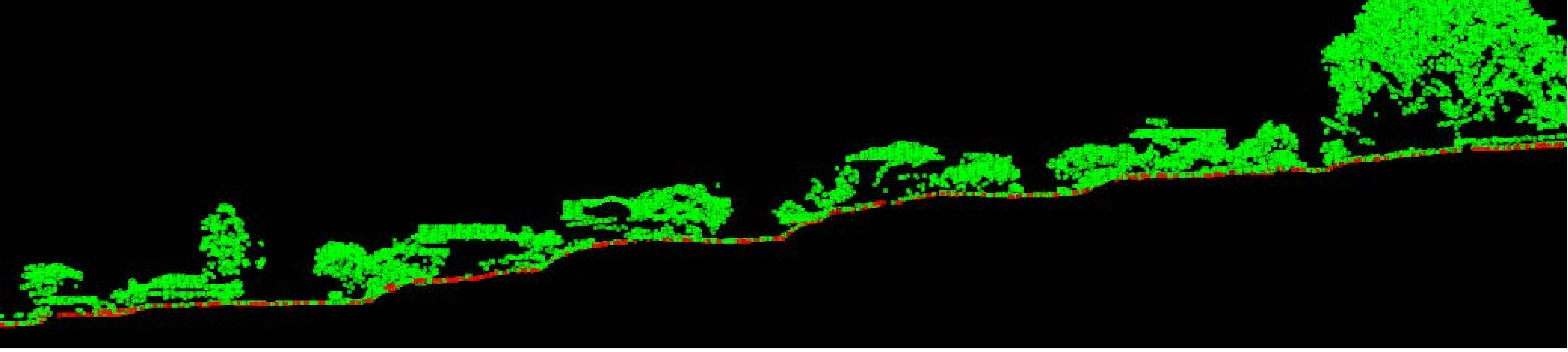


Figure 2: PSLC King County LiDAR Project Delivery 3 ground survey location map

This 10 foot LiDAR cross section shows a view of a suburb east of downtown Seattle in the King County LiDAR project area, colored by point classification.



LiDAR Data

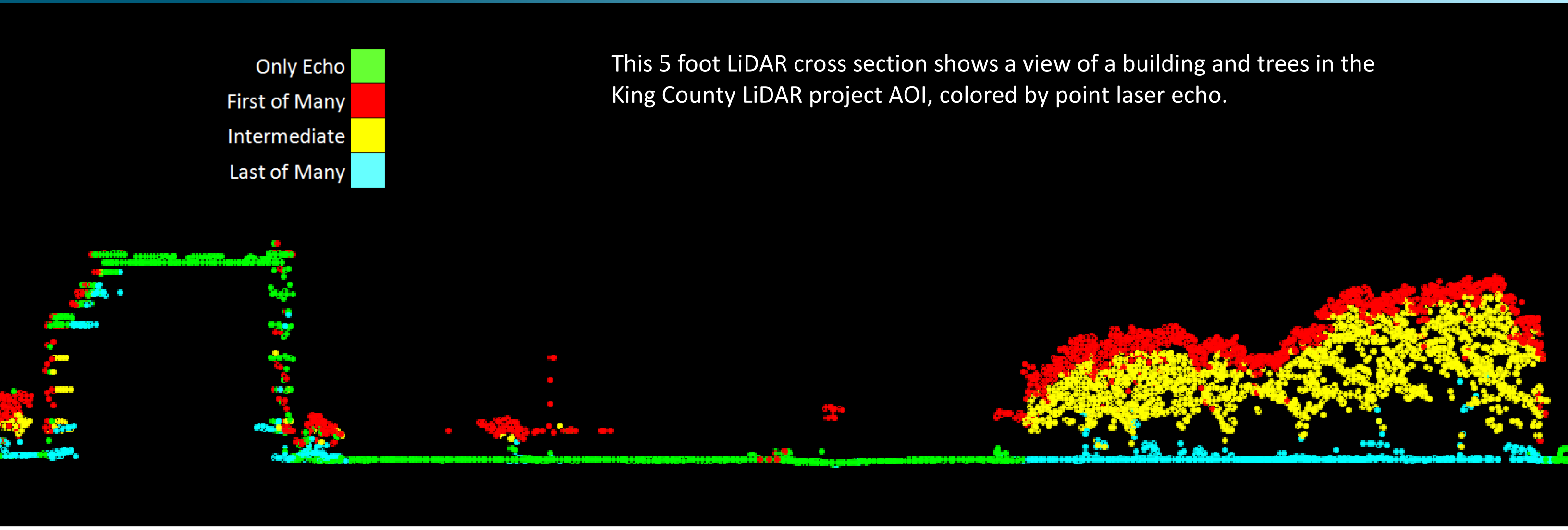
Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8.

Table 7: ASPRS LAS classification standards applied to the King County dataset

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

Table 8: 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. 1.2.2
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.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 7). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.16 TerraModeler v.16
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 foot pixel resolution.	TerraScan v.16 TerraModeler v.16 ArcMap v. 10.2.2
Export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	Las Monkey (QSI proprietary) LAS Product Creator (QSI proprietary) TerraScan v.16 TerraModeler v.16 ArcMap v. 10.2.2



LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 0.74 points/ft^2 (8.0 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 King County Delivery 3 project area was 1.29 points/ft^2 (13.91 points/m^2) while the average ground classified density was 0.23 points/ft^2 (2.46 points/m^2) (Table 9). The statistical and spatial distributions of first return densities and classified ground return densities per 100 ft x 100 ft cell are portrayed in Figure 3 through Figure 6. The King County Delivery 1 & 2 project area density statistics are documented in Appendix B (**Error! Reference source not found.**).

Table 9: Delivery 3 average LiDAR point densities

Classification	Point Density
First-Return	1.29 points/ft^2 13.91 points/m^2
Ground Classified	0.23 points/ft^2 2.46 points/m^2

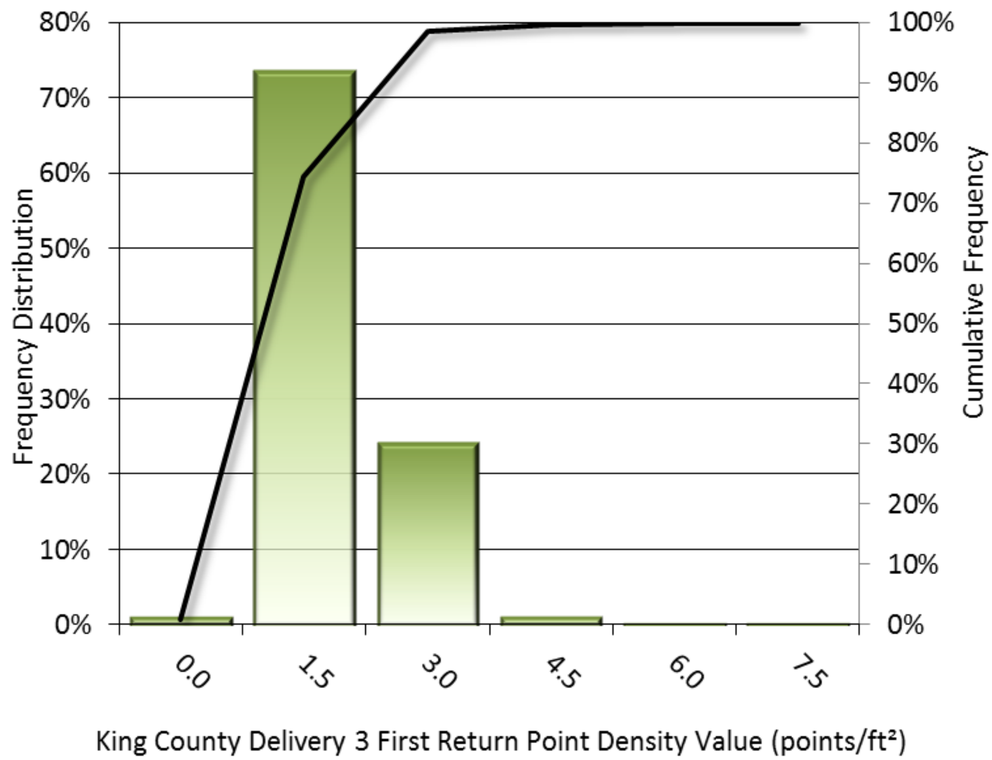


Figure 3: Frequency distribution of first return point density values per 100 ft x 100 ft cell

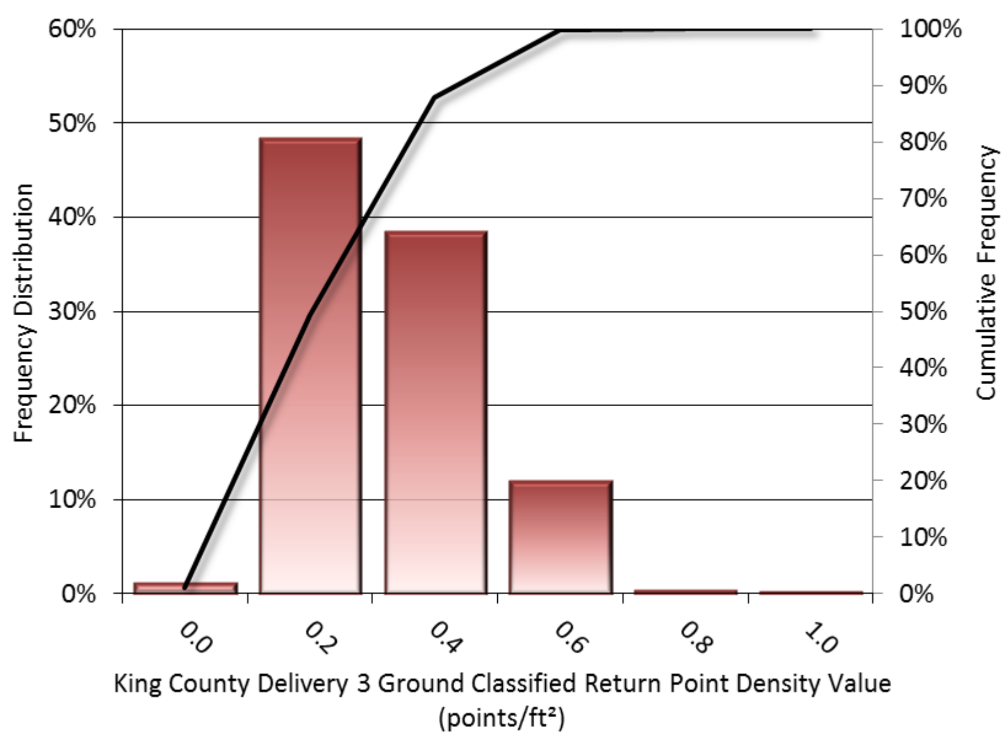


Figure 4: Frequency distribution of ground-classified return point density values per 100 ft x 100 ft cell

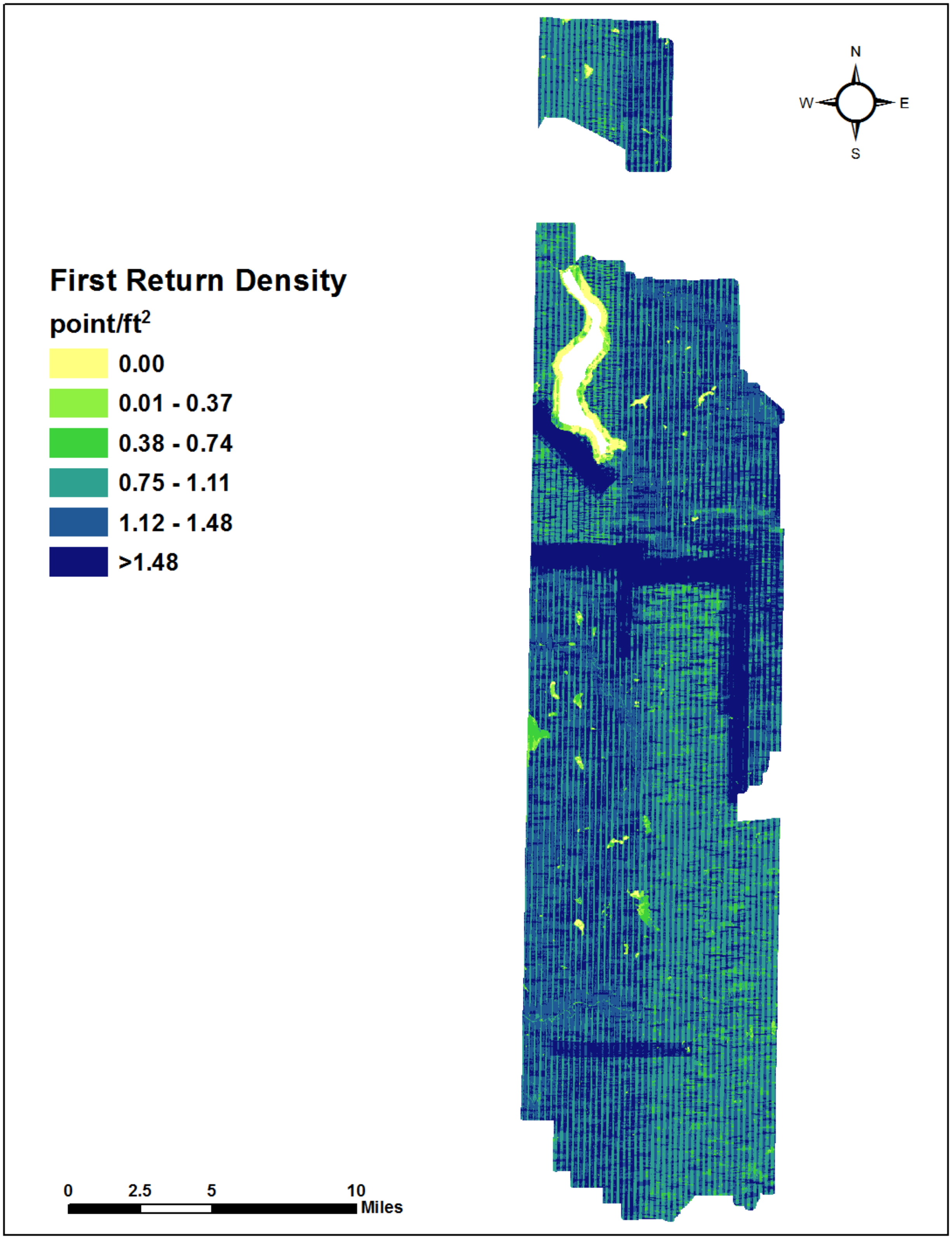


Figure 5: First return classified point density map for the King County Delivery 3 sites (100 ft x 100 ft cells)

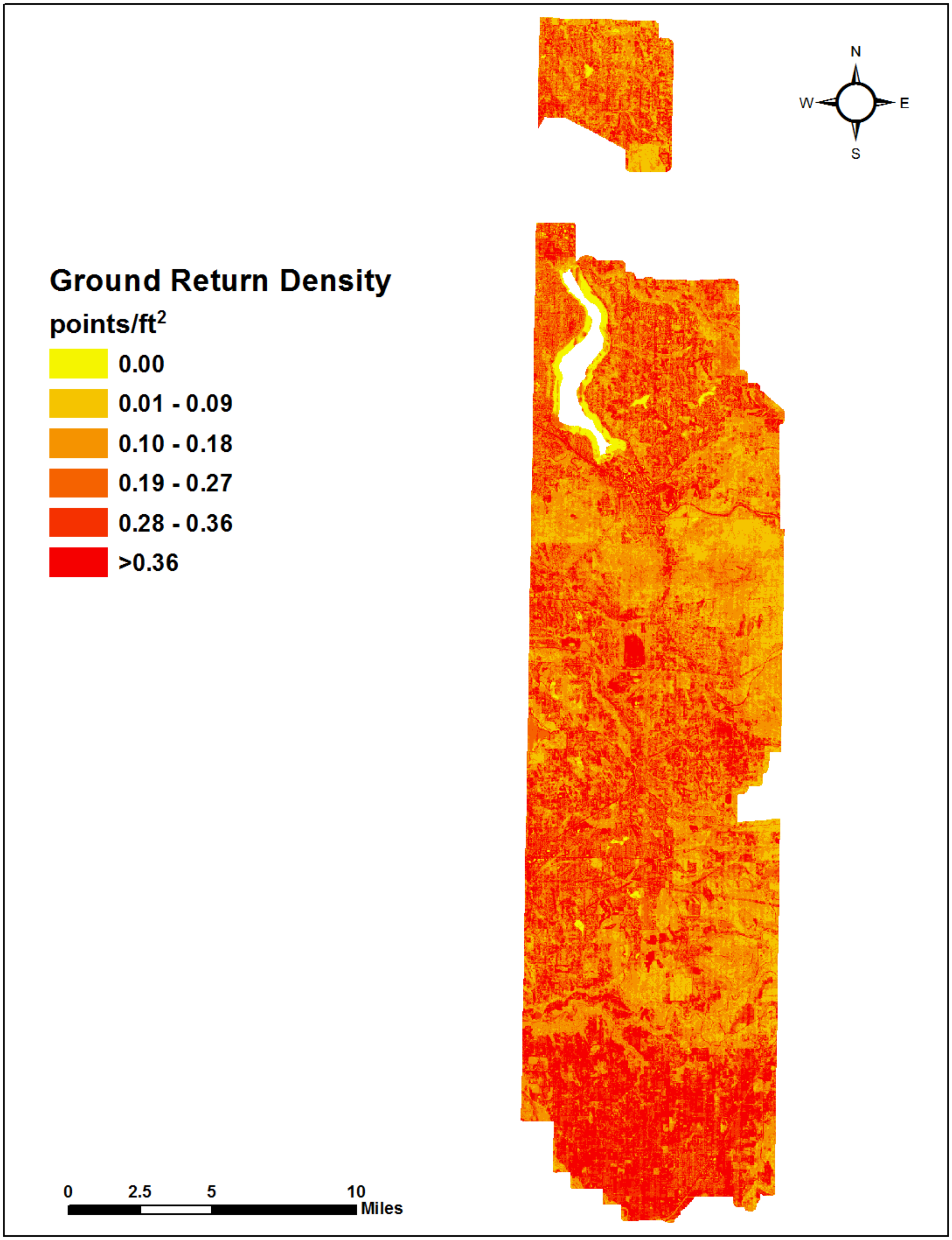


Figure 6: Ground density map for the King County Delivery 3 sites (100 ft x 100 ft cells)

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 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 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 10. The absolute accuracy statistics for the King County Delivery 1 & 2 project areas are documented in Appendix B (**Error! Reference source not found.**).

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 King County Delivery 3 survey area, 35 quality assurance points were withheld in total resulting in a non-vegetated vertical accuracy of 0.154 feet (0.047 meters) (Figure 7).

QSI also assessed absolute accuracy using 673 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 10 and Figure 8.

Table 10: Delivery 3 absolute accuracy results

Delivery 3 Absolute Accuracy		
	Quality Assurance Points (NVA)	**Ground Control Points**
Sample	35 points	673 points
NVA (1.96*RMSE)	0.154 ft 0.047 m	0.162 ft 0.049 m
Average	-0.030 ft -0.009 m	-0.043 ft -0.013 m
Median	-0.036 ft -0.011 m	-0.043 ft -0.013 m
RMSE	0.079 ft 0.024 m	0.083 ft 0.025 m
Standard Deviation (1σ)	0.074 ft 0.022 m	0.071 ft 0.022 m

[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.

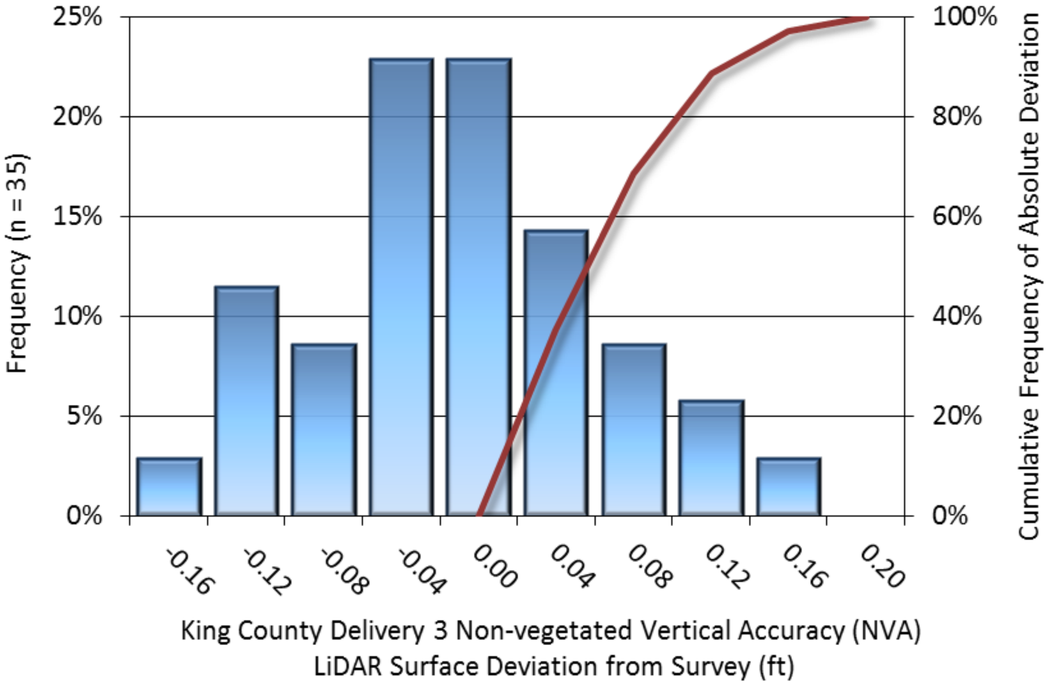


Figure 7: Frequency histogram for LiDAR surface deviation from quality assurance point values

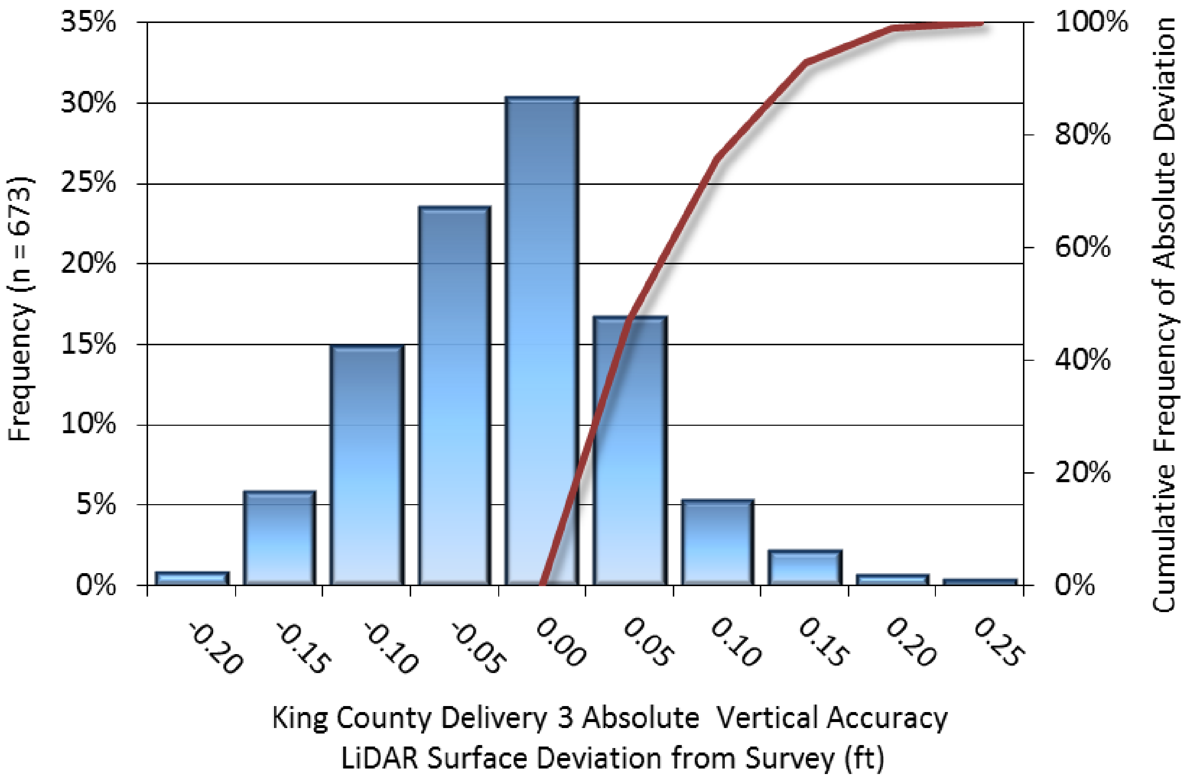


Figure 8: Frequency histogram for LiDAR surface deviation from ground control point values

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 King County Delivery 3 LiDAR project area is 0.114 feet (0.035 meters) (Table 11, Figure 9). The relative vertical accuracy statistics for the King County Delivery 1 & 2 areas are documented in Appendix B (**Error! Reference source not found.**).

Table 11: Delivery 3 relative accuracy results

Delivery 3 Relative Accuracy	
Sample	104 surfaces
Average	0.114 ft 0.035 m
Median	0.113 ft 0.035 m
RMSE	0.124 ft 0.038 m
Standard Deviation (1σ)	0.025 ft 0.008 m
1.96σ	0.048 ft 0.015 m

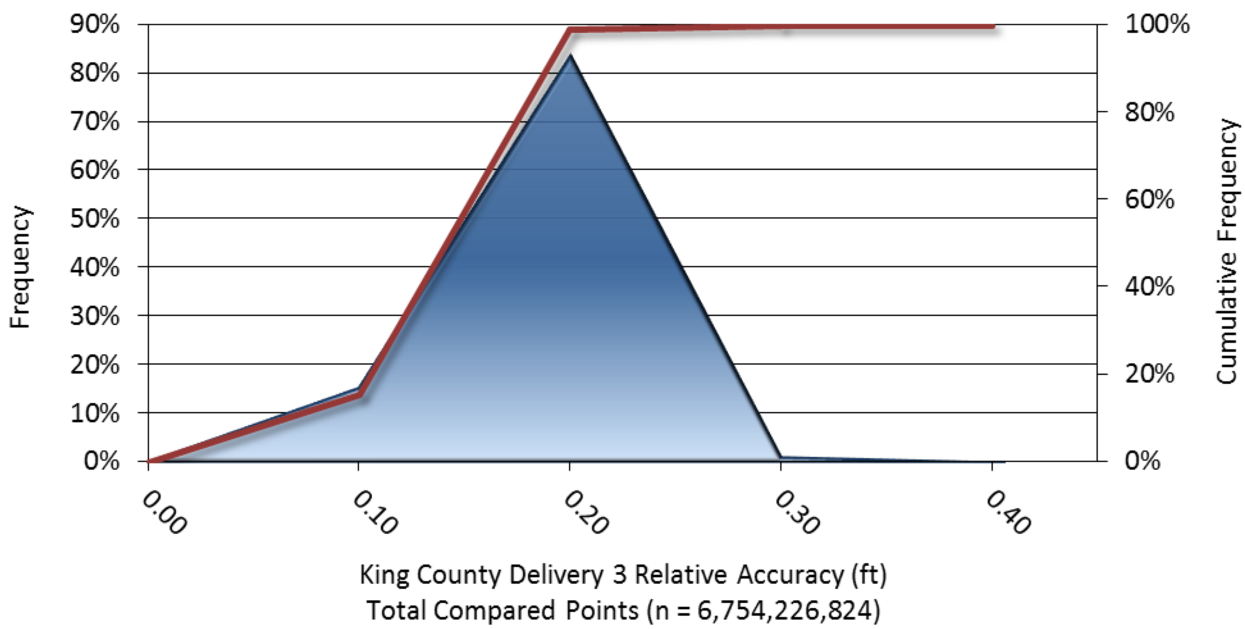


Figure 9: Frequency plot for the PSLC King County LiDAR project Delivery 3 area relative vertical accuracy between flight lines

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 $\pm 15^{o}$ 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.

LiDAR First Return and Ground Classified Density Results

Table 12: King County Delivery 1 & 2 average LiDAR point densities

Classification	Point Density	
	Delivery 1	Delivery 2
First-Return	1.07 points/ft^2 11.51 points/m^2	1.13 points/ft^2 12.20 points/m^2
Ground Classified	0.24 points/ft^2 2.61 points/m^2	0.24 points/ft^2 2.58 points/m^2

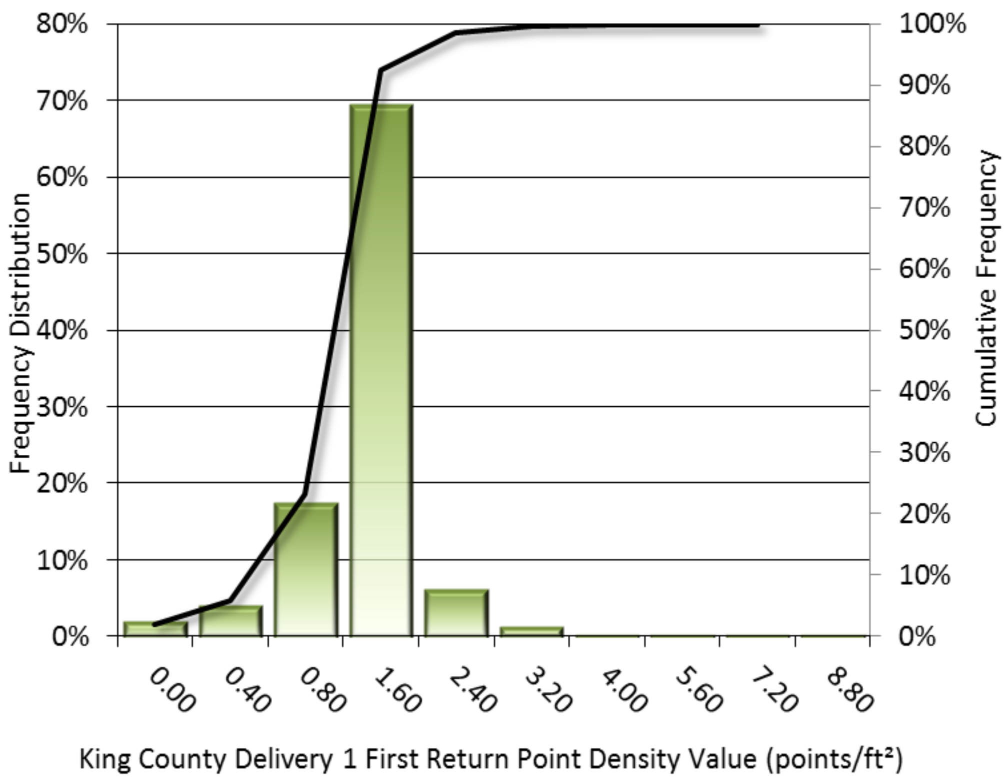


Figure 10: Frequency distribution of Delivery 1 first return point density values per 100 ft x 100 ft cell

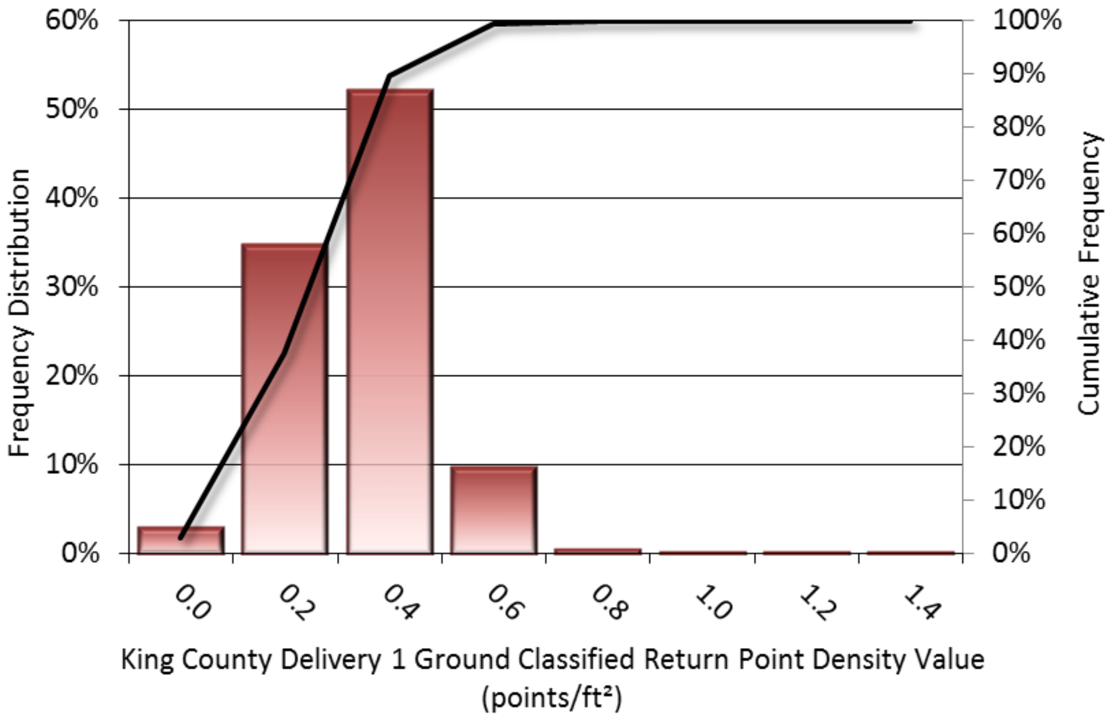


Figure 11: Frequency distribution of Delivery 1 ground classified point density values per 100 ft x 100 ft cell

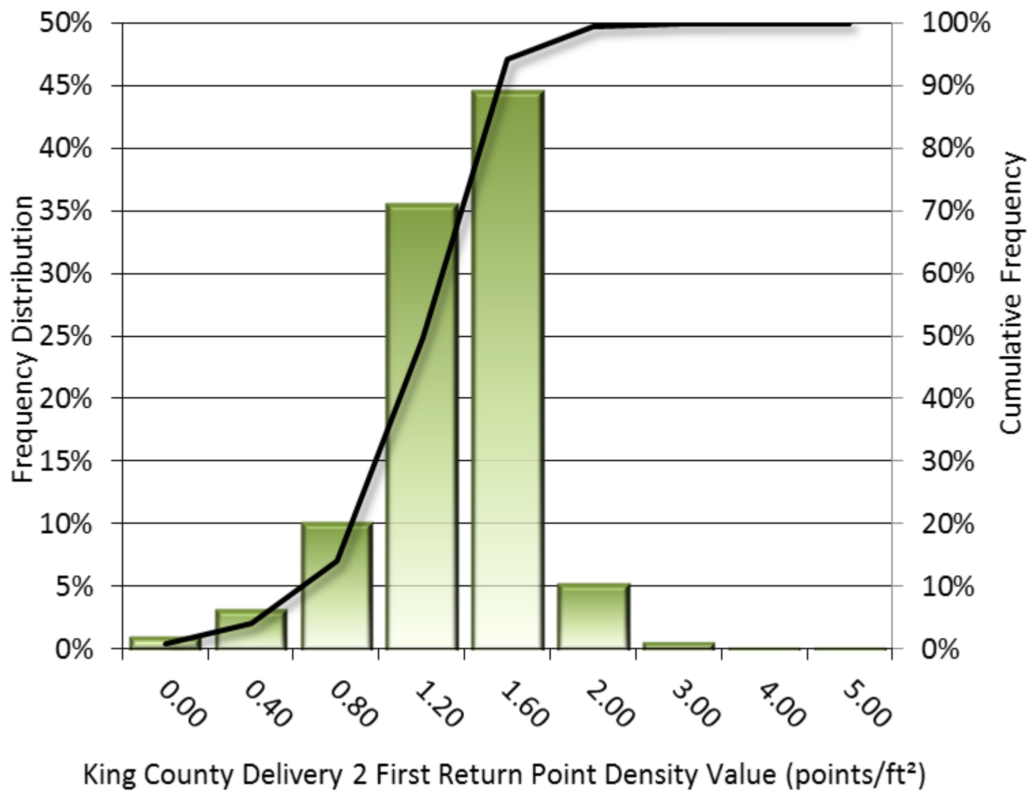


Figure 12: Frequency distribution of Delivery 2 first return point density values per 100 ft x 100 ft cell

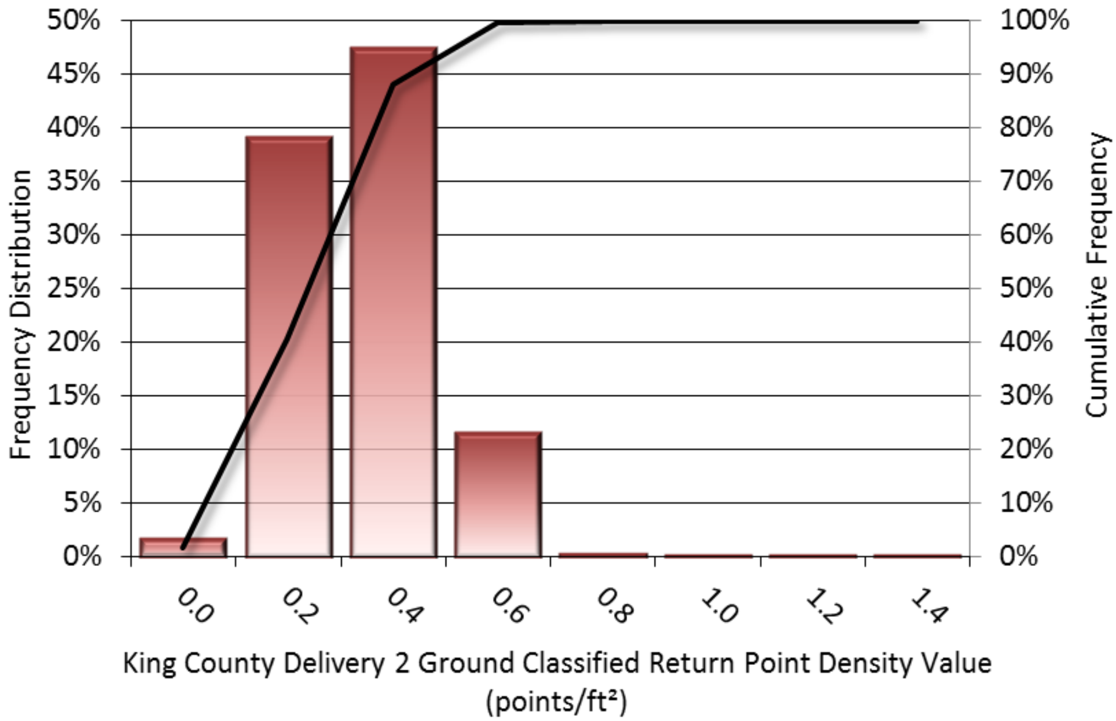


Figure 13: Frequency distribution of Delivery 2 ground classified point density values per 100 ft x 100 ft cell

LiDAR Absolute Accuracy Results

Table 13: Delivery 1 & 2 Absolute Accuracies

Delivery 1 & 2 Absolute Accuracies				
	Delivery 1 Quality Assurance Points (NVA)	**Delivery 2 Quality Assurance Points (NVA)**	**Delivery 1 Ground Control Points**	**Delivery 2 Ground Control Points**
Sample	20 points	43 points	379 points	784 points
NVA (1.96*RMSE)	0.172 ft 0.052 m	0.260 ft 0.079 m	0.199 ft 0.061 m	0.258 ft 0.079 m
Average	-0.030 ft -0.009 m	-0.089 ft -0.027 m	-0.055 ft -0.017 m	-0.071 ft -0.022 m
Median	-0.015 ft -0.004 m	-0.075 ft -0.023 m	-0.064 ft -0.020 m	-0.060 ft -0.018 m
RMSE	0.088 ft 0.027 m	0.133 ft 0.040 m	0.102 ft 0.031 m	0.132 ft 0.040 m
Standard Deviation (1σ)	0.166 ft 0.051 m	0.100 ft 0.030 m	0.168 ft 0.051 m	0.111 ft 0.034 m

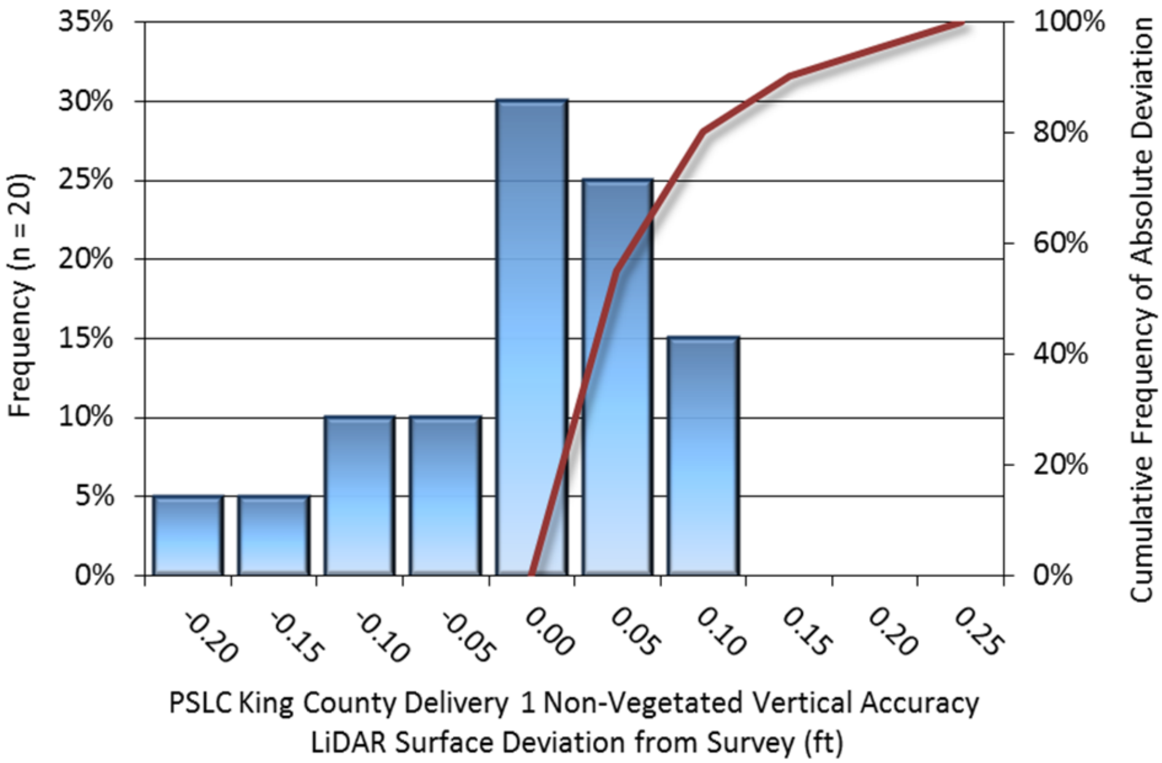


Figure 14: Frequency histogram for LiDAR surface deviation from Delivery 1 quality assurance point values

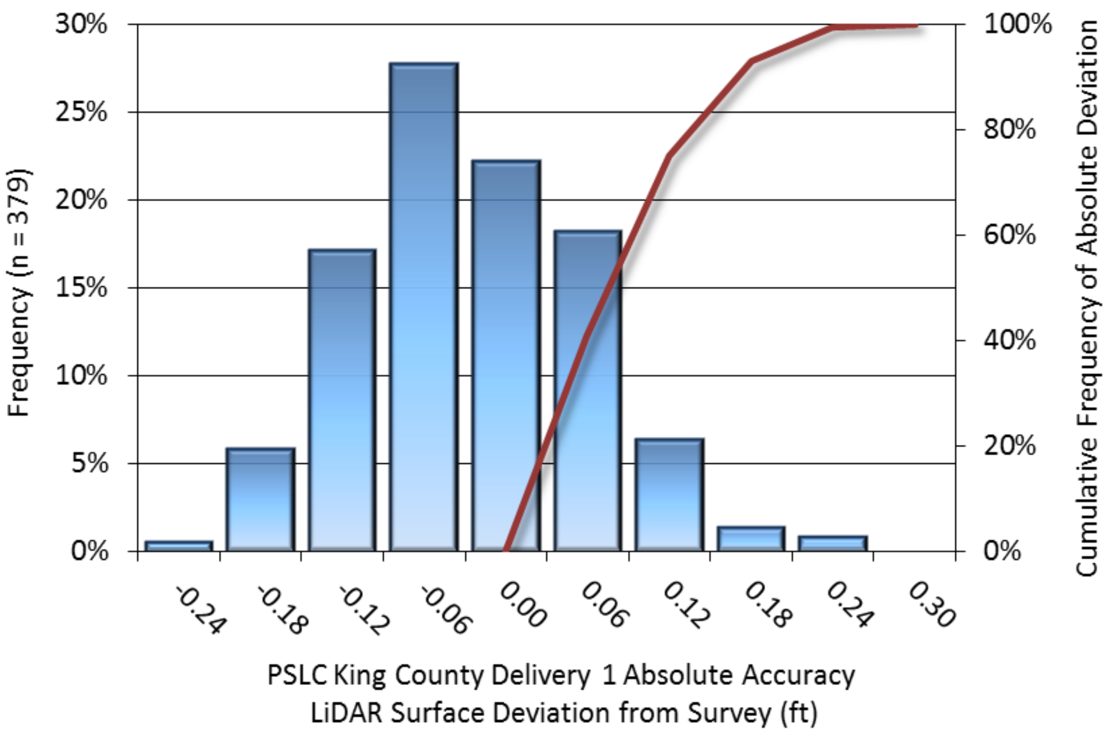


Figure 15: Frequency histogram for LiDAR surface deviation from Delivery 1 ground control point values

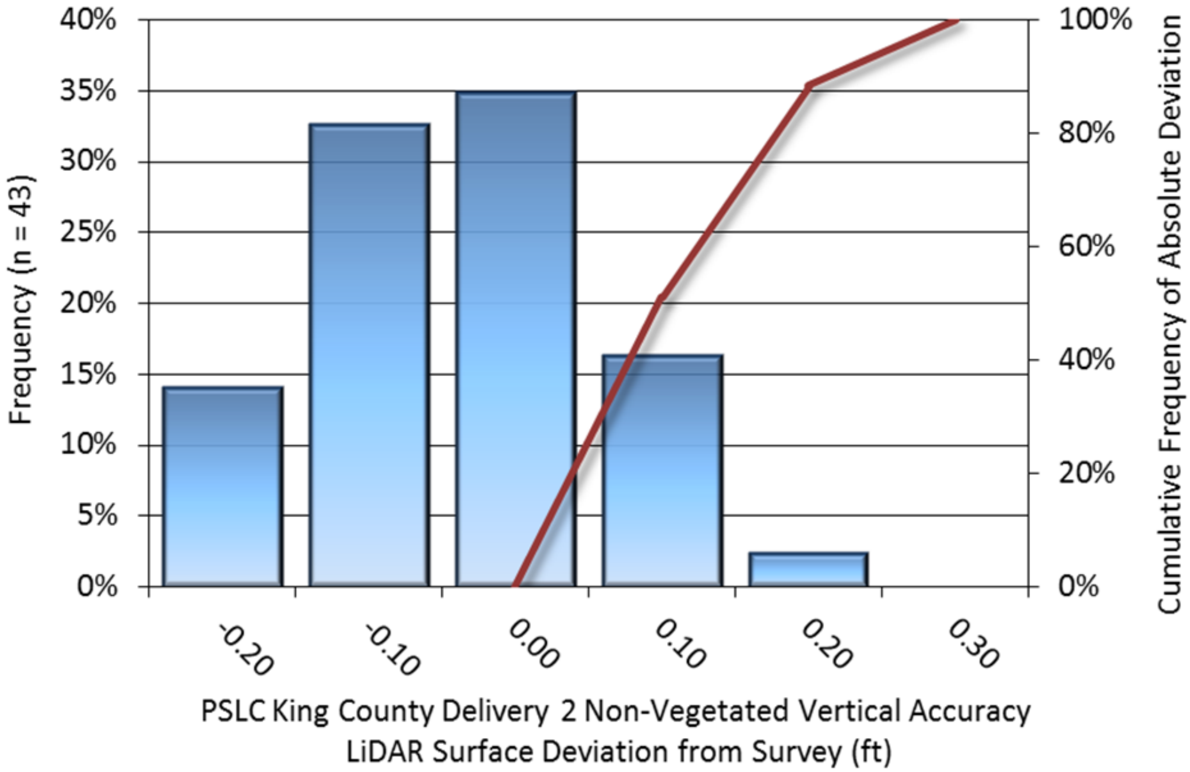


Figure 16: Frequency histogram for LiDAR surface deviation from Delivery 2 quality assurance point values

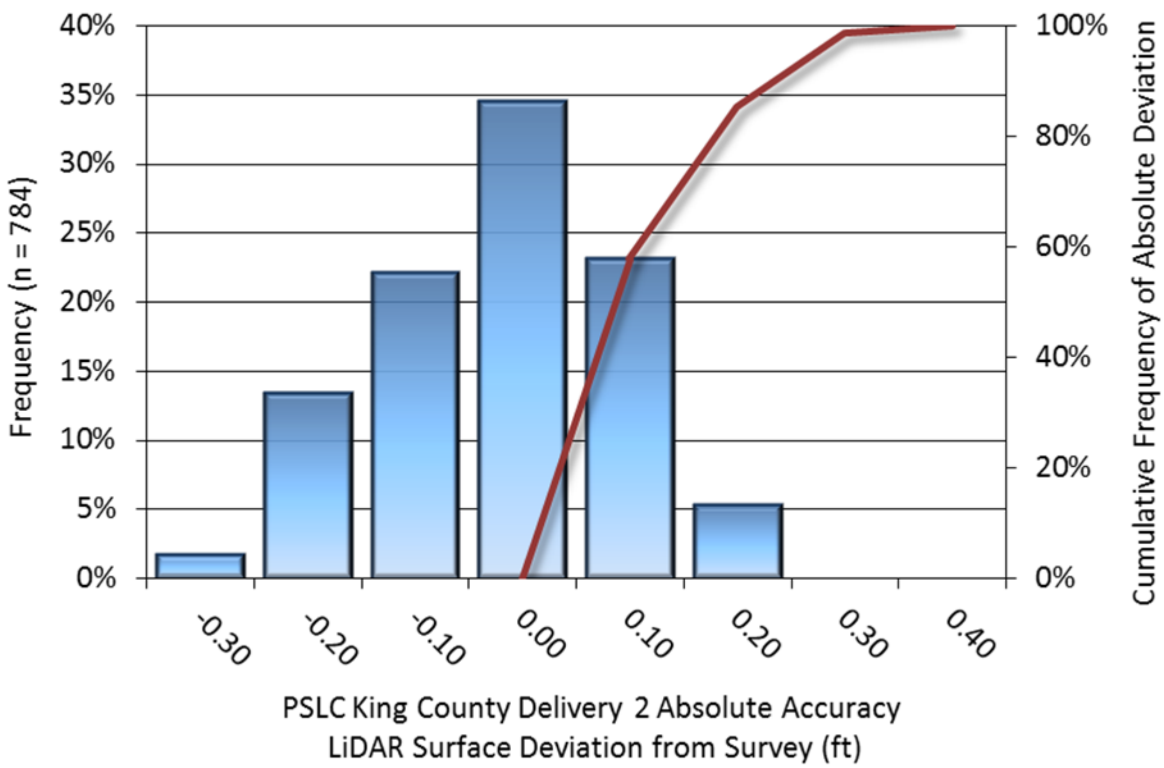


Figure 17: Frequency histogram for LiDAR surface deviation from Delivery 2 ground control point values

LiDAR Relative Vertical Accuracy Results

Table 14: Delivery 1 & 2 Relative Accuracy Results

Delivery 1 & 2 Relative Accuracies		
	Delivery 1	**Delivery 2**
Sample	146 surfaces	113 surfaces
Average	0.103 ft 0.031 m	0.104 ft 0.032 m
Median	0.102 ft 0.031 m	0.102 ft 0.031 m
RMSE	0.113 ft 0.035 m	0.113 ft 0.034 m
Standard Deviation (1σ)	0.029 ft 0.009 m	0.028 ft 0.009 m
1.96σ	0.058 ft 0.018 m	0.055 ft 0.017 m

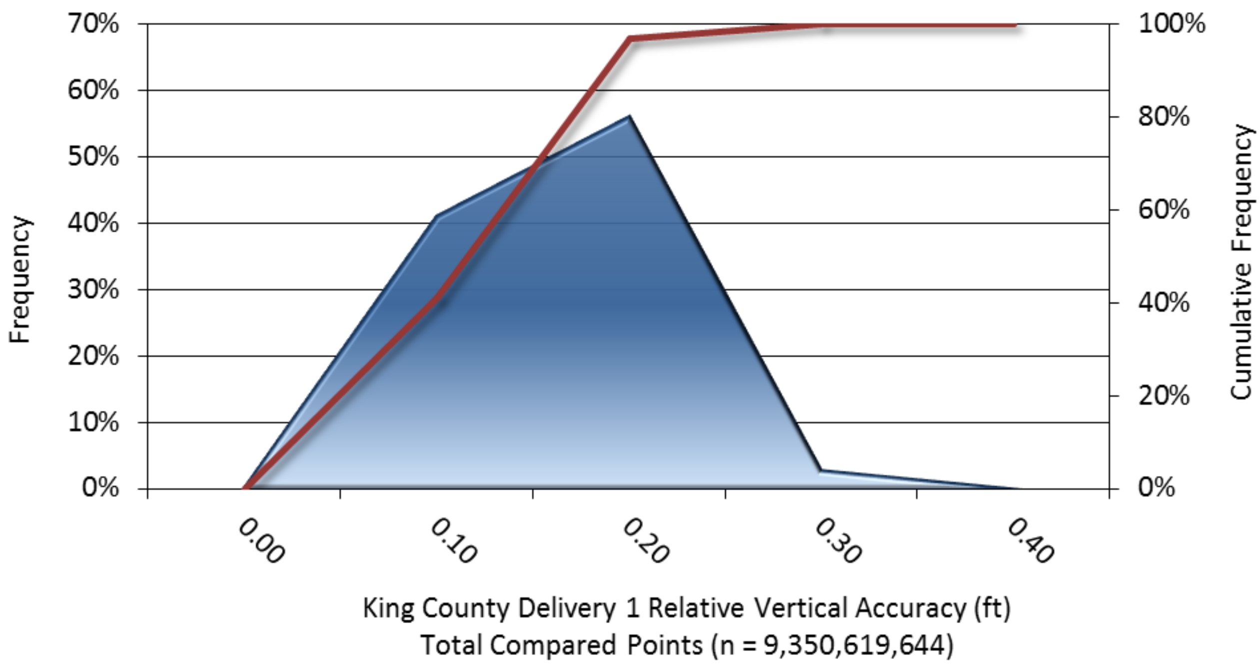


Figure 18: Frequency plot for the PSLC King County LiDAR project Delivery 1 area relative vertical accuracy between flight lines

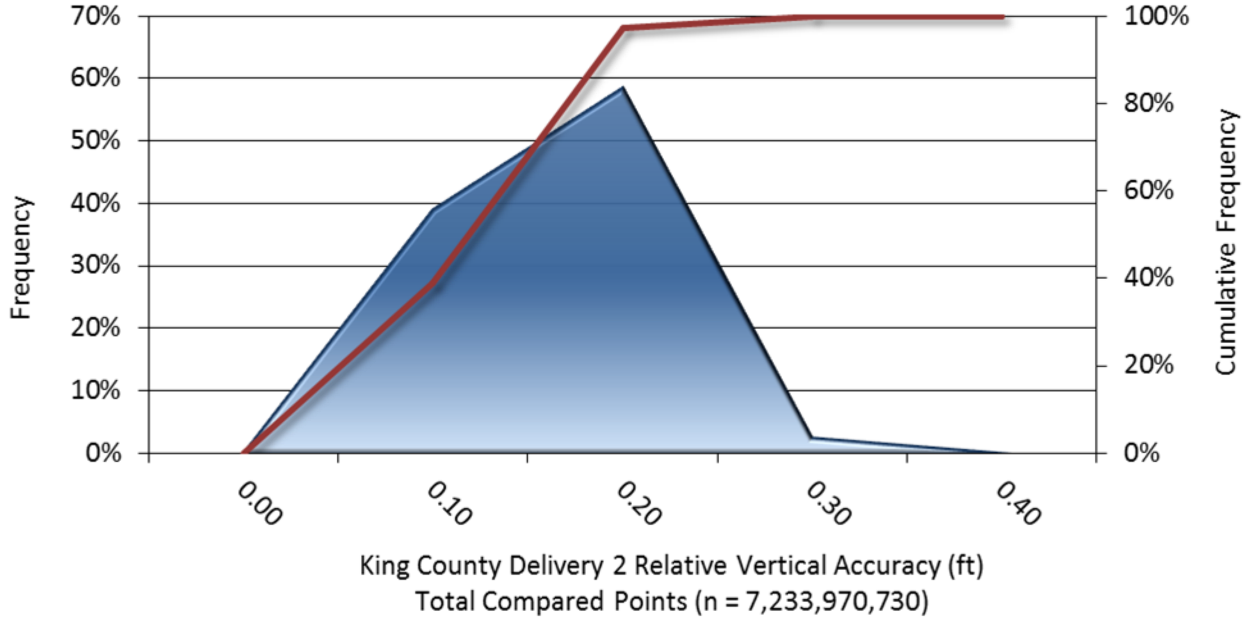


Figure 19: Frequency plot for the PLSC King County project Delivery 2 area relative vertical accuracy between flight lines