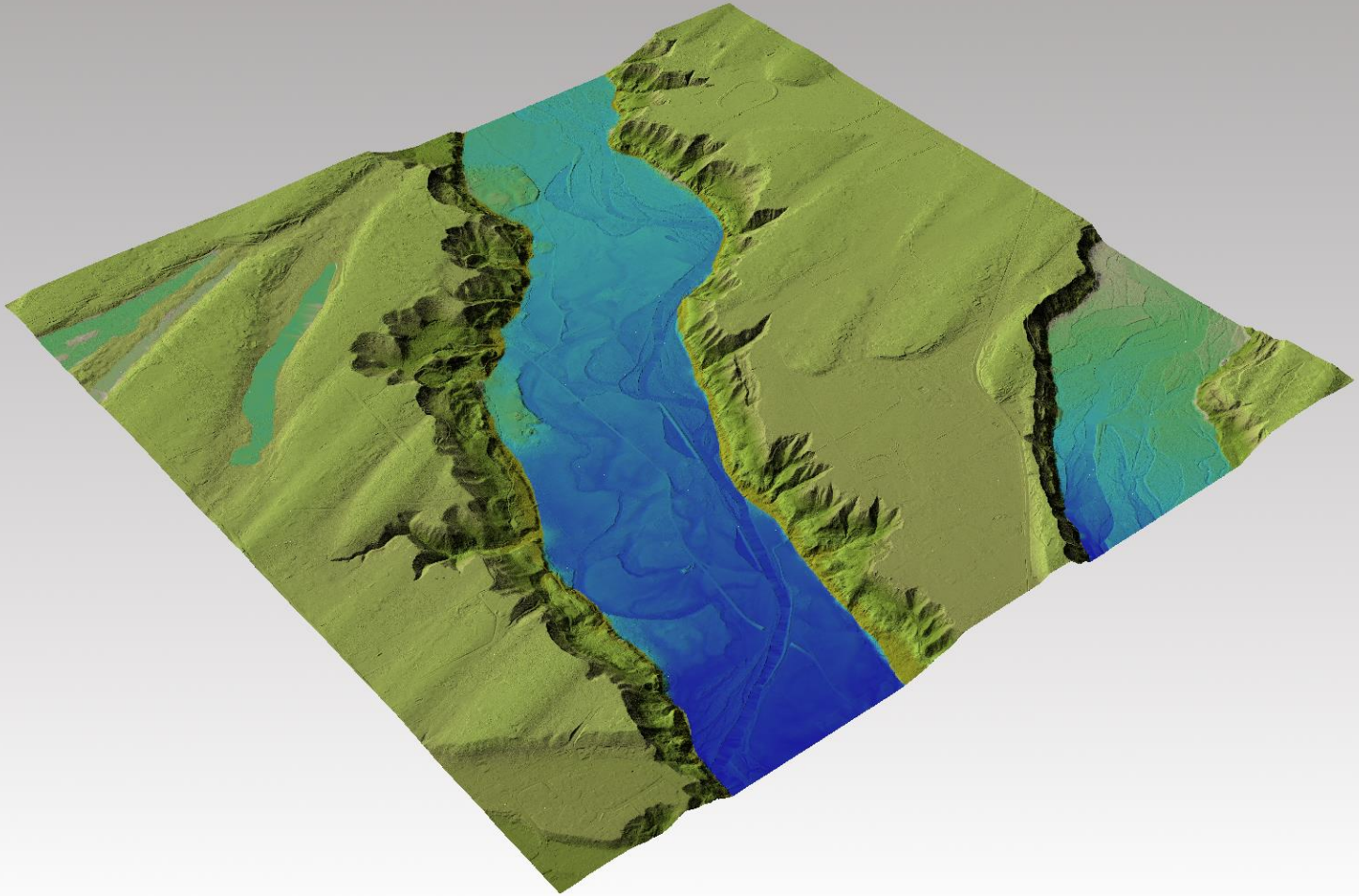


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USGS 3DEP King County, Washington Delivery 1 Lidar

Technical Data Report

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Cover Photo: A view looking southeast over a stretch of the Green River within the USGS 3DEP King County, Washington Delivery 1 area of interest. The image was created from the lidar bare earth model colored by elevation.

INTRODUCTION

This lidar point cloud image shows a view of the Space Needle and surrounding downtown cityscape of Seattle in the USGS 3DEP King County, Washington Delivery 1 site. Points in this image are colored by intensity. View is to the southeast.



In March 2021, NV5 Geospatial (NV5) was contracted by United States Geological Survey (USGS) to collect Quality Level 1 Light Detection and Ranging (lidar) data in the spring and summer of 2021 for the USGS 3DEP King County, Washington Delivery 1 site. Data were collected to aid USGS in assessing the topographic and geophysical properties of the study area to support the Washington DNR (and their local partners), U.S. Forest Service, and the USGS 3DEP.

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 USGS 3DEP King County, Washington Delivery 1 site

Project Site	Delivery Number	Delivery Acres	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
USGS 3DEP King County, Washington Delivery 1	1 of 2	568,991	1,523,388	1,537,029	04/01/2021 – 04/15/2021 & 08/24/2021	QL1 - lidar

Deliverable Products

Table 2: Products delivered to USGS for the USGS 3DEP King County, Washington Delivery 1 Site

USGS 3DEP King County, Washington Lidar Products Projection: Washington State Plane North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID18) Units: US Survey Feet	
Points	LAS v 1.4 <ul style="list-style-type: none"> All Classified Returns
Rasters	1.5 Foot GeoTIFFs <ul style="list-style-type: none"> Hydroflattened Bare Earth Digital Elevation Models (DEM) Maximum Surface Height Rasters (DSM) Intensity Images Swath Separation Images
Vectors	Index Shapefiles (*.shp) <ul style="list-style-type: none"> Delivery 1 Project Boundary Delivery 2 Project Boundary Delivery 1 Tile Index Delivery 2 Tile Index File Geodatabase (*.gdb) <ul style="list-style-type: none"> 3D Water’s Edge and Bridge Breaklines Flightline Index Flightline Swaths Ground Control Points Ground Check Points Ground Control Base Stations Ground Survey Photos (*.jpg) Ground Survey Points (*.csv)

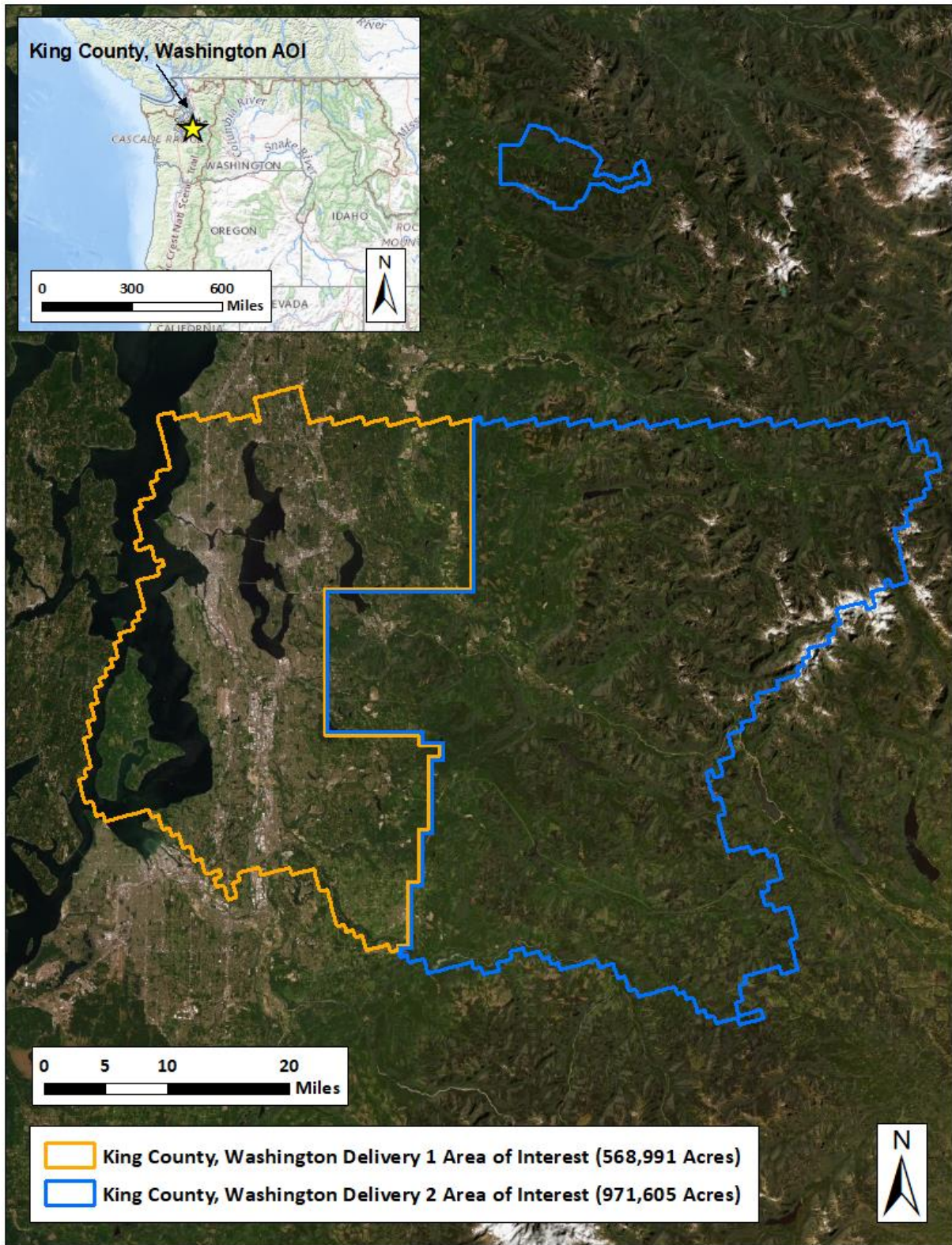


Figure 1: Location map of the USGS 3DEP King County, Washington Delivery 1 site

NV5 Geospatial's ground acquisition equipment set up for the collection of vegetated vertical accuracy check point collection in the USGS 3DEP King County, Washington Delivery 1 Lidar study area.



Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the USGS 3DEP King County, Washington Delivery 1 lidar study area at the target point density of ≥ 8.0 points/m² (0.74 points/ft²). 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. Acquisition was to occur during leaf-off season while ground conditions were free of snow and smoke. The project area was split into two delivery areas due to the presence of snow in the Cascade Mountains. Delivery 1 was collected in the spring of 2021 and encompasses the western half of the project area, including Puget Sound and lowland areas without snow. Delivery 2 covers the eastern half of the project area, containing the Northern Cascades. Acquisition of the Delivery 2 area occurred during the summer of 2021 in order to minimize the presence of snow cover. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access, tribal land access, and potential air space restrictions were reviewed. Figure 2 displays acquisition mission flightlines for the USGS 3DEP King County, Washington Delivery 1 dataset.

Airborne Lidar Survey

The lidar survey was accomplished using a Riegl VQ-1560ii system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥ 8 pulses/m² over the USGS 3DEP King County, Washington Delivery 1 project area. The Riegl VQ-1560ii laser system can record unlimited range measurements (returns) per pulse, however a maximum of 15 returns can be stored due to LAS v1.4 file limitations. 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	04/01/2021 – 04/15/2021 & 08/24/2021
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ-1560ii
Maximum Returns	15
Resolution/Density	Average 8 pulses/m ²
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	2078 m
Survey speed	145 knots
Field of View	58.5°
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	639 kHz
Pulse Length	3.0 ns
Laser Pulse Footprint Diameter	52 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.25 mrad
Swath Width	2327 m
Swath Overlap	55%
Intensity	16-bit
Accuracy	RMSE _z (Non-Vegetated) ≤ 10 cm
	NVA (95% Confidence Level) ≤ 19.6 cm
	VVA (95 th Percentile) ≤ 30 cm



Riegl VQ-1560ii lidar sensor

All areas were surveyed with an opposing flight line side-lap of $\geq 50\%$ ($\geq 100\%$ 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.

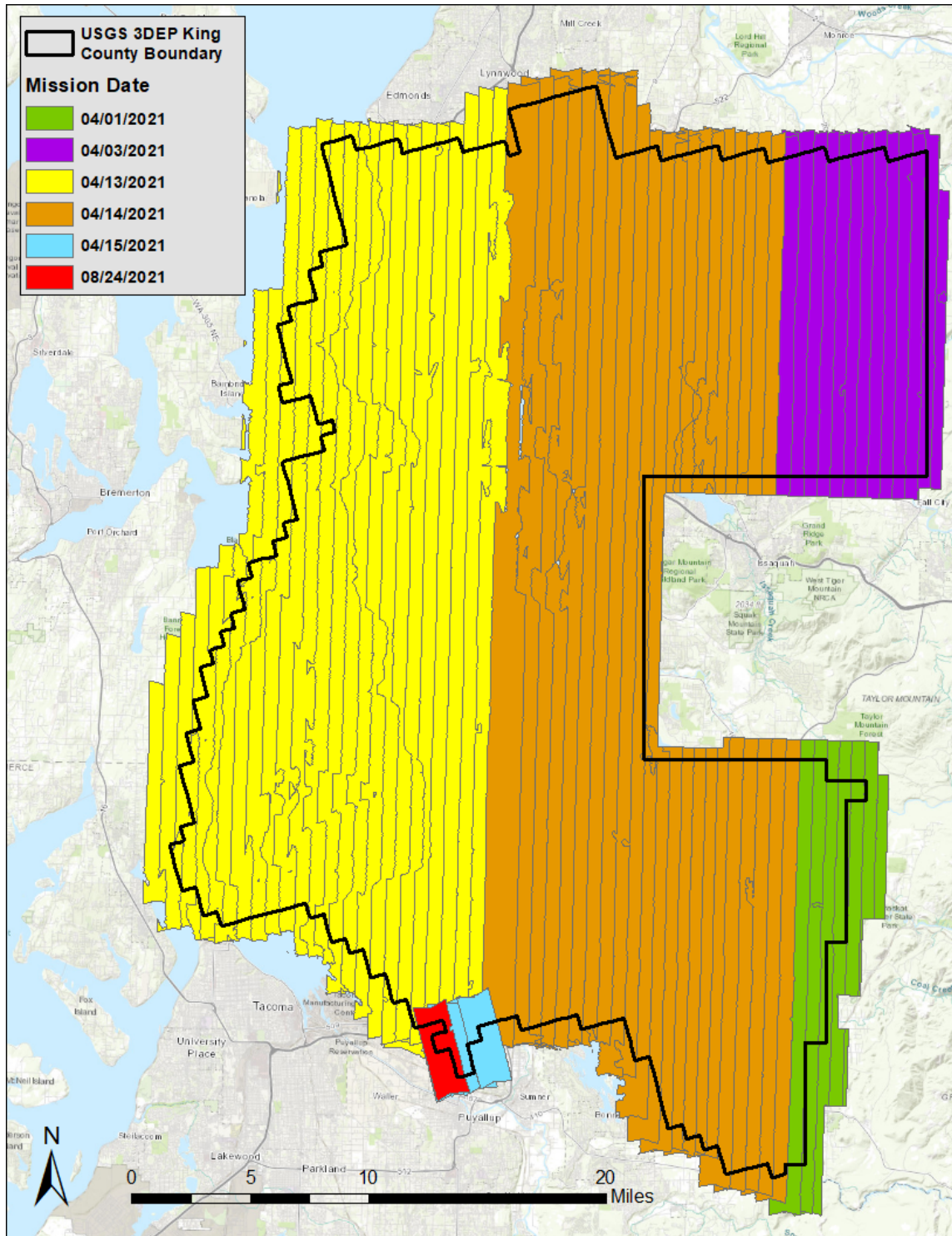


Figure 2: USGS 3DEP King County, Washington Delivery 1 Mission Flightline Map

Ground Survey

Ground control surveys including base stations 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.

Base Stations

Base stations were utilized for collection of ground survey points using real time kinematic (RTK), fast static (FS), and total station (TS) survey techniques.

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. NV5 Geospatial utilized fourteen permanent real-time network (RTN) base stations from the Washington State Reference Network, one permanent RTN base station from the Hexagon SmartNet network, and one previously established NV5 ground survey monument for the USGS 3DEP King County, Washington Delivery 1 Lidar project (Table 4, Figure 3). NV5 Geospatial's professional land surveyor, Evon Silvia (WAPLS#53957) oversaw and certified the ground survey.

Table 4: Base station positions for the USGS 3DEP King County, Washington Delivery 1 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Owner / Type	Latitude	Longitude	Ellipsoid (meters)
CBLV	WSRN RTN	47° 36' 51.07453"	-122° 11' 29.27092"	46.146
CLEM	WSRN RTN	47° 12' 17.72020"	-120° 58' 11.21394"	634.011
CSKI	WSRN RTN	47° 22' 50.04263"	-122° 14' 08.82186"	10.610
CULM	WSRN RTN	47° 58' 31.47277"	-121° 41' 12.64379"	437.569
ENUM	WSRN RTN	47° 12' 22.32993"	-121° 57' 20.04105"	227.393
HAHD	WSRN RTN	47° 17' 26.86772"	-121° 47' 17.03837"	854.322
LSIG	WSRN RTN	47° 41' 42.70790"	-121° 41' 22.37198"	527.505
NINT	WSRN RTN	47° 29' 42.33613"	-121° 47' 49.44311"	127.616
PFLD	WSRN RTN	47° 53' 54.60954"	-122° 16' 55.79448"	160.628
SAMM	WSRN RTN	47° 32' 23.49238"	-122° 01' 59.35950"	7.474
SMAI	WSRN RTN	47° 31' 24.84355"	-122° 20' 42.14745"	113.784
SNOQ	WSRN RTN	47° 23' 28.69923"	-121° 23' 17.75108"	770.443
SSHO	WSRN RTN	47° 40' 56.26370"	-122° 18' 54.53169"	74.455
TACO	WSRN RTN	47° 13' 43.90770"	-122° 28' 17.36492"	81.449
WASQ	SmartNet RTN	47° 31' 35.91523"	-121° 49' 34.08469"	116.146
KING_COUNTY_01	NV5 Monument	48° 05' 29.36771"	-121° 46' 51.33656"	272.567

NV5 Geospatial utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS¹) 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 USGS 3DEP King County, Washington Delivery 1 Lidar project, the monument coordinates contributed no more than 5.6 cm of positional error to the geolocation of the final ground survey points and lidar, with 95% confidence.

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>

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), fast-static (FS), and total station (TS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK surveys record data while stationary for at least five seconds, calculating the 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. 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. See Table 6 for Trimble unit specifications.

Forested check points are collected using total stations in order to measure positions under dense canopy. Total station backsight and setup points are established using GNSS survey techniques.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 3).






Table 6: NV5 Geospatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R10	Integrated Antenna	TRMR10	Rover
Trimble R10 Model 2	Integrated Antenna	TRMR10-2	Rover
Nikon NPL-322+ 5" P Total Station		n/a	VVA
Trimble M3 Total Station		n/a	VVA

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 7, see Lidar Accuracy Assessments, page 23).

Table 7: Land Cover Types and Descriptions

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

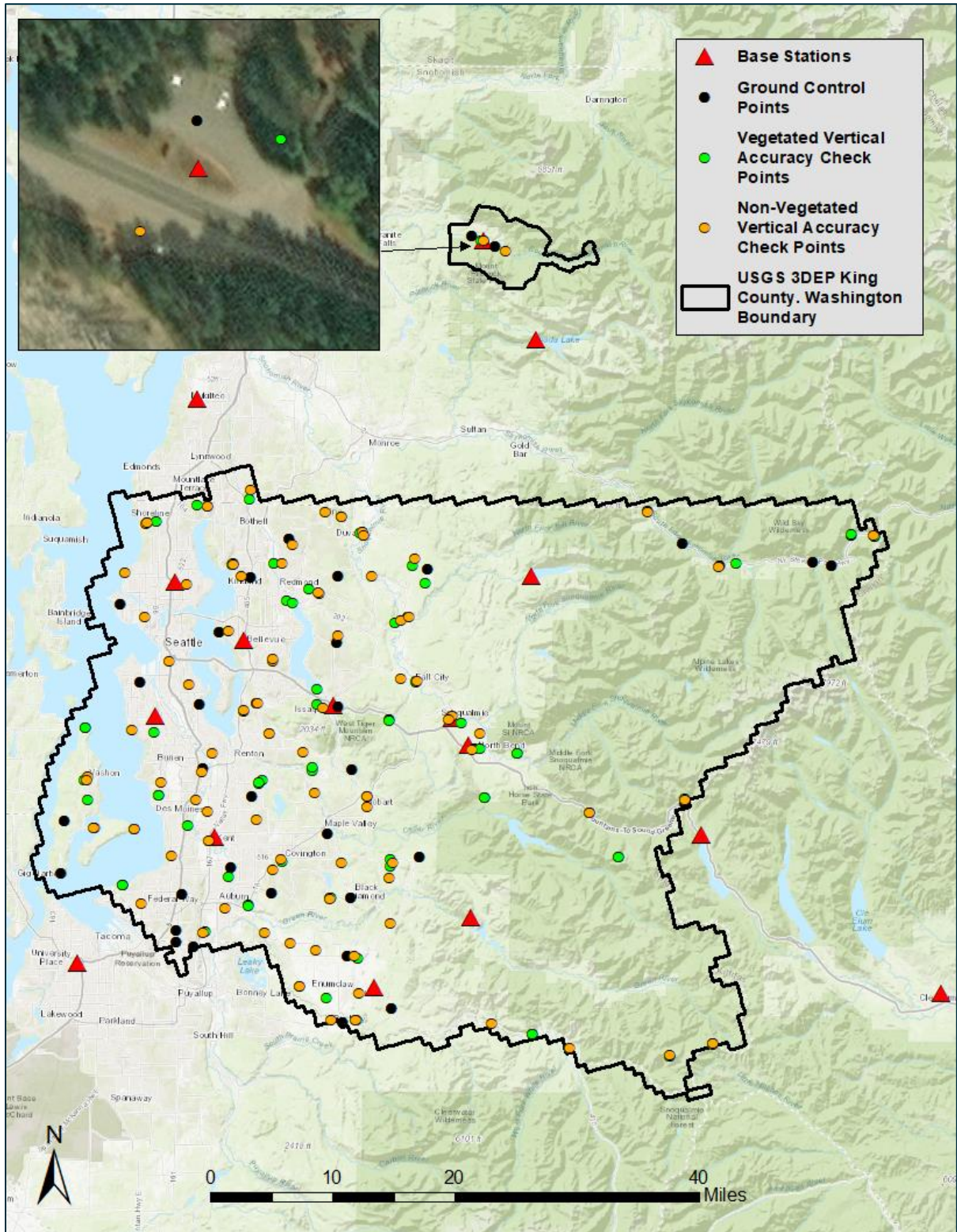
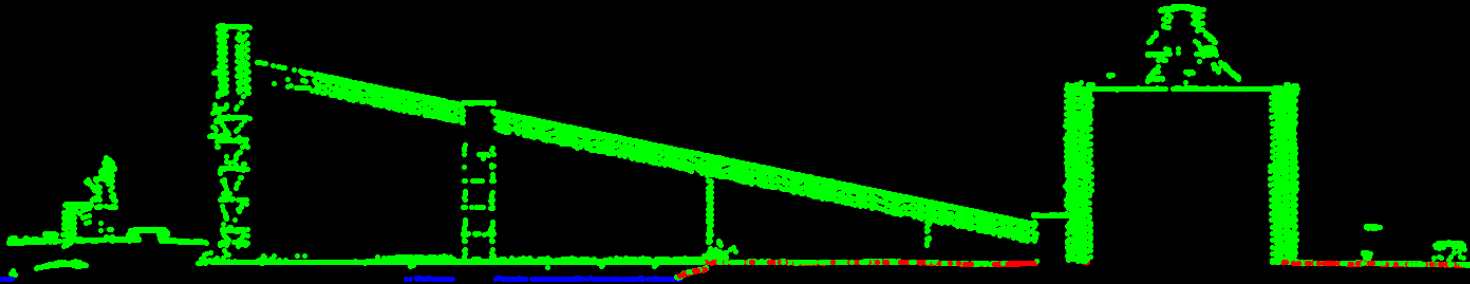


Figure 3: Ground survey location map

PROCESSING

■ Default
■ Ground
■ Water

This 3 foot lidar cross section shows a view of the Elliot Bay loading dock in the USGS 3DEP King County, Washington Delivery 1 dataset. Points in this image are colored by point classification.



Lidar Data

Upon completion of data acquisition, NV5 Geospatial 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 USGS 3DEP King County, Washington Delivery 1 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
1W	Edge Clip/Withheld	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7W	Noise/Withheld	Laser returns that are often artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	Bridge decks
18W	High Noise/Withheld	Laser returns that are often associated with birds, scattering from reflective surfaces.
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation
22	Temporal Exclusion	Laser returns that are determined to be due to temporal differences in flightlines and are excluded

Table 9: Lidar processing workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.3
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	POSPac MMS v.8.3 RiProcess v.1.8.5
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), 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.	Bays-StripAlign v2.19
Import calibrated laser points into manageable blocks for manual editing.	TerraScan v.19.005
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.19.005 TerraModeler v.19.003
Generate bare earth models as triangulated surfaces. Generate maximum surface height models as a surface expression of all classified points. Export all surface models as Cloud Optimized GeoTIFFs at a 1.5 foot pixel resolution.	LAS Product Creator 3.0 (NV5 Geospatial proprietary)
Correct intensity values for variability and export intensity images as Cloud Optimized GeoTIFFs at a 1.5 foot pixel resolution.	Las Monkey 2.6.3SP2 (NV5 Geospatial proprietary) LAS Product Creator 3.0 (NV5 Geospatial proprietary)

Feature Extraction

Hydroflattening and Water's Edge Breaklines

The Puget Sound, White, Green, Sammamish, Cedar, Duwamish, Snoqualmie, and Tolt Rivers along with other water bodies within the USGS 3DEP King County, Washington Delivery 1 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, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. Islands greater than 1 acre are also represented in the water's edge breaklines used for hydroflattening. 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. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 4).

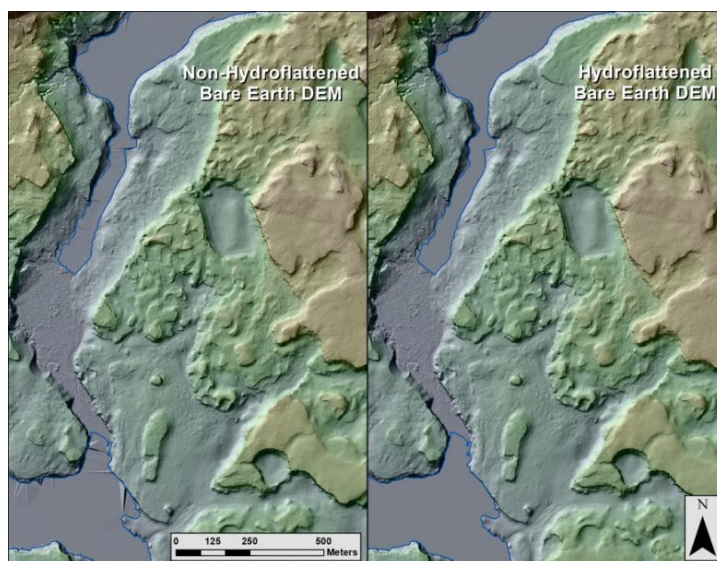
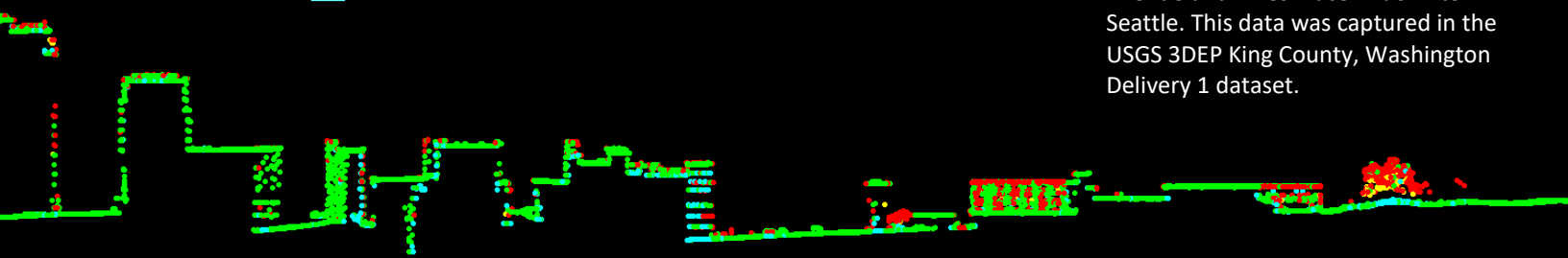


Figure 4: Example of hydroflattening in the USGS 3DEP King County, Washington Delivery 1 Lidar dataset



This 3 foot lidar cross section shows a view colored by point laser echo of ground and city structures along Western Avenue and Pikes Place in downtown Seattle. This data was captured in the USGS 3DEP King County, Washington Delivery 1 dataset.



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m² (0.74 points/ft²). First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified lidar returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of lidar data for the USGS 3DEP King County, Washington Delivery 1 project was 0.91 points/ft² (9.81 points/m²) while the average ground classified density was 0.24 points/ft² (2.61 points/m²) (Table 10). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 5 through Figure 7.

Table 10: Average lidar point densities for the USGS 3DEP King County, Washington Delivery 1 dataset

Classification	Point Density
First-Return	0.91 points/ft ² 9.81 points/m ²
Ground Classified	0.24 points/ft ² 2.61 points/m ²

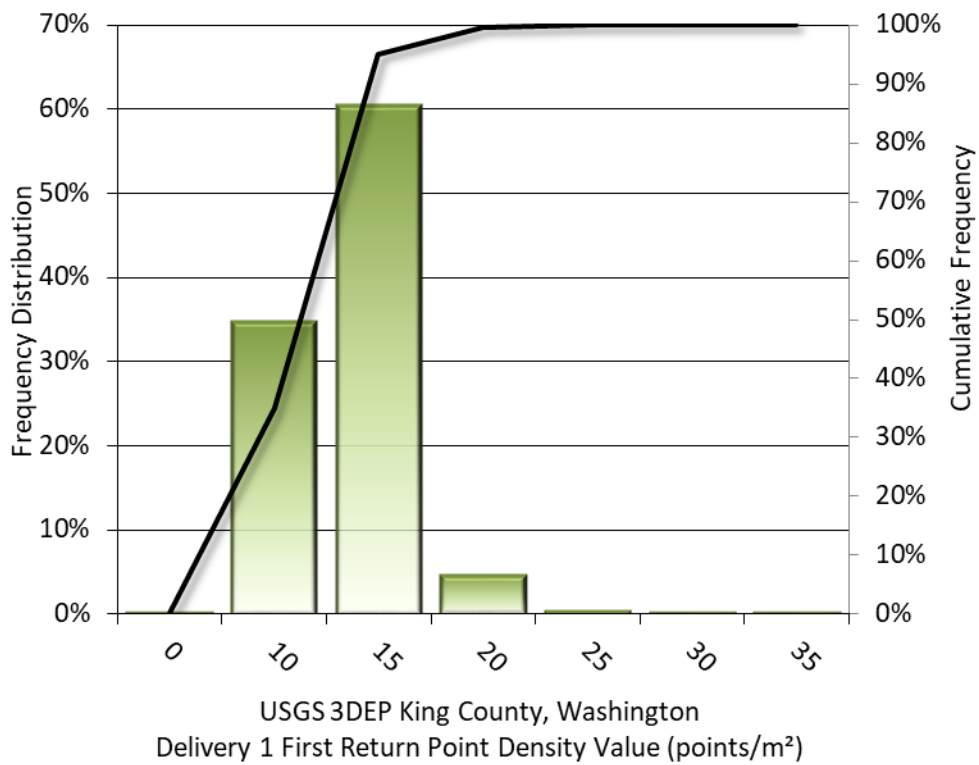


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

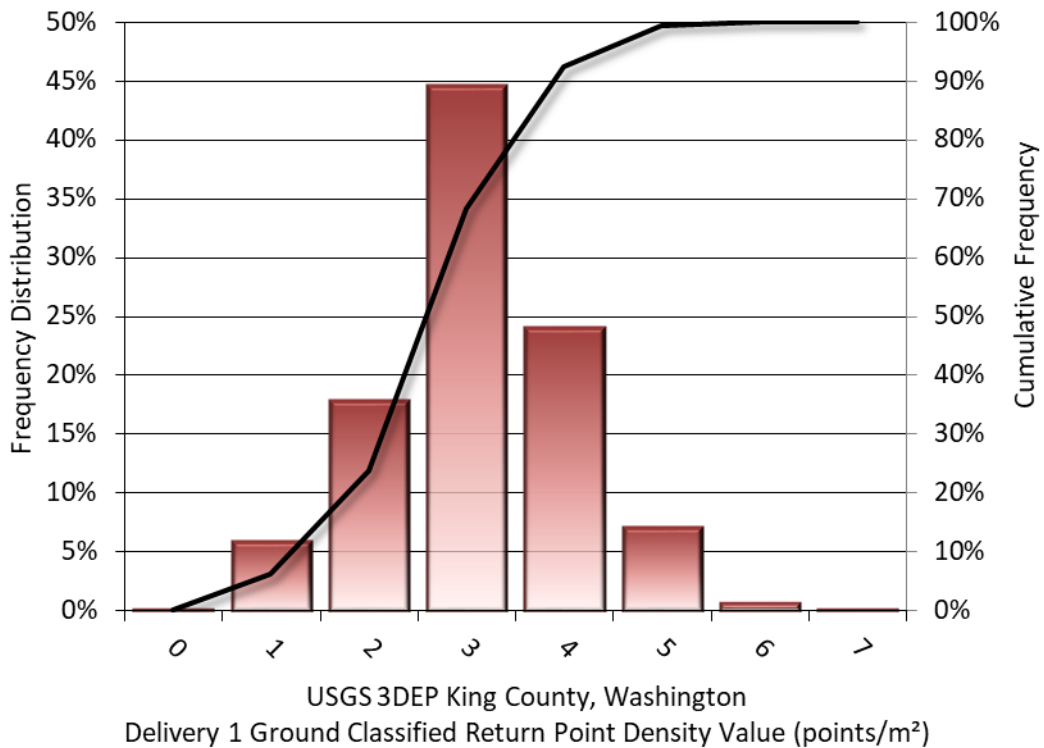


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

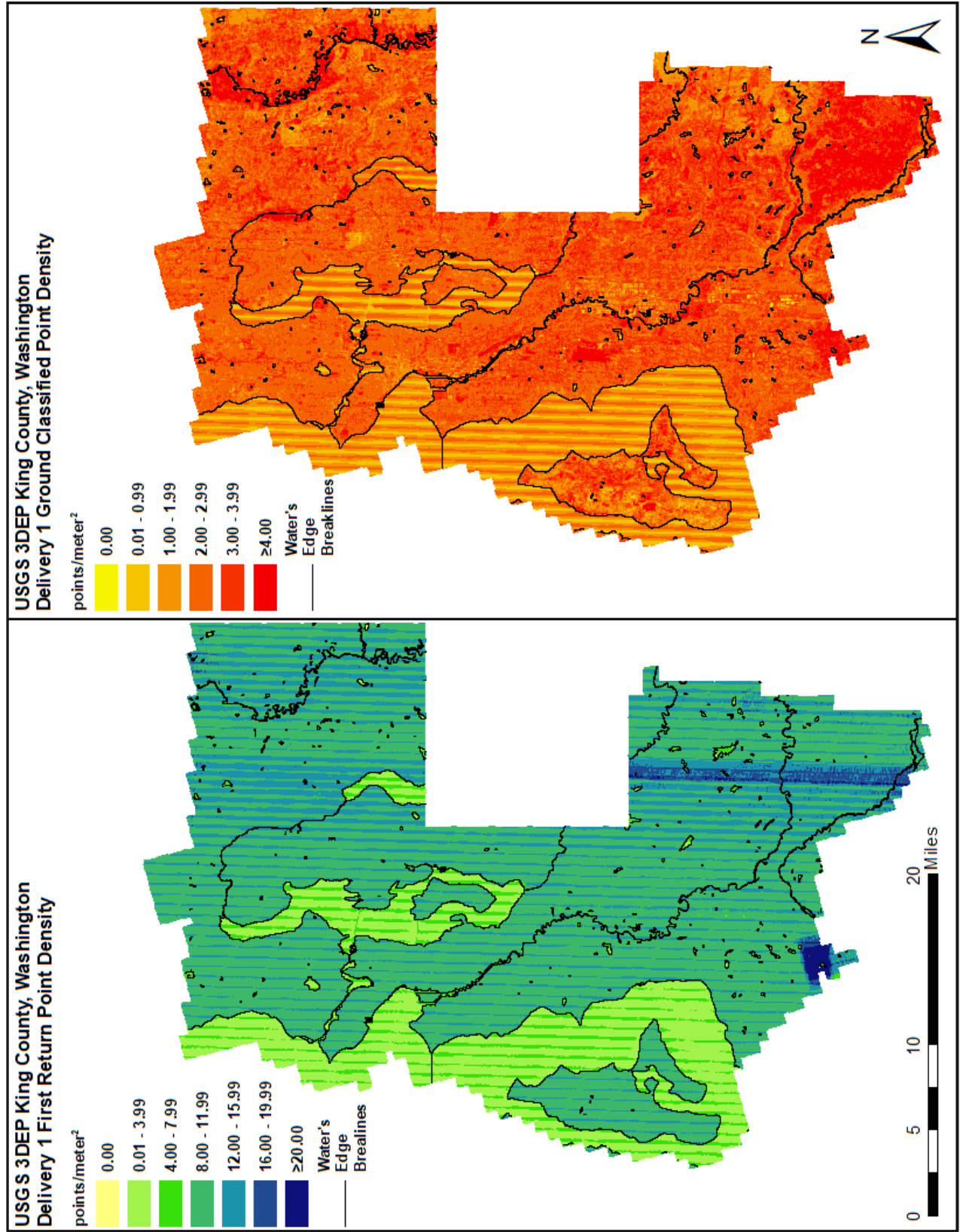


Figure 7: First return and ground-classified point density map for the USGS 3DEP King County, Washington Delivery 1 site (100 m x 100 m cells)

Lidar Accuracy Assessments

The accuracy of the lidar data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy³. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the classified lidar point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of lidar point data in open areas where the lidar system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval ($1.96 * RMSE$), as shown in Table 11.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from 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 USGS 3DEP King County, Washington Delivery 1 survey, 59 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.196 feet (0.060 meters) as compared to classified LAS, and 0.195 feet (0.060 meters) as compared to the bare earth DEM, with 95% confidence (Figure 8, Figure 9).

NV5 Geospatial also assessed absolute accuracy using 34 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 10.

³ Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014.

https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 11: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	59 points	59 points	34 points
95% Confidence (1.96*RMSE)	0.196 ft 0.060 m	0.195 ft 0.060 m	0.172 ft 0.052 m
Average	0.014 ft 0.004 m	0.009 ft 0.003 m	-0.008 ft -0.002 m
Median	0.016 ft 0.005 m	0.003 ft 0.001 m	-0.002 ft 0.000 m
RMSE	0.100 ft 0.031 m	0.100 ft 0.030 m	0.088 ft 0.027 m
Standard Deviation (1σ)	0.100 ft 0.030 m	0.100 ft 0.031 m	0.089 ft 0.027 m

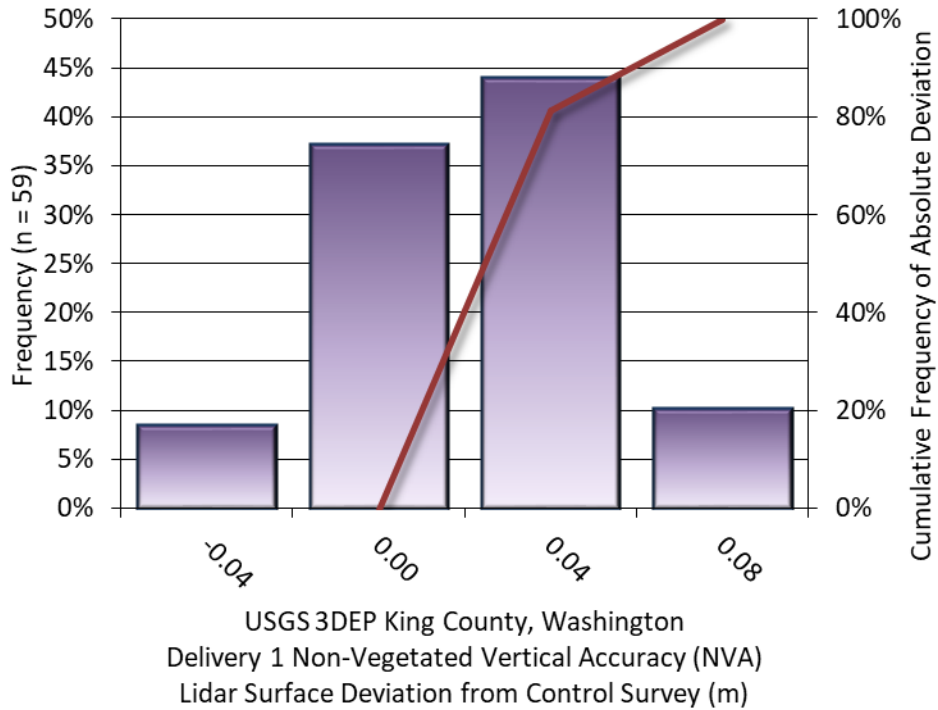


Figure 8: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA)

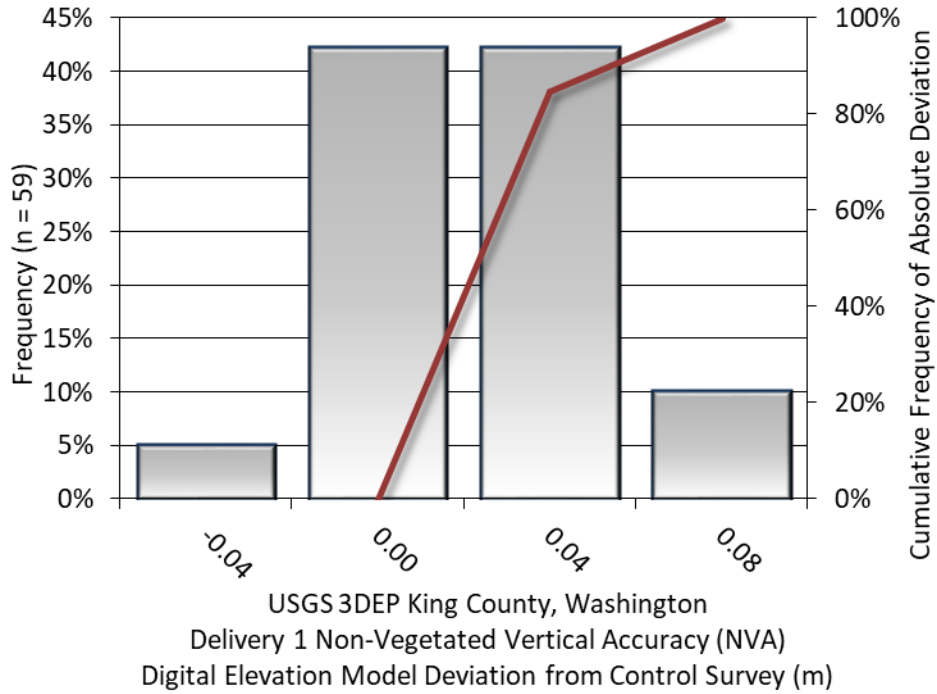


Figure 9: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA)

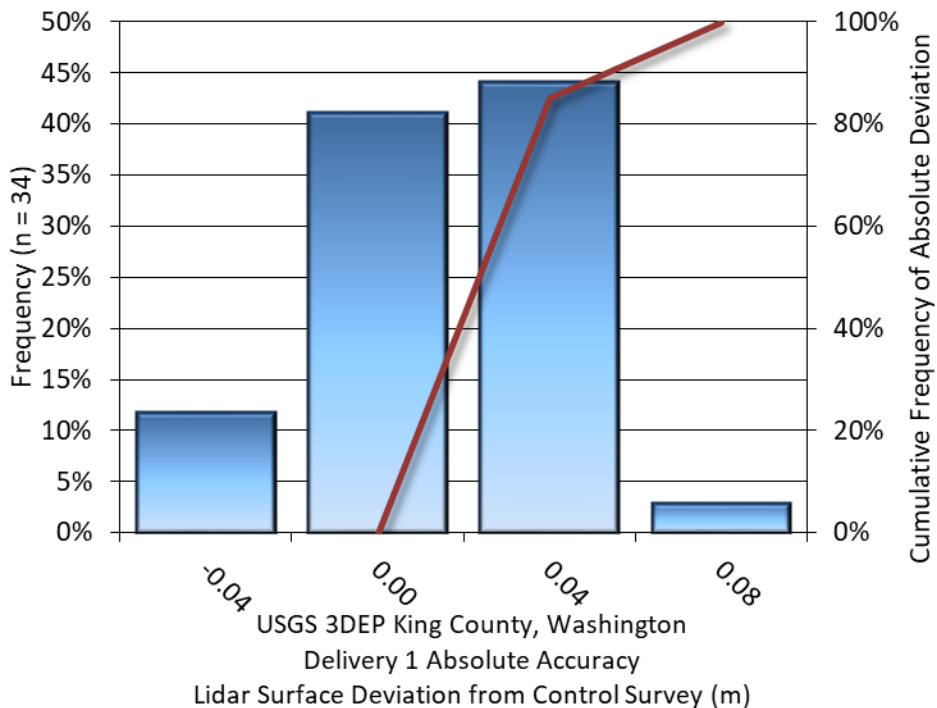


Figure 10: Frequency histogram the for lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracies

NV5 Geospatial also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified lidar points. For the USGS 3DEP King County, Washington Delivery 1 survey, 37 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.826 feet (0.252 meters) as compared to the classified LAS, and 0.851 feet (0.259 meters) as compared to the bare earth DEM evaluated at the 95th percentile (Table 12, Figure 11, Figure 12).

Table 12: Vegetated vertical accuracy results

Vegetated Vertical Accuracy		
	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
Sample	37 points	37 points
95th Percentile	0.826 ft 0.252 m	0.851 ft 0.259 m
Average	0.260 ft 0.079 m	0.284 ft 0.086 m
Median	0.164 ft 0.050 m	0.194 ft 0.059 m
RMSE	0.412 ft 0.126 m	0.421 ft 0.128 m
Standard Deviation (1σ)	0.324 ft 0.099 m	0.316 ft 0.096 m

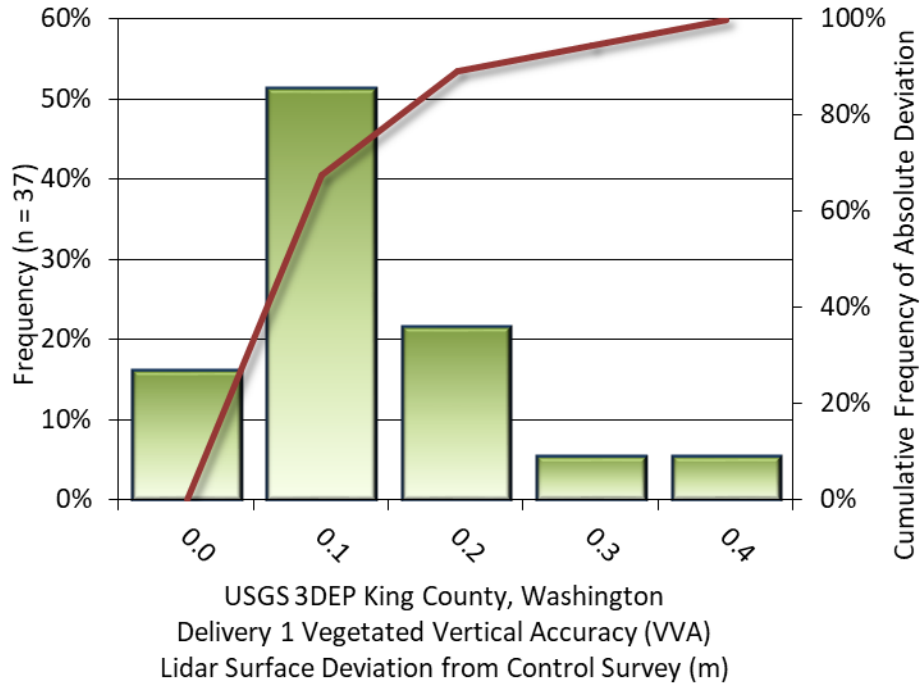


Figure 11: Frequency histogram for the lidar surface deviation from vegetated check point values (VVA)

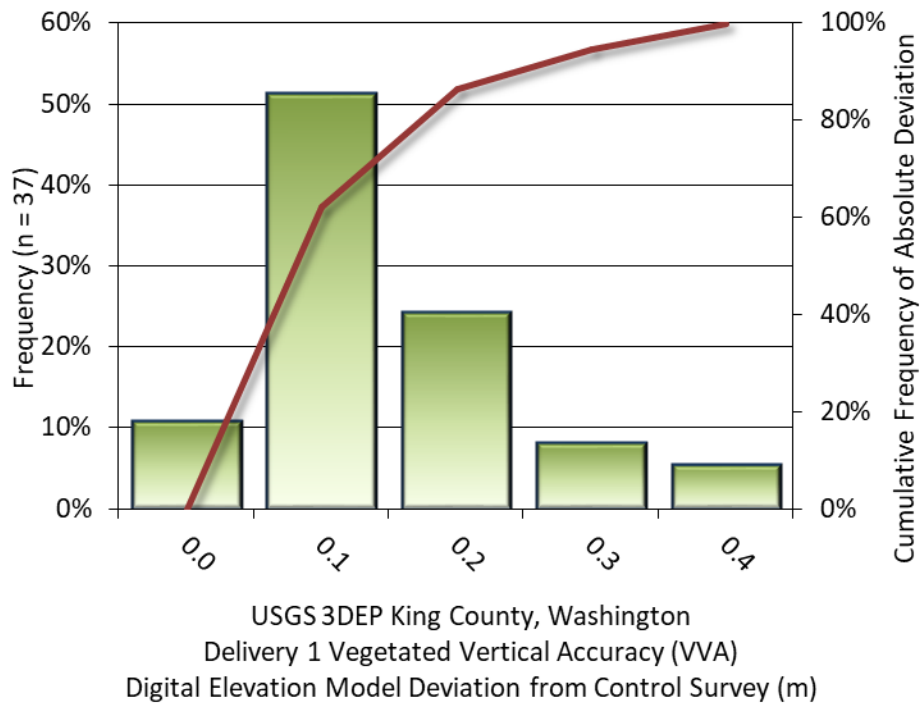


Figure 12: Frequency histogram for the lidar bare earth DEM deviation from vegetated check point values (VVA)

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 USGS 3DEP King County, Washington Delivery 1 Lidar project was 0.109 feet (0.033 meters) (Table 13, Figure 13).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	75 flight line surfaces
Average	0.109 ft 0.033 m
Median	0.112 ft 0.034 m
RMSE	0.112 ft 0.034 m
Standard Deviation (1σ)	0.010 ft 0.003 m
1.96 σ	0.020 ft 0.006 m

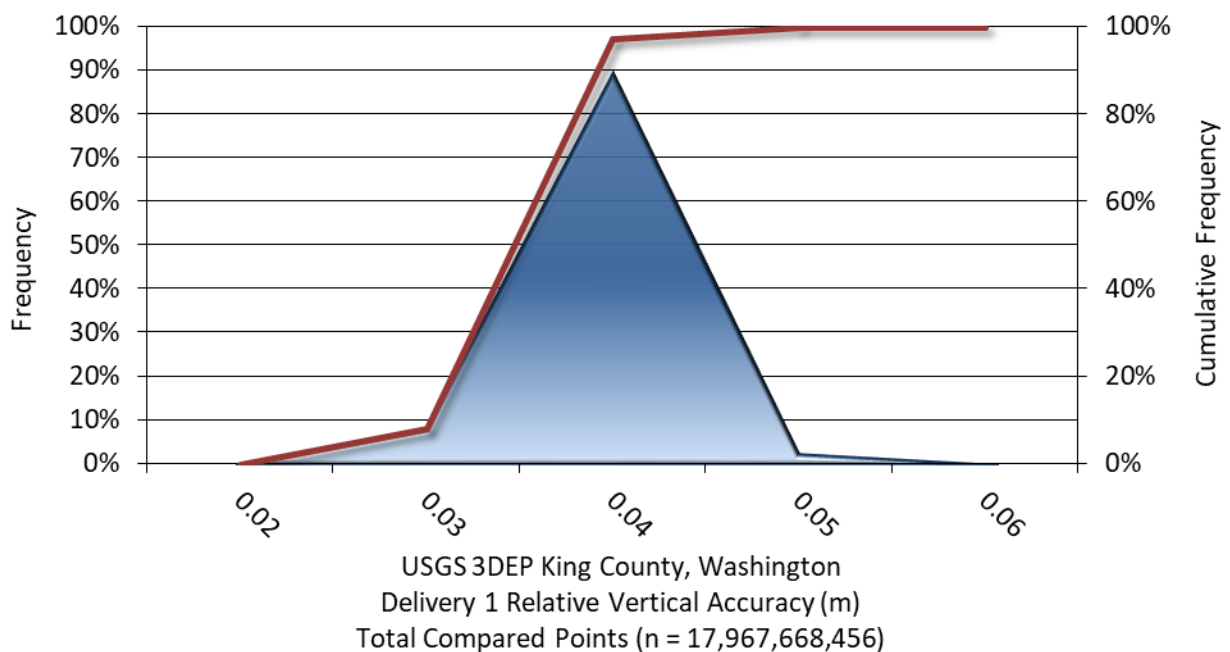


Figure 13: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. Based on a flying altitude of 2,078 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, this project was produced to meet 0.74 feet (0.23 m) horizontal accuracy at the 95% confidence level.

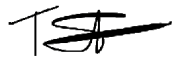
Table 14: Horizontal Accuracy

Horizontal Accuracy	
RMSE_r	0.43 ft
	0.13 m
ACC_r	0.74 ft
	0.23 m

CERTIFICATIONS

NV5 Geospatial provided lidar services for the USGS 3DEP King County, Washington Delivery 1 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.



Nov 2, 2021

Tucker Selko
Project Manager
NV5 Geospatial

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 on April 1-30, 2021 and on August 2-24, 2021.

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".



Nov 2, 2021

Evon P. Silvia, PLS
NV5 Geospatial
Corvallis, OR 97330



SELECTED IMAGES

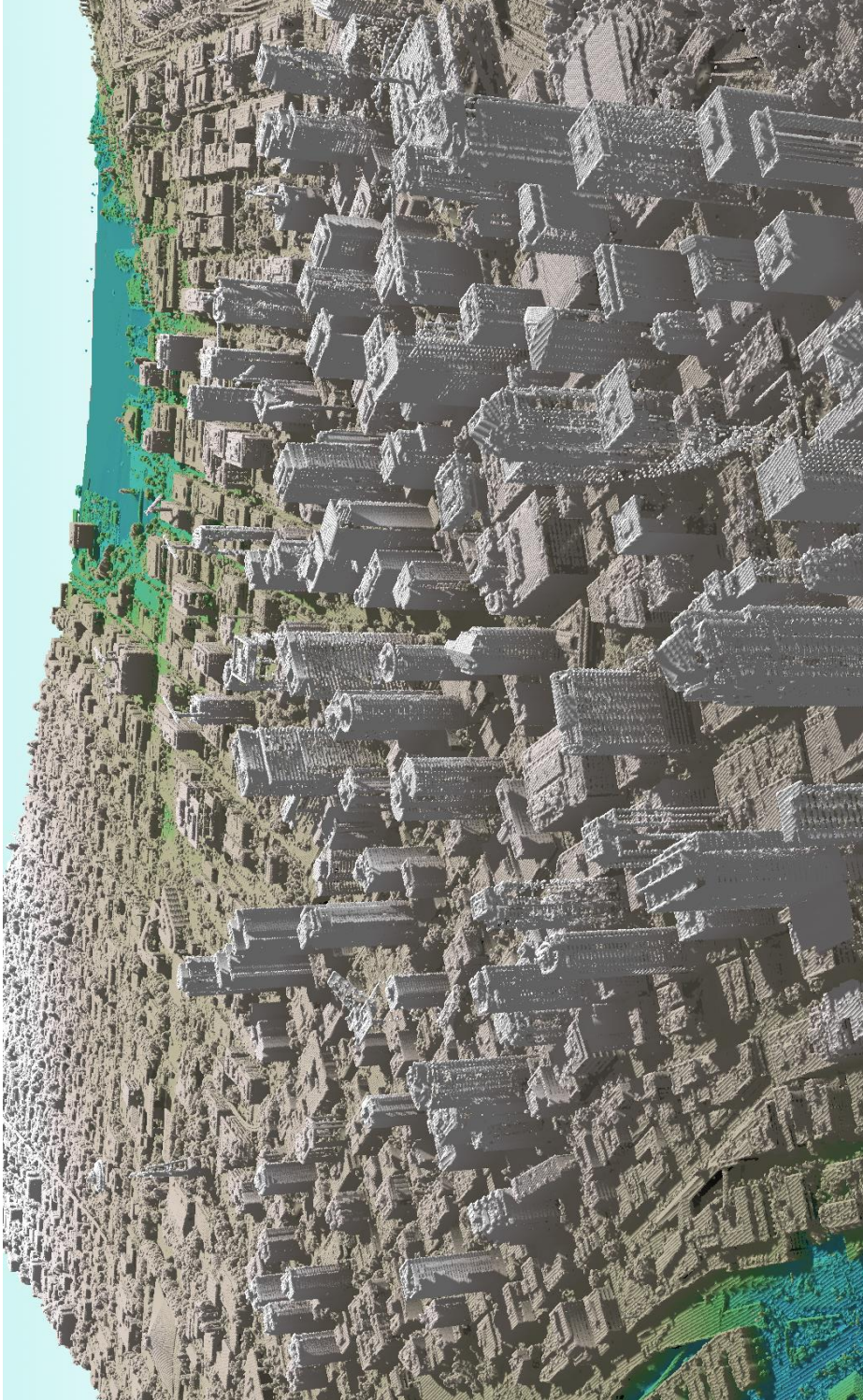


Figure 14: View looking North over Seattle, within the USGS 3DEP King County, Washington Delivery 1 area of interest. Image was created from the lidar bare earth model overlaid with the above-ground point cloud.

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 (σ) and root mean square error (RMSE).

Absolute Accuracy: The vertical accuracy of lidar data is described as the mean and standard deviation (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., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Real-Time Kinematic (RTK) Survey: A type of surveying conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

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

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 $\pm 29.25^\circ$ 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.