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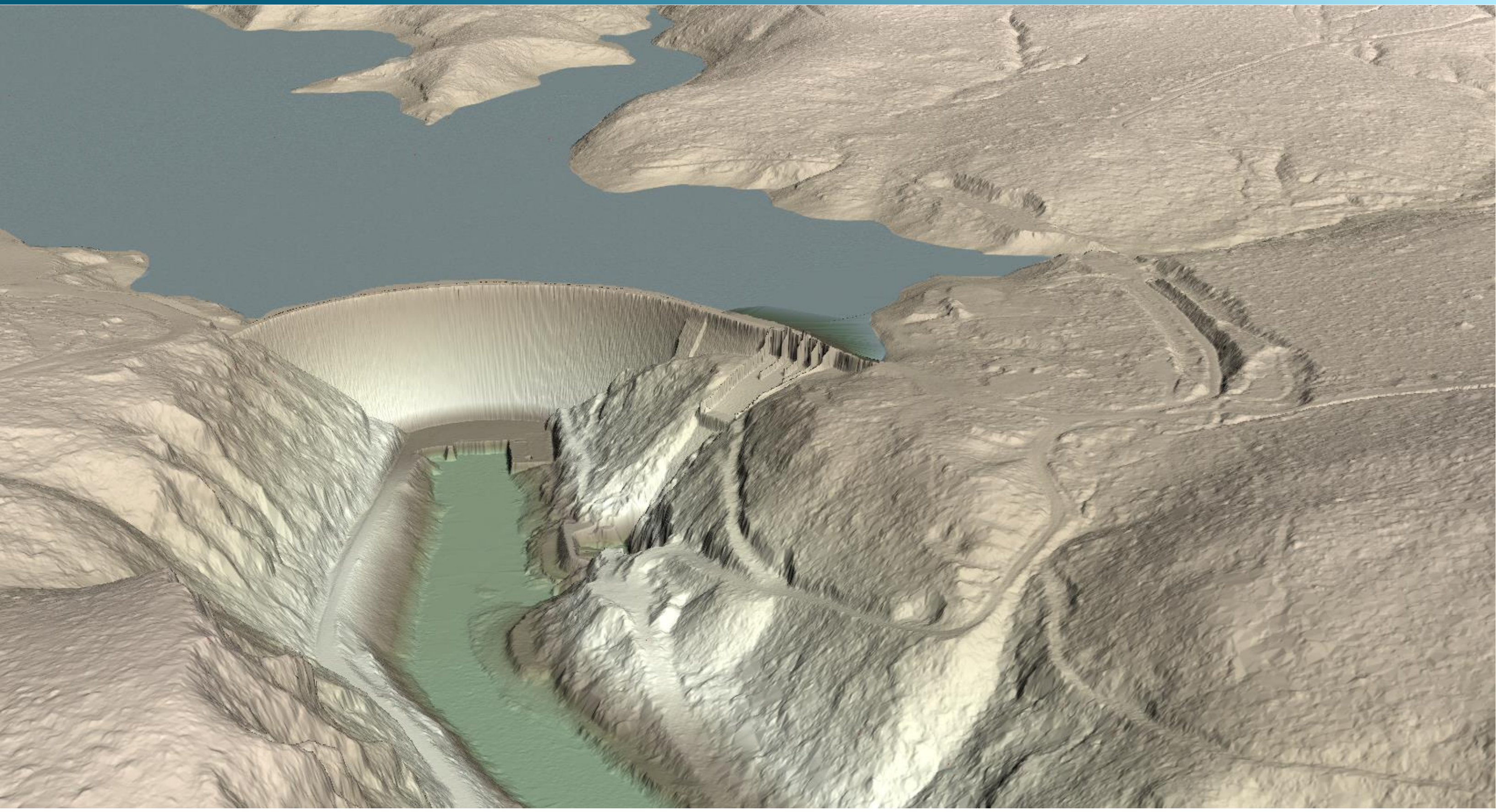

Thurston County, Washington Lidar Technical Data Report

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USGS science for a changing world

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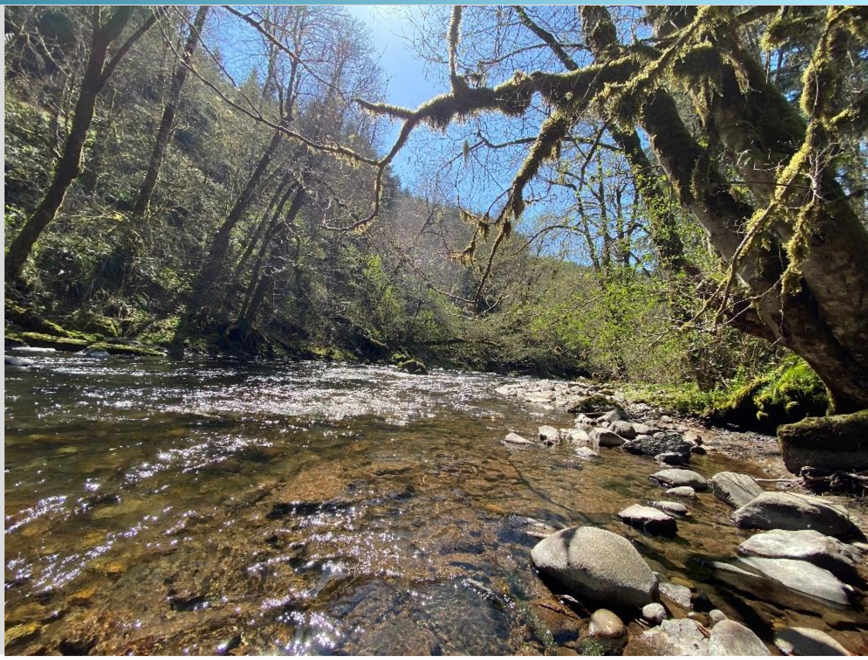
Cover Photo: A view looking south west over the Alder Dam and Alder Lake upstream of the Nisqually river. The image was created from the lidar bare earth model colored by elevation.

INTRODUCTION

This photo taken by NV5 acquisition staff shows a view of the Nisqually River within the Thurston County project area in Washington.



In April 2021, NV5 Geospatial (NV5) was contracted by the United States Geologic Survey (USGS) to collect high density NIR Light Detection and Ranging (lidar) data in the spring of 2021 for the Thurston County project in Washington. The Thurston County project area covers roughly 199,464 acres of Thurston County, Washington. Data were collected to aid WADNR in natural resource planning and management and to suppor the USGS 3DEP mission.

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 Thurston County site

Project Site	Contracted Acres	Acquisition Dates	Data Type
Thurston County, Washington	199,464	03/27/2021, 03/31/2021, 04/01/2021, 04/03/20201	NIR-Lidar

Deliverable Products

Table 2: Products delivered to USGS for the Thurston County site

Thurston County 2021 Lidar Products Projection: WA State Plane South Zone Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID18) Units: US Survey Feet	
NIR Lidar	
Points	LAS v 1.4 • All Classified Returns
Rasters	1.5 Foot GeoTiffs • Bare Earth Digital Elevation Models – Hydroflattened and Bridge Enforced (DEM) • First Return Digital Surface Models (DSM) • Intensity Images • Swath Separation Images
Vectors	ESRI file geodatabase (*.gdb) • Project Boundary • Lidar Tile Index • 3D Hydroflattened-Breaklines • 3D Bridge Breaklines • Ground Survey Shapes • Flightline Index • Flightline Swath Coverage Extents

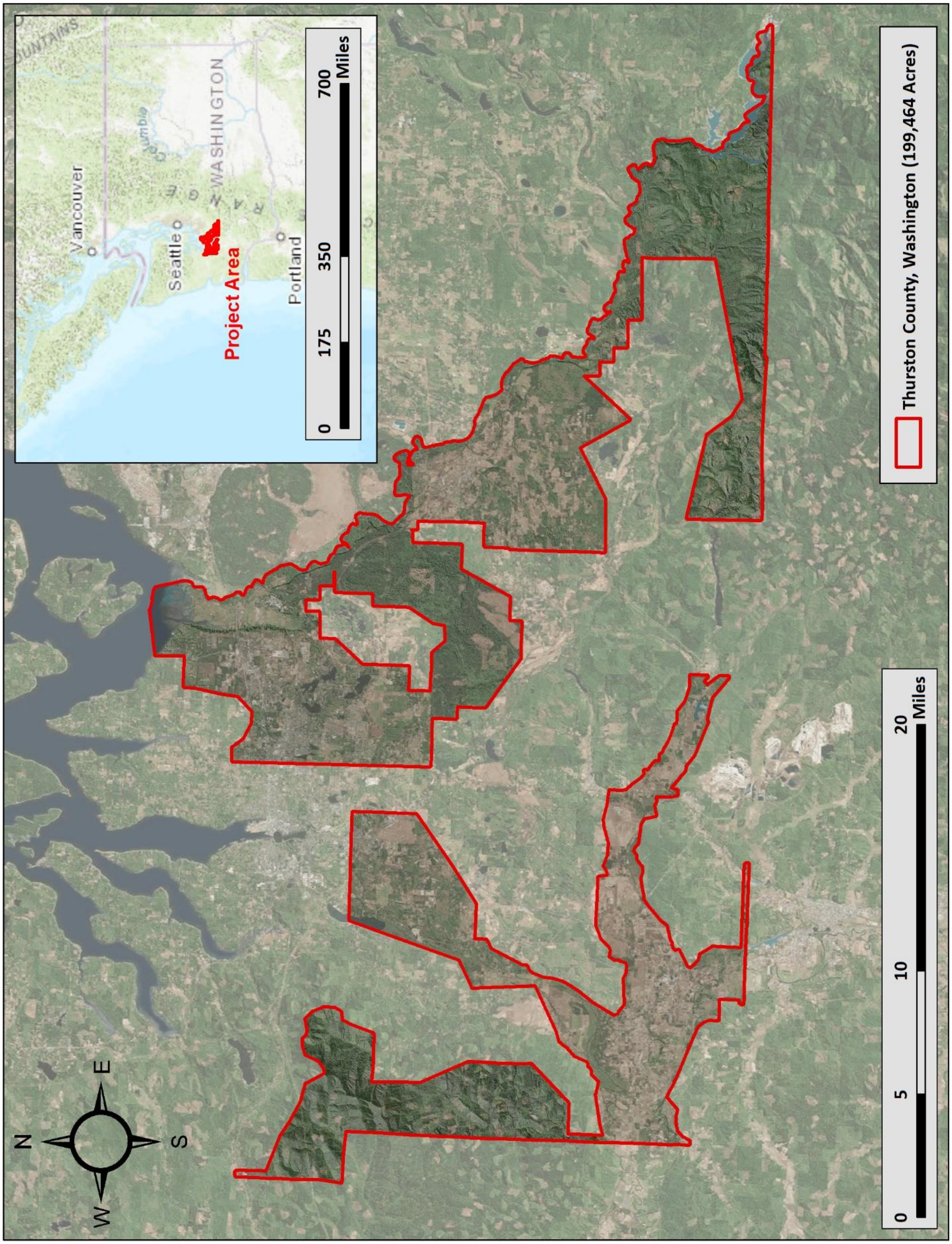


Figure 1: Location map of the Thurston County site in Washington

NV5's ground acquisition equipment set up in the Thurston County Lidar area near Hogum Bay.

Planning

In preparation for data collection, NV5 reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Thurston County Lidar study area at the target combined point density of ≥8 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property, tribal lands access, and potential air space restrictions were reviewed.

Airborne Lidar Survey

The lidar survey was accomplished using a Riegl VQ-1560II laser system mounted in a Cessna Caravan (Table 3). Table 4 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Thurston County 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: Flight Date Table

Date	Flight Line #	Start Time (Adjsted GPS)	End Time (Adjusted GPS)
03/27/2021	100-122	300889365.948	300903291.994
03/31/2021	200-235	301220728.189	301238016.118
04/01/2021	301-312, 315-318	301305239.427	301315696.326
04/03/2021	400-402	301475611.519	301477298.566

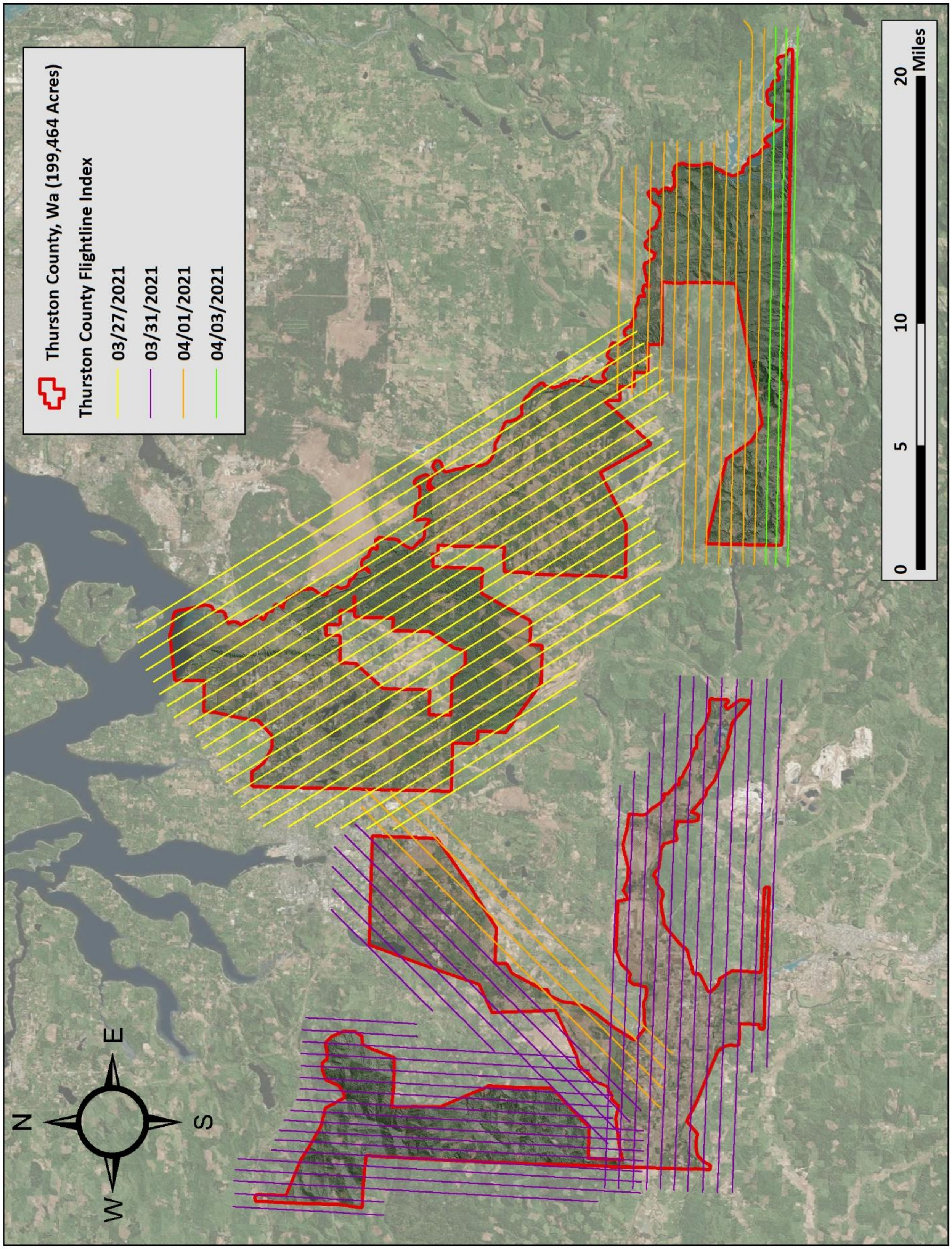


Figure 2: 2021 Aerial Acquisition Flightline Map

Table 4: Lidar specifications and survey settings

Lidar Survey Settings & Specifications	
Acquisition Dates	03/27/2021, 03/31/2021, 04/01/2021, 04/03/20201
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)	2,083 m
Survey speed	145 knots
Field of View	58.5^o
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	635 kHz
Pulse Length	3 ns
Laser Pulse Footprint Diameter	37.5 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.18 mrad
Swath Width	2,333 m
Swath Overlap	55%
Intensity	16-bit
Accuracy	$RMSE_Z \leq 15$ cm

Riegl VQ-1560II 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

NV5 Geospatial-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.

Base Stations

Monuments were used for collection of ground survey points using real time kinematic (RTK) 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 utilized six permanent active base stations from the Washington State Reference Network (WSRN) and established one new temporary monument for the Thurston County lidar acquisition (Table 5, Figure 3). New monumentation was set using 6” mag hub nails topped with orange identification washers. NV5’s professional land surveyor, Evon Silvia (WAPLS#53957) oversaw and certified the occupation of all base stations.

Table 5: Monument positions for the Thurston County acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Owner	Latitude	Longitude	Ellipsoid (meters)
CPXF	WSRN	46” 50’ 24.29151”	122” 15’ 23.40720”	533.975
GRMD	WSRN	46° 47’ 43.73508”	123° 01 21’.28893”	31.066
OLAR	WSRN	46° 57’ 40.28899”	122° 54’ 30.41255”	41.391
OLMP	WSRN	47° 02’ 41.43490”	122° 53’ 42.72317”	2.933
PKWD	WSRN	46° 35’ 59.25656”	121° 40’ 37.07022”	307.099
ROKY	WSRN	47° 01’ 10.69343”	122° 20’ 46.11498”	128.678
Thurston_01	NV5	46° 46’ 36.72189”	122° 35’ 23.98705”	345.341

NV5 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 was 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.

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

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 6.

Table 6: Federal Geographic Data Committee monument rating for network accuracy

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

For the Thurston County Lidar project, the monument coordinates contributed no more than 2.8 cm of positional error to the geolocation of the final ground survey points and lidar, with 95% confidence.

[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) and total station (TS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. RTK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. 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 7 for NV5 ground survey equipment information.

Forested check points were collected using a total station in order to measure positions under dense canopy. Total staion backsight and setup points were established using RTK survey techniques with long occupation times.

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 7: NV5 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		n/a	Total Station

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 8, see Lidar Accuracy Assessments, page 21).

Table 8: 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

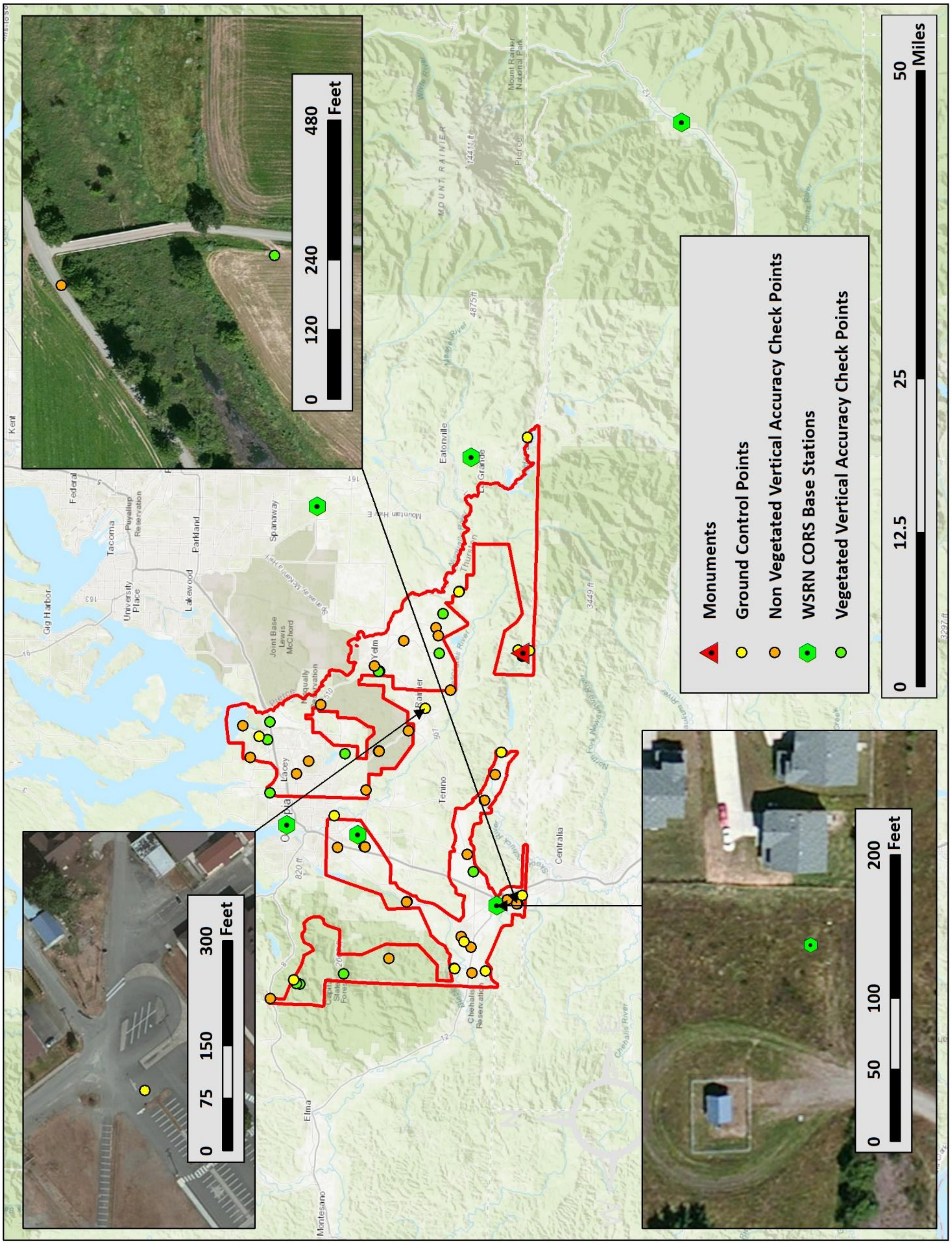
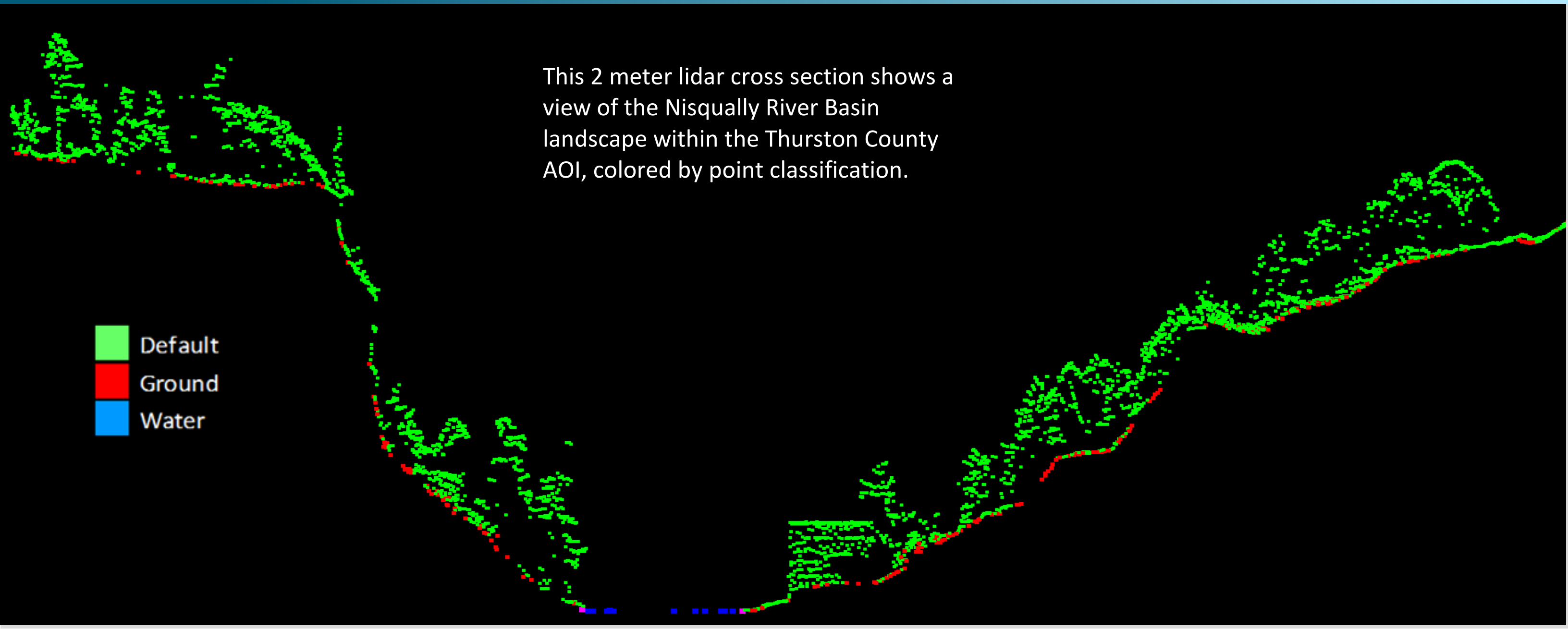


Figure 3: Ground survey location map



This 2 meter lidar cross section shows a view of the Nisqually River Basin landscape within the Thurston County AOI, colored by point classification.

Lidar Data

Upon completion of data acquisition, NV5 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 9). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 10.

Table 9: ASPRS LAS classification standards applied to the Thurston County dataset

Classification Number	Classification Name	Point Count	Classification Description
1	Default/Unclassified	12,851,573,169	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-W	Unclassified Withheld / Edge Clip	704,846,051	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	2,137,920,972	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7-W	Low Noise / Withheld	153,830,547	Laser returns that are often associated with artificial points below the ground surface
9	Water	36,620,213	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	963,058	Bridge decks
18-W	High Noise	33,528,994	Laser Returns that are often associated with birds and scattering from reflective surfaces
20	Ignored Ground	1,416,657	Ground points proximate to water’s edge breaklines; ignored for correct model creation

Table 10: 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.8.5
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	RiProcess v1.8.5
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), 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.	Bays-StripAlign v2.19
Import calibrated points into manageable blocks for editing.	TerraScan v.19.005
Classify resulting data to ground and other client designated ASPRS classifications (Table 9). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.002
Generate bare earth models as triangulated surfaces. Generate highest hit 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 proprietary software) ArcMap v. 10.3.1
Export intensity images and swath separation images as Cloud Optimized GeoTIFFs at a 1.5 foot pixel resolution.	Las Product Creator 3.0 (NV5 proprietary software)

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Portions of the Nisqually, Chehalis, and Black Rivers along with other water bodies within the 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 tidal waters bordering the project, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

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

Once polygons were developed the initial ground classified points falling within 1 meter outside of water polygons were reclassified as ignored ground 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**).

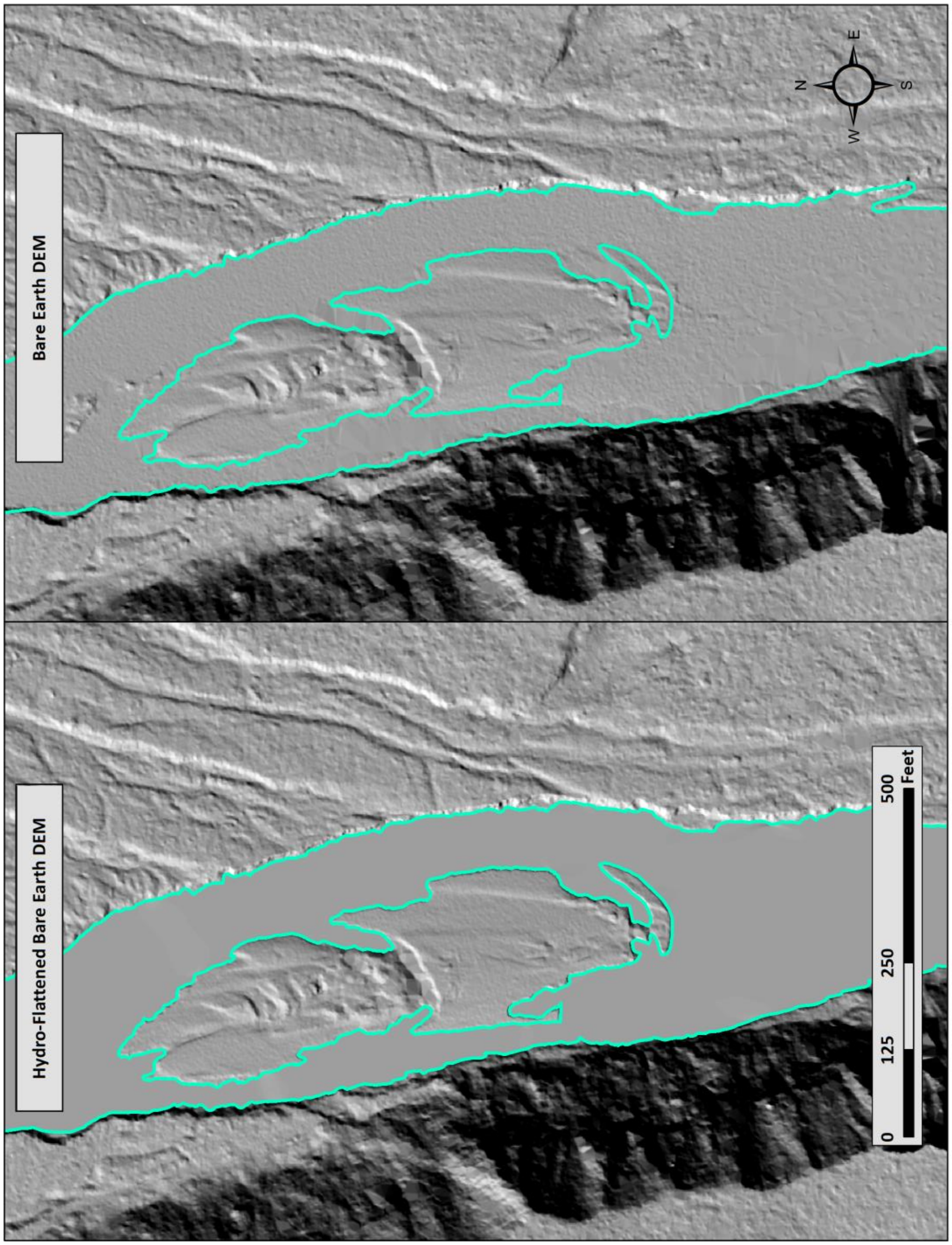
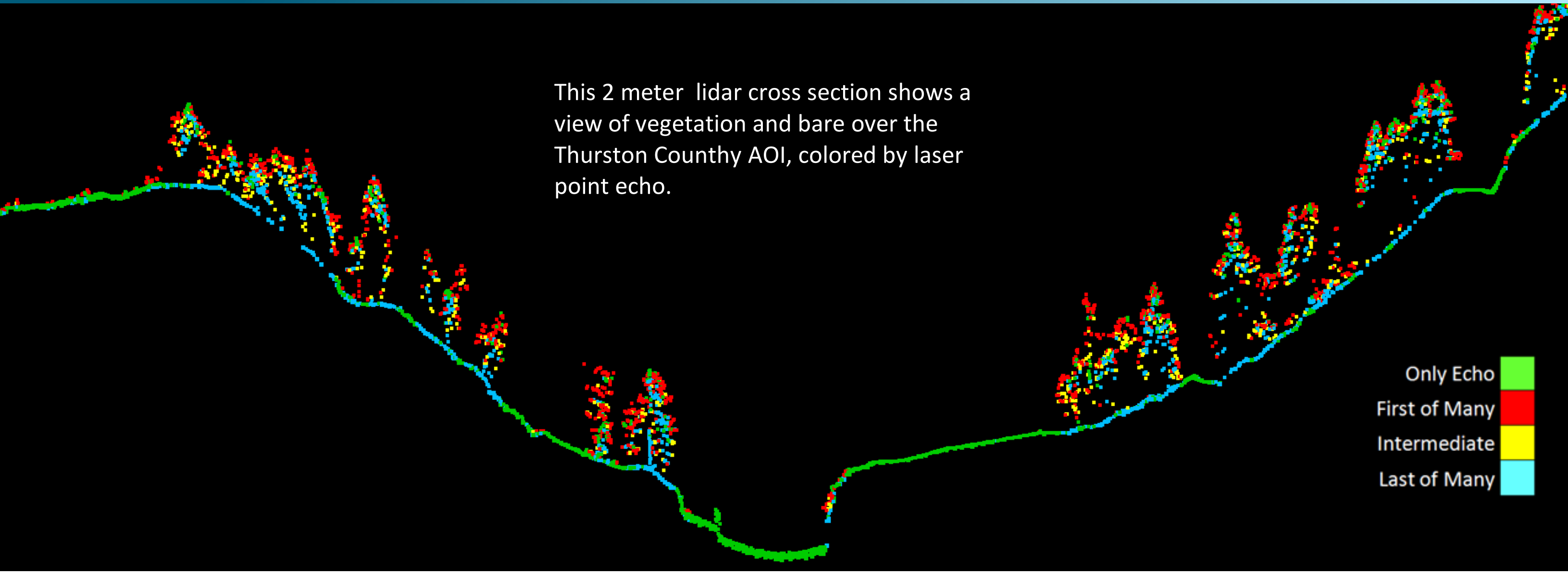


Figure 4: Example of hydroflattening in the Thurston County Lidar dataset



Lidar Point Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 points/ft^2). First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground classified lidar returns returns were 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 have penetrated the canopy, resulting in lower ground density. The average first-return density of the Thurston County Lidar project was 13.14 points/m^2 (1.22 it'points/m^2) while the ground classified density was 2.68 points/m^2 (0.25 points/ft^2) (Table 11). The statistical and spatial distributions of all first return densities per 100 m x 100 m cell are portrayed in Figure 5 and Figure 8.

Table 11: Average Lidar point densities

Density Type	Point Density
First Returns	1.22 points/ft^2 13.14 points/m^2
Ground Classified Returns	0.25 points/ft^2 2.68 points/m^2

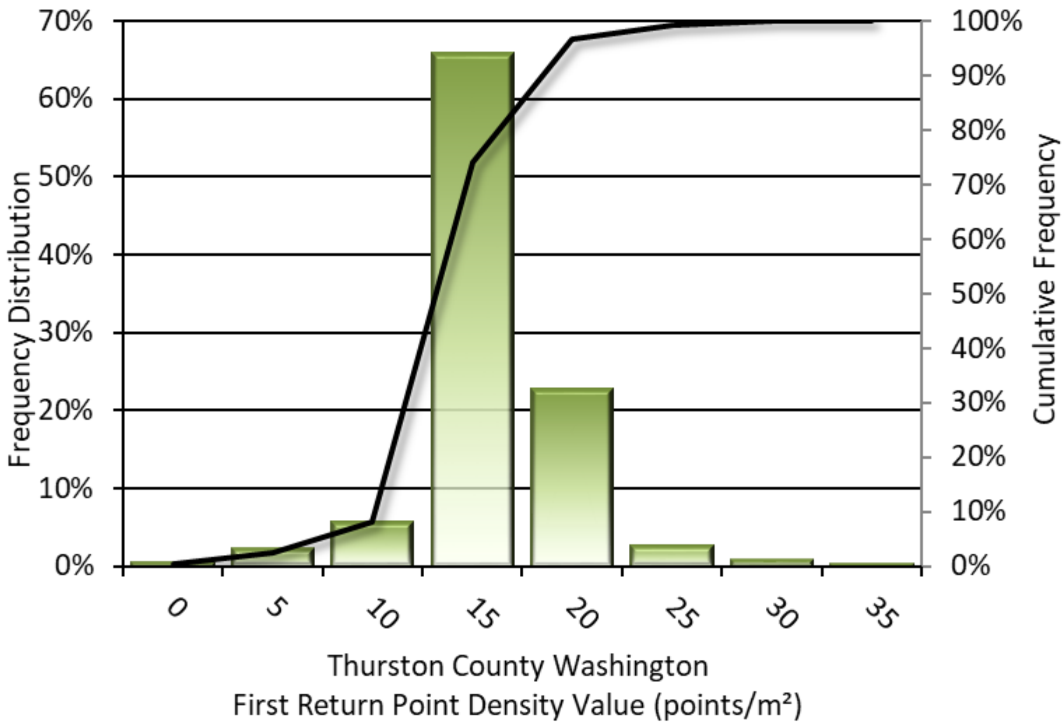


Figure 5: Frequency distribution of first return densities per 100 x 100 m cell

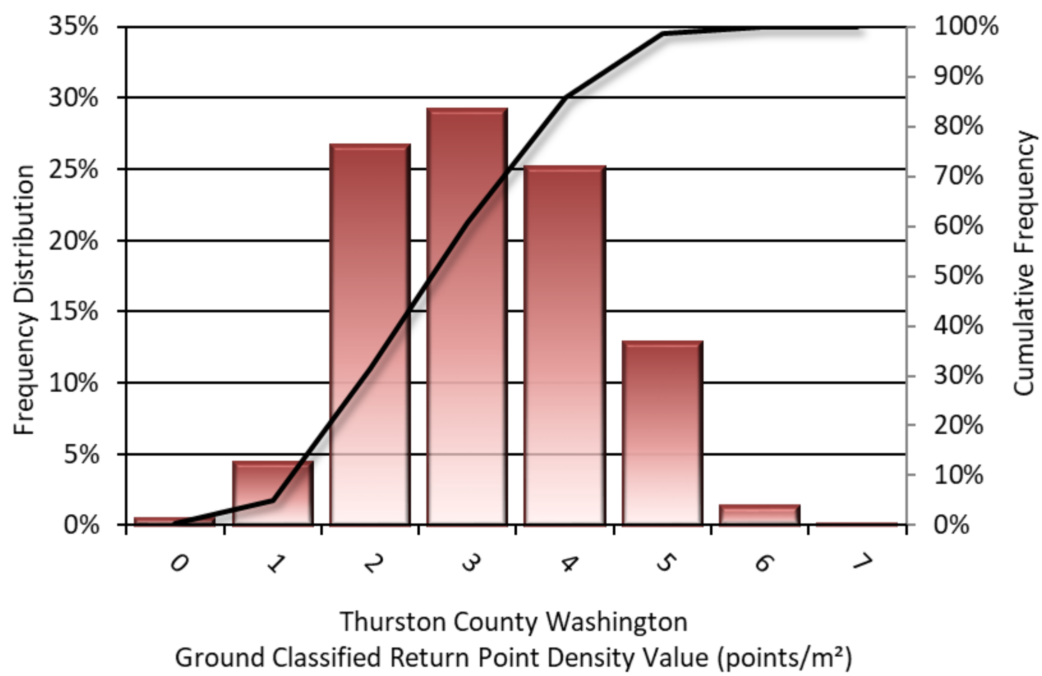


Figure 6: Frequency distribution of ground classified return densities per 100 x 100 m cell

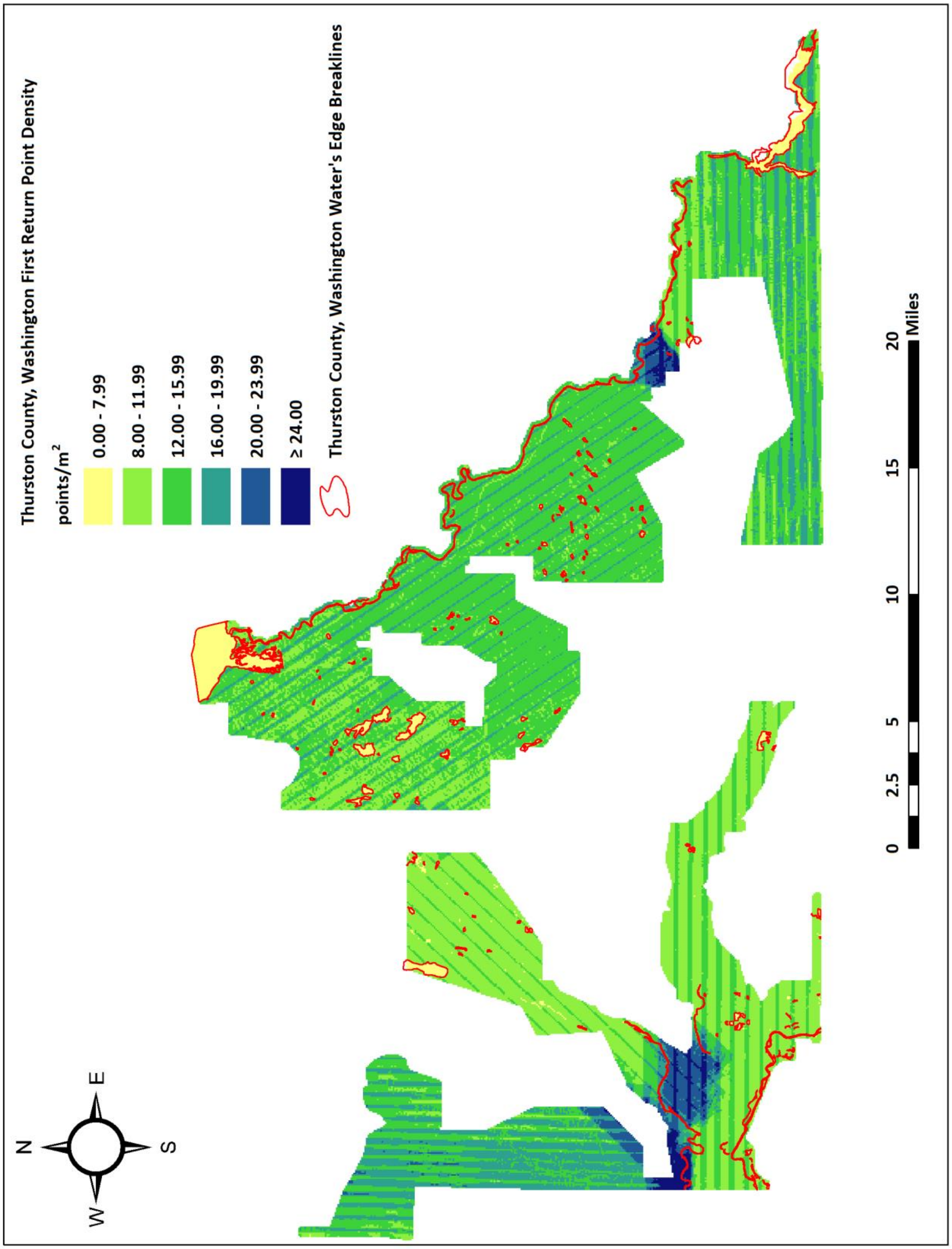


Figure 7: First Return point density map for the Thurston County site (100 m x 100 m cells)

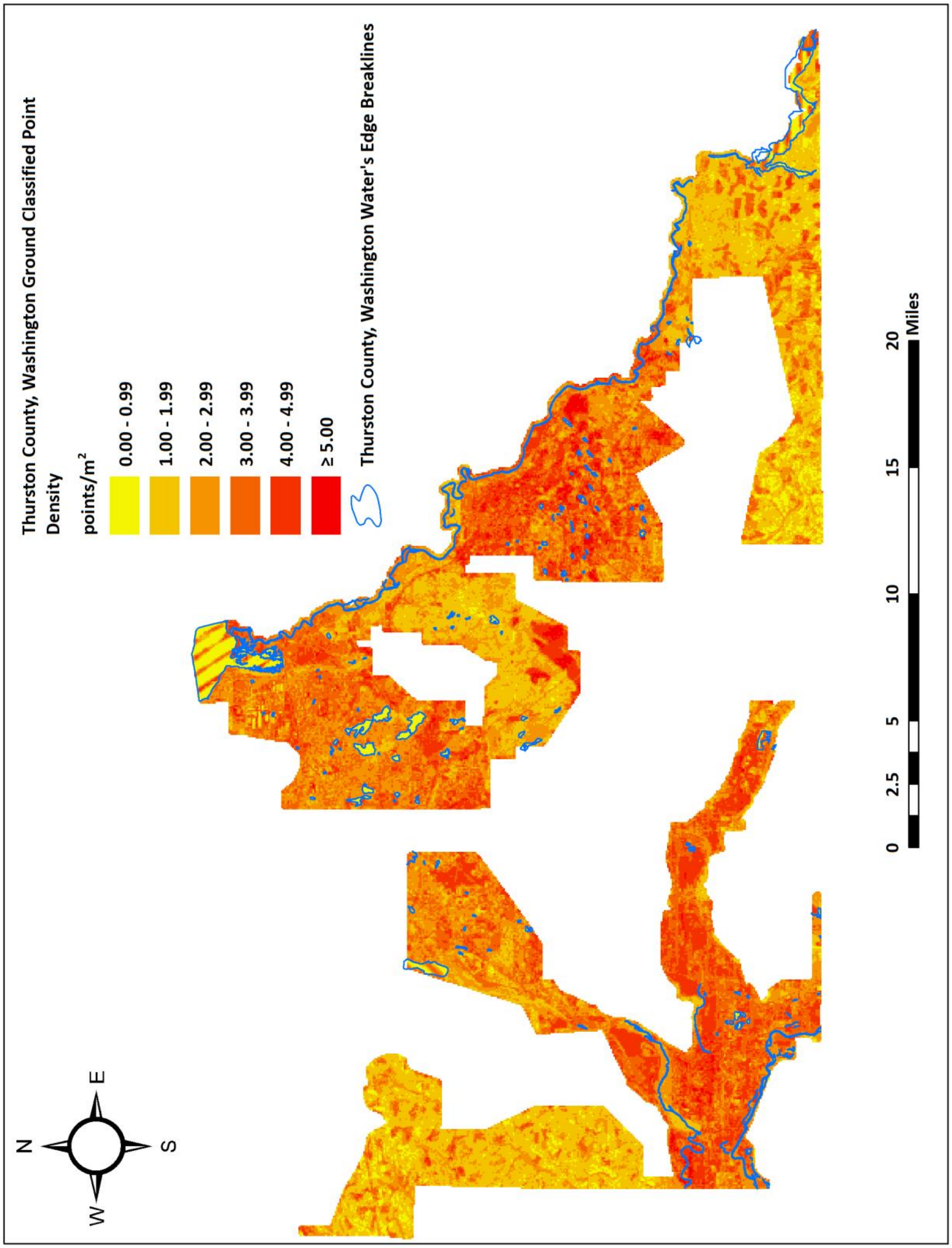


Figure 8: Ground density map for the Thurston County site (100 m x 100 m cells)

Lidar Accuracy Assessments

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

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the 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 12.

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 Thurston County survey, 30 ground check points were withheld from the calibration and post-processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.043 meters (0.142 feet) as compared to the classified LAS and 0.042 meters (0.138 feet) against the bare earth DEM, with 95% confidence (Figure 9 and Figure 10).

NV5 also assessed absolute accuracy using 14 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 12 and Figure 11.

[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 12: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to Classified LAS	**NVA, as compared to Bare Earth DEM**	**Ground Control Points**
Sample	30 points	30 points	14 points
95% Confidence (1.96*RMSE)	0.142 ft 0.043 m	0.138 ft 0.042 m	0.214 ft 0.065 m
Average	0.021 ft 0.006 m	0.024 ft 0.007 m	0.016 ft 0.005 m
Median	0.016 ft 0.005 m	0.028 ft 0.008 m	0.005 ft 0.001 m
RMSE	0.072 ft 0.022 m	0.071 ft 0.022 m	0.109 ft 0.033 m
Standard Deviation (1σ)	0.071 ft 0.022 m	0.068 ft 0.021 m	0.112 ft 0.034 m

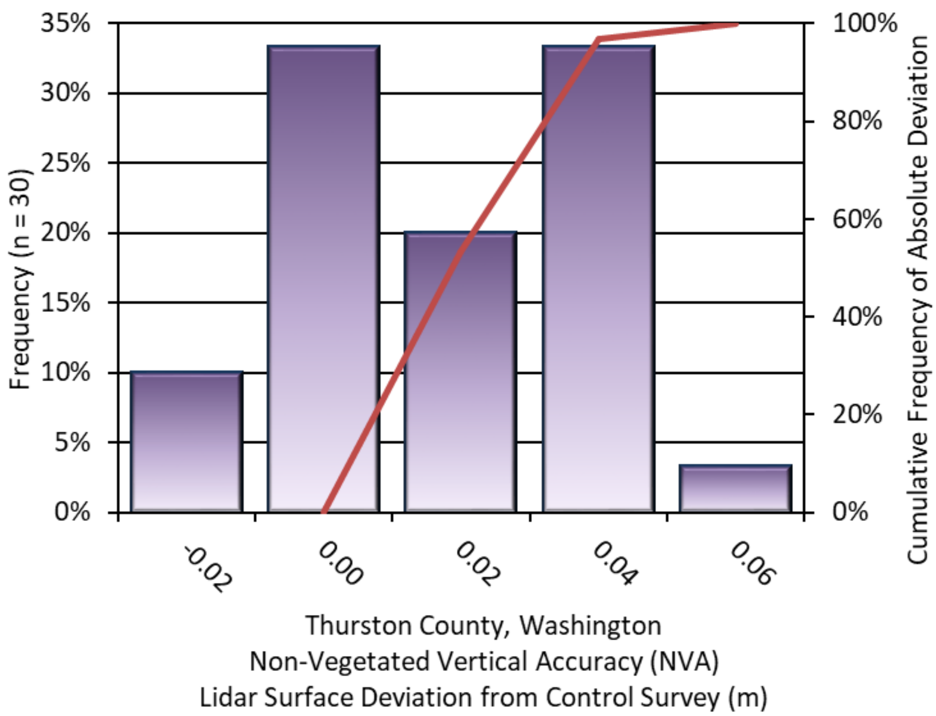


Figure 9: Frequency histogram for classified LAS deviation from ground check point values

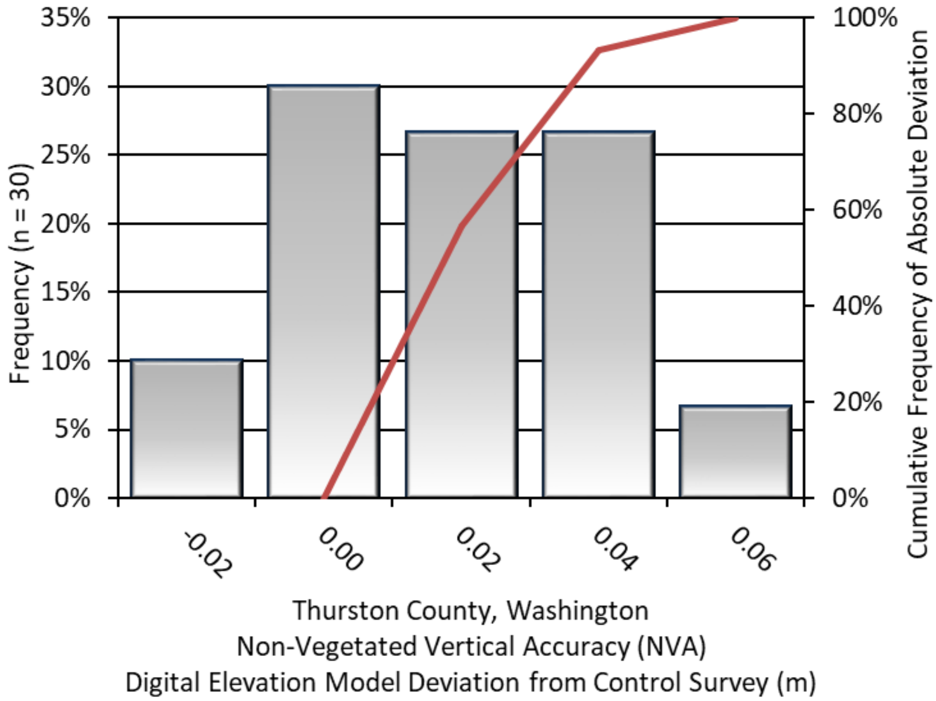


Figure 10: Frequency histogram for lidar bare earth DEM deviation from ground check point values

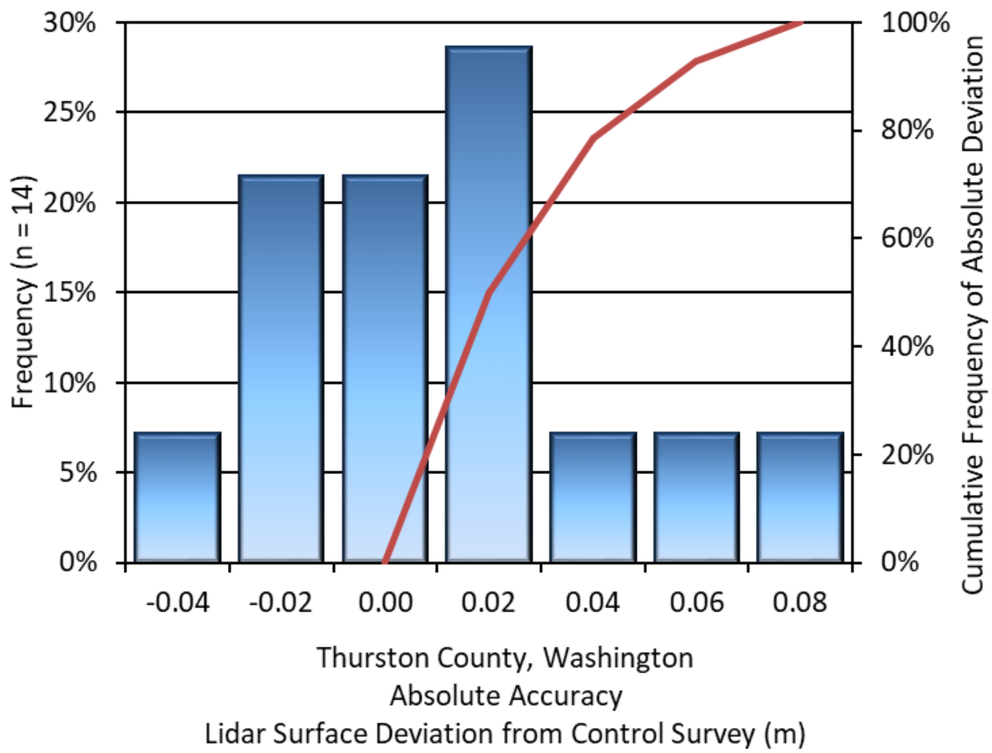


Figure 11: Frequency histogram for lidar surface deviation ground control point values

Lidar Vegetated Vertical Accuracies

NV5 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 surface generated by the classified lidar point cloud as well as the derived gridded bare earth DEM. VVA is evaluated at the 95th percentile (Table 13, Figure 12, Figure 13).

Table 13: Vegetated Vertical Accuracy for the Thurston County Project

Vegetated Vertical Accuracy (VVA)		
	VVA, as compared to Classified LAS	**VVA, as compared to Bare Earth DEM**
Sample	25 points	25 points
Average Dz	0.248 ft 0.076 m	0.239 ft 0.073 m
Median	0.236 ft 0.072 m	0.236 ft 0.072 m
RMSE	0.329 ft 0.100 m	0.326 ft 0.099 m
Standard Deviation (1σ)	0.221 ft 0.067 m	0.226 ft 0.069 m
95th Percentile	0.567 ft 0.173 m	0.581 ft 0.177 m

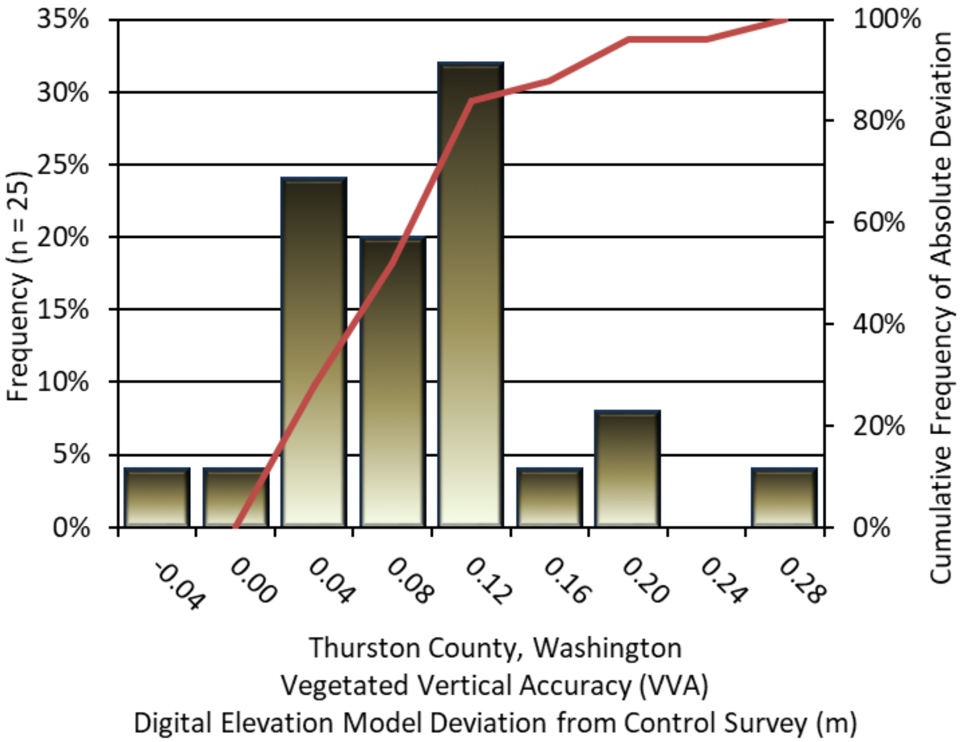


Figure 12: Frequency histogram for the DEM deviation from ground check point values from all land cover class point values (VVA)

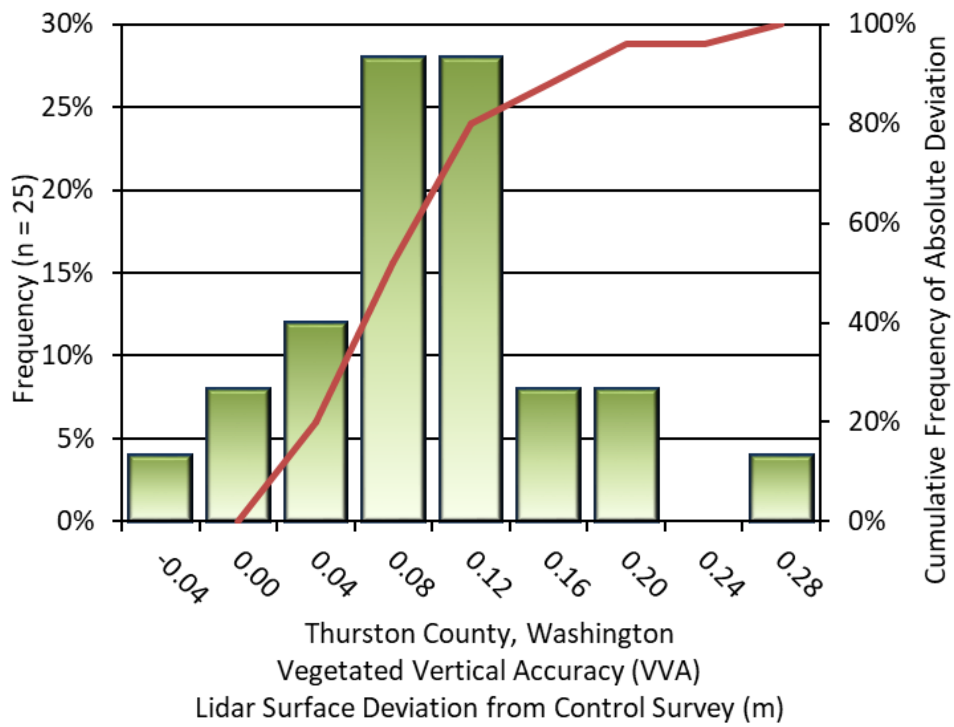


Figure 13: Frequency histogram for the lidar surface deviation from ground check point values from all land cover class point values (VVA)

Lidar Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Thurston County Lidar project was 0.038 meters (0.124 feet) (Table 14, Figure 14).

Table 14: Relative accuracy results

Relative Accuracy	
Sample	78 surfaces
Average	0.124 ft 0.038 m
Median	0.124 ft 0.038 m
RMSE	0.139 ft 0.042 m
Standard Deviation (1σ)	0.032 ft 0.010 m
1.96σ	0.062 ft 0.019 m

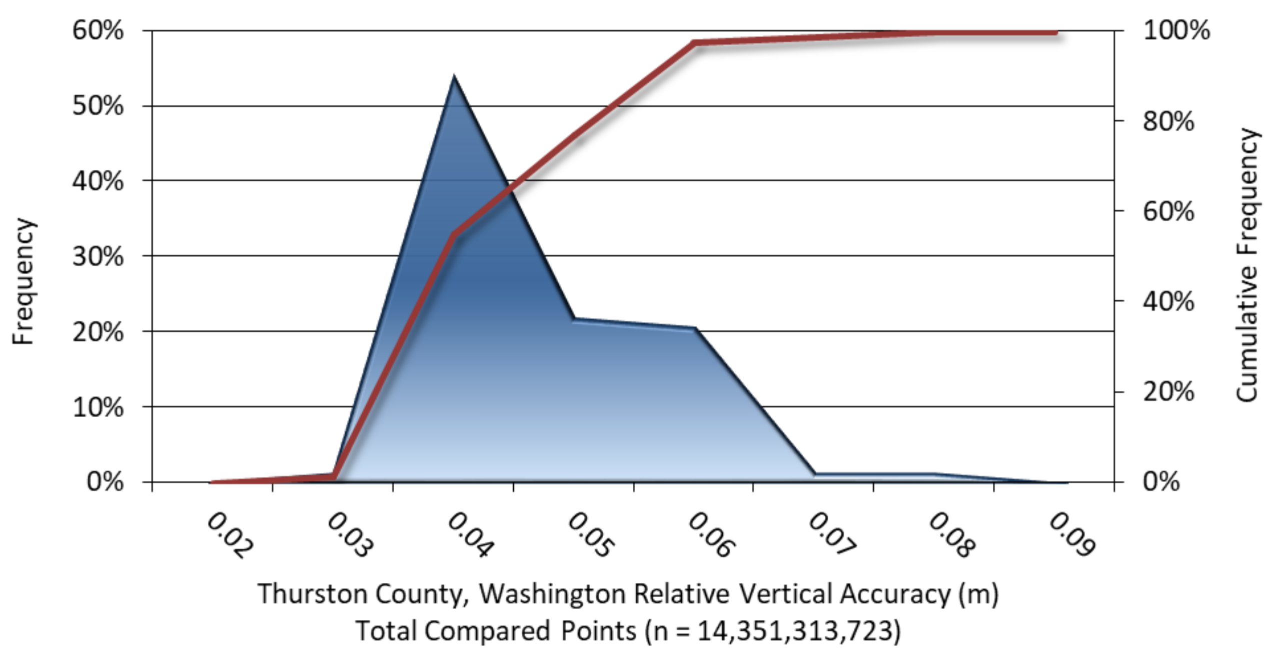


Figure 14: Frequency plot for relative vertical accuracy between flight lines

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 2,083 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, this project was produced to meet 0.23 meters (0.74 feet) horizontal accuracy at the 95% confidence level.

Table 15: Horizontal Accuracy

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

NV5 Geospatial, Inc. provided lidar services for the Thurston County project as described in this report.

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

Oct 20, 2021

Steven J. Miller.
Project Manager
NV5 Geospatial, Inc.

I, Evon P. Silvia, PLS, being duly registered as a Professional Land Surveyor in and by the state of Washington, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between March 27 and April 20, 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".

Oct 20, 2021

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

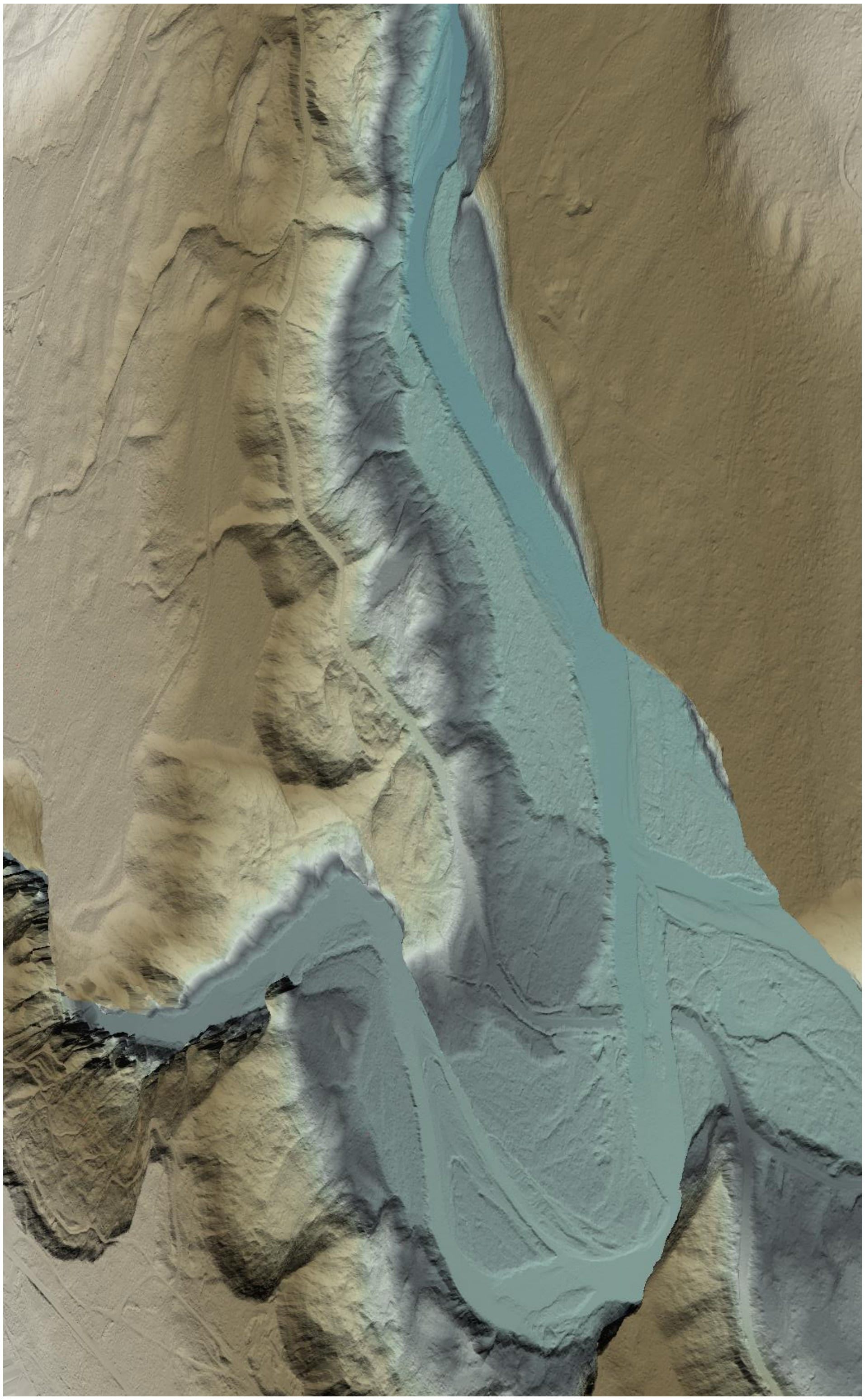


Figure 15: A view looking south east over the Nisqually river within the Thurston County project area. This image was created using the lidar derived bare earth surface and colored by elevation.

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 Non-vegetated 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., 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 was 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 ±29.25^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.
Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple 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.