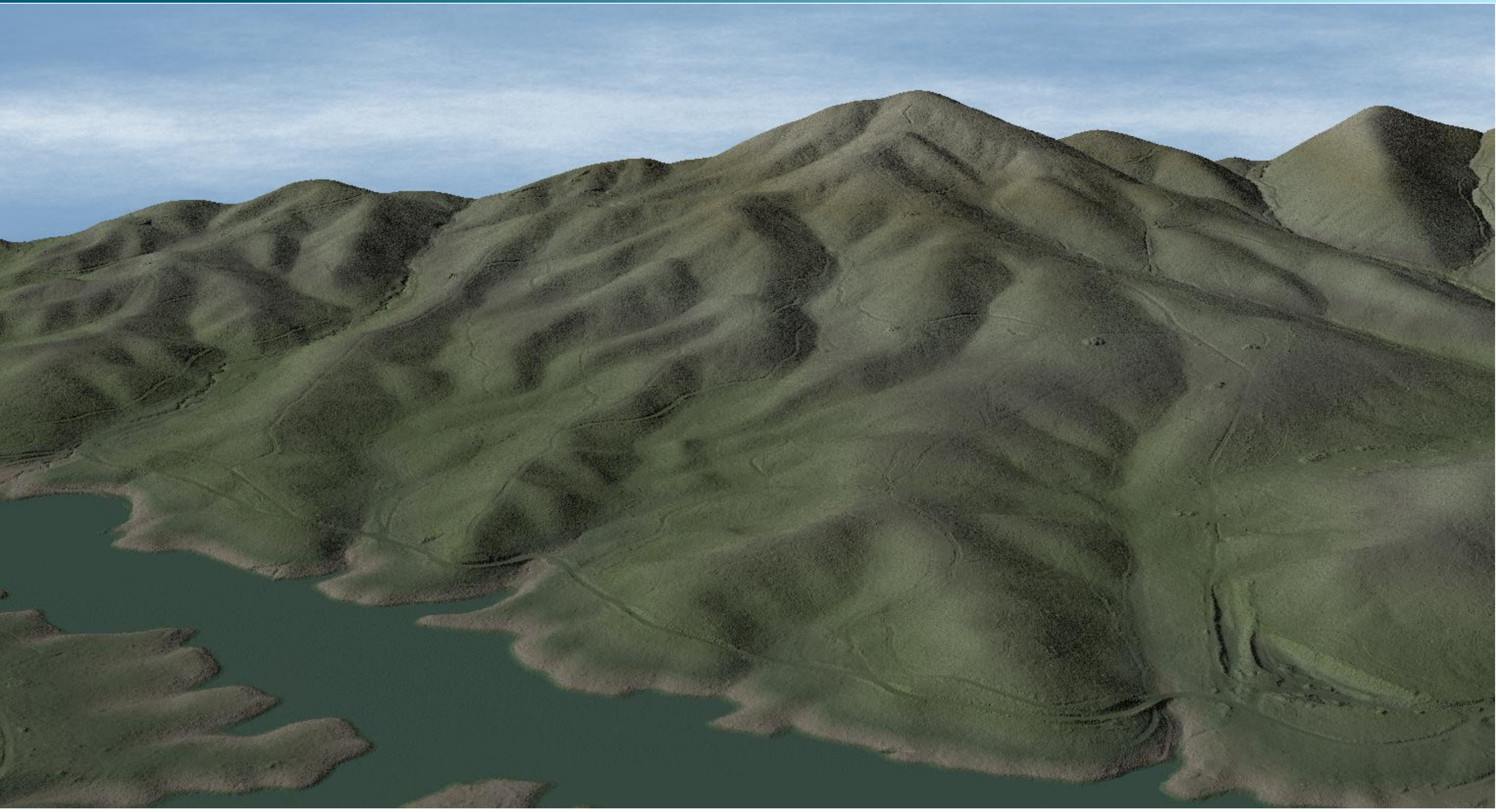
January 29, 2020



Washington DNR 3DEP Processing

Technical Data Report

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Cover Photo: A view looking North East over Ponderosa Lake. The image was created from the Lidar bare earth model colored by elevation.

INTRODUCTION

This photo taken by NV5 Geospatial acquisition staff shows a view of Long Lake dam in the Washington DNR 3DEP Processing site in Washington.

In September 2020, NV5 Geospatial (NV5) was contracted by the United States Geological Survey (USGS) to reprocess to 3DEP standards Light Detection and Ranging (lidar) data originally collected and delivered to the Washington Department of Natural Resources (WADNR) for the Springdale and North Spokane County areas of interest in eastern Washington State. The data were initially collected by NV5 Geospatial (formerly Quantum Spatial) in the spring of 2019 to aid WADNR in natural resource planning and management. The data is being reprocessed and redelivered to USGS to support the 3D Elevation Program initiative.

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 Washington DNR 3DEP Processing site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Washington DNR 3DEP Processing	561,762	562,137	04/29/19 – 05/03/19	NIR-Lidar

Deliverable Products

Table 2: Products delivered to USGS for the Washington DNR 3DEP Processing site

Washington DNR 3DEP Processing Lidar Products Projection: Washington State Plane North Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID18) Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns
Rasters	2.0 Foot GeoTiffs • Hydroflattened Bare Earth Model (DEM) • Highest Hit Digital Surface Model (DSM) • Intensity Images • dZ Orthos
Vectors	Shapefiles (*.shp) • Buffered Boundary • Lidar Tile Index Geodatabase (*.gdb) • 3D Bridge Breaklines Polyline • 3D Water's Edge Breaklines Polygon • Ground Survey Shapes • Flightline Index

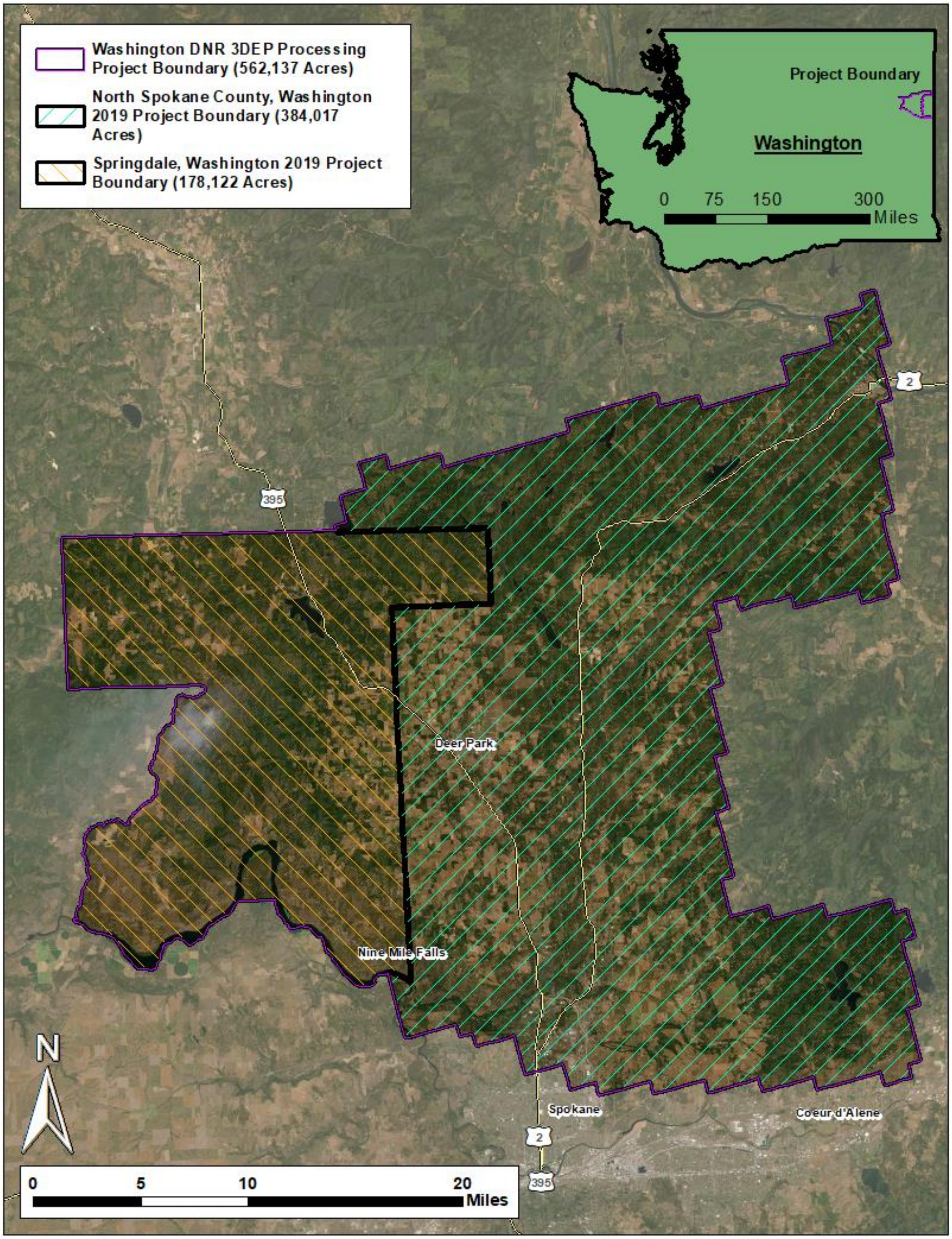


Figure 1: Location map of the Washington DNR 3DEP Processing site in Washington

NV5 Geospatial's Cessna Caravan

Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Washington DNR 3DEP Processing 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 Riegl VQ-1560i system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Washington DNR 3DEP Processing project area. The Riegl VQ-1560i 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	04/29/19 – 05/03/19
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ-1560i
Maximum Returns	15
Resolution/Density	8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	1,830 m
Survey speed	145 knots
Field of View	58.5°
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	700 kHz
Pulse Length	3 ns
Laser Pulse Footprint Diameter	32 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.18 mrad
Swath Width	2,050 m
Swath Overlap	55%
Intensity	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 9 cm
	NVA (95% Confidence Level) ≤ 19.6 cm
	VVA (95th Percentile) ≤ 29.4 cm

Riegl VQ-1560I 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.

Table 4: Flight Missions by Date

Date	Flight #	Start Time (Adjusted GPS)	End Time (Adjusted GPS)
04/29/2019	1	240561400	240581267
04/30/2019	1	240647420	240664128
05/01/2019	1	240737590	240750688
05/02/2019	1	240820654	240825566
05/03/2019	1	240905206	240921807

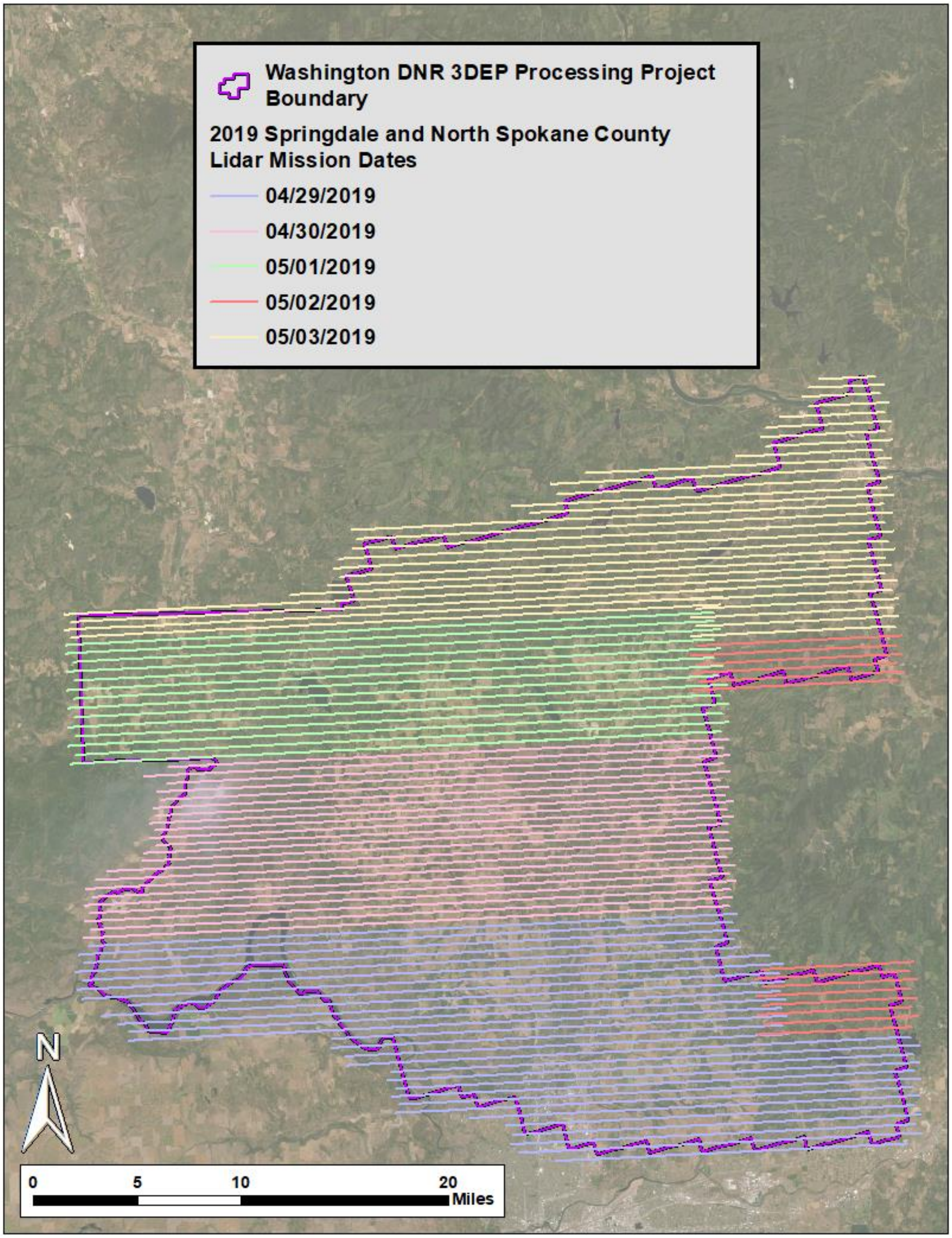


Figure 2: 2019 Aerial Acquisition Flightline Map

Ground Survey

Ground control surveys, including base station and ground survey points (GSPs) were conducted to perform quality assurance checks on final lidar data. For the reprocessing of the Washington DNR 3DEP data, no new calibration control points or vertical accuracy check points were required to meet USGS 3DEP standards.

Base Stations

Base stations were utilized 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 Geospatial utilized four existing permanent active base stations from the Washington State Reference Network (WSRN) Real-Time Network (RTN) and two base stations from the Hexagon SmartNet GNSS RTN were utilized for the Washington DNR 3DEP lidar acquisitions (Table 5, Figure 3). NV5 Geospatial's professional land surveyor, Evon Silvia (WAPLS#53957) oversaw and certified the occupation of all monuments.

Table 5: Base Station positions for the Washington DNR 3DEP Processing acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Base Station ID	Type	Latitude	Longitude	Ellipsoid (meters)
IDCA	Hexagon SmartNet	47 ° 44' 29.61947"	-116° 47' 47.49273"	685.049
WASK	Hexagon SmartNet	47° 39' 56.58405"	-117° 25' 14.01702"	573.440
GRCK	WSRN	48° 08' 36.89036"	-117° 39' 52.39033"	670.167
KOOT	WSRN	47° 46' 14.67800"	-116° 48' 34.65028"	686.211
SPKN	WSRN	47° 37' 39.57163"	-117° 30' 09.22643"	695.039
DVPT	WSRN	47° 39' 21.83779"	-118° 08' 52.07016"	728.024

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 (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.

Ground Survey Points (GSPs)

Ground survey points were collected using RTK and total station (TS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or 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. 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 were collected using total stations in order to measure positions under dense canopy. Total station 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 6: NV5 Geospatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	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 7, see Lidar Accuracy Assessments, page 20).

Table 7: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrub	SHRUB		Areas dominated by lowland brush and woody vegetation	VVA
Tall Grass	TALL_GRASS		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FOREST		Forested areas dominated by trees	VVA
Bare Earth	BARE		Areas of bare earth surface	NVA
Urban	URBAN		Areas dominated by urban development, including parks	NVA

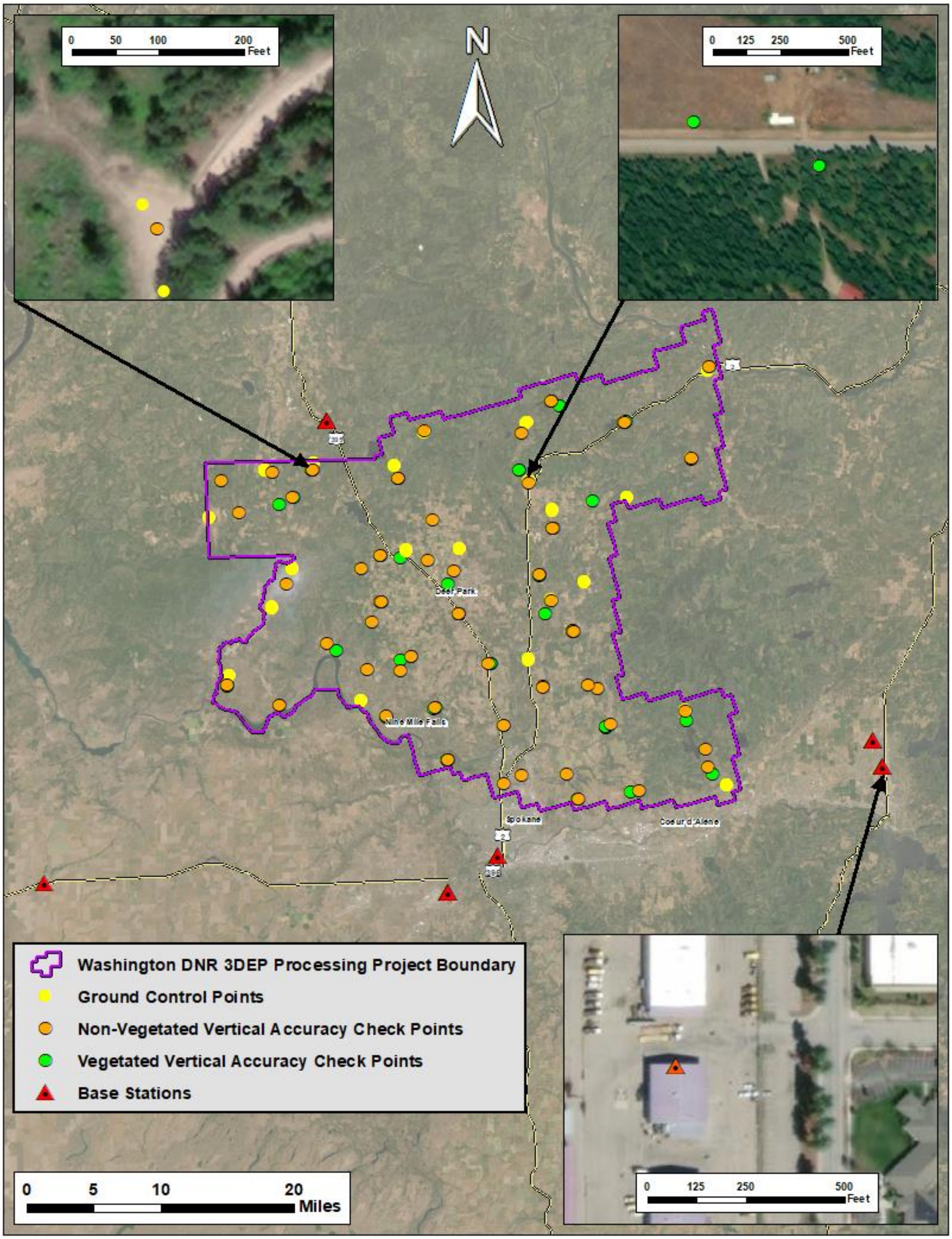
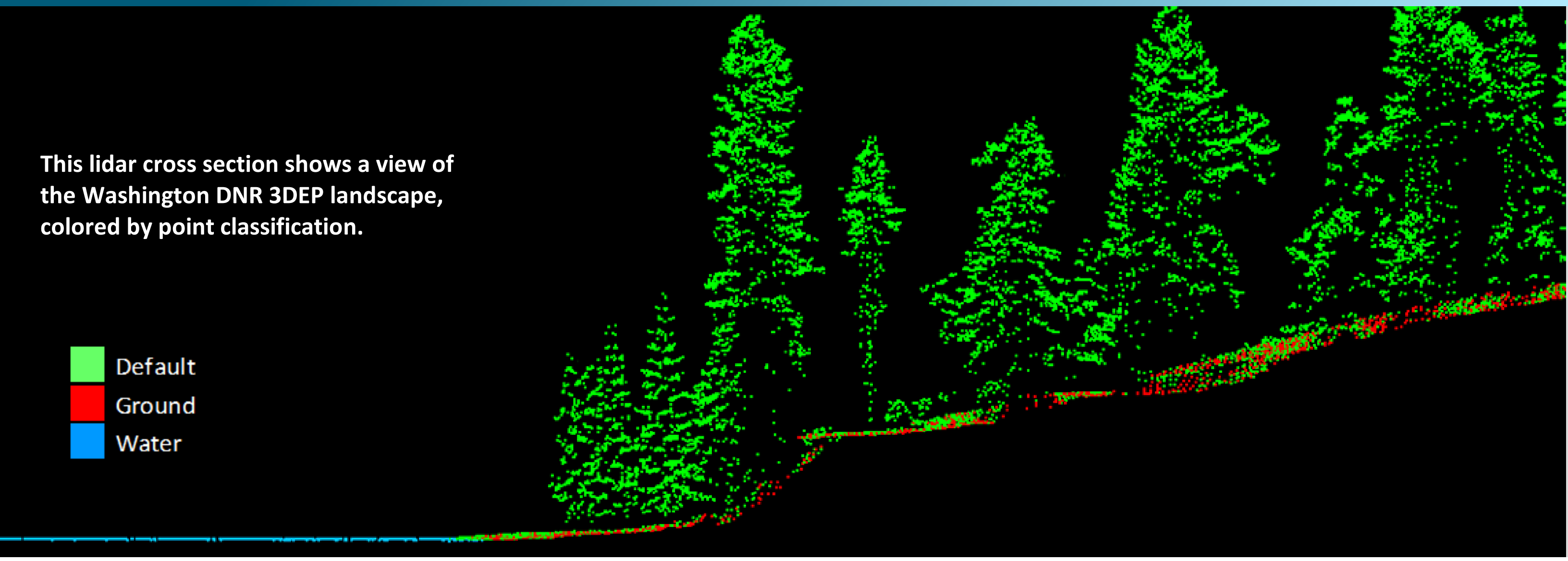


Figure 3: Ground survey location map



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 Washington DNR 3DEP Processing dataset

Classification Number	Classification Name	Point Count	Classification Description
1	Default/Unclassified	48,054,452,896	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-W	Unclassified Withheld	4,302,000,547	Edge-clipped laser returns. These points should not be used for analysis purposes
2	Ground	9,386,778,334	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7-W	Low Noise	104,968,725	Laser returns that are often associated with scattering from reflective surfaces, or artificial points below the ground surface
9	Water	120,140,256	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	1,507,084	Bridge decks
18-W	High Noise	140,004,049	Above ground laser returns that are often associated with birds or scattering from reflective surfaces.
20	Ignored Ground	1,028,801	Ground points proximate to water's edge breaklines; ignored for correct model creation

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 to Geoid12B.	RiProcess 1.8.5 RiWorld 5.1.4
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines. Transform points from NAD83(CORS96) to NAD83(2011).	TerraScan v.19.005
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.19.002
Transform points from Geoid12B to Geoid18 and from Washington State Plane South to Washington State Plane North.	LasProjector v1.3 (NV5 Geospatial proprietary)
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 highest hit models as a surface expression of all classified points. Export all surface models, as Cloud Optimized GeoTIFFs at a 2.0 foot pixel resolution.	LAS Product Creator 3.0 (NV5 Geospatial proprietary) ArcMap v. 10.3.1
Correct intensity values for variability and export intensity images as Cloud Optimized GeoTIFFs at a 2.0 foot pixel resolution.	Las Monkey 2.6.2 (NV5 Geospatial proprietary) LAS Product Creator 3.0 (NV5 Geospatial proprietary)

Feature Extraction

Hydroflattening and Water's Edge Breaklines

Rivers and 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, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

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

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered lidar returns to create the final breaklines. Lakes were assigned a consistent elevation for an entire polygon while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 4).

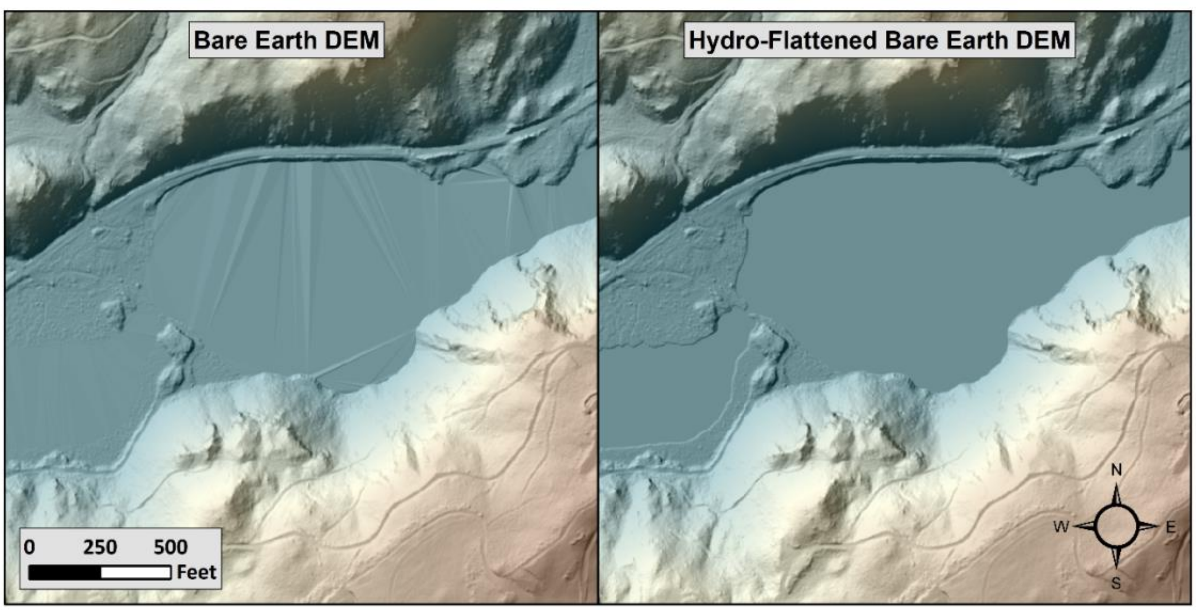
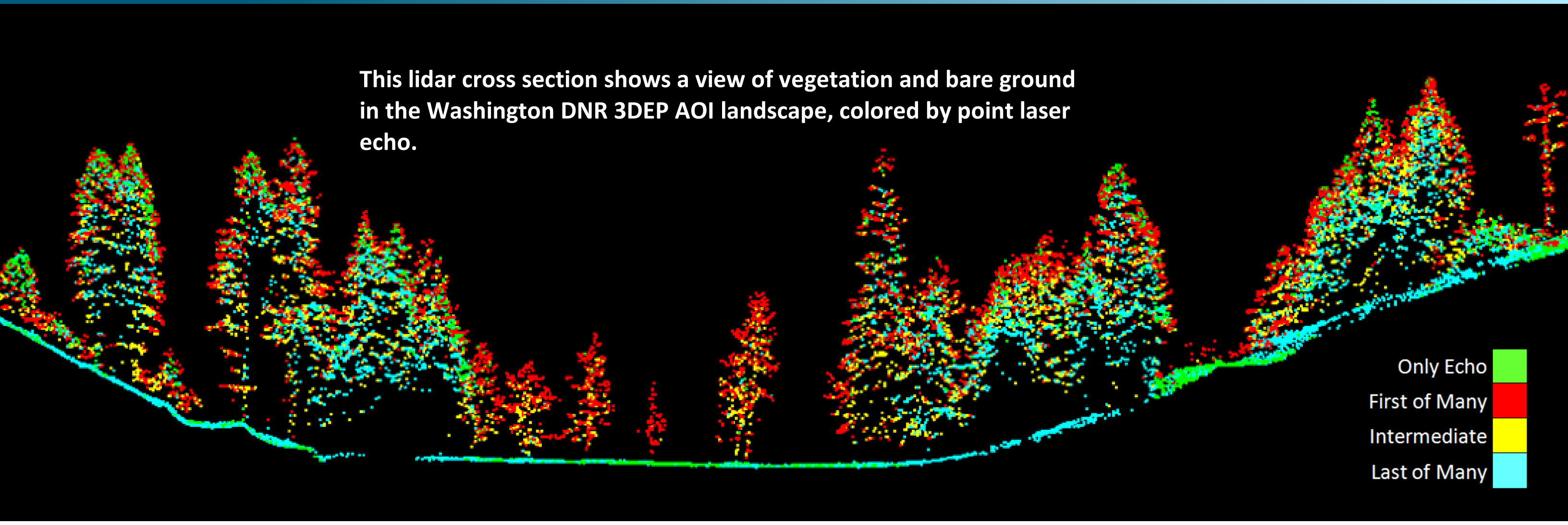


Figure 4: Example of hydroflattening in the Washington DNR 3DEP Lidar dataset



Lidar 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 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 Washington DNR 3DEP Processing project is 1.65 points/ft^2 (17.75 points/m^2) while the average ground classified density was 0.39 points/ft^2 (4.18 points/m^2) (Table 10). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 5 through Figure 7.

Table 10: Average lidar point densities

Classification	
First-Return	1.65 points/ft^2 17.75 points/m^2
Ground Classified	0.39 points/ft^2 4.18 points/m^2

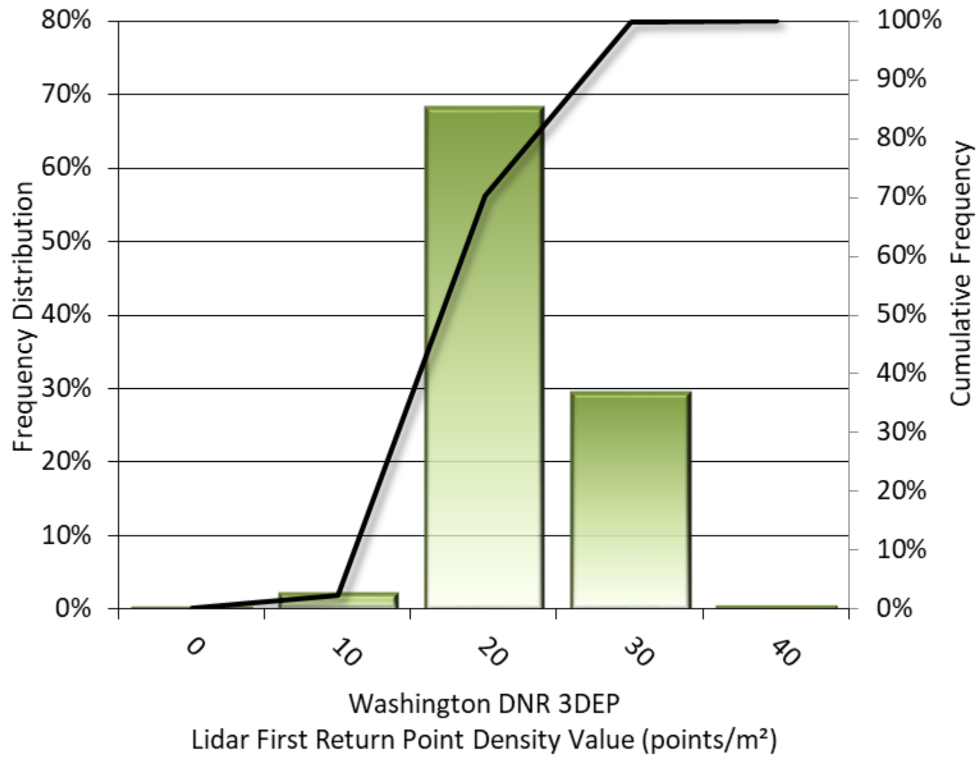


Figure 5: Frequency distribution of lidar first return point density values per 100 x 100 m cell for the Washington DNR 3DEP site

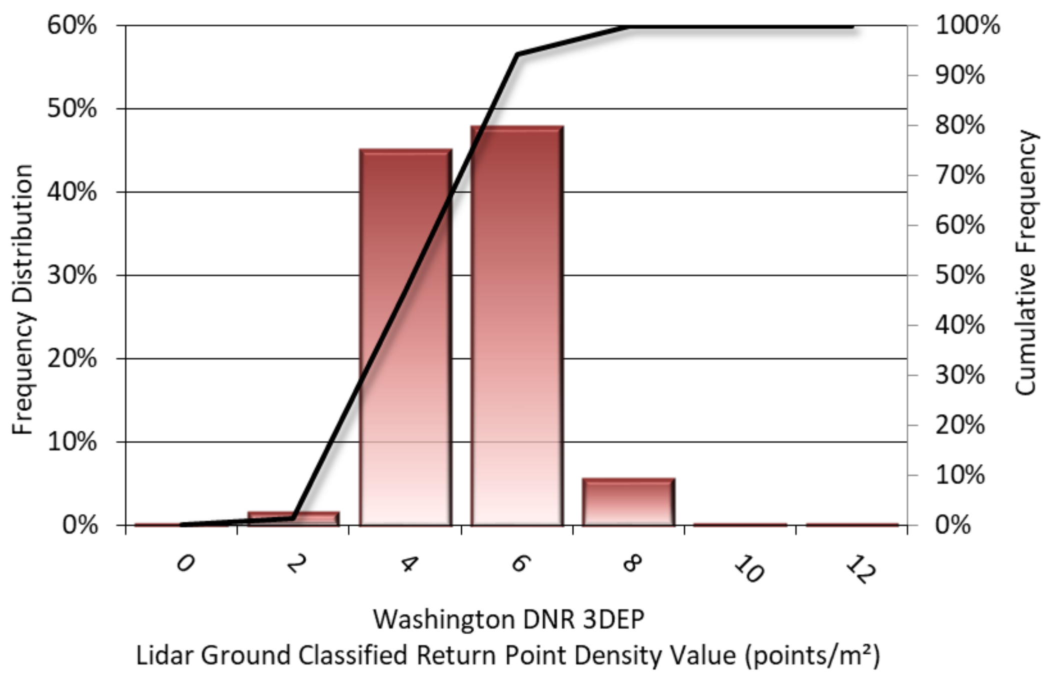


Figure 6: Frequency distribution of lidar ground classified return point density values per 100 x 100 m cells for the Washington DNR 3DEP site

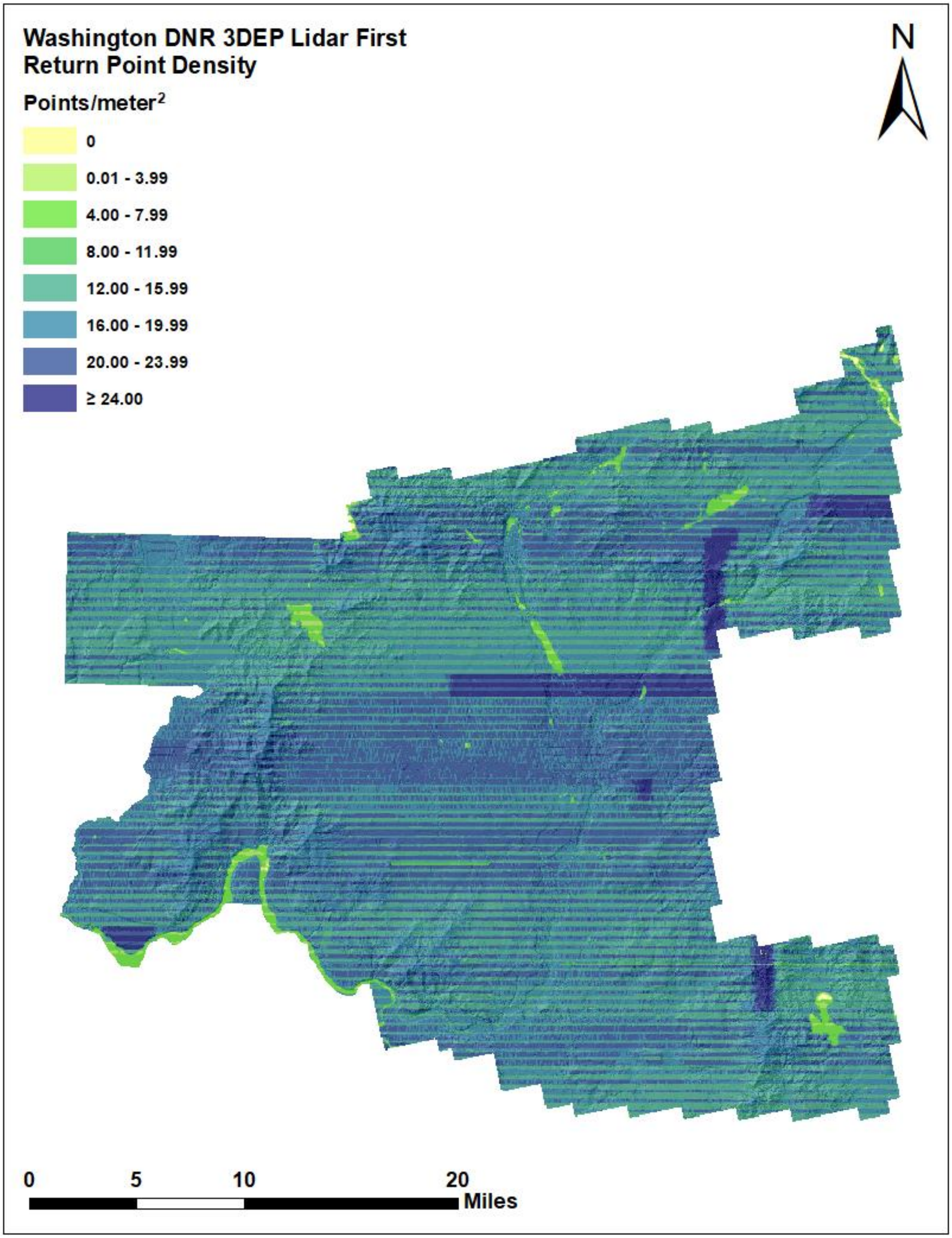


Figure 7: First Return point density map for the Washington DNR 3DEP Processing site (100 m x 100 m cells)

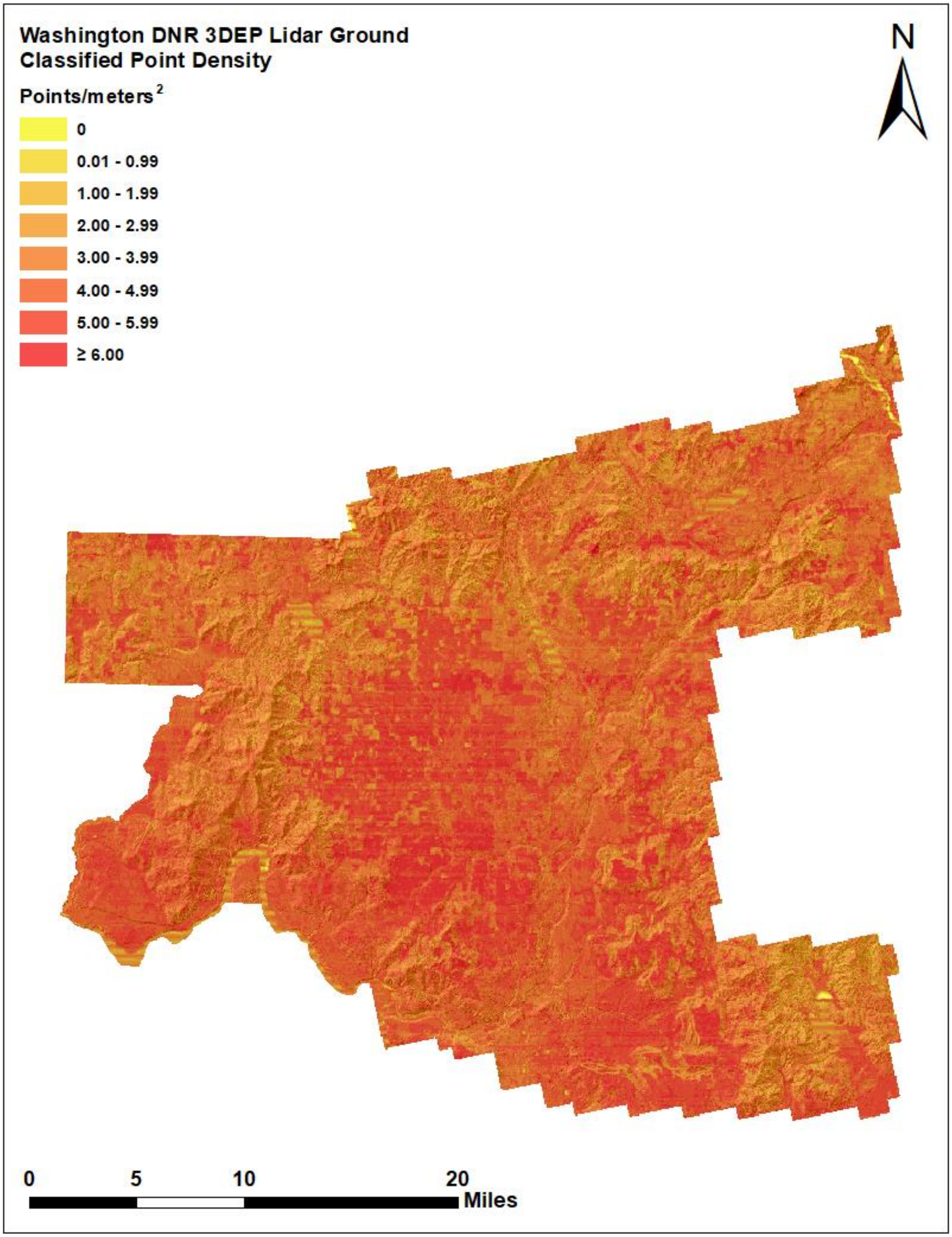


Figure 8: Ground point density map for the Washington DNR 3DEP Processing site (100 m x 100 m cells)

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[2]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated ground 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 Washington DNR 3DEP Processing project 64 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.150 feet (0.046 meters) as compared to ground classified LAS, and 0.147 feet (0.045 meters) as compared to the bare earth DEM, with 95% confidence (Figure 9, Figure 10).

NV5 Geospatial assessed absolute accuracy for the Washington DNR 3DEP Processing project using 221 ground control points respectively. 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 11.

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[2] 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

Washington DNR 3DEP Absolute Vertical Accuracy			
	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	64 points	64 points	221 points
95% Confidence (1.96*RMSE)	0.150 ft 0.046 m	0.147 ft 0.045 m	0.158 ft 0.048 m
Average	0.036 ft 0.011 m	0.035 ft 0.011 m	0.020 ft 0.006 m
Median	0.045 ft 0.014 m	0.042 ft 0.013 m	0.023 ft 0.007 m
RMSE	0.077 ft 0.023 m	0.075 ft 0.023 m	0.081 ft 0.025 m
Standard Deviation (1σ)	0.068 ft 0.021 m	0.067 ft 0.020 m	0.078 ft 0.024 m

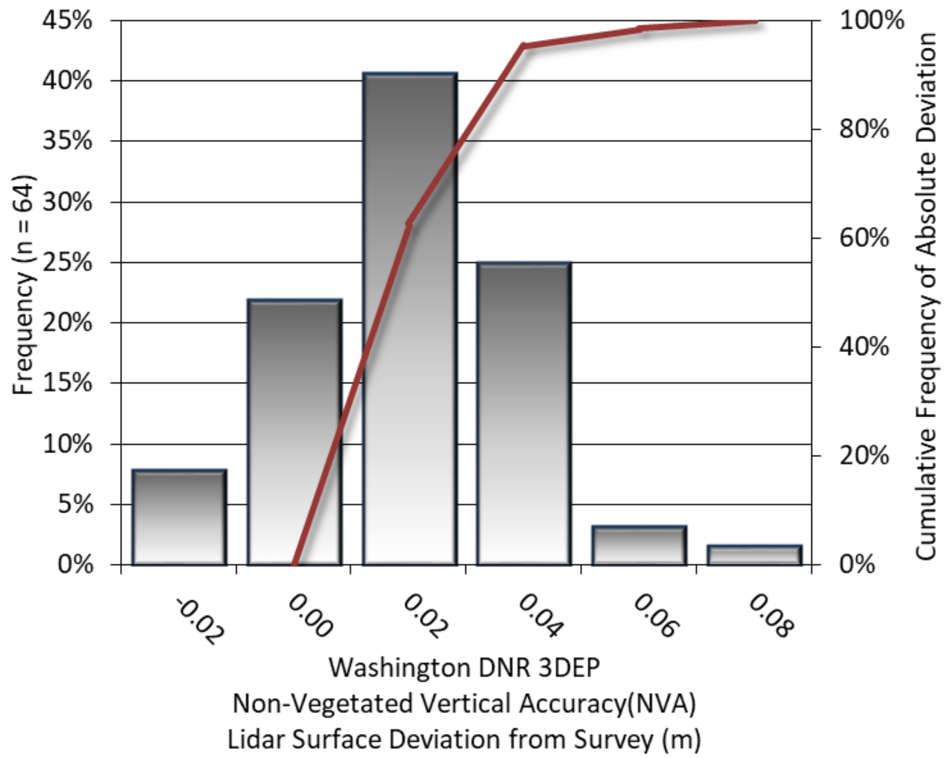

Figure 9: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA) for the Washington DNR 3DEP site

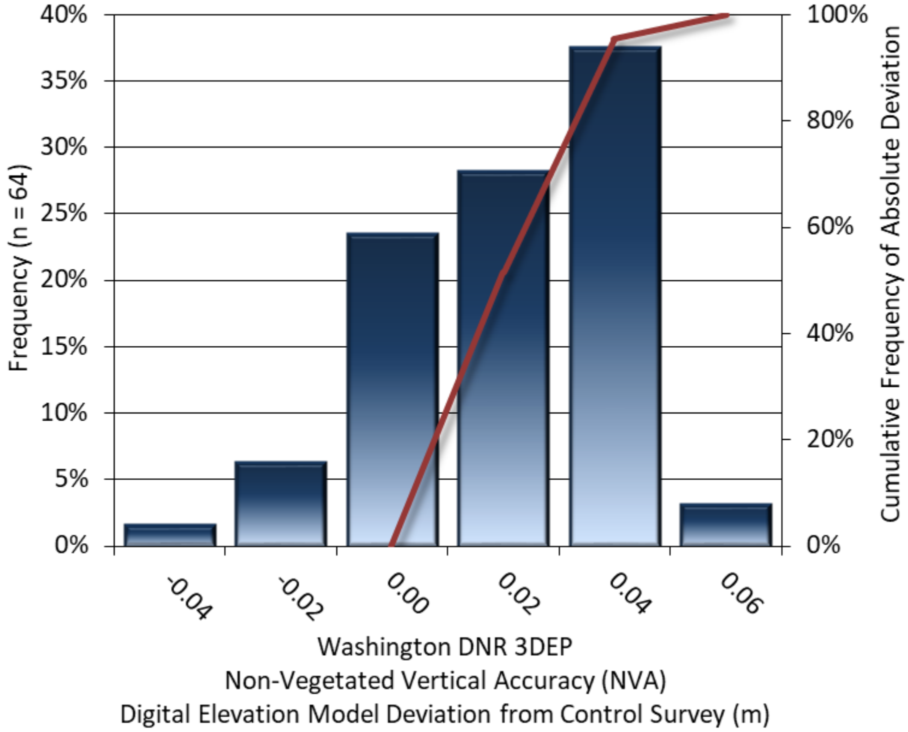

Figure 10: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA) for the Washington DNR 3DEP site

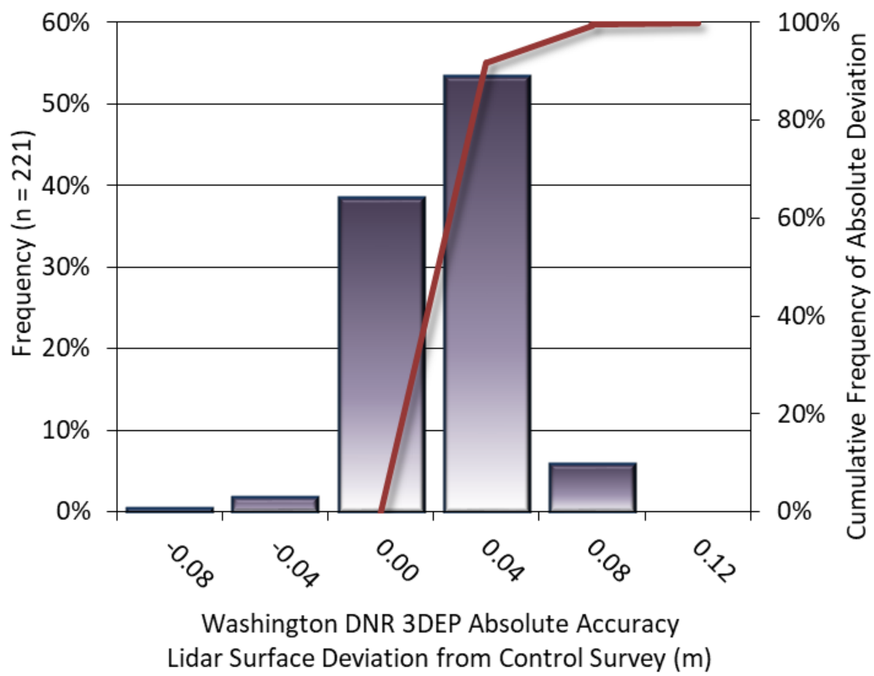

Figure 11: Frequency histogram the for lidar surface deviation from ground control point values for the Washington DNR 3DEP site

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 Washington DNR 3DEP survey, 43 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.463 feet (0.141 meters) as compared to the ground classified LAS, and 0.447 feet (0.136 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 12, Figure 13).

Table 12: Vegetated vertical accuracy results

Vegetated Vertical Accuracy (VVA)		
	VVA, as compared to classified LAS	**VVA, as compared to bare earth DEM**
Sample	43 points	43 points
95th Percentile	0.463 ft 0.141 m	0.447 ft 0.136 m
Average	0.252 ft 0.077 m	0.256 ft 0.078 m
Median	0.228 ft 0.069 m	0.214 ft 0.065 m
RMSE	0.320 ft 0.098 m	0.331 ft 0.101 m
Standard Deviation (1σ)	0.200 ft 0.061 m	0.213 ft 0.065 m

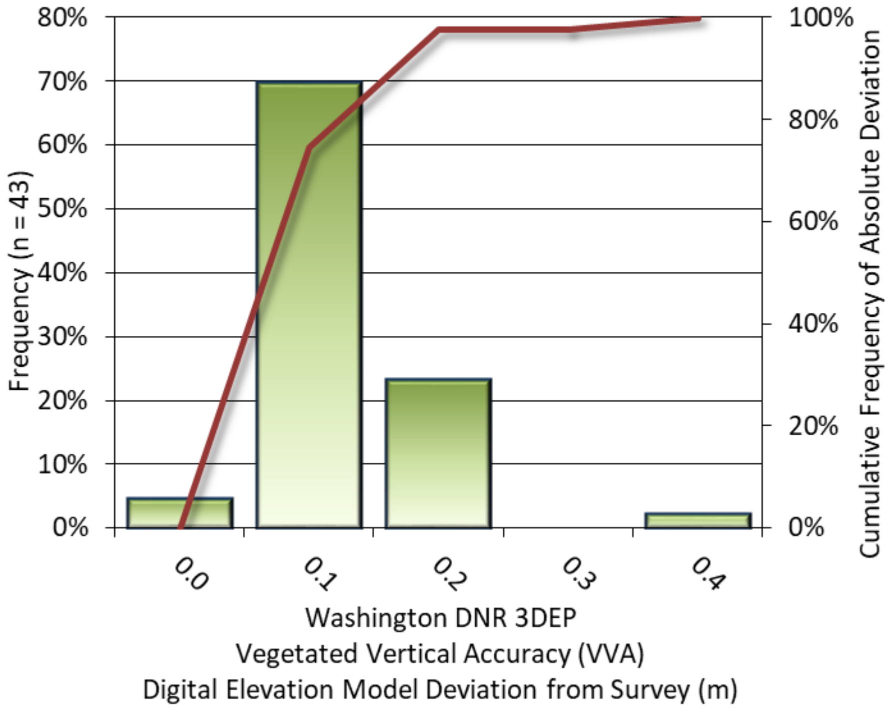

Figure 12: Frequency histogram for the lidar bare earth digital elevation model deviation from vegetated check point values (VVA)

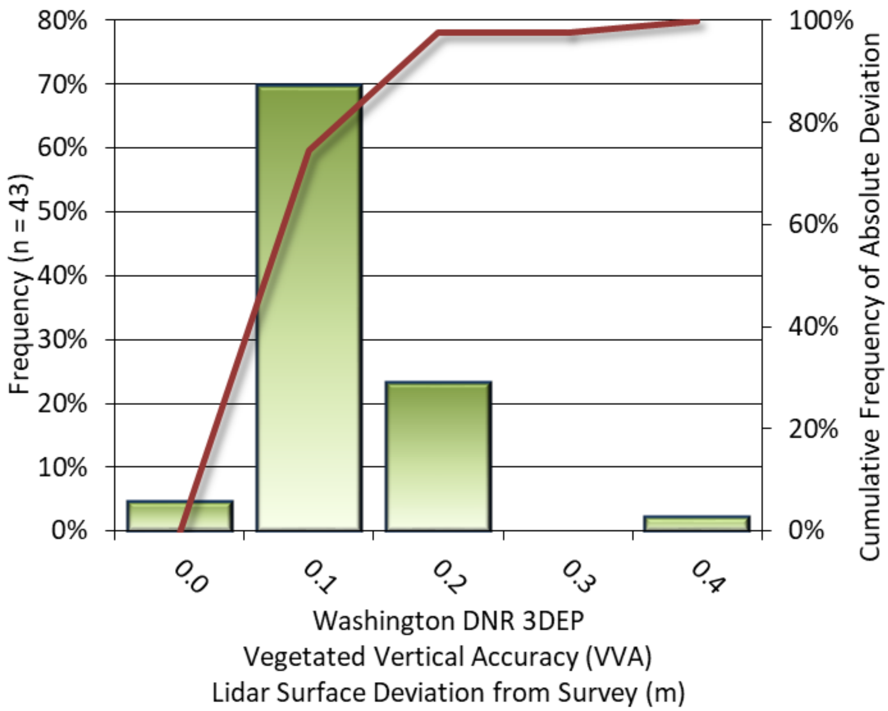

Figure 13: Frequency histogram for the lidar surface deviation from vegetated check point values (VVA)

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 Washington DNR 3DEP Processing lidar project was 0.084 feet (0.026 meters) (Table 13).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	169 flight line surfaces
Average	0.084 ft 0.026 m
Median	0.084 ft 0.026 m
RMSE	0.089 ft 0.027 m
Standard Deviation (1σ)	0.012 ft 0.004 m
1.96σ	0.024 ft 0.007 m

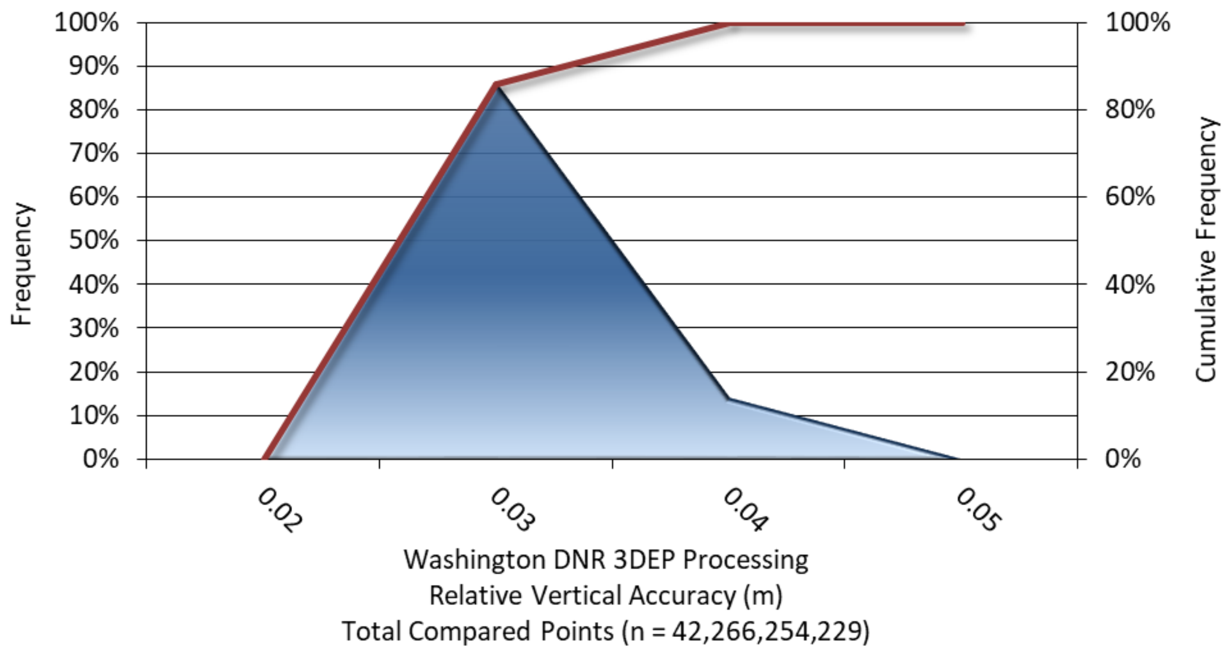

Figure 14: Frequency plot for relative vertical accuracy between flight lines for the Washington DNR 3DEP Processing site

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 1,830 meters, an IMU error of 0.003 decimal degrees, and a GNSS positional error of 0.015 meters, the Washington DNR 3DEP Processing site was compiled to meet 0.98 feet (0.30 meters) horizontal accuracy at the 95% confidence level (Table 14).

Table 14: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.56 ft 0.17 m
ACC_r	0.98 ft 0.30 m

CERTIFICATIONS

NV5 Geospatial, Inc. provided lidar services for the Washington DNR 3DEP Processing 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.

Feb 1, 2021

Tucker Selko
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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 April 29 and May 03, 2019.

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”.

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Figure 15: A view looking east over Swamp Creek, Washington located within the Springdale and North Spokane County project area. This image was created with the lidar derived bare earth surface and is colored by imagery.

GLOSSARY

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68th percentile) of a normally distributed data set.

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (NVA) reporting.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma σ) and root mean square error (RMSE).

> **Absolute Accuracy:** The vertical accuracy of lidar data is described as the mean and standard deviation (sigma σ) of divergence of lidar point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
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> **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).
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> **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.

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 ±29.25° 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.