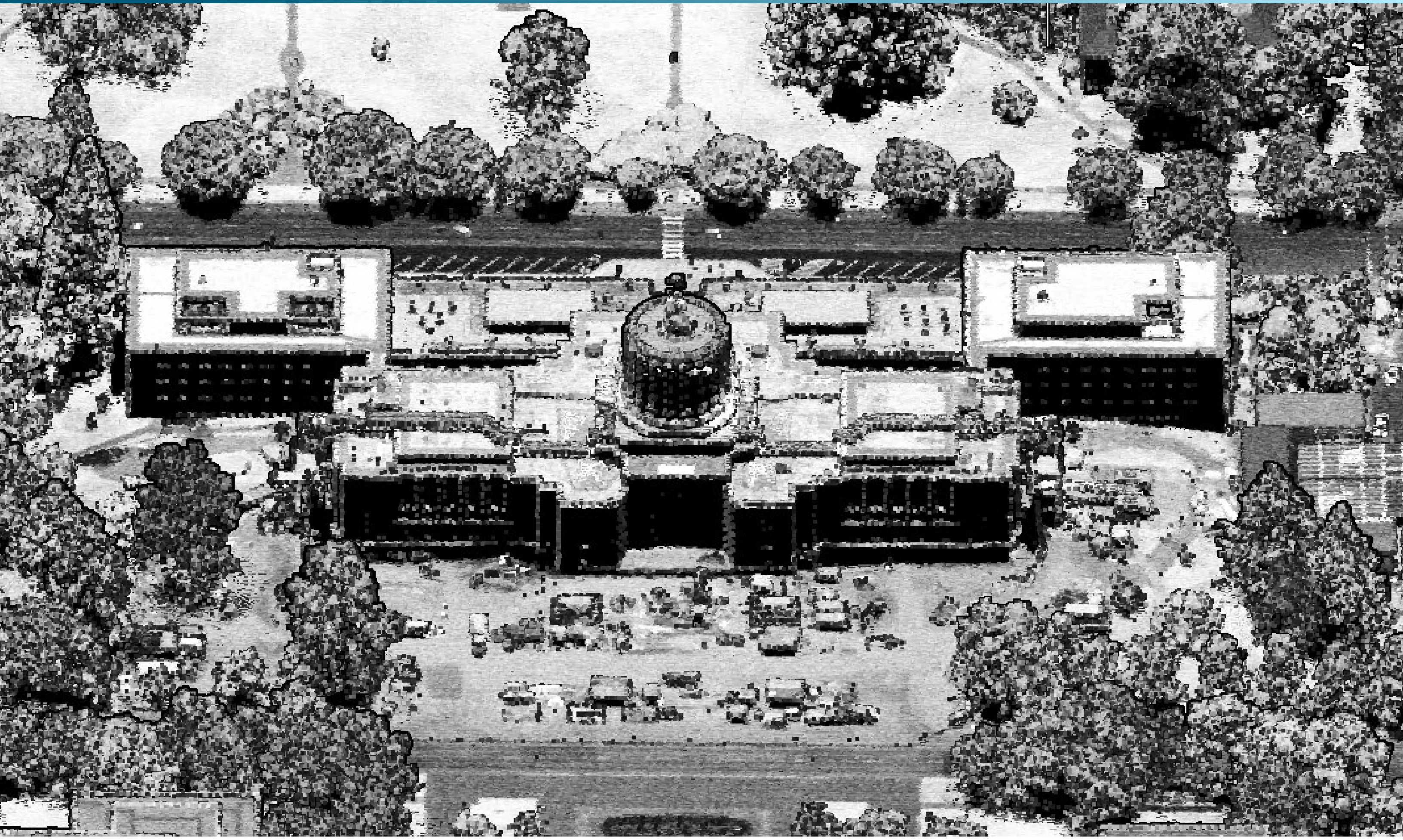
December 6, 2023



OLC Willamette Valley, Oregon NIR Lidar

2023 Technical Data Report

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Cover Photo: A view looking southeast over the Oregon State Capitol Building in Salem. The image was created from the OLC Willamette Valley data lidar point cloud and symbolized by intensity values.

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INTRODUCTION

This photo, taken by NV5 Survey crew shows a view of the valley flora in the OLC Willamette Valley sites in Oregon.

In January 2023, NV5 Geospatial (NV5) was contracted by Oregon Lidar Consortium (OLC), the Department of Geology and Mineral Industries (DOGAMI) to collect Quality Level 1 (QL1) Light Detection and Ranging (lidar) data during the summer of 2023 for the OLC Willamette Valley sites in Oregon. The Willamette Valley is the largest valley in the state of Oregon stretching between the Coast Mountain and Cascade Mountain ranges. This project covers two areas of interest. The first encompassing Salem, while the second area of interest covers the city of Eugene and outlying areas. This project was designed to support OLC and DOGAMI mission to obtain elevation data to better manage and protect lives, property, and the environment as well as improve planning for future projects.

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, deliverable projection information is shown in Table 2, a complete list of contracted deliverables provided to DOGAMI is shown in Table 3, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, square miles, and data type collected for OLC Willamette Valley 2023 sites

Project Sites	Contracted Square Miles	Aerial Acquisition Dates	Data Type
OLC Willamette Valley, Oregon	667	7/21/2023 and 7/22/2023	NIR - Lidar

Deliverable Products

Table 2: Deliverable product projection information

Projections	Horizontal Datum	Vertical Datum	Units
Oregon Statewide Lambert (EPSG 6557)	NAD83 (2011)	NAVD88 (GEOID18)	International Feet

Table 3: Products delivered to DOGAMI for the OLC Willamette Valley sites

Product Type	File Type	Product Details
Points	LAZ v.1.4 (*.laz)	• All Classified Returns with RGB encodings
Rasters	3.0 Foot Cloud-Optimized GeoTiffs (*.tif)	• Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM)
Rasters	1.5 foot Cloud-Optimized GeoTIFFs (*.tif)	• Intensity Images • Swath Separation Images
Vectors	Shapefiles (*.shp)	• Defined Project Area • Total Area Flown • Lidar Tile Index • Ground Survey Shapes • Aerial Acquisition Shapes (Lidar Flightlines and Swaths)
Metadata	Extensible Markup Language (*.xml)	• Metadata
Reports	Adobe Acrobat (*.pdf)	• Lidar Technical Data Report

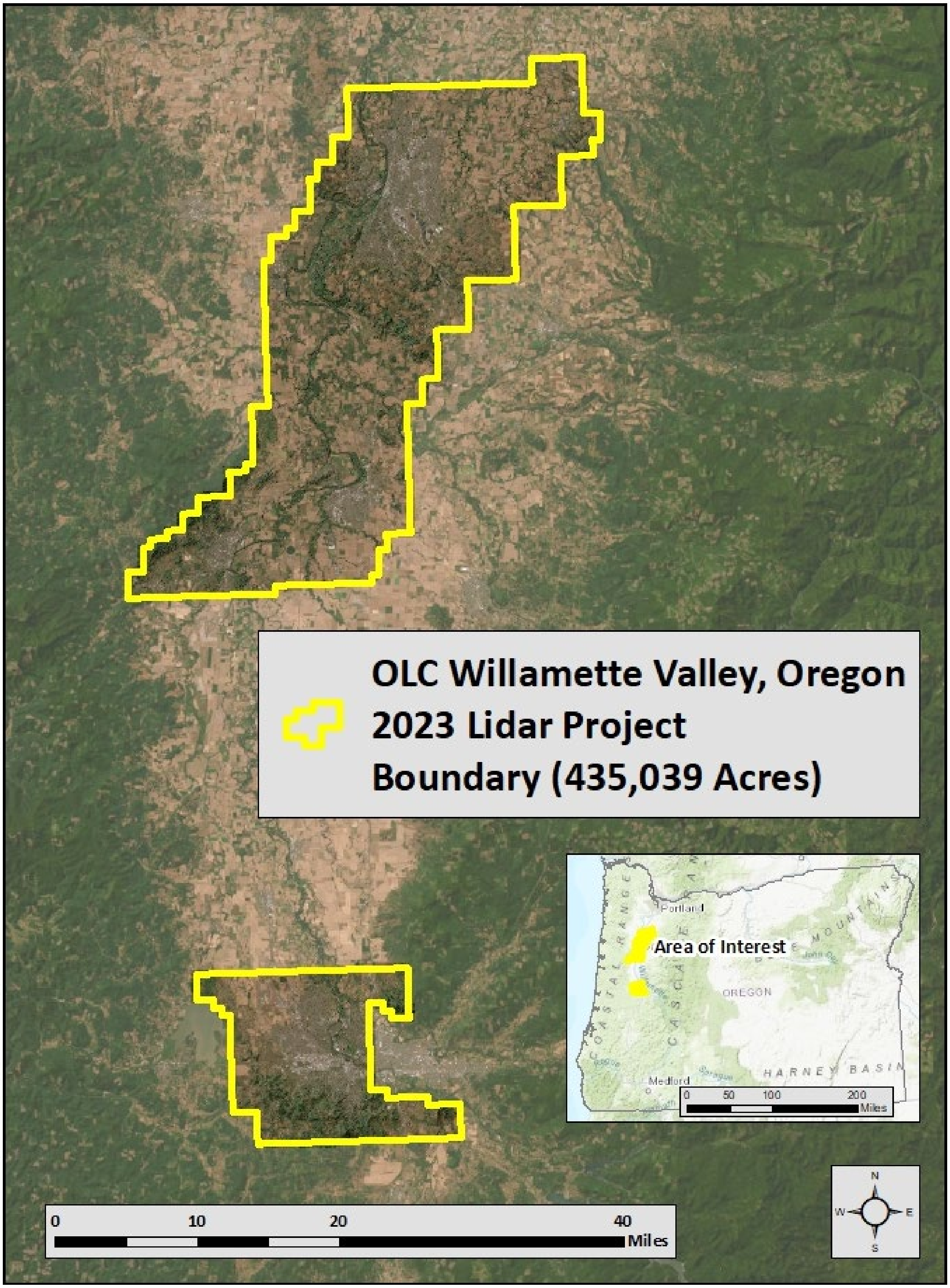


Figure 1: Location map of the OLC Willamette Valley sites in Oregon

ACQUISITION

NV5 Geospatial's ground acquisition equipment set up in the OLC Willamette Valley 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 OLC Willamette Valley lidar study area at the target point density of greater than or equal to 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. Figure 2 and Table 4 show these optimized flight paths and the date of acquisition.

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 access and potential air space restrictions were reviewed.

Table 4: Flight Date Table

Date	Flight Line Number	Start Time (Adjusted GPS)	End Time (Adjusted GPS)
7/21/2023	101 – 110, 112 – 116, 118 – 122, 124 - 126	373971675	373988022
7/22/2023	200 – 217, 300, 302-313, 315 - 320	374052191	374084405

Airborne Lidar Survey

The lidar survey was accomplished using a Riegl VQ-1560ii-S system mounted in a Cessna Grand Caravan. Table 5 summarizes the settings used to yield an average pulse density of greater than or equal to 8 pulses/m^2 over the OLC Willamette Valley project area. The Riegl VQ-1560ii-S 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. The typical number of returns digitized from a single pulse range from 1 to 15 for the OLC Willamette Valley project area. 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. Figure 2 shows the flightlines acquired using these lidar specifications.

Table 5: Lidar specifications and aerial survey settings

Parameter	NIR Laser
Acquisition Dates	7/21/2023 and 7/22/2023
Aircraft Used	Cessna Grand Caravan
Sensor	Riegl
Laser Channel	VQ-1560ii-S
Maximum Returns	15
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	2,532 m
Survey speed	145 knots
Field of View	58.5°
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	767 kHz
Pulse Length	3 ns
Laser Pulse Footprint Diameter	58 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.23 mrad
Swath Width	2,836 m
Swath Overlap	55%
Intensity	16-bit
Vertical Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
Horizontal Accuracy	Horizontal Accuracy ≤ 30 cm
Relative Accuracy	Relative Accuracy ≤ 6 cm

Riegl VQ-1560ii-S

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) 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 orientation of the aircraft to the horizon (attitude) 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.

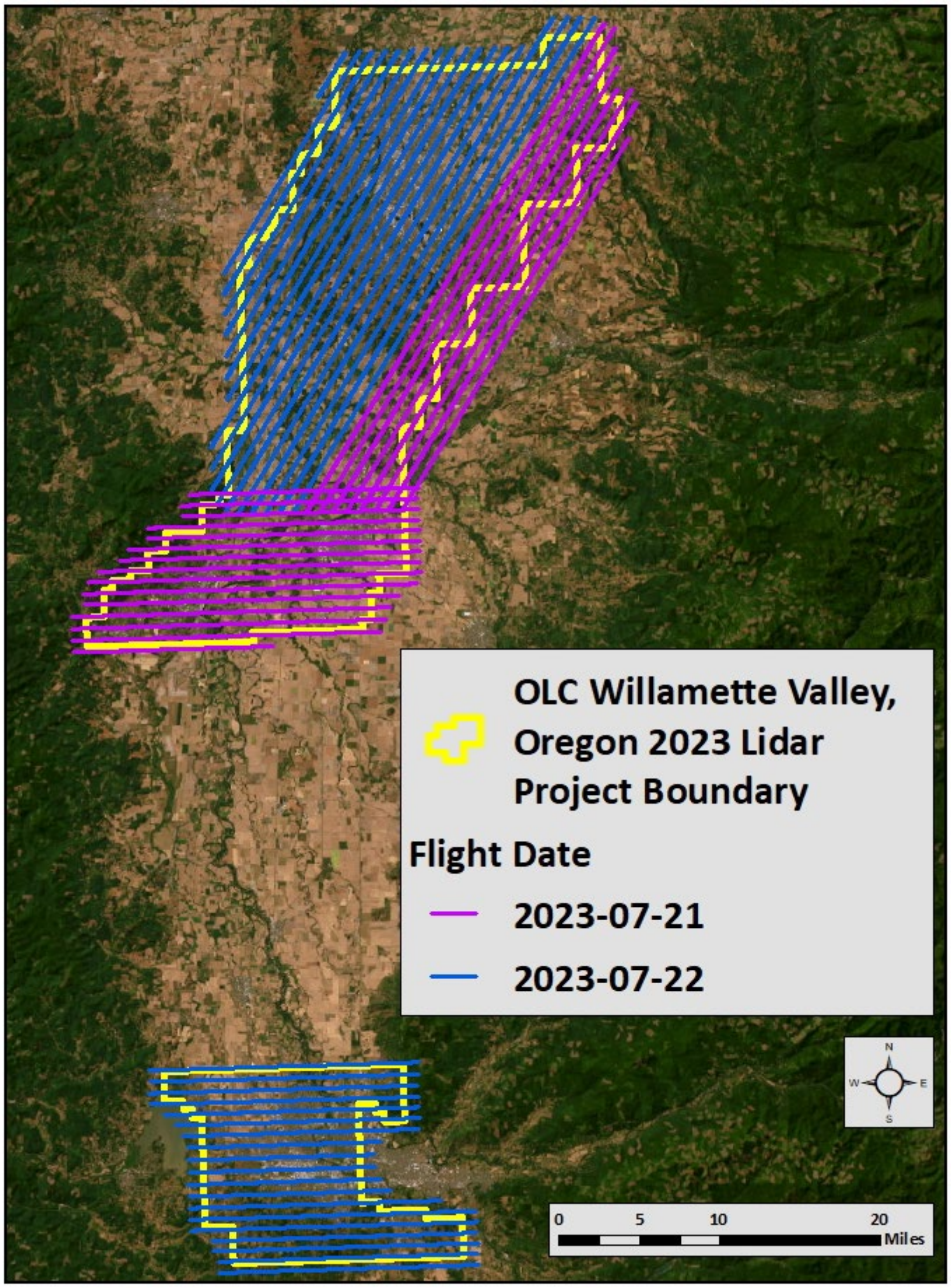


Figure 2: Flightlines map

Ground Survey

Ground control surveys, including 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

Base stations were utilized for collection of ground survey points using real time kinematic (RTK) survey techniques.

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. NV5 Geospatial utilized a total of eleven permanent real-time network (RTN) base stations. Two from the Oregon Real-time GNSS Network (ORGN), three from Hexagon SmartNet network (SMARTNET), and six from the Trimble VRSNow Network (VRSNOW) for the OLC Willamette Valley Lidar project. NV5's professional land surveyor. Evon Silvia (ORPLS#81104) oversaw and certified the ground survey.

Table 6: Base station position for the OLC Willamette Valley acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Owner	Latitude	Longitude	Ellipsoid (meters)
DOWL	ORGN / VRSNOW	44° 03' 57.45920"	-123° 05' 53.27962"	112.197
LPSB	ORGN	44° 03' 04.40923"	-123° 05' 24.24845"	118.098
ORCO	VRSNOW	44° 33' 08.49709"	-123° 16' 06.84133"	56.234
ORDA	VRSNOW	44° 55' 08.66755"	-123° 19' 40.16392"	95.806
OREU	SMARTNET	44° 02' 42.15594"	-123° 09' 42.80356"	106.173
ORLE	VRSNOW	44° 32' 24.91817"	-122° 54' 22.28904"	88.787
ORMO	VRSNOW	45° 09' 18.00812"	-122° 36' 39.62080"	73.771
ORSL	SMARTNET	44° 58' 22.73600"	-122° 57' 19.12064"	46.499
ORST	VRSNOW	44° 47' 50.12988"	-122° 49' 02.18606"	116.806
ORTA	SMARTNET	44° 33' 30.04568"	-123° 06' 39.83928"	61.065
ORVE	VRSNOW	44° 03' 16.93881"	-123° 20' 28.43531"	114.749

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 real time kinematic (RTK) 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 Trimble unit specifications.

Table 7: NV5 Geospatial ground survey equipment identification

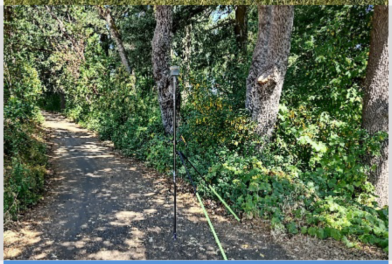
Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R12	Integrated Antenna	TRMR12	Rover

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as sandy beaches and gravel 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 equably distributed throughout the study area (Figure 3).

Land Cover Class

In addition to ground survey points, land cover class checkpoints 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 17).

Table 8: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrub	SH		Low growth shrub	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

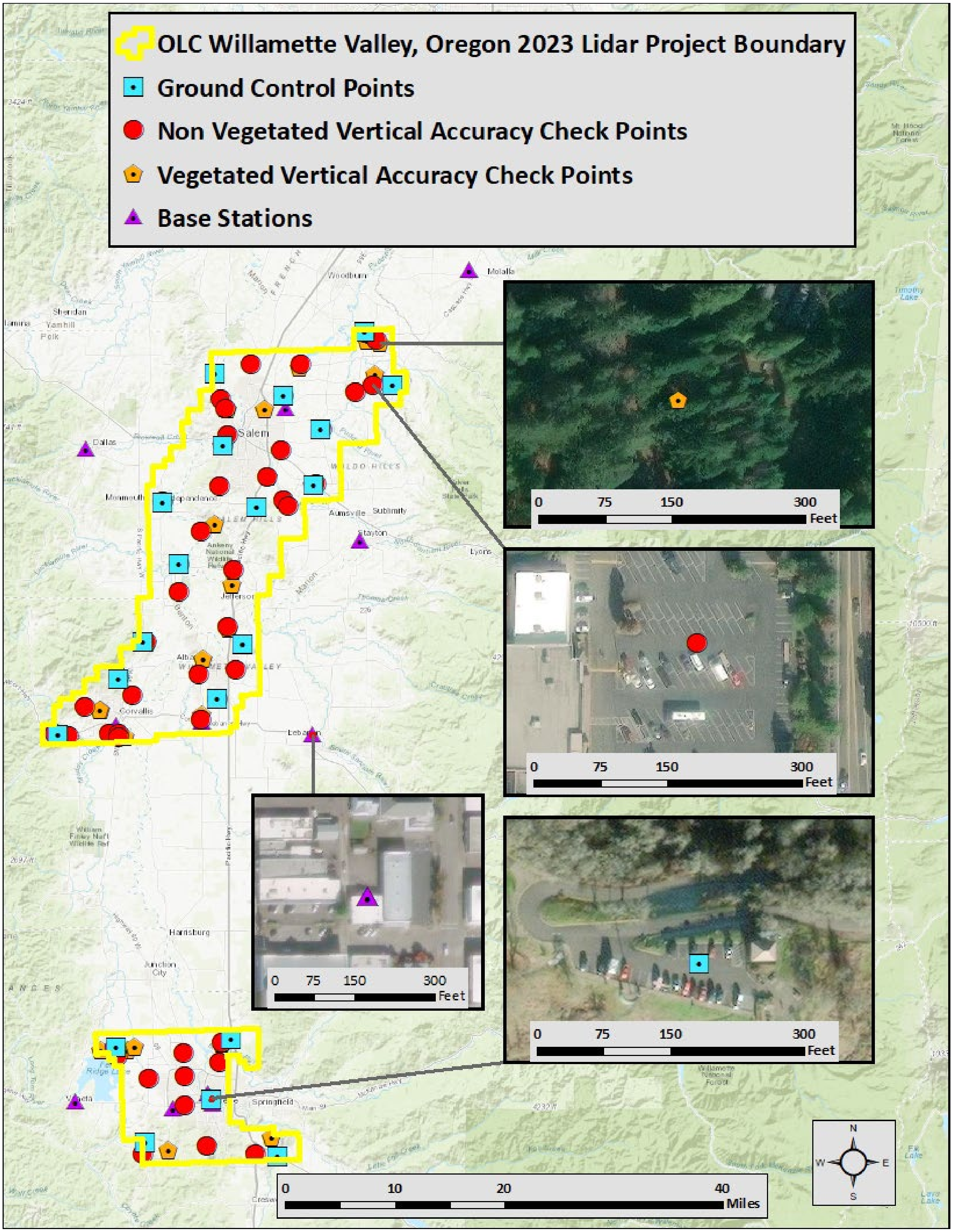
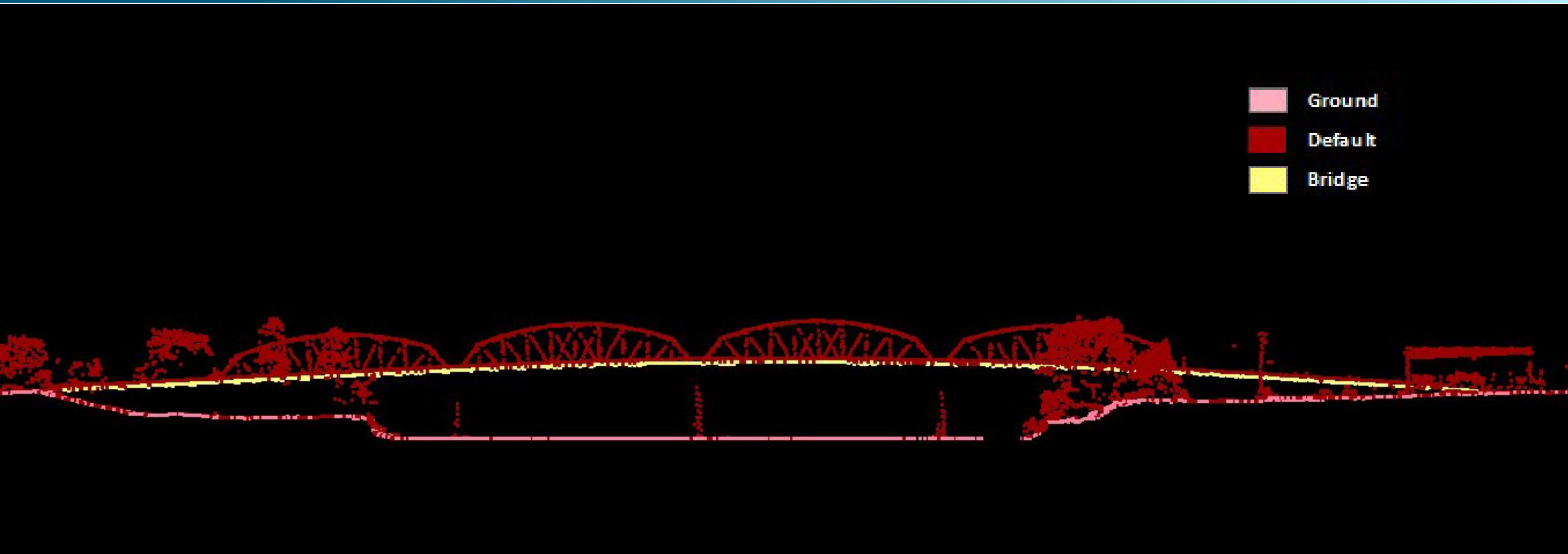


Figure 3: Ground survey location map



This 15 foot lidar cross section shows a view of the Highway 20 bridge over the Willamette River into the city of Albany, colored by point classification.

NIR Lidar Data

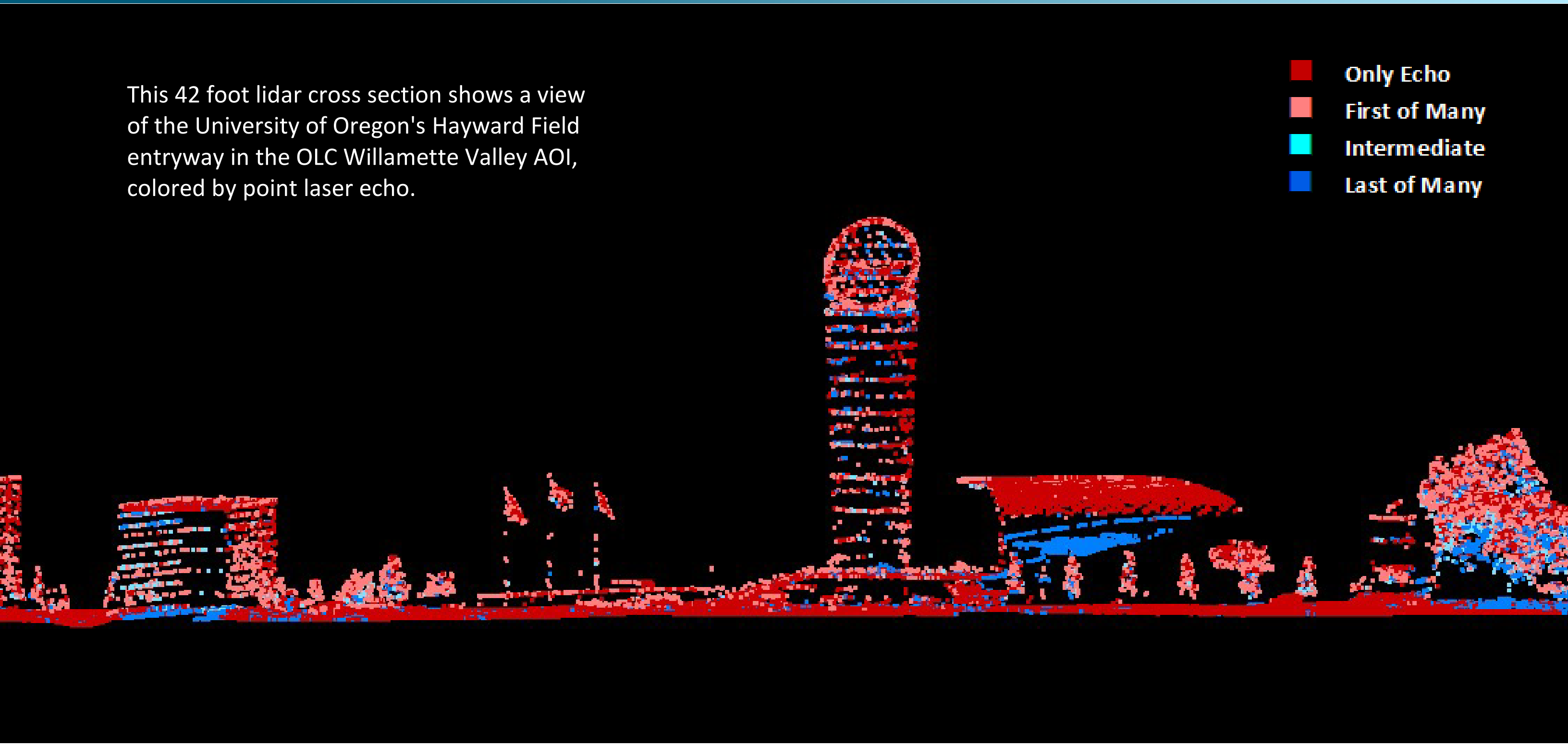
Upon completion of data acquisition, NV5 Geospatial processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor, and data calibration for optimal relative and absolute accuracy, and lidar point classification (Table 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 OLC Willamette Valley dataset

Classification Number	Classification Name	Point Count	Classification Description
1	Default/Unclassified	16,584,849,686	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1W	Edge Clip/Withheld	1,306,878,063	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	8,767,809,031	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7W	Noise/Withheld	12,854,157	Laser returns that are often associated with pitting, scattering from reflective surfaces, or artificial points below the ground surface
17	Bridge	5,664,221	Bridge decks
18W	High Noise	8,838,050	Laser returns that are often associated with birds, scattering from reflective surfaces.

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.8.9
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.	RiUnite v.1.0.3
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.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.	StripAlign v.2.24b
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.19.003
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 3.0 foot pixel resolution.	LAS Product Creator 4.0 (NV5 Geospatial proprietary)
Correct intensity values for variability and export intensity images as Cloud Optimized GeoTIFFs at a 1.5 foot pixel resolution.	LAS Product Creator 4.0 (NV5 Geospatial proprietary)



This 42 foot lidar cross section shows a view of the University of Oregon's Hayward Field entryway in the OLC Willamette Valley AOI, colored by point laser echo.

Lidar Density

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

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

The average first-return density of lidar data for the OLC Willamette Valley project was 1.13 points/ft^2 (12.16 points/m^2) while the average ground classified density was 0.47 points/ft^2 (5.08 points/m^2) (Table 11, Figure 4, and Figure 5). 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 6.

Table 11: Average lidar point densities

Classification	Point Density
First-Return	1.13 points/ft^2 12.16 points/m^2
Ground Classified	0.47 points/ft^2 5.08 points/m^2

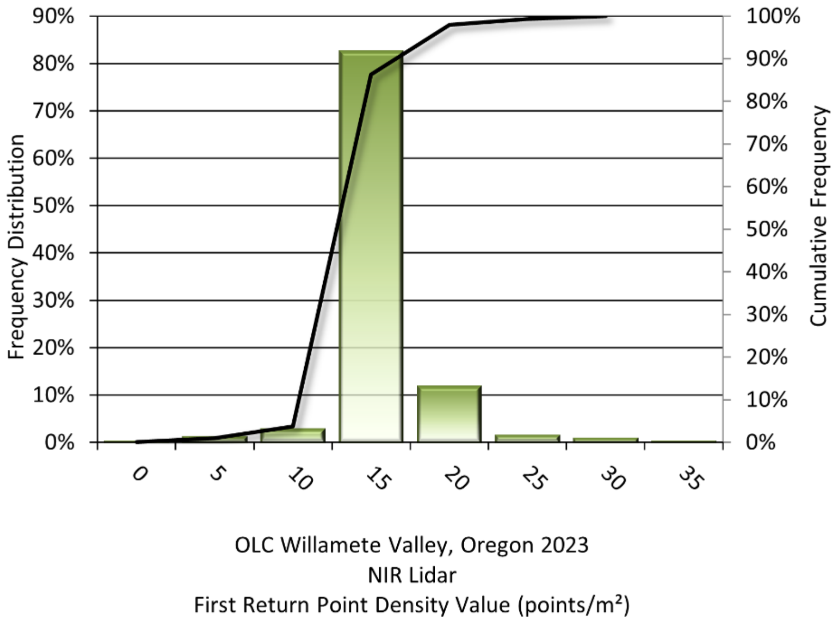


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

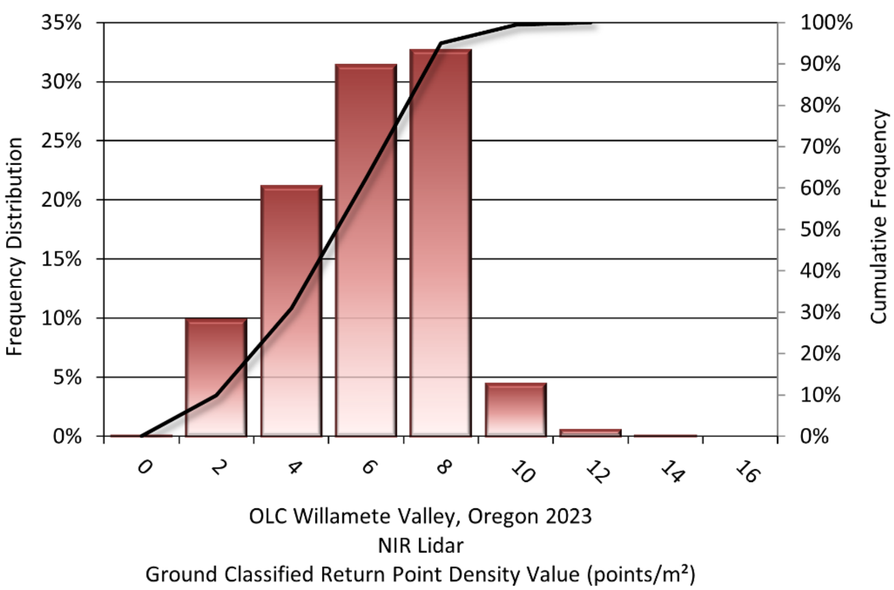


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

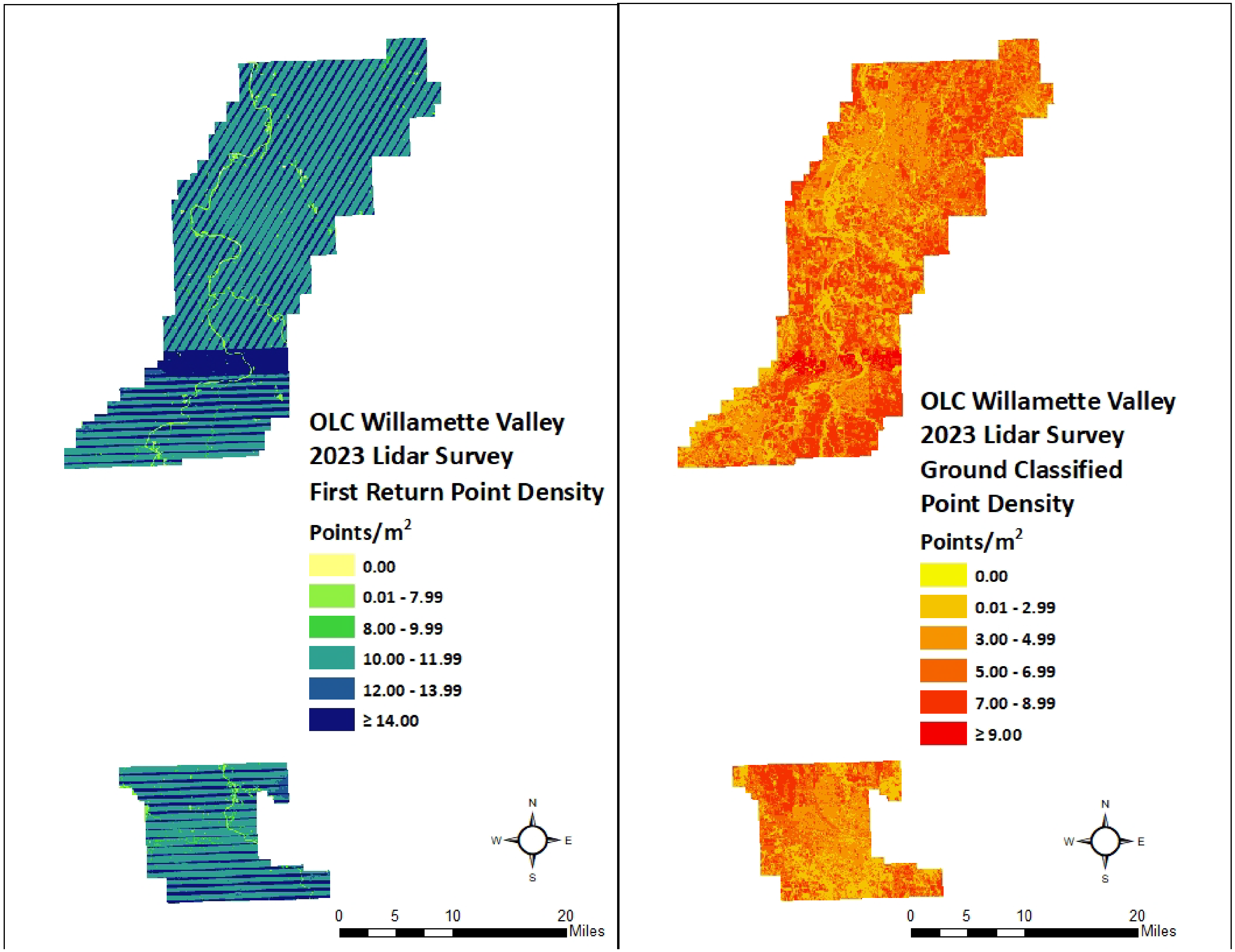


Figure 6: First return and ground-classified point density map for the OLC Willamette Valley sites (100 m x 100 m cells).

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 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) 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 OLC Willamette Valley survey, 48 ground checkpoints were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.152 feet (0.046 meters) as compared to classified LAS, and 0.174 feet (0.053 meters) as compared to the bare earth DEM, with 95% confidence (Figure 7, Figure 8).

NV5 Geospatial also assessed absolute accuracy using 20 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 9.

[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 12: Absolute accuracy results

Parameter	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	48 points	48 points	20 points
95% Confidence (1.96*RMSE)	0.152 ft 0.046 m	0.174 ft 0.053 m	0.119 ft 0.036 m
Average	-0.006 ft -0.002 m	-0.008 ft -0.002 m	-0.001 ft 0.000 m
Median	-0.010 ft -0.003 m	-0.018 ft -0.006 m	0.013 ft 0.004 m
RMSE	0.078 ft 0.024 m	0.089 ft 0.027 m	0.061 ft 0.018 m
Standard Deviation (1σ)	0.078 ft 0.024 m	0.089 ft 0.027 m	0.062 ft 0.019 m

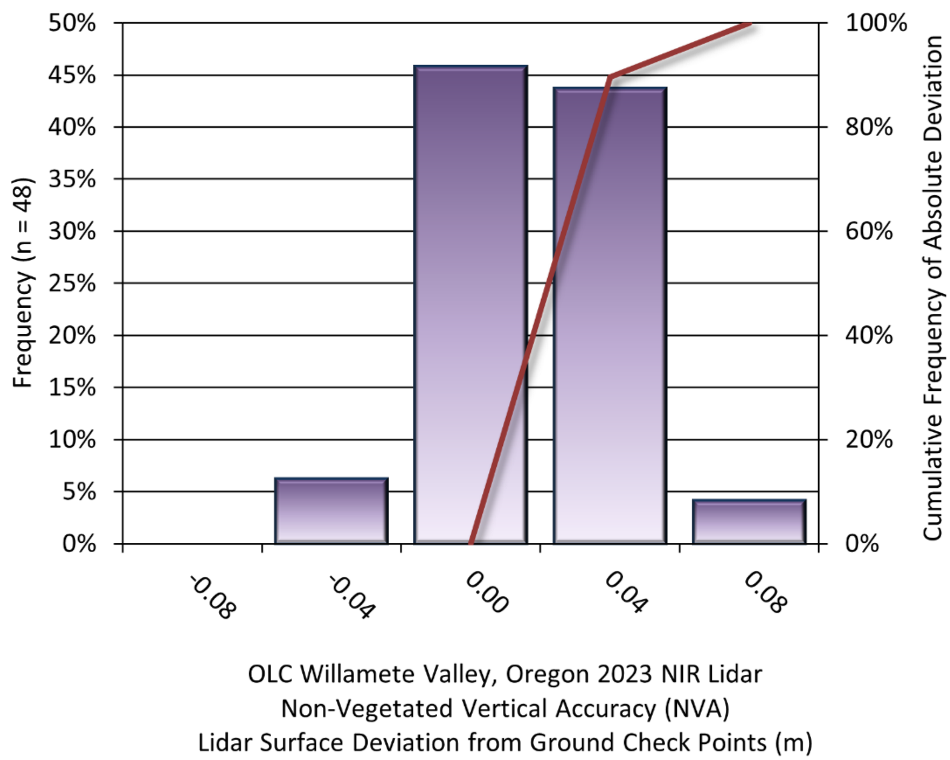


Figure 7: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA)

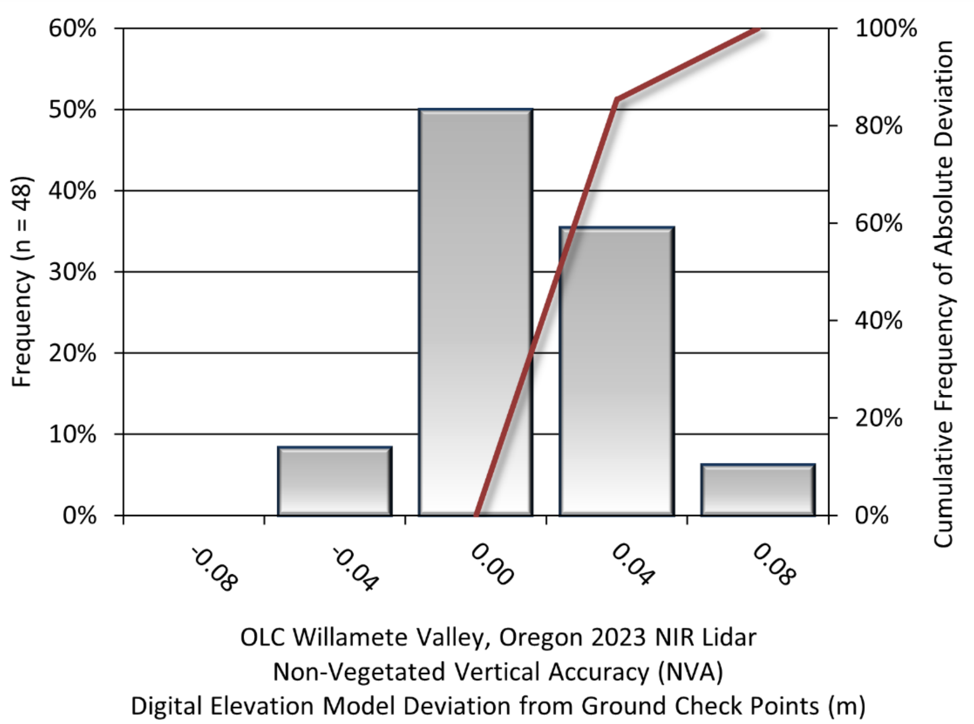


Figure 8: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA)

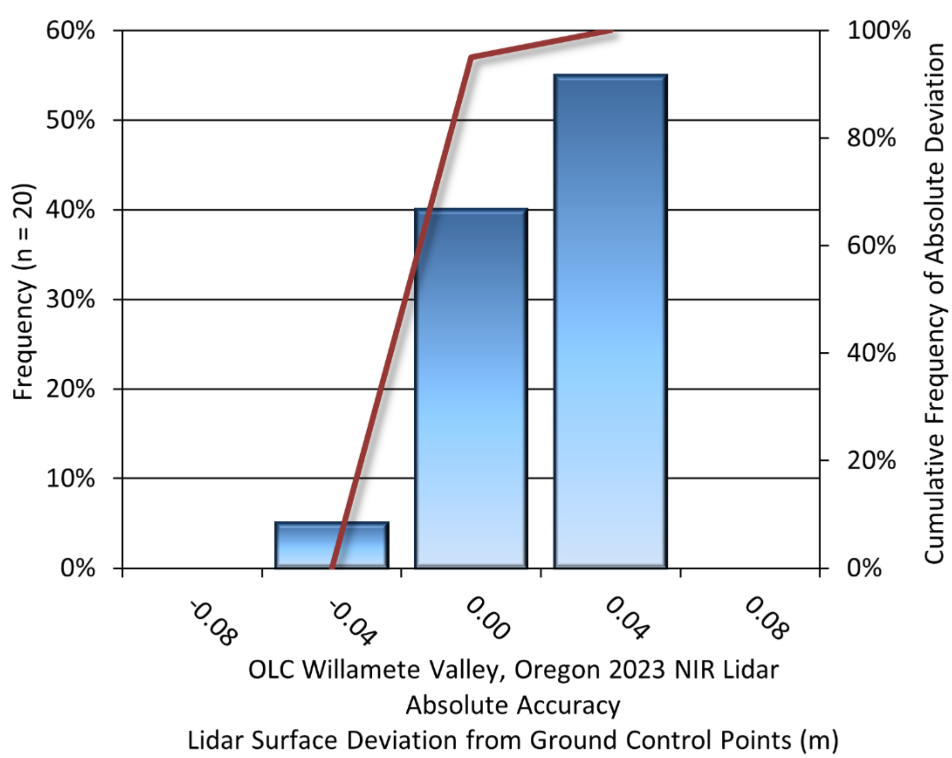


Figure 9: Frequency histogram for the lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracy

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 OLC Willamette Valley survey, 38 vegetated checkpoints were collected, with resulting vegetated vertical accuracy of 0.849 feet (0.259 meters) as compared to the classified LAS, and 1.038 feet (0.316 meters) as compared to the bare earth DEM evaluated at the 95th percentile (Table 13, Figure 10, and Figure 11).

Table 13: Vegetated vertical accuracy results

Parameter	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
Sample	38 points	38 points
95th Percentile	0.849 ft 0.259 m	1.038 ft 0.316 m
Average	0.248 ft 0.075 m	0.241 ft 0.073 m
Median	0.187 ft 0.057 m	0.131 ft 0.040 m
RMSE	0.412 ft 0.126 m	0.438 ft 0.133 m
Standard Deviation (1σ)	0.334 ft 0.102 m	0.370 ft 0.113 m

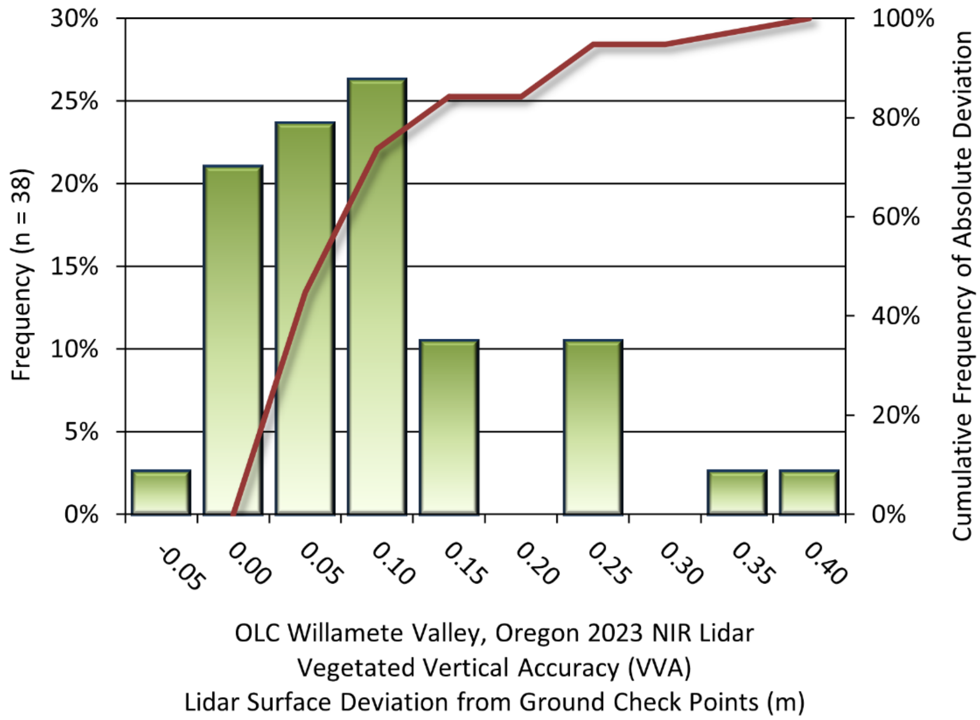


Figure 10: Frequency histogram for the lidar surface deviation from all land cover class point values (VVA)

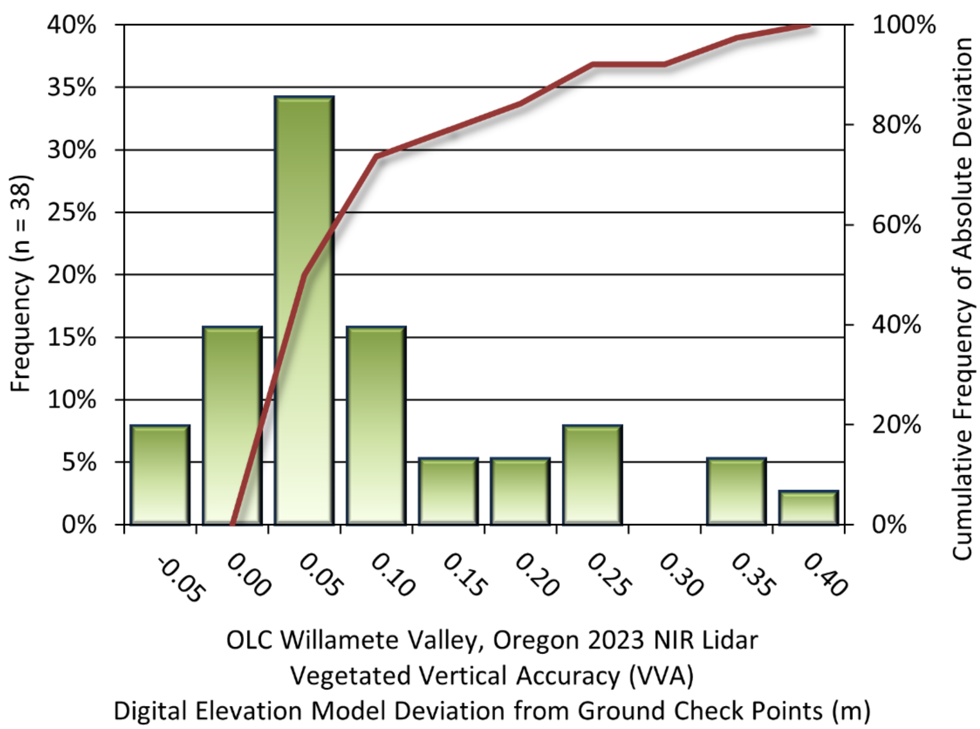


Figure 11: Frequency histogram for the lidar bare earth DEM deviation from vegetated check point values (VVA)

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 OLC Willamette Valley Lidar project was 0.064 feet (0.020 meters) (Table 14, Figure 12).

Table 14: Relative accuracy results

Parameter	Relative Accuracy
Sample	60 surfaces
Average	0.064 ft 0.020 m
Median	0.063 ft 0.019 m
RMSE	0.065 ft 0.020 m
Standard Deviation (1σ)	0.007 ft 0.002 m
1.96σ	0.014 ft 0.004 m

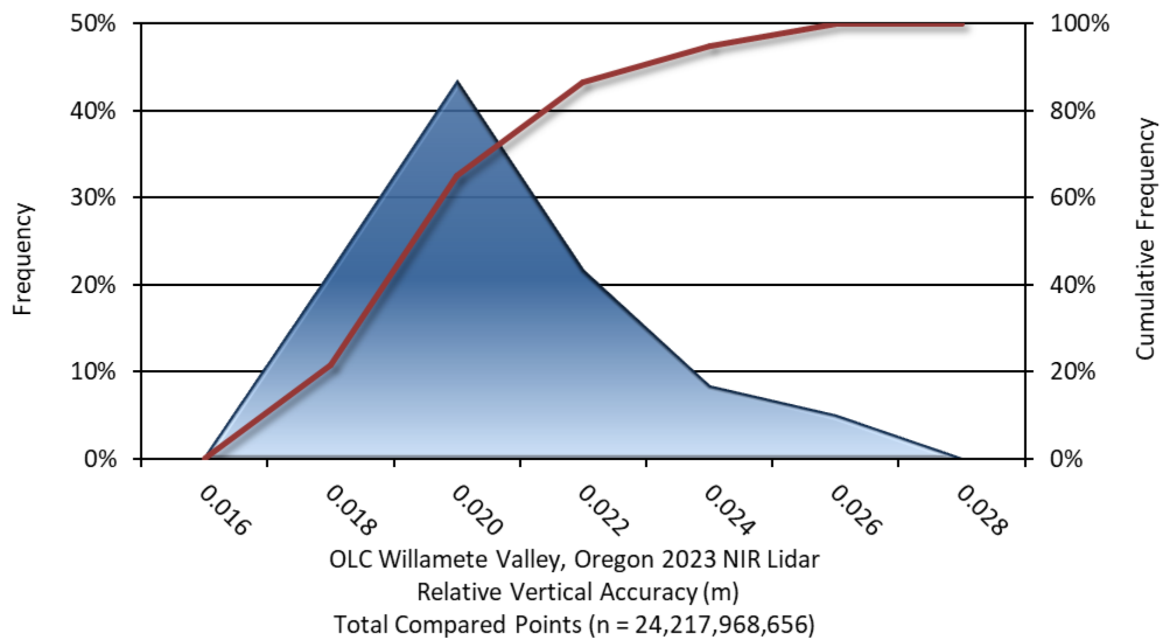


Figure 12: Frequency plot for relative vertical accuracy between flight lines

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 2,532 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.023 meters, this project was produced to meet 0.907 feet (0.277 meters) horizontal accuracy at the 95% confidence level (Table 15).

Table 15: Horizontal accuracy

Parameter	Horizontal Accuracy
$RMSE_r$	0.520 ft 0.160 m
ACC_r	0.907 ft 0.277 m

Certifications

NV5 Geospatial provided lidar services for the OLC Willamette Valley project as described in this report.

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

John English (Dec 7, 2023 08:11 PST) Dec 7, 2023

John English
Project Manager
NV5 Geospatial

I, Evon P. Silvia, PLS, being duly registered as a Professional Land Surveyor in and by the state of Oregon 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 July 21-22, 2023 for the airborne survey and on June 23 to July 31, 2023 for the ground survey.

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”.

Evon P. Silvia Dec 6, 2023

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

REGISTERED
PROFESSIONAL
LAND SURVEYOR
Evon P. Silvia
OREGON
JUNE 10, 2014
EVON P. SILVIA
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EXPIRES: 06/30/2024

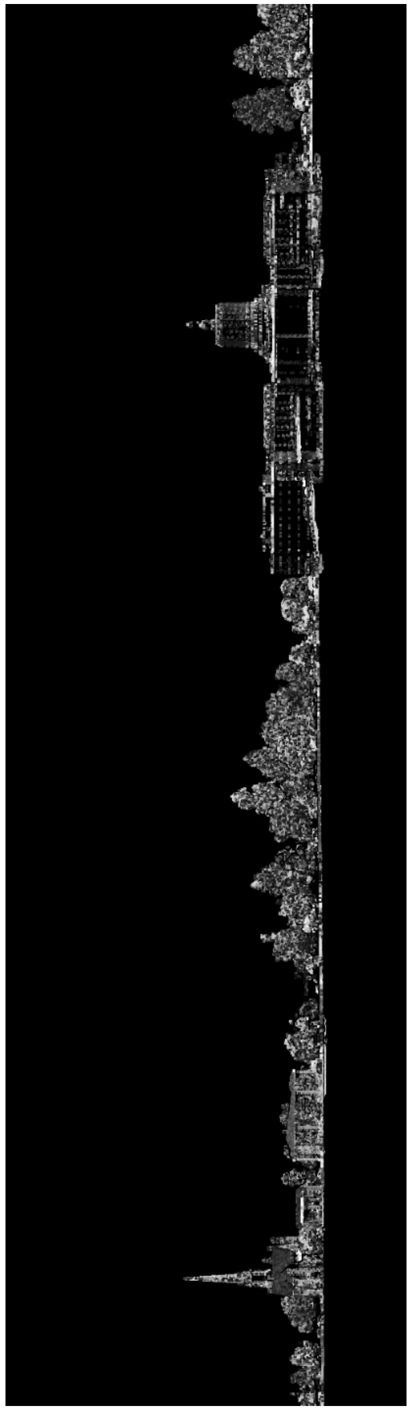

Figure 13: Lidar point cloud cross section of State Street in Salem, Oregon, points by intensity values

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.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the dataset, 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.

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:

Source	Type	Post Processing Solution
Long Base Lines	GPS	None
Poor Satellite Constellation	GPS	None
Poor Antenna Visibility	GPS	Reduce Visibility Mask
Poor System Calibration	System	Recalibrate IMU and sensor offsets/settings
Inaccurate System	System	None
Poor Laser Timing	Laser Noise	None
Poor Laser Reception	Laser Noise	None
Poor Laser Power	Laser Noise	None
Irregular Laser Shape	Laser Noise	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.

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.

OLC_WillametteValley_NIR_Lidar_Report_Final

Final Audit Report 2023-12-07

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