August 21, 2020

Blue Pool, Oregon Lidar & Orthoimagery Technical Data Report

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Cover Photo: A view taken within the Blue Pool, Oregon Lidar & Orthoimagery project area.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the Blue Pool, Oregon site.

In December 2019, Quantum Spatial (QSI) was contracted by the State of Oregon's Department of Administrative Services (DAS) on behalf of Oregon State Parks and the Oregon Department of Transportation to collect Light Detection and Ranging (lidar) data and digital imagery in the spring of 2020 for the Blue Pool Lidar & Imagery site in Oregon. Data were collected to aid DAS in assessing the topographic and geophysical properties of the study area to support various Department of Transportation needs, including road engineering.

This report accompanies the delivered lidar data and imagery, 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 DAS 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 Blue Pool, Oregon site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Blue Pool, Oregon	80,640	82,328	06/18/2020-06/19/2020	NIR - Lidar
			6/23/2020	4 band (RGB-NIR) Digital Imagery

Deliverable Products

Table 2: Products delivered to DAS for the Blue Pool, Oregon site

Blue Pool Lidar & Imagery Products	
Oregon Statewide Lambert Conformal Conic **Horizontal Datum: NAD83 (2011)** **Vertical Datum: NAVD88 (GEOID12B)** **Units: International Feet**	**OCRS Cottage Grove-Canyonville** **Horizontal Datum: NAD83 (2011)** **Vertical Datum: NAVD88 (Geoid12B)** **Units: International Feet**
Points	LAS v 1.2 • All Classified Returns LAS v 1.4 • All Classified Returns
Rasters	3.0 Foot GeoTiffs, Delineated in USGS 7.5 Quads • Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM) 1.5 Foot GeoTiffs, Delineated in USGS 1/100th 7.5 Quad • Intensity Images
Vectors	Shapefiles (*.shp) • Area of Interest • Lidar Tile Index • Ground Survey Data • Smoothed Best Estimate Trajectory (SBETs)
Digital Imagery	Imagery Support Files • 0.5 Foot Tiff Frames • Camera Exterior Orientations • Camera Calibration Report

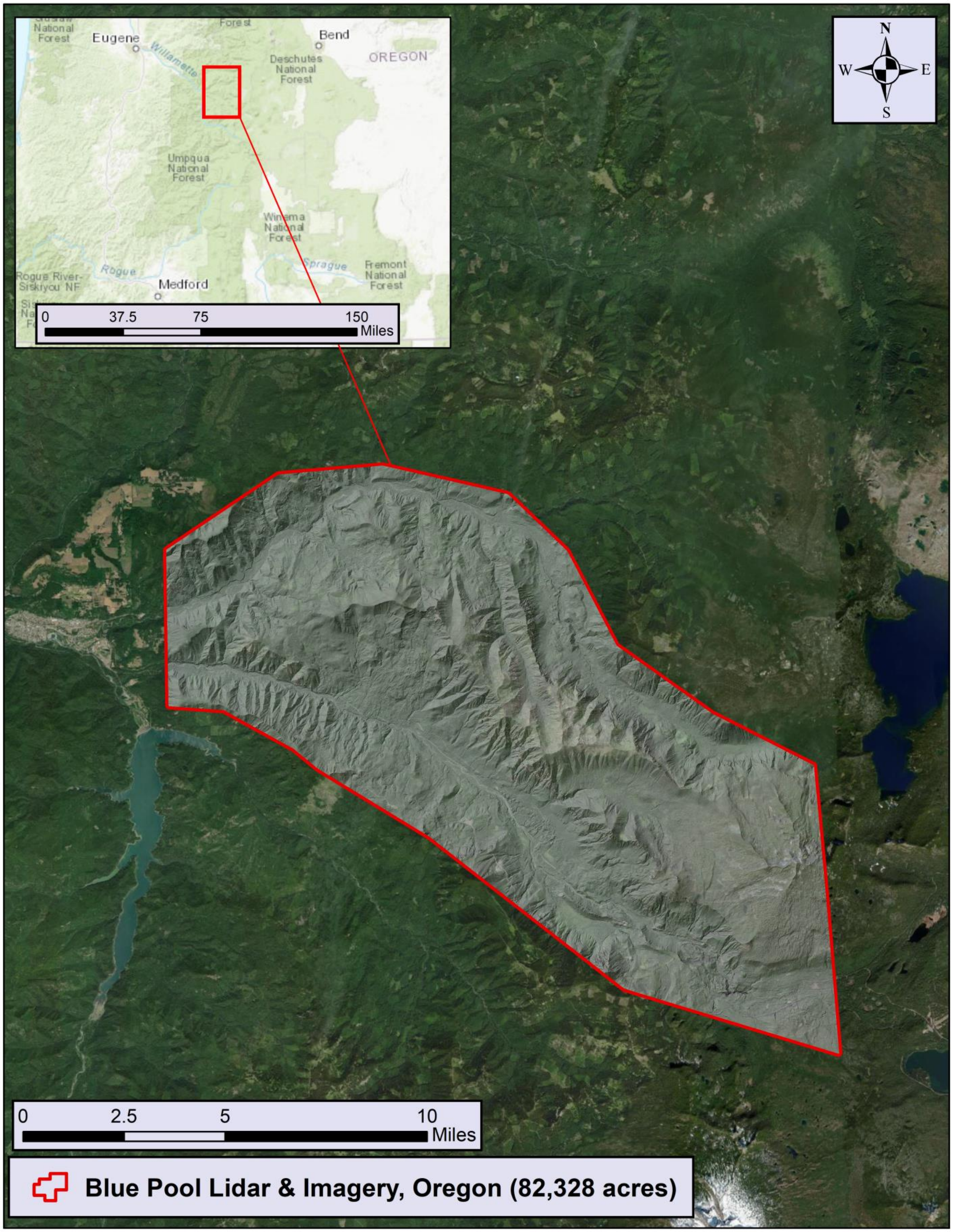
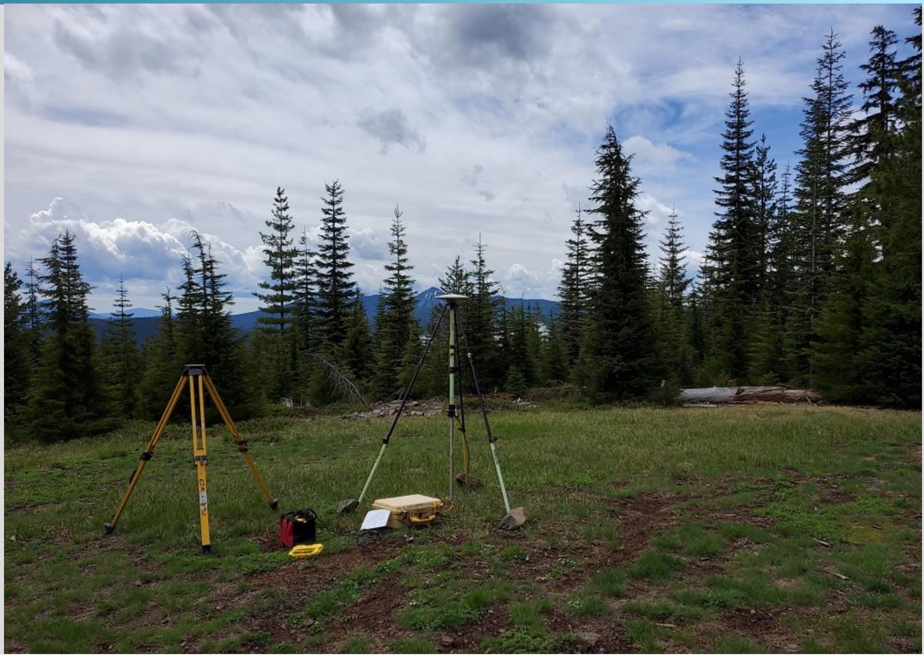


Figure 1: Location map of the Blue Pool, Oregon site

ACQUISITION



QSI's ground acquisition equipment set up in the Blue Pool, Oregon study area.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Blue Pool, Oregon study area at the target point density of ≥ 20.0 points/m^2 (1.85 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 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.

Airborne Survey

Lidar

The lidar survey was accomplished using a Riegl VQ 1560ii system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥20 pulses/m^2 over the Blue Pool, Oregon project area. The Riegl laser system can record unlimited range measurements (returns) per pulse, although only up to 15 pulses can be stored due to restraints of the LAS v1.4 format. 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	June 18 - 19, 2020
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ 1560ii
Maximum Returns	15
Resolution/Density	20 pulses/m^2
Nominal Pulse Spacing	0.22 m
Survey Altitude (AGL)	1670 m
Survey speed	105 knots
Field of View	58.5^o
Mirror Scan Rate	128 lines per second per scanner
Target Pulse Rate	882 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	935 m
Swath Overlap	55 %
Intensity	16-bit
Vertical Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
Horizontal Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 30 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.

Digital Imagery

The aerial imagery was collected by Geoterra Inc. using an UltraCam Falcon camera. The UltraCam Falcon is a large format digital aerial camera manufactured by Vexcel Corporation, camera specifications can be found in (Table 4). The system is gyro-stabilized and simultaneously collects panchromatic and multispectral (RGB, NIR) imagery.

Table 4: Camera manufacturer's specifications

UltraCam Falcon	
Focal Length	100.5 mm
Data Format	RGB NIR
Pixel Size	6.0 µm
Image Size	17,310 x 11,310 pixels
Frame Rate	2.0 seconds
FOV	55° x 37°

For the Blue Pool, Oregon site, 2,345 images were collected in four spectral bands (red, green, blue, and NIR) with 80% along track overlap and 60% sidelap between frames. The acquisition flight parameters were designed to resolve a ground sampling distance (GSD) of ≤ 0.5 ft. Orthophoto specifications particular to the Blue Pool, Oregon project are in Table 5.

Table 5: Project-specific orthophoto specifications

Digital Orthophotography Specifications	
Equipment	UltraCam Falcon
Spectral Bands	Red, Green, Blue, NIR
Ground Sampling Distance (GSD)	≤0.5 ft
Along Track Overlap	≥80%
Cross Track Overlap	≥60%
Flight Altitude (MSL)	2,200 meters
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Image	8-bit GeoTiff

Ground Survey

Ground control surveys, including monumentation, aerial targets 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 and orthoimagery products.

Base Stations

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

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized nine existing base stations for the Blue Pool, Oregon project (Table 6, Figure 2). Base stations were set with a 9" MAG spike marked with orange flagging. QSI's professional land surveyor, Evon Silvia (ORPLS#81104) oversaw and certified the establishment of all monuments.

Table 6: Monument positions for the Blue Pool, Oregon acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
BLUEPOOL_RTK_01	43° 37' 45.22425"	-122° 04' 51.26263"	1679.789
BLUEPOOL_RTK_02	43° 40' 16.13721"	-122° 07' 55.71831"	1757.35
BLUEPOOL_RTK_03	43° 45' 34.86597"	-122° 21' 05.19717"	935.018
BLUEPOOL_RTK_04	43° 49' 17.24301"	-122° 14' 15.18592"	1554.877
BLUEPOOL_RTK_05	43° 38' 55.41182"	-122° 13' 14.30864"	852.125
BLUEPOOL_RTK_06	43° 40' 27.30629"	-122° 15' 51.97857"	871.47
BLUEPOOL_RTK_07	43° 43' 57.48323"	-122° 09' 10.88494"	1629.344
BLUEPOOL_RTK_08	43° 41' 32.46789"	-122° 20' 03.48166"	1379.544
OROR	43° 44' 46.95598"	-122° 29' 06.90928"	327.703

QSI 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.

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

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 7.

Table 7: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.050 m

For the Blue Pool, Oregon project, the monument coordinates contributed no more than 5.6 cm of positional error to the geolocation of the final ground survey points and lidar, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), post-processed kinematic (PPK), and fast-static (FS) 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. PPK and FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK and PPK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See for Trimble unit specifications.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

Table 8: QSI ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R8.2	Integrated Antenna	TRM_R8_GNSS	Rover

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[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

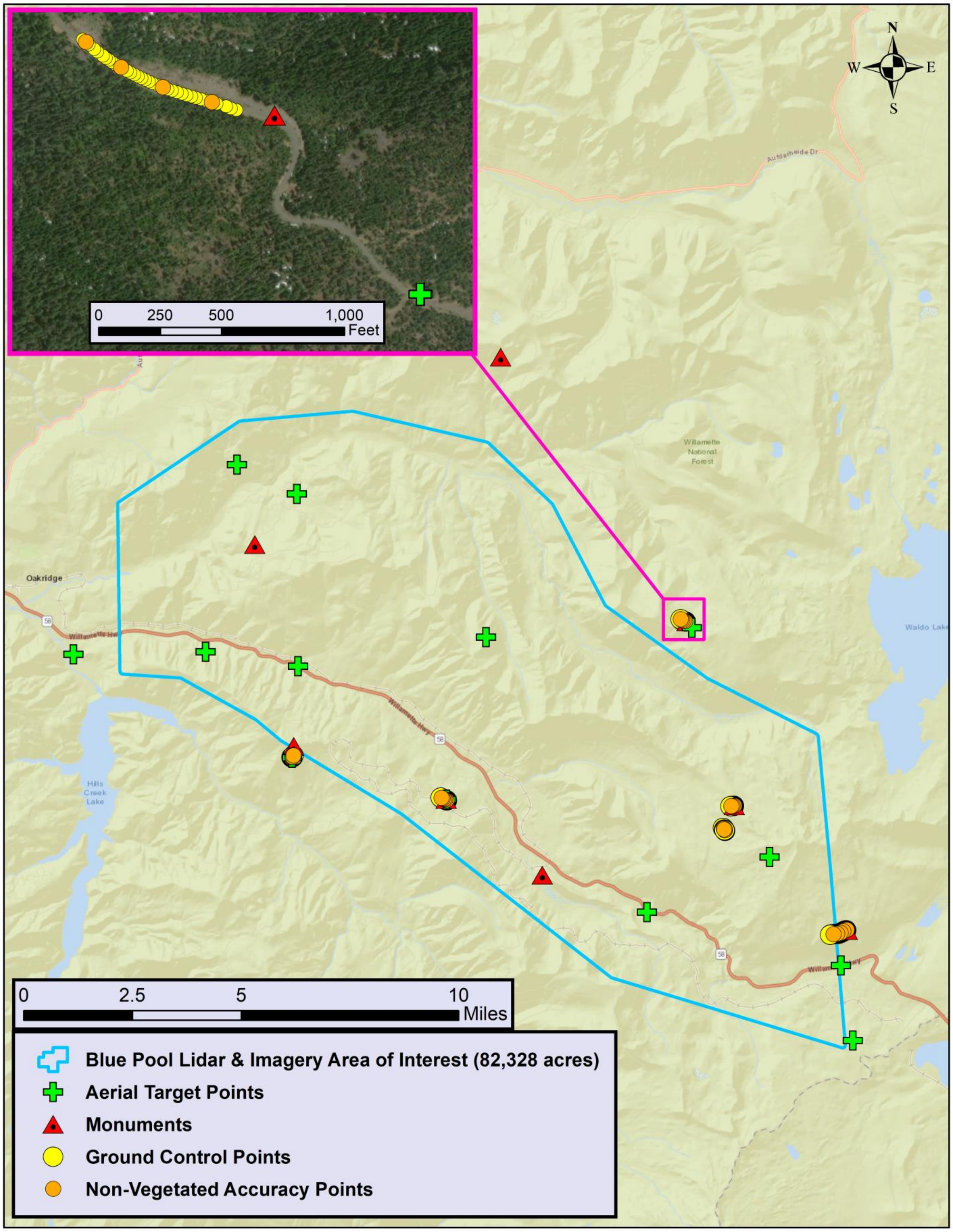


Figure 2: Ground Survey Location Map

Aerial Targets

Aerial targets in the form of white chevron panels were placed throughout the project area prior to imagery acquisition. Each target was secured with surveyor's nails and surveyed using RTK or Fast-Static techniques; targets are typically located within four to ten miles of monumentation.

Aerial Target acquisition equipment set up in the Blue Pool Lidar & Imagery project area.

PROCESSING


This 2 meter lidar cross section shows a view of the Blue Pool Lidar & Imagery AOI landscape, colored by point classification.

Lidar Data

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

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7	Noise	Laser returns that are often associated with birds or scattering from reflective surfaces or artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms

Table 10: Lidar processing workflow

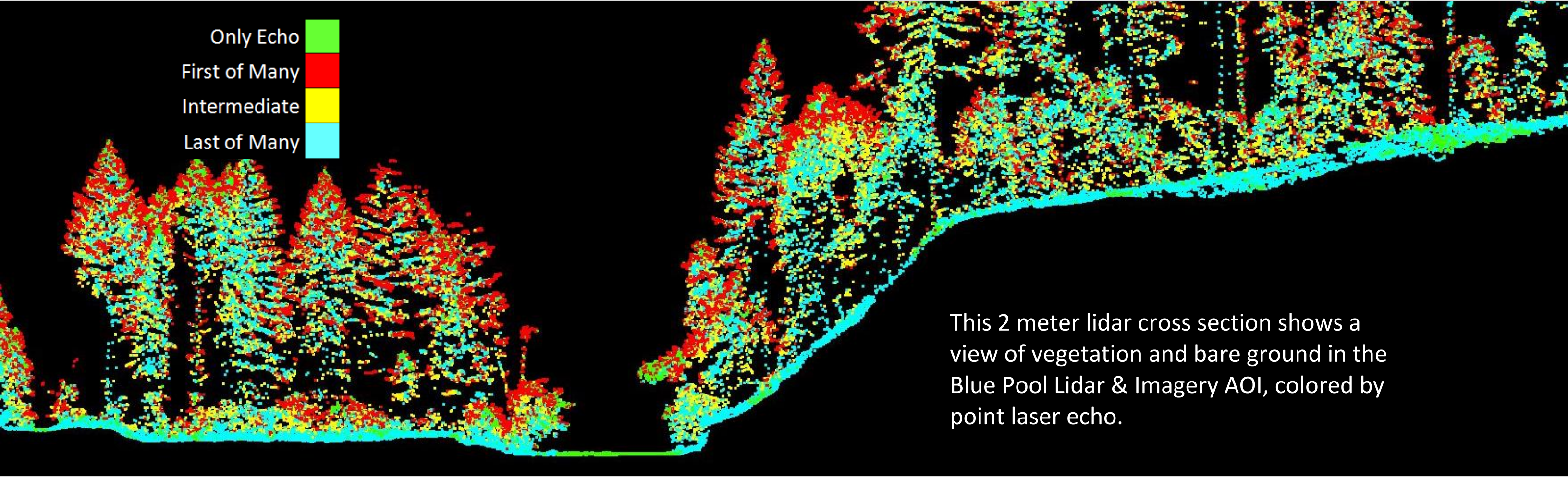
Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.3
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.	RiProcess v.1.8.5
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
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
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 TerraModeler v.19 Las Monkey 2.5.0 (QSI Proprietary)
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as GeoTIFF format at a 1.0 meter (3.0 ft) pixel resolution.	LAS Product Creator 3.4 (QSI proprietary)
Correct intensity values for variability and export intensity images as GeoTIFFs at a 0.5 meter (1.5 foot) pixel resolution.	LAS Product Creator 3.4 (QSI proprietary)

Digital Imagery

Aerial imagery products are provided to ODOT for further photogrammetric processing; pre-processing steps are summarized in Table 11. Initially, images were corrected for geometric distortion to yield level02 image files. Next, images were color balanced and levels were adjusted to exploit the full 14bit histogram and finally output as level03 pan-sharpened 16bit TIFF images. Camera position and orientation were calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET).

Table 11: Orthophoto processing workflow

Orthophoto Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft position data using kinematic aircraft GPS (collected at 2 Hz), onboard IMU (collected at 200 Hz) and local CORS network (performed by Geoterra, Inc.)	Inertial Explorer v8.90
Develop a smooth best estimate trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey (performed by Geoterra, Inc.).	Inertial Explorer v8.90
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa (performed by Geoterra, Inc.).	Inertial Explorer v8.90
Convert Level 00 raw imagery data into geometrically corrected Level 02 image (performed by Geoterra, Inc.).	UltraMap v4
Apply radiometric adjustments to Level 02 image files to create Level 03 Pan-sharpened TIFFs (performed by Geoterra, Inc.).	UltraMap v4



This 2 meter lidar cross section shows a view of vegetation and bare ground in the Blue Pool Lidar & Imagery AOI, colored by point laser echo.

Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 20 points/m^2 (1.85 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 Blue Pool, Oregon project was 121.67 points/m^2 (11.30 points/ft^2) while the average ground classified density was 3.05 points/m^2 (0.28 points/ft^2). 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 3 through Figure 6.

Table 12: Average Lidar point densities

Classification	Point Density
First-Return	11.30 points/ft^2 121.67 points/m^2
Ground Classified	0.28 points/ft^2 3.05 points/m^2

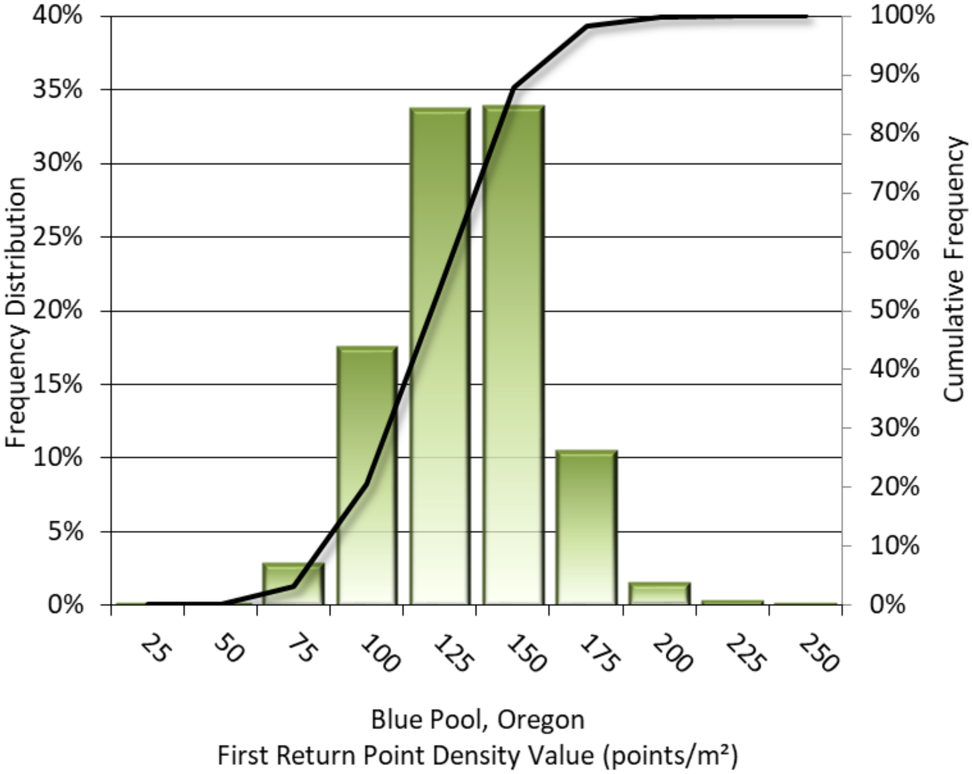


Figure 3: Frequency distribution of first return point density values per 100 x 100 m cell

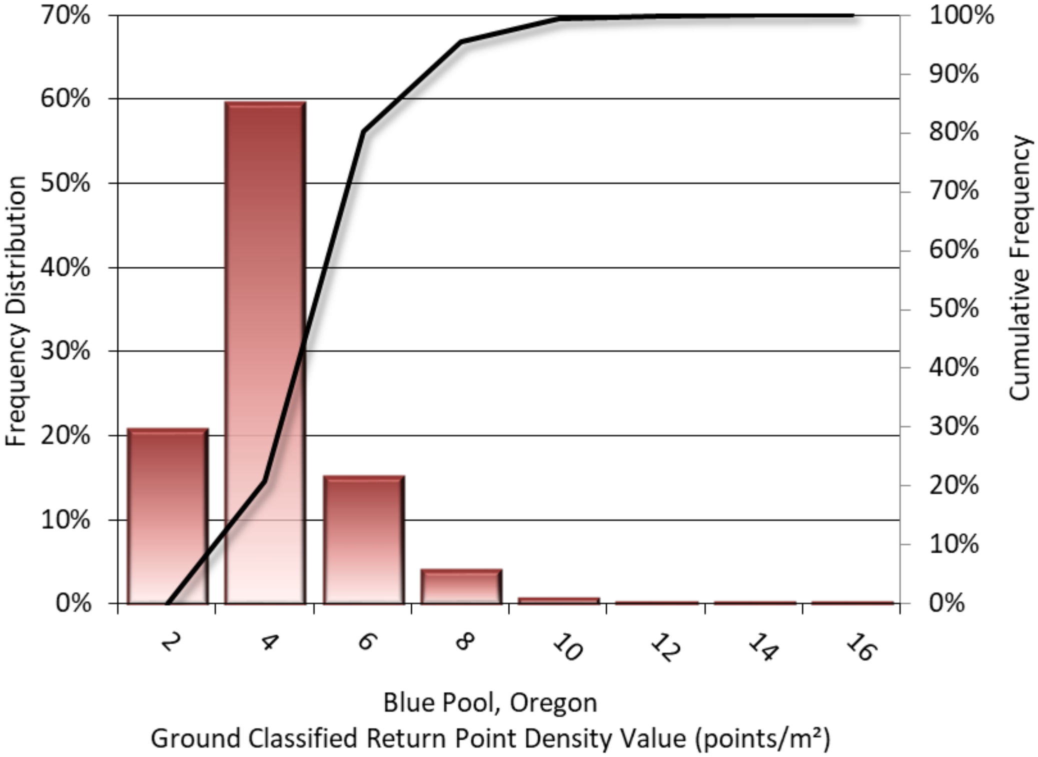


Figure 4: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

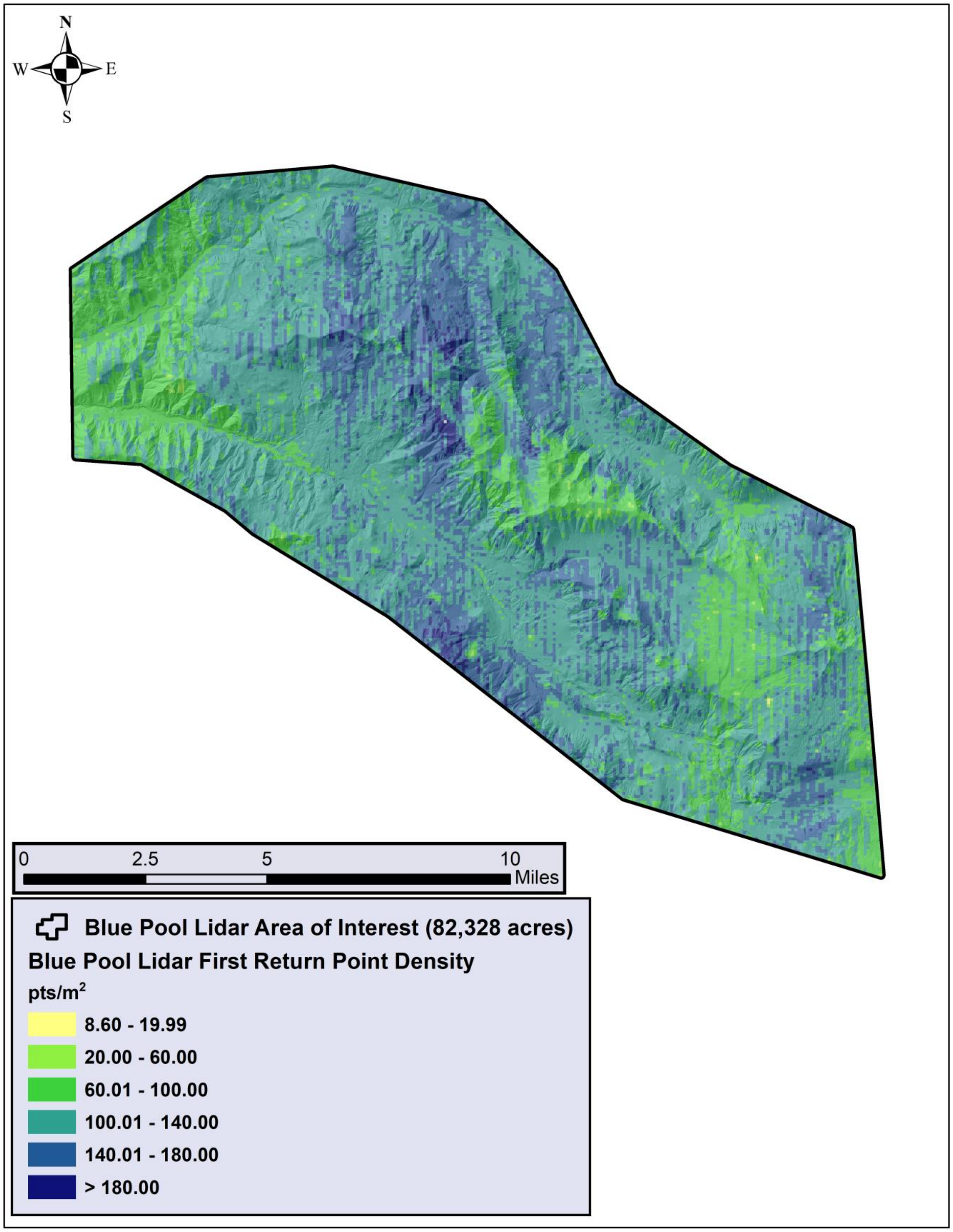


Figure 5: First return point density map for the Blue Pool, Oregon site (100 m x 100 m cells)

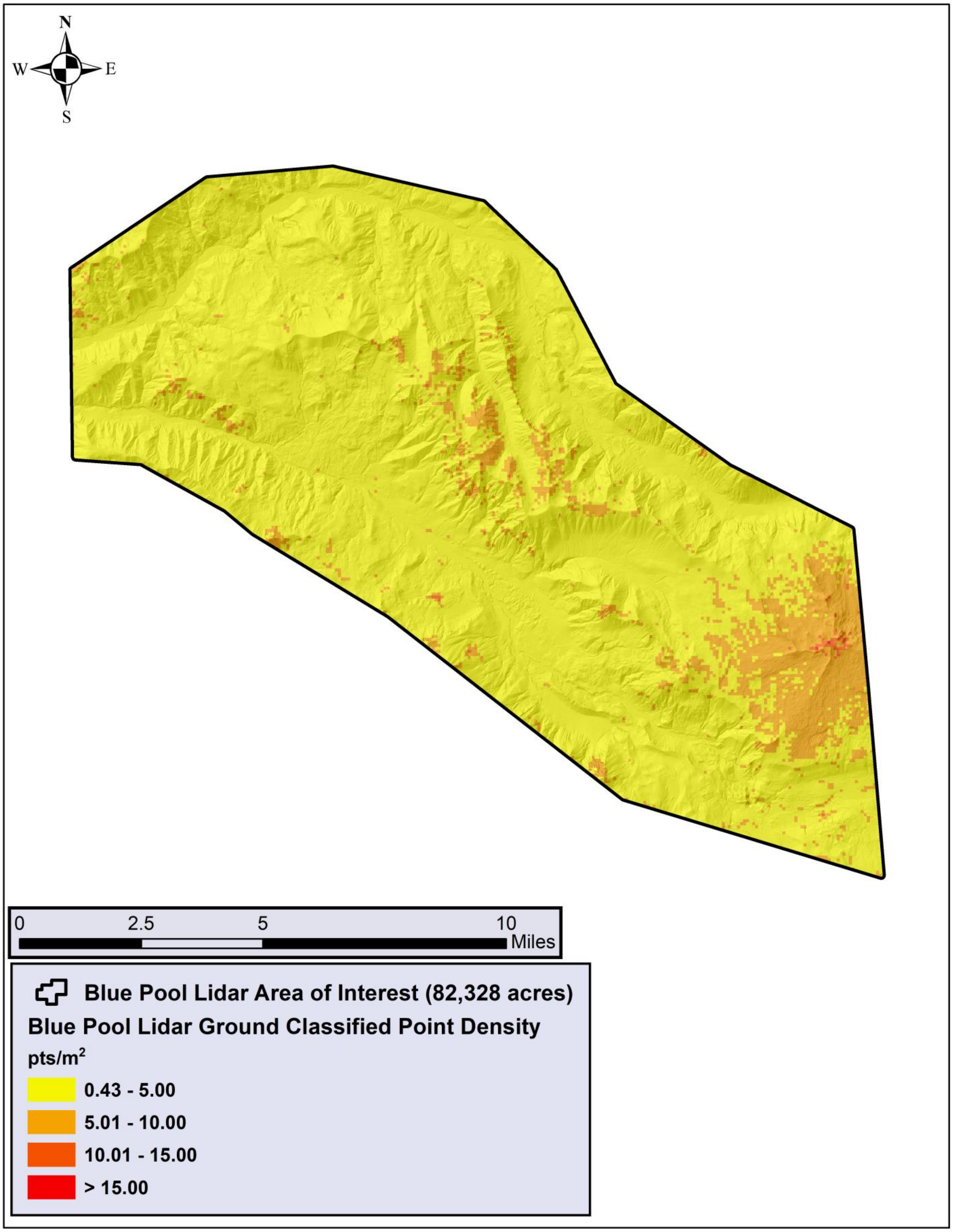


Figure 6: Ground point density map for the Blue Pool, Oregon site (100 m x 100 m cells)

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 unclassified 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 13.

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 Blue Pool, Oregon survey, 24 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.147 feet (0.045 meters) as compared to unclassified LAS, and 0.181 feet (0.055 meters) as compared to the bare earth DEM, with 95% confidence (Figure 7, Figure 8).

QSI also assessed absolute accuracy using 208 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 13 and Figure 9.

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[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 13: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	**NVA, as compared to bare earth DEM**	**Ground Control Points**
Sample	24 points	24 points	208 points
95% Confidence (1.96*RMSE)	0.147 ft 0.045 m	0.181 ft 0.055 m	0.123 ft 0.038 m
Average	0.059 ft 0.018 m	-0.068 ft -0.021 m	-0.001 ft 0.000 m
Median	0.066 ft 0.020 m	-0.059 ft -0.018 m	0.000 ft 0.000m
RMSE	0.075 ft 0.023 m	0.092 ft 0.028 m	0.063 ft 0.019 m
Standard Deviation (1σ)	0.047 ft 0.014 m	0.064 ft 0.020 m	0.063 ft 0.019 m

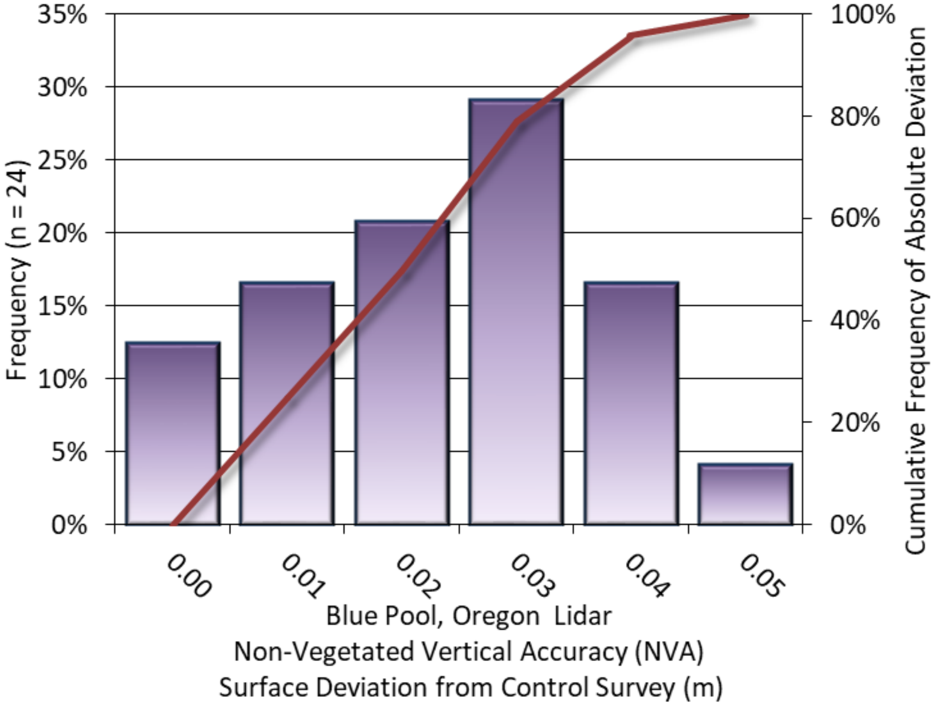

Figure 7: Frequency histogram for lidar unclassified LAS deviation from ground check point values (NVA)

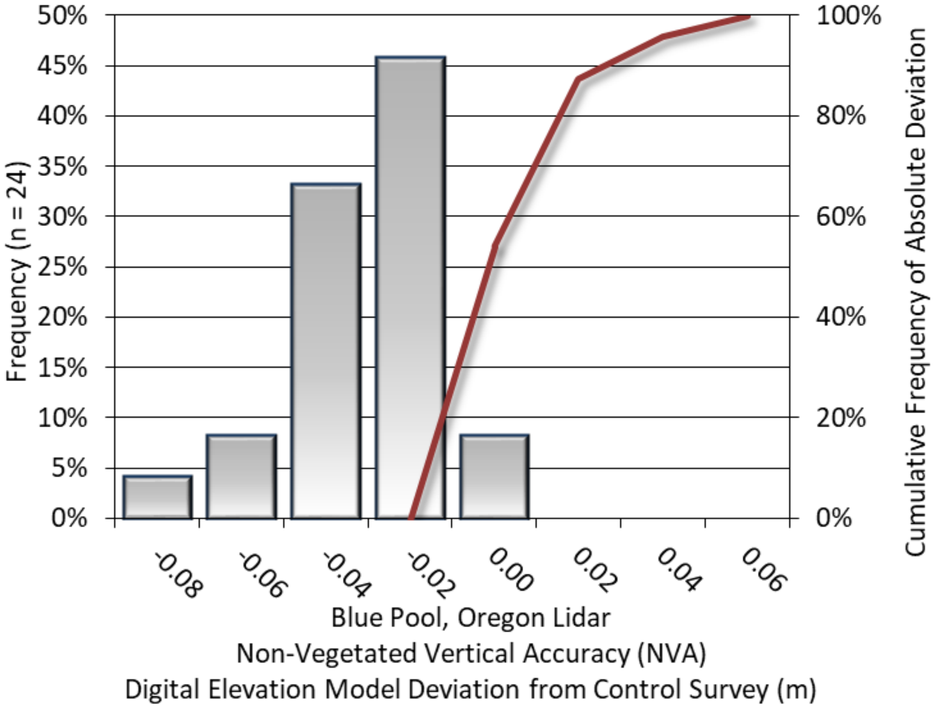

Figure 8: Frequency histogram for lidar bare earth DEM surface deviation from ground check point values (NVA)

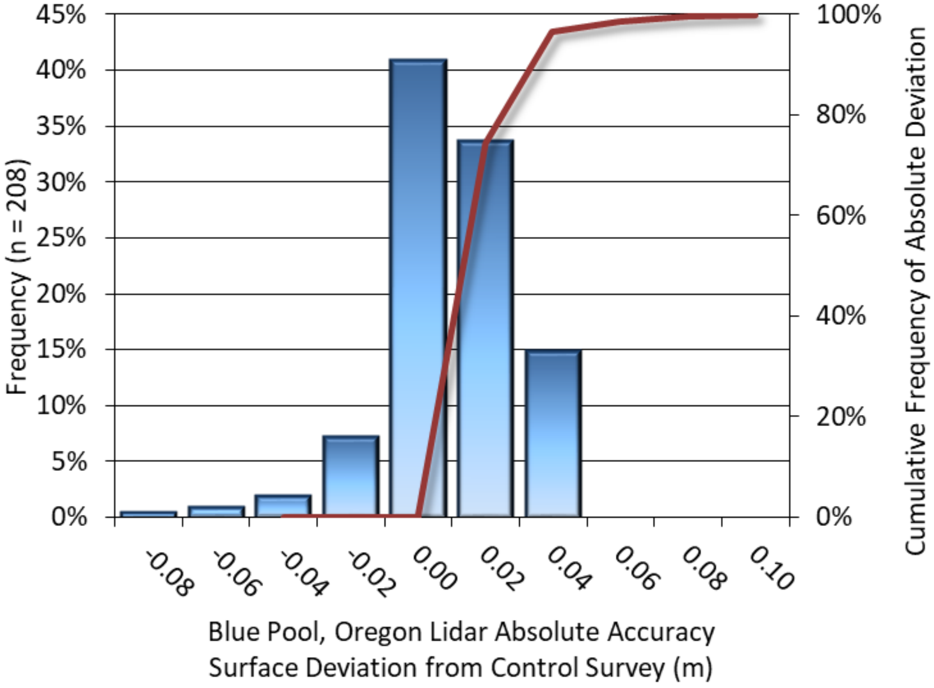

Figure 9: Frequency histogram for lidar surface deviation from ground control point values

Lidar Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Blue Pool, Oregon lidar project was 0.072 feet (0.022 meters) (Table 14, Figure 10).

Table 14: Relative accuracy results

Relative Accuracy	
Sample	79 surfaces
Average	0.072 ft 0.022 m
Median	0.075 ft 0.023 m
RMSE	0.074 ft 0.023 m
Standard Deviation (1σ)	0.009 ft 0.003 m
1.96σ	0.017 ft 0.005 m

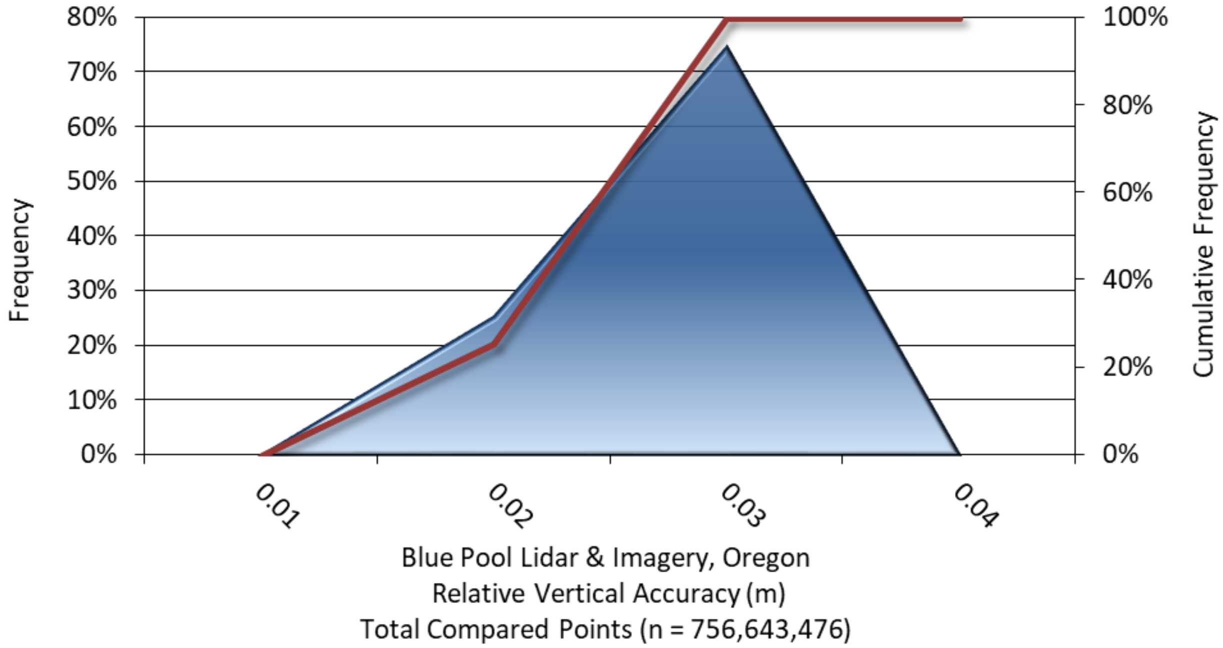

Figure 10: Frequency plot for relative vertical accuracy between flight lines

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 1670 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, this project was compiled to meet 0.60 feet (0.18 m) horizontal accuracy at the 95% confidence level.

Table 15: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.350 ft 0.105 m
ACC_r	0.60 ft 0.18 m

CERTIFICATIONS

Quantum Spatial, Inc. provided lidar services for the Blue Pool, Oregon 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 T. English Aug 21, 2020

John English
Project Manager
Quantum Spatial, Inc.

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 between June 18 and 19, 2020.

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".

REGISTERED
PROFESSIONAL
LAND SURVEYOR
Evon P. Silvia
OREGON
JUNE 10, 2014
EVON P. SILVIA
81104LS
EXPIRES: 06/30/2022

Evon P. Silvia Aug 21, 2020

Evon P. Silvia, PLS
Quantum Spatial, Inc.
Corvallis, OR 97330

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.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the lidar system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the lidar points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Data Density: A common measure of lidar resolution, measured as points per square meter.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Overlap: The area shared between flight lines, typically measured in percent. 100% overlap is essential to ensure complete coverage and reduce laser shadows.

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

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

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

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

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

APPENDIX A - ACCURACY CONTROLS

Relative Accuracy Calibration Methodology:

Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

lidar accuracy error sources and solutions:

Type of Error	Source	Post Processing Solution
GPS (Static/Kinematic)	Long Base Lines	None
	Poor Satellite Constellation	None
	Poor Antenna Visibility	Reduce Visibility Mask
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings
	Inaccurate System	None
Laser Noise	Poor Laser Timing	None
	Poor Laser Reception	None
	Poor Laser Power	None
	Irregular Laser Shape	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th AGL flight altitude).

Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return (i.e., intensity) is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±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.